Research and Innovation perspective of the mid - and long-term Potential for Advanced Biofuels in Europe

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Abstract

Research and Innovation (R&I) plays a central role in developing advanced biofuels technologies to help achieve the EU's climate and energy targets. This study examines the R&I potential for feedstock production, advanced biofuels production, and use of advanced biofuels. The study quantifies R&I potential under future scenarios where EU targets are met. Improving feedstock supply and reducing conversion costs through research and innovation resulting in an increase of feedstock availability by 40-50 %, will contribute to the development of advanced biofuels. With successful R&I and attainment of the 2050 EU targets, advanced biofuels could achieve (i) close to a 50 % share of the overall transport sector energy mix, (ii) achieving 330 Mt of net emission savings, in case they replace fossil fuels, or 65 % of the required emission savings needed, compared to 1990 levels, in order to meet the target of the transport sectors emissions by 60 %[1], (iii) a market volume of 1.6 % of EU's GDP, and (iv) significantly improve energy security. This would result in a net increase of 108 000 jobs, even taking into account the 11 000 jobs reduction in fossil fuel sectors and the reduced employment in other sectors, without impacting negatively EU's GDP. This is a particularly noteworthy positive impact, considering that it mainly comes from the substitution of currently existing energy demands.

In the extreme case of a transition to an energy system relying heavily on advanced biofuels, achieving EU targets would put considerable pressure on feedstock availability, driving up feedstock prices. Yet, in a system characterized by a balanced energy mix with several renewable options and an important role for advanced biofuels, R&I plays a paramount role in both (i) safeguarding the amount of affordable sustainable biomass and (ii) improving the efficiency of the whole biomass to biofuel process chain, needed for the transition to a bioenergy system. The transition could take more than 15-20 years and require substantial efforts and extensive coordination between stakeholders.

1 As set in the White Paper for transport in 2011.

Executive Summary

I. Context and Objectives of the Study

The EU has agreed ambitious climate change and energy objectives and targets for the period 2020 to 2030. These targets are designed to put the EU on the path towards a low carbon economy by 2050.[2] The EU transport sector, which accounts for nearly a quarter of EU's greenhouse gas emissions, will be crucial to achieving the EU's goals. In this, research and innovation (R&I) to develop breakthrough technologies for a more sustainable transport fuel mix has a central role to play. Technologies for the production of advanced biofuels is one such area that is especially interesting in those transport sectors where electrification and other renewable alternatives are not viable.

Biofuels cover a multitude of product types that are subject to an assortment of classifications, ranging from 'first', 'second', 'third', or 'next generation' biofuels, to 'sustainable', 'renewable' and 'advanced' biofuels. These classifications reflect ongoing discussion on the social and environmental impacts of biofuel production. The production of biofuels from food crops and the resulting competition of biofuels production with food production is one controversial issue. Another is indirect land use change (ILUC), addressed in current EU regulation[3]. Regarding the three sustainability dimensions for biofuels, i.e. social, economic and environmental, and given advances in technology, advanced biofuels seem to be the way forward. We discuss the sustainability of advanced biofuels in more detail under section 1.4.

This study aims to examine the future potential role of R&I for advanced biofuels. The study is organised in three main tasks: **Task 1** assesses the potential for R&I to enable secure, low-cost, and low ILUC biomass feedstock for energy for the 2030 and 2050 time-horizons; **Task 2** addresses the potential contribution of advanced biofuels to achieving the EU's ambitious climate change objectives; and finally, **Task 3** compares advanced biofuels with alternative fuel options for the road, maritime, and aviation transport sectors.

The study uses a broadly accepted definition of advanced biofuels based on the European Industrial Bioenergy Initiative (EIBI).[4] Thus, advanced biofuels are biofuels that **(1)** are produced from lignocellulosic feedstocks (i.e. agricultural and forestry residues), non-food crops (i.e. grasses, miscanthus, algae), or industrial waste and residue streams; **(2)** produce low CO_2 emissions or high GHG reductions; and **(3)** reach zero or low ILUC impact. Bio-CCU and CO_2 fuels are also considered as advanced biofuels, although these technologies have not been included in the quantitative part of the analysis as they are not part of the existing modelling suite and because it is difficult to predict the future potential contribution of CCU technologies to the advanced (bio)fuel market.

2 European Commission, see especially the 2020 climate and energy package, the 2030 climate and energy framework and the 2050 low-carbon economy roadmap.

3 In 2015 the Renewable Energy Directive and the Fuel Quality Directive came into force to limit the risk of ILUC and prepare a transition towards biofuels.

4 The definition can be found on http://www.biofuelstp.eu/advancedbiofuels.htm#whatare.

The R&I potential for sustainable, low ILUC biomass assessed in this study is defined as the absolute maximum amount of lignocellulosic biomass potentially available for energy use, while considering agreed **sustainability standards** for agriculture, forestry and land management. This definition is based on a biomass typology developed in the recent EU project S2Biom[5] (Panoutsou 2017). This potential considers agreed sustainability standards in Common Agricultural Policy (CAP) for agricultural farming practices[6] and land management and in agreed (national and regional) forest management and biomass harvesting guidelines for forests. It also includes the consideration of legal restrictions such as restrictions from management plans in protected areas and sustainability restrictions from current legislation. Further restrictions resulting from RED (Renewable Energy Directive) and CAP are considered as well. CAP sustainable agricultural farming practices include applying conservation of Soil Organic Carbon (e.g. Cross Compliance issues of 'maintaining agricultural land in good farming and management condition' and avoiding soil erosion). In order to avoid impacts related to indirect land use change (ILUC), the potential for dedicated energy crops has been defined assuming that they are only grown on fallow land or on land, which is released from agricultural production. Other areas in conflict with sustainability objectives have been excluded from the potential as well.[7] For the use of straw and prunings, carbon balance related sustainability limits have been adopted from Miterra model estimates.[8] All quantifications in this report are based on these sustainability criteria.

II. Methodology and Approach

To examine the potential effect of R&I for advanced biofuels, the study uses an integrated quantitative and qualitative methodological approach.

A range of different (qualitative) scientific tools, such as bibliometric analyses, literature reviews, and stakeholder consultations, have been employed. Bibliometric analyses support the assessment of the technological leadership of European and non-European countries with respect to R&I in feedstock production and biofuels conversion technologies. The literature reviews, which are integrated into multiple tasks, include a review of scientific literature and research on R&I options for improving feedstock production and conversion, the identification of major players in the area of R&I in feedstock production and conversion, and the assessment of different alternative fuel options for transport. Finally, stakeholder consultations are used throughout the project to validate findings and deepen insights. These include interviews and workshops with external stakeholders to discuss the scenarios and validate input data for the modelling exercises, together with a final workshop to validate the main modelling results and collect feedback on conclusions and recommendations.

The collected information is integrated into the quantitative approach through the updating of input assumptions. This concerns, for example, quantitative development of feedstock availability, technological maturity and maturation pathways, the efficiency, capex and open of conversion technologies, and development of alternative fuel options.

5 S2Biom, see: http://s2biom.alterra.wur.nl/web/guest/biomass-supply.

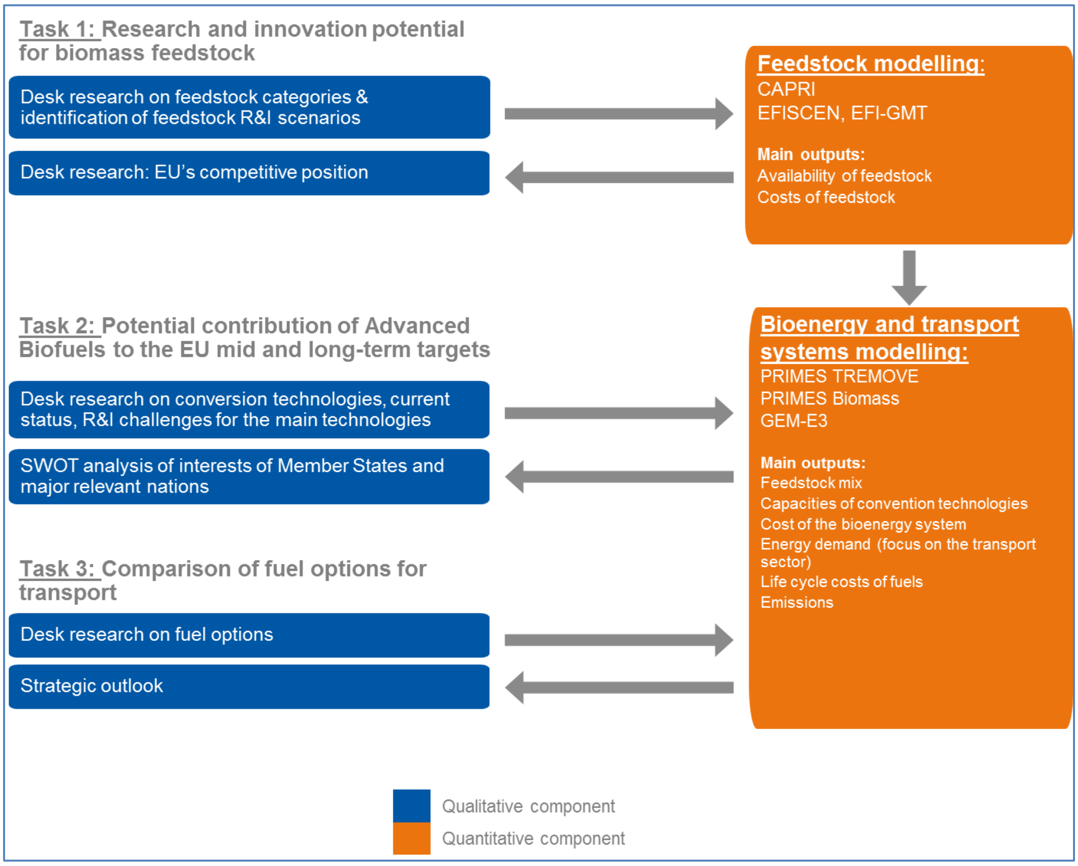
6 CAP sustainable agricultural farming practices include the conservation of Soil Organic Carbon (SOC), e.g. cross compliance issues of maintaining agricultural land in good farming and management conditions and avoiding soil erosion.

7 Natura 2000 areas, High Nature Value farmland, wetlands, peatlands, and permanent grassland areas.

8 Based on the Miterra model estimates; see S2Biom Deliverable 1.6 for more details.

The quantitative analysis uses several (interconnected) models implemented under different scenarios. The scenarios are a key element of the modelling approach, enabling the potential of different feedstock types, as well as the production and demand of advanced biofuels, to be assessed under assumptions of different R&I effort levels. Furthermore, they help illustrate how advanced biofuels are expected to compete with other alternatives under certain conditions. The next figure presents an overview of the followed approach in relation to the various tasks.

Figure 1 Followed approach: ***The figure shows the integrated qualitative and quantitative approach across the tasks***



Task 1, which aims to evaluate the availability and cost of biomass production, uses different feedstock models and extensive desk research to analyse the four main feedstock categories (i.e. feedstock from agriculture, forestry, waste, and aquatic biomass). The biomass potential of the agriculture and forestry sectors is assessed under four R&I scenarios using two specialised feedstock models. Whereas, the potential for aquatic and waste biomass is addressed through desk research.

The results from Task 1 provide information on the potential availability of feedstock and the development of feedstock prices under different R&I assumptions (feedstock scenarios). In turn, these results feed into a bioenergy and a transport modelling suite used in **Tasks 2 and 3** to quantitatively estimate prices and consumption of advanced biofuels under three different future scenarios. Further, under these scenarios, the feedstock types and conversion technologies used to meet consumption demand are identified, and the competition between biofuels and other fuel alternatives is investigated. The bioenergy scenarios, as outlined below, are constructed using three pillars, namely: biomass feedstock, conversion technologies, and demand for biofuels.

Scenario	Biomass feedstock	Conversion technologies	Demand for biofuels
BASE	Reference	Low learning rates for technologies at low Technology Readiness Levels (TRL's)	Low demand for biofuels
MEDIUM	High R&I case	High learning rates for all technologies	Moderate biofuels demand
HIGH	High R&I case	High learning rates for all technologies	High biofuels demand

Unlike the BASE scenario, the MEDIUM and HIGH scenarios are both designed to meet the EU's energy and climate objectives. This is a crucial point for interpretation of the results, as meeting the EU objectives forces the energy system to move towards low-carbon fuel options. Under each scenario, the biomass feedstock sectors and the biofuels markets operate to satisfy the demand for bioenergy in the most cost-effective way to help reach EU climate and energy targets.

III. Main Findings of the Study

Task 1: Research and Innovation Potential for Sustainable Biomass Feedstock

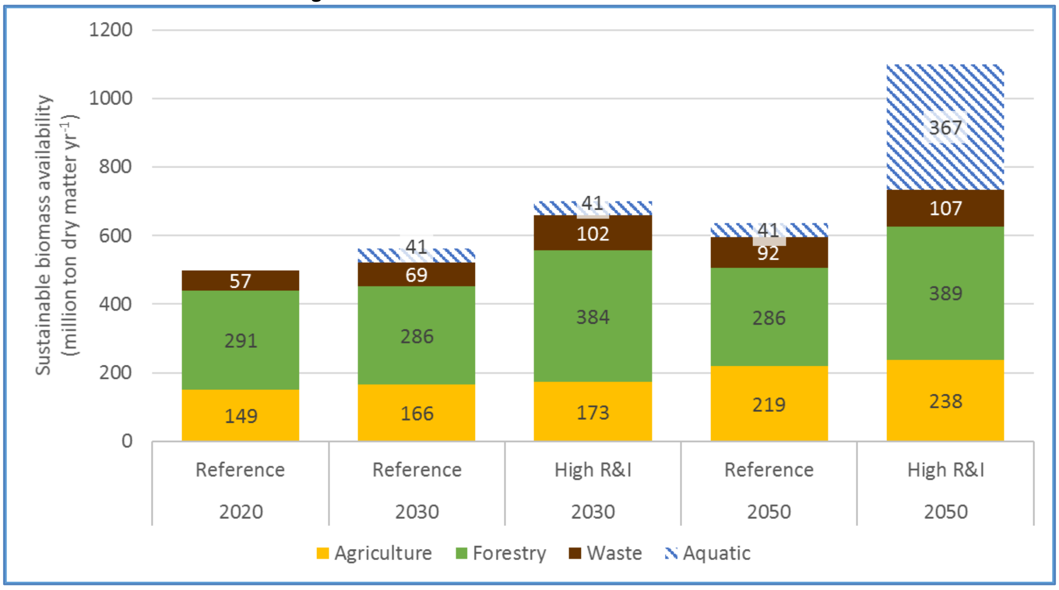
R&I measures can significantly increase the availability of sustainable biomass by 2050

Primary crop residues and cellulosic energy crops constitute the most relevant **agricultural** feedstock categories. The modelling projections indicate that agricultural biomass potential can increase by 21,4 % in 2030 and 59,8 % in 2050 in the BASE scenario, where R&I measures can result in an additional 4.5 % in 2030 and 8.6 % in 2050. This is rather moderate as sustainability considerations constrain the available area and assumptions are based on cautious projections of agricultural yields and residue availability. Although almost two-thirds of the agricultural feedstock potential in 2030 comes from agricultural residues, energy crops make up 55 % of the total potential by 2050. For the 2030 and 2050 time horizons, the most effective R&I measures are those targeting enhanced agricultural biomass production through breeding (e.g. greater plant robustness) and precision farming. The **forestry** sector is projected to remain the largest potential supplier of biomass. Measures to improve supply (e.g. harvesting technology and logistics) have a significant positive impact on the availability and costs of woody biomass until 2050; increasing potential availability by 27 % in 2050 compared to the BASE scenario. Due to long rotation cycles, measures to enhance production (e.g. use of more appropriate breeding materials – i.e. more productive varieties) are shown to be less effective, accounting for a potential increase of only 3 % until 2050. Organic solid municipal **waste** and non-hazardous post-consumer wood offer sizeable feedstock options that are available at very low costs, since collection and processing costs are covered by households and the private and public bodies responsible for disposing of their waste. While current production of **aquatic biomass** from microalgae in Europe is negligible, recent R&I developments suggest that the technical potential of aquatic biomass is large, as shown in **Figure 2**. Assumptions applied to derive aquatic biomass figures are presented in section 3.2.4. Notwithstanding R&I efforts and its large theoretical potential, due to its high cost, aquatic biomass from microalgae is unlikely to be competitive by 2030 or 2050.

The maximum feedstock potential per sector for energy use is shown in the following figure. The estimated potential is available for all energy uses, including advanced biofuels (see under Task 2).[9]

[9] The potentials that are estimated and presented are considered to be available for all energy uses. Biomass for other uses (e.g. stemwood biomass for material production) have been excluded. The use of these biomass potentials for advanced biofuels and other energy uses is considered under Task 2 (chapter 4).

Figure 2 Estimated potential: ***the figure shows the availability of sustainable biomass for energy use in the EU for the reference and high R&I scenario***



Source: Team analysis.

NB. The estimates for aquatic biomass availability (striped blue) are much more uncertain than for the other biomass sources. The full potential for aquatic biomass is not expected to be used because of its high cost compared to other feedstock sources. Furthermore, A sensitivity analysis for aquatic biomass has been performed and is reported in the findings" with cross reference to section where the findings are reported.

R&I increases the future competitiveness of EU sustainable feedstocks, but many other factors are also at play

Currently, trade in feedstock for the production of advanced biofuels is limited. Even in the future, much of the sustainable feedstock is unlikely to be traded due to a disadvantageous share of calorific value and volume. Only forest sector biomass and, possibly, energy crops may be traded on a substantial scale in the future. Competition is likely to emerge downstream at the level of (intermediary) advanced biofuels, as transport costs for these high value products represents a relatively lower share than for sustainable feedstock. When comparing the EU's competitiveness with other world regions, China, India and Brazil have large biomass potentials and are already producing biofuels (Europe's share in worldwide biofuels production was 16,7 % in 2016, whereas the shares were 2,5 %, 0,6 % and 22,5 % for China, India and Brazil respectively). Biofuels are prominent in these countries' future energy strategies, and it is likely that they will focus on developing their own advanced biofuels sectors, which may open-up opportunities for the operations of European companies. With respect to biomass from forests, the US and Canada are likely to stay the most important source of imports of (low quality) wood pellets for the EU. Also, Russia is already a source of forest biomass, with wood chips being imported by Finland and Sweden. Regarding energy crops, the future potential of the US is estimated to be large and competitive. R&I measures in the EU are needed to produce energy crops which can compete with US imports. However, the competitiveness of EU biomass from forests and energy crops relative to non-EU imports will be determined by the development of domestic demand (in the EU, US and Canada), the exchange rate, and the development of transportation costs to and within Europe. At the same time, changes in EU policies supporting bioenergy could have an impact on imports.

Task 2: Potential Contribution of Advanced Biofuels to the EU Climate and Energy Targets

Advanced biofuels have the potential to help achieve the EU climate and energy goals

Regardless of the degree of electrification in the transport system, advanced biofuels have the potential to play a significant role in decarbonisation of the EU transport sector. Advanced biofuels have much lower well-to-wheel emissions[10] than conventional fuels. Under targeted R&I policies for feedstock utilisation and conversion technologies, advanced biofuels will be able to meet around 50 % of the EU transport sector's energy demand by 2050. This corresponds to 65 % of the required emission savings needed, compared to 1990 levels (or to achieving 330Mt of net emission savings, in case they replace fossil fuels), in order to meet the target of reducing the transport sector's emissions by 60 %, as set in the White Paper for transport in 2011.

Furthermore, by substituting the use of imported petroleum products, the wide penetration of advanced biofuels in the energy mix will enhance energy security.

Flexibility in feedstock utilisation and conversion technology application is an advantage

By 2050, advanced biofuels will have the potential to cover almost half of the EU transport sector's energy needs, using mainly domestic feedstock resources. It is not currently possible to predict which conversion technologies will prevail, as a wide range of conversion technologies are at (very) low technology readiness levels. Flexibility in terms of the feedstock utilised and bioenergy commodities produced is considered an advantage for conversion technologies. Gasification and pyrolysis might be most promising in these regards. Overall, a manageable and scaled-up feedstock stream, feedstock flexibility for the conversion process, and flexibility for processing intermediate products into final fuel outputs are key. Also, R&I that helps to improve the energy efficiency of biofuel production processes will reduce the quantity of feedstock needed per unit of output.

To achieve the climate goals, significant investments in advanced biofuels' capacity are needed

To achieve the 2020 targets, the currently installed capacity for advanced biofuels must increase from 0,2 GW to close to 1,1 GW, at an estimated cost of € 4,5-5 billion. Advanced biofuels also have the potential to reach the 2030 and 2050 targets if capacity is increased to 30 GW in 2030 and to 250 GW in 2050.

R&I can drive down costs, but can also create knock-on effects

Many different factors drive the evolution of costs for advanced biofuels. On the one hand, R&I and economies of scale reduce capital costs and drive down the price of biofuels. While on the other hand, increased demand for advanced biofuels puts upward pressure on the costs of fuels as producers need to look for more expensive feedstock. High demand for advanced biofuels under a scenario where EU decarbonisation objectives are met is expected to drive up average costs of the bioenergy system, since R&I and scale-driven cost reductions are not expected to be sufficient to offset demand-driven higher feedstock prices, which could affect the competitiveness of the wider European bioeconomy and transport system. The enormous quantity of feedstock needed to achieve economies of scale, for example the need for complete and large-scale feedstock production regions to bio-refinery gate logistics chains, presents a major bottleneck for advanced biofuels and points to the need for R&I to develop more efficient logistic legs.

[10] Well to wheel emissions are determined through life cycle analysis of emissions of fuels used in transport.

Targeted R&I policies for advanced biofuels are key

Due to its sustainable feedstock potential and demand for bioenergy and technology leadership, the EU, together with the US, China, Brazil, and Canada, is a major current and possibly future player in the advanced biofuels sector. Finland, France, Germany, Italy, Poland, the Netherlands, Spain, Sweden, and the UK are the (potential future) leading countries in the advanced biofuels sector within the EU. Targeted policies, for instance R&I for feedstock and conversion technology, are crucial to unlocking this potential. Such policies should also address the substantial investments needed for the market transition to large-scale advanced biofuels production, which could otherwise become the greatest threat for the development of advanced biofuels in these countries. These policies may include efforts to attract foreign capital. Whereas most of the remaining EU countries do not yet produce advanced biofuels, they also have some future potential in sustainable feedstock and advanced biofuels production.

Task 3: Comparison of Fuel Options for Transport up to 2030 and 2050

Fossil fuels are the main competitors of advanced biofuels in the short term

Fossil fuels currently dominate all transport sectors. The main fossil fuels in the road sector are gasoline and diesel, while low quality residual fuels dominate the fuel mix in the maritime sector, and conventional kerosene is the main fuel in the aviation sector. The current use of alternatives (electrification, hydrogen, natural gas, and advanced biofuels) is limited in all these sectors. However, the need to decarbonise is expected to increase the chance that potential for change will be exploited, especially for electrification and advanced biofuels.

Competition between advanced biofuels and electrification in passenger transport

For the passenger road sector and light duty freight, there are more alternative fuel options than just advanced biofuels. Passenger cars are front runners in the adoption of electric powered motors; although, as electric vehicles are not yet cost-competitive compared to fossil fuelled vehicles, stimulation by public authorities may be needed. The market is showing signs of gradual change: new electric models are entering the market and sales of electric vehicles are increasing, while the density of the charging network is improving. The model projections show a drop of fossil fuels in the fuel mix from around 80 % in 2030 to around 40 % by 2050, with biomass and electricity substantially increasing their shares of the fuel mix. Both alternative options are necessary to cover overall demand, with electricity being able to cover between 8 %-22 % and biofuels between 30 %-48 % of the fuel mix. The projected share of fossil natural gas and hydrogen in light road transportation is, on the other hand, limited.

Advanced biofuels are the main alternative for aviation, maritime and heavy-duty road transport

Both model outcomes and desk research project that the share of alternatives fuels other than advanced biofuels is low in the 2050 fuel mix for heavy duty road, maritime, and aviation transport sectors. Biokerosene is the only alternative foreseen for the decarbonisation of the aviation sector. Biodiesel is one of the few viable options for long-distance road freight and maritime transportation. Advanced biofuels are the main viable alternative fuel option for these sectors because of the capital-intensive nature and long investment cycles of their industries. For the maritime sector, the limited and scattered international regulation also plays a role. For aviation, the high fuel certification standards are an additional barrier to entry. Electrification and hydrogen may become long-term alternatives (with commercialisation after 2050) for both maritime and aviation.

No significant net impact on EU GDP growth, and positive effects on employment

Despite higher average transport costs, the net impact of advanced biofuels development on EU GDP over the period 2020-2050 is neutral. The positive impact of development of an advanced biofuels industry on GDP is offset by negative impacts caused by increased transport costs throughout the European economy. Moreover, the projections show that some sectors are positively affected: e.g. those delivering the services, equipment, and biofuels for the transition to a low carbon economy (e.g. construction, agriculture, electric vehicles). Although there is an inevitable level of uncertainty over model projections, a significant number of new jobs is expected to arise from the shift towards low carbon transport. In the EU economy, the net positive effect in employment is 108,000 new jobs in the period 2020 – 2050 or a 0,05 % increase from the total employment levels under the baseline scenario. The knowledge created through R&I not only leads to production costs reduction, the creation of new products, and to improved production processes, but can also be transferred and absorbed by other sectors that do not necessarily compete with the sectors which have generated the knowledge.

IV. Conclusions and recommendations

This study assesses the highly complex global interactions of R&I developments in feedstock production and conversion to biofuels, as well as the demand for these and other fuels within the EU transport sector. The complexity of these interactions is driven by a strong heterogeneity in the potential of advanced biofuels from a geographic, technological, and market perspective. Actual R&I progress is difficult to predict, especially considering the 'chicken-and-egg' issues regarding technology push and market pull mechanisms. Nonetheless, it is crucial to analyse the R&I potential and to produce quantitative estimates even under high uncertainty, as they enable us to obtain a glimpse of the possible future market potential. The study findings suggest a rationale for investments in R&I linked to the advanced biofuels sector, whether through measures concerning the development of feedstock supply, conversion technologies, or stimulating advanced biofuels demand.

Overall, enabling the development of advanced biofuels requires R&I instruments on several fronts:

- R&I can improve the supply of biomass feedstock. The study results show that in the 2050 horizon, total sustainable feedstock availability can increase by some 50 % for agricultural, forestry and waste biomass feedstock. With aquatic biomass, the feedstock availability would increase by 120 % instead of 50 %. Despite this technical potential, we expect, based on an extensive literature review, algae feedstock would not be available at a competitive price;
- R&I can improve advanced biofuels production processes to reduce conversion costs. It is difficult to predict which conversion technologies will dominate, and not only one conversion pathway may prevail. Feedstock availability, feedstock flexibility, energy efficiency, and fuel versatility will be the key characteristics of a successful conversion technology. R&I synergies between various conversion technologies, with conventional (bio)fuel sectors and with biochemical co-production can be exploited;
- A stable demand outlook for advanced biofuels will be needed to establish a market and to spur development. Maximising the cost-competitiveness of biofuels will require production levels sufficient to achieve economies of scale, which may rely on public policy instruments to stimulate market demand.

If successfully developed, the contribution of advanced biofuels to achieving EU targets can be significant. The share of advanced biofuels in the overall transport sector energy mix can reach almost 50 % by 2050. By substituting imported fossil fuels with domestically produced biofuels, energy security (as measured by the share of required fuel that is imported) would improve significantly. When comparing with a Reference case (BASE scenario), the energy security for oil improves by 1 percentage point – with much lower demand implying a significant reduction in absolute imports – and 13 percentage points for bioenergy. The overall energy security (which includes various bioenergy sources) improves by 23 percentage points. The absolute market volume could reach € 365 billion (1,6 % of EU's GDP), although net GDP growth is negligible. The estimated employment impact could amount to a net increase of 108 000 extra jobs.

However, even with significant R&I developments and resulting cost reductions, achieving the levels of biofuel production needed to reach EU targets may require continuous support to allow advanced biofuels to compete with conventional fuels. The high cost of biofuels would be structural by nature, as high demand levels risk destabilising the market for biomass feedstock. Destabilisation would push prices up and have knock-on effects throughout the bioenergy and transport systems. Thus, the levels of biofuel production, as assessed in our scenarios, is probably in the upper range of future possibilities. At the same time, over the coming decades, the relative cost competitiveness of advanced biofuels will depend strongly on price developments for crude oil and sugar crop based feedstocks and fuels.

Feedstock limitations suggest that R&I investments should steer towards the long-term use of advanced biofuels, complementary with renewable alternative fuels. The R&I focus would then be to facilitate the market penetration of advanced biofuels in the transport sectors with limited fuel alternatives, such as aviation and shipping. The successful diffusion of advanced biofuels in the EU energy mix depends on the right market transformation and coordination between various stakeholders, which cannot be taken as given. Immense efforts are needed by farmers and forestry owners, who enhance biomass production and invest in the cultivation of new lignocellulosic crops. Their efforts need to be supported by innovators and industrial investors, who develop advanced conversion technology capacities. Consumers, especially in the transportation sector, need to become aware that the use of biofuels in their vehicles is safe and that it is cost-effective to fully adopt advanced biofuels. However, even if the aforementioned actions are followed by all stakeholders, scaling up towards a substantial advanced biofuels sector in the EU will take time – the transition period may last more than 15-20 years. Alternative "competing" technologies will also be evolving simultaneously, possibly at a faster pace (e.g. electrification of vehicles which is already happening).

1 Introduction

1.1 Scope and objectives of the study

The study "*Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels" implemented within the "Framework Contract for Studies in Support to Research and Innovation Policy in the areas of Renewable Energy, Carbon Capture and Storage and Clean Coal*" ran from 28 June 2016 until 28 October 2017.

Objective

The study aims to contribute to future policy developments in the area of advanced biofuels; in particular, it will feed into further consideration by the DG Research & Innovation of the current and potential role of research and innovation for advanced biofuels.

The study has three specific objectives: (1) to provide an assessment of the potential for research and innovation for biomass feedstock for energy for the time horizon of up until 2030 and 2050; (2) to assess the potential contribution of advanced biofuels for achieving EU targets; and (3) to compare different fuel options for transport. The outcome of these three parts is integrated based on an analysis of the whole value chain for advanced biofuels in Europe for 2030 and 2050, also taking into account life cycle costs of various options as well as market-push and market-pull factors. The overall strategic (long term) implications are discussed and an overall strategy is proposed.

Implementation of the study

The study is a common effort of researchers from Ecorys, E3MLab, WIP Renewable Energies, European Forest Institute, EuroCARE and IUNG. Whereas colleagues from **WIP**, **EFI**, **EuroCARE** and **IUNG** contributed predominantly to Task 1 (research on sustainable feedstock options) using the EFISCEN/EFI-GTM and CAPRI models, the results of their research were utilized by **E3MLab** as inputs for the quantitative analysis using different model suits, such as GEM-E3, PRIMES BIOMASS and PRIMES TREMOVE. All partners, together with **Ecorys**, have contributed to the qualitative and economic analyses throughout the study. Due to the complexity and inter-dependency of the study outcomes, the results are not attributed to specific partners, but marked as team effort.

1.2 Relation with other deliverables in the study

The separate deliverables, which are individual documents or databases and can be read as standalone reports, present results at a more detailed level than this final report. Similarly, more background and methodological explanation and substantiation is provided in these separate documents. The following deliverable reports have been produced:

- D1.1. Overview on the research and innovation potential of biomass production for bioenergy;
- D1.2 Research and innovation scenarios for biomass potential;
- D1.3 Impact of feedstock related R&I on the EU's competitive position;
- D1.4 Forecast of feedstock availability generated from residues/waste;
- D2.1 Potential contribution of advanced biofuels for achieving the 2020 RED/ILUC targets;
- D2.2 Potential of advanced biofuels for achieving 2030 Energy and Climate Package and 2050 targets;

- D2.3 Evaluation of the advanced biofuels contribution to Europe's societal challenges and Energy Union vision and action points;
- D2.4 SWOT analysis of interests of member states and major relevant nations on advanced biofuels;
- D3.1 Comparison of fuel options for transport up to 2030 and 2050.

In addition, two further deliverables have been produced, with a more specific focus:
- D4. Report on the validation workshop;
- D5. Database of all data sources and references analysed in the study.

1.3 Outline of the report

This final report is a synthesis of the results, as presented in separate deliverables of the study. The purpose of the final report is to present the key results, highlighting policy implications in an accessible way. The structure of the report is as follows:
- Chapter 1 serves as an introduction, also on the concept of Advanced Biofuels;
- Chapter 2 provides a description of the study methodology, specifically going into the study methods and the scenario approach;
- Chapter 3 analyses the R&I potential of biomass feedstock. We first outline the R&I potential for forestry, agriculture, waste, and aquatic biomass. These are translated into R&I scenarios, which are analysed from the perspective of the EU's competitive position regarding the production of feedstock. Finally, we present an outlook on the feedstock potential for residues and waste from a biophysical perspective;
- Chapter 4 builds on the quantified feedstock estimates by assessing what volume of advanced biofuels can be produced in future scenarios, depending on R&I scenarios for conversion technologies. We assess this in the short (2020), medium (2030), and long (2050) term. The volumes produced of advanced biofuels are placed into perspective by comparing them to Europe's societal challenges and the vision and action points of the Energy Union. Finally, we take a closer look at the results at the level of clusters of Member States;
- Chapter 5 adds another perspective by comparing the potential of advanced biofuels from Chapter 4, with other renewable alternative fuel options. This is done for a variety of transport sectors and subsectors;
- Chapter 6 discusses key socio-economic impacts for the EU under the different scenarios;
- We conclude the report with Chapter 7, providing a strategic R&I outlook and our conclusions and recommendations.

1.4 Introduction to Advanced Biofuels

In industry, science, and politics, a wide range of terms are used to refer to biofuels, such as first generation, second generation, third generation, next generation, sustainable, renewable, advanced, etc. This classification is based on the type of feedstock used, the conversion technology used, and the properties of the fuel molecules produced, the reason for the different approaches to classification being the great variety of biofuels feedstocks and processes.

The term 'advanced biofuels' is also typically used to describe biofuels produced by advanced processes from non-food feedstocks, biofuels with advanced properties, and biofuels produced from non-food crops or residues. These different definitions are described below.

Biofuels produced by advanced processes from non-food feedstocks (e.g. wastes, agricultural and forestry residues, energy crops, algae) may be equivalent for chemical properties to fuels produced by first generation technology, such as ethanol or FAME, or may be a different type of advanced biofuel, such as BioDME or bio-kerosene. Generally, these “next generation” biofuels are considered to be more sustainable as the feedstock and processes used allow for greater levels of GHG reduction and do not even eventually compete with food crops for land use.

Biofuels with advanced properties, such as HVO, bio-petroleum, bio-jet fuel, and bio-butanol, may be more compatible with existing fuel infrastructure or offer other technical benefits, although they may be made from a range of feedstocks, such as oil crops or plant sugars. The aim, however, is to ultimately produce biofuels with advanced properties from abundant sustainable feedstocks.

Biofuels produced from non-food crops or residues (e.g. oil crops grown on marginal land or used cooking oils and animal fats) via first generation technology may also be referred to as next generation or sustainable, or sometimes grouped with advanced biofuels, even if no advanced processing technology is used.

To overcome the difficulties in nomenclature, a more scientific definition of the various generation biofuels can be described based on the carbon source from which the biofuel is derived; using the terminology of 1st, 2nd, and 3rd Generation Biofuels. 1st Generation Biofuels use sugar, lipid, or starch directly extracted from a plant as the source of carbon for the biofuel. The crop is actually or potentially considered to be in competition with food. 2nd Generation Biofuels use carbon derived from cellulose, hemicellulose, lignin, or pectin. For example, this may include agricultural, forestry wastes or residues, or purpose-grown non-food feedstocks (e.g. short rotation coppice, energy grasses). 3rd Generation Biofuels use carbon derived from aquatic autotrophic organisms (e.g. algae). Light, carbon dioxide, and nutrients are used to produce the feedstock, "extending" the carbon resource available for biofuel production. This means, however, that a heterotrophic organism (using sugar or cellulose to produce biofuels) would not be considered as 3G.

For the purposes of this study, we use a definition of advanced biofuels based on that of the European Industrial Bioenergy Initiative (EIBI),[11] which is considered to be best suited to the requirements of this study. Thus, Advanced Biofuels are biofuels, which are:

- produced from lignocellulosic feedstocks (i.e. agricultural and forestry residues, e.g. wheat straw/corn, stover/bagasse, wood-based biomass), non-food crops (i.e. grasses, miscanthus, algae), or industrial waste and residue streams;
- having low CO_2 emissions or high GHG reductions; and
- reaching zero or low ILUC impact.

This implies that advanced biofuels are not necessarily without any CO_2, GHG impact or ILUC impact.

In the set-up of this study there are a number of limitations, which are addressed below:

- First, we note that we have not focused solely on the commodities covered by the ILUC definition, in order to get the overall picture of the bioenergy system and not isolate the exercise to specific energy carriers;
- Further, we acknowledge that, although we used an extensive combination of well-known models, the current modelling suite does not cover all that is available. An example is the Carbon Capture and Utilisation (CCU), which is assessed qualitatively, but has not been included in the quantitative part of the analysis;

[11] The definition can be found on http://www.biofuelstp.eu/advancedbiofuels.htm#whatare.

- Chapter 5 presents an assessment of the societal life cycle cost of the various transport fuels across the EU. Although many aspects are systematically included in the used model suits, there are also societal cost elements which are not covered. These are assessed in a qualitative way;
- By nature, impacts of R&I efforts are difficult to predict. This translates into uncertainty regarding for example availability and cost of feedstock and conversion. This uncertainty is higher as technologies are less mature and where production at scale is not expected within a short time frame. Most notably for aquatic biomass, we find that the long term potential is still heavily debated, and that consensus has not yet been reached.

2 Methodology

2.1 Introduction

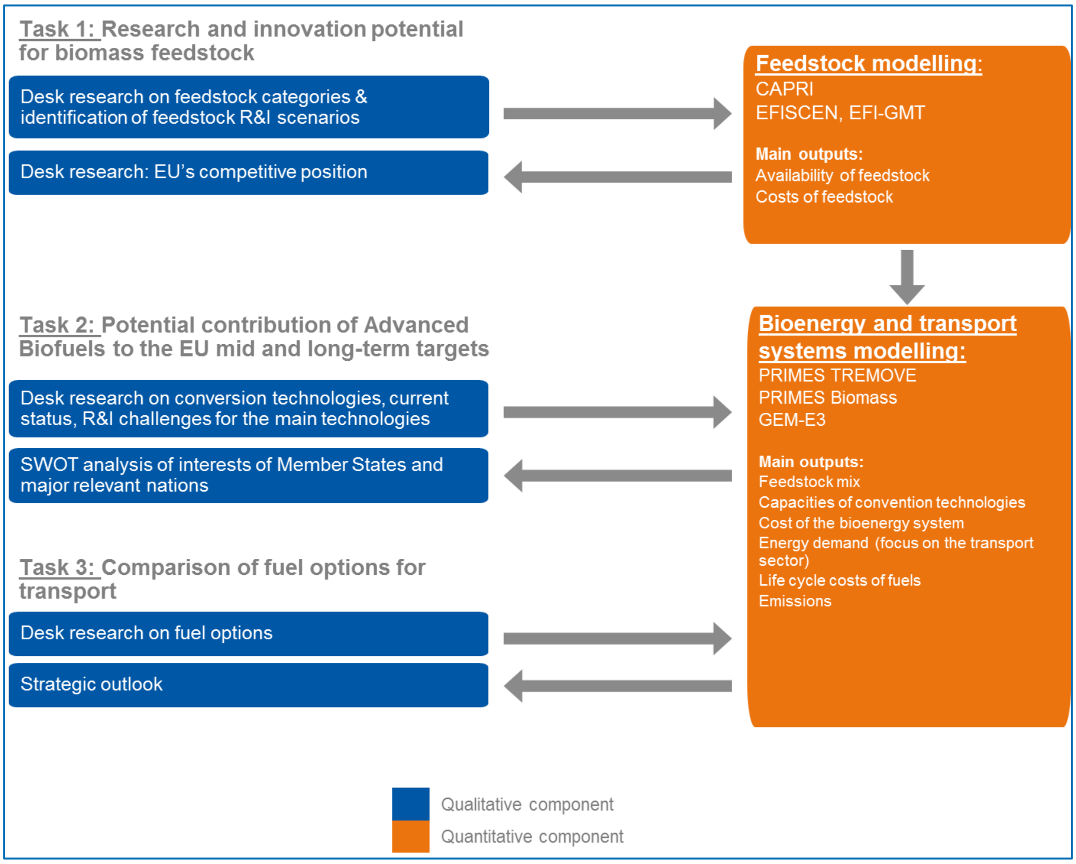
The overall methodology follows the task structure of the study, namely:

1. Production of feedstock:
   Research and Innovation potential of biomass feedstock (Task 1);
2. Production of advanced biofuels from feedstock:
   Potential contribution of advanced biofuels for achieving the 2020 RED/ILUC directive targets, and the 2030 Energy and Climate Package and 2050 targets (Task 2);
3. Demand for advanced biofuels:
   Comparison of the fuel options for transport based on long term scenarios (Task 3).

Followed approach

In order to examine the potential effect of R&I for advanced biofuels, the study uses an integrated quantitative and qualitative methodological approach. A range of different (qualitative) scientific tools, such as bibliometric analyses, literature reviews, and stakeholder consultations, have been employed. The collected information is integrated into the quantitative approach through the updating of input assumptions. This concerns, for example, quantitative development of feedstock availability, technological maturity and maturation pathways, the efficiency, capex and open of conversion technologies, and development of alternative fuel options. The quantitative analysis uses several (interconnected) models implemented under different scenarios. The next figure presents an overview of the followed approach in relation to the various tasks.

Figure 3 Followed approach: ***The figure shows the integrated qualitative and quantitative approach across the tasks***



The modelling suite served to quantitatively integrate these different tasks. We discuss this modelling suite under Section 2.2. The scenarios in particular have been key for the modelling approach. They provide hypothetical pictures of what the advanced biofuel sector would look like under different levels of R&I applied to progressing advanced biofuels, and what the impact is of competition with renewable alternative fuels. We discuss the scenario approach in detail under Section 2.3.

Potential of research and innovation

The key perspective in the study is specifically the potential of research and innovation to advance the advanced biofuels sector. With the dual purpose of developing inputs for scenarios as well as reflecting on wider R&I perspectives, the study:

- Elaborated the 'intervention logic' of R&I actions, discussing in detail the challenges and potential impact of R&I in the field of feedstock and advanced biofuel production;
- Identified of key players and countries active in the advanced biofuels sector;
- Reflected on strategic implications for the EU and clusters of Member States based on both the qualitative findings and quantitative outlooks of the scenarios.

The qualitative findings on potential R&I impact for feedstock and advanced biofuel production were translated into quantitative modelling inputs. These inputs were determined at an aggregated level, covering a range of identified R&I challenges per (sub)type of feedstock or conversion technology. Although quantitative information on potential R&I impact was often available at the level of individual R&I challenges, this was insufficiently exhaustive nor consistent to develop an aggregated breakdown.

Information on the R&I impacts for feedstock is provided under section 3.2. The aggregation of R&I impacts, coming from the literature review, towards one modelling input was based on the team's expert judgement. These assumptions were subsequently validated in an expert workshop (see section 2.2).

Information on R&I challenges and impacts for conversion technologies is provided in the deliverable report D2.2. The literature review and interviews usually provided information on cost reductions at an aggregate technology level. These figures were used to update existing modelling assumptions on the capital, fixed and variable cost and learning rates for 23 conversion pathways. This required a separation of expected cost reductions found in literature and interviews into endogenous 'learning-by-doing and scale-driven cost reductions' on the one hand and exogenous cost reductions over time on the other, which relied on the modelling team's expert judgement.

Used sustainability criteria

The R&I potential for sustainable, low ILUC biomass assessed in this study is defined as the absolute maximum amount of lignocellulosic biomass potentially available for energy use, while considering agreed **sustainability standards** for agriculture, forestry and land management. This definition is based on a biomass typology developed in the recent EU project S2Biom[12] (Panoutsou 2017). This potential considers agreed sustainability standards in Common Agricultural Policy (CAP) for agricultural farming practices[13] and land management and in agreed (national and regional) forest management and biomass harvesting guidelines for forests. It also includes the consideration of legal restrictions such as restrictions from management plans in protected areas and sustainability restrictions from current legislation. Further restrictions resulting from RED

12 S2Biom, see: http://s2biom.alterra.wur.nl/web/guest/biomass-supply.

13 CAP sustainable agricultural farming practices include the conservation of Soil Organic Carbon (SOC), e.g. cross compliance issues of maintaining agricultural land in good farming and management conditions and avoiding soil erosion.

(Renewable Energy Directive) and CAP are considered as well. CAP sustainable agricultural farming practices include applying conservation of Soil Organic Carbon (e.g. Cross Compliance issues of 'maintaining agricultural land in good farming and management condition' and avoiding soil erosion).

In order to avoid impacts related to indirect land use change (ILUC), the potential for dedicated energy crops has been defined assuming that they are only grown on fallow land or on land, which is released from agricultural production. Other areas in conflict with sustainability objectives have been excluded from the potential as well.[14] For the use of straw and prunings, carbon balance related sustainability limits have been adopted from Miterra model estimates.[15] All quantifications in this report are based on these sustainability criteria.

Biofuels: from food-based biofuels to advanced biofuels

With regard to the development of first generation (food-based) biofuels the following is important in the followed approach: although a full phase-out of first generation biofuels is not assumed in the modelling per se, the further penetration in the energy mix is constrained by the European sustainability criteria that are modelled. Therefore, the importance of first generation biofuels as an energy carrier in the future energy mix decreases. If relevant, we explicitly refer to first generation biofuels.

2.2 Methods applied

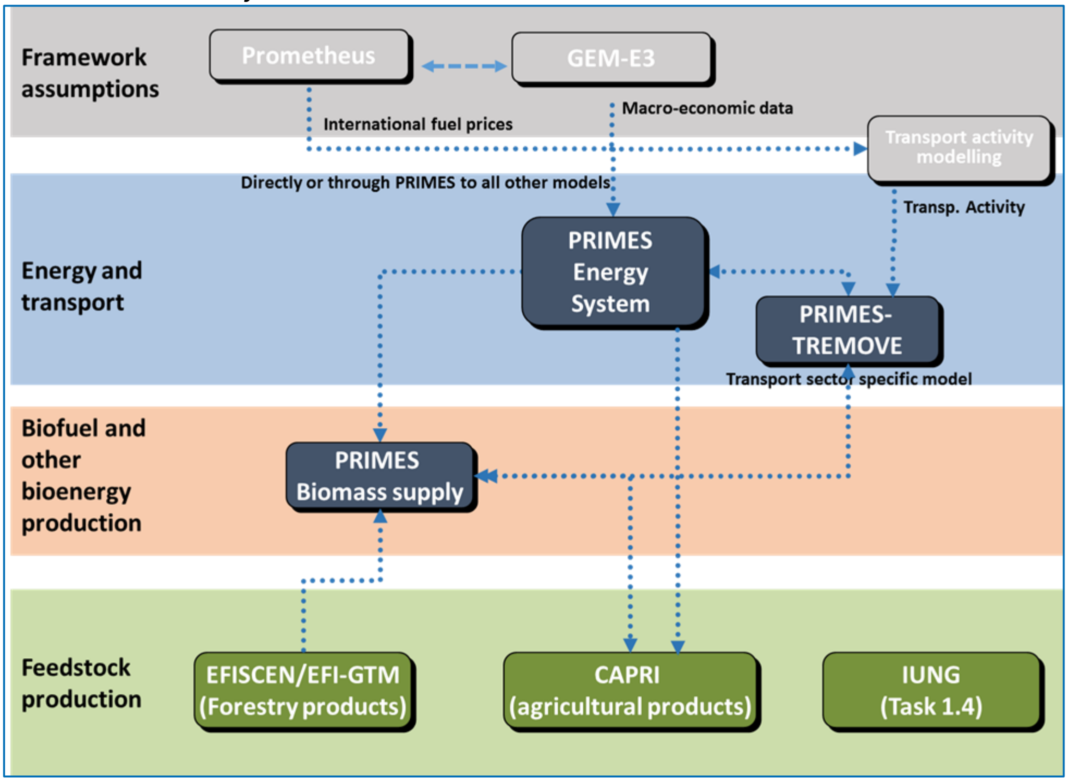
Overview of modelling instruments

This section describes the methodology and the modelling tools that have formed the basis for the quantitative assessment of the contribution of advanced biofuels to the 2030 and 2050 EU energy and climate targets. For an overview of the interrelation of all the models used in the study, please refer to Figure 4 below.

[14] Natura 2000 areas, High Nature Value farmland, wetlands, peatlands, and permanent grassland areas.

[15] Based on the Miterra model estimates; see S2Biom Deliverable 1.6 for more details.

Figure 4 Overview of the models used in the study: ***The figure shows the interlinkages between the models used in the study***



The dashed lines and arrows in Figure 4 schematically depict the typology and interlinkages between the models in the study. It becomes clear that we have ensured that the modelling inputs are determined endogenously to the extent that is possible, wherever there is an interrelation between feedstock production, biofuel production, energy and transport, and framework assumptions. This serves to improve the overall consistency of the results. More details on how the main modelling tools are interlinked are outlined Table 1.

Table 1 Interlinkages of the different models involved in the study

Model	Linkages
CAPRI	CAPRI has provided cost-supply curves for agricultural lignocellulosic crops and agricultural residues.
EFISCEN/EFI-GTM	EFI-GTM has provided cost-supply curves for forestry stemwood, residues and primary wood waste (sawdust from wood industries etc.). The EFISCEN model has provided to EFI-GTM the maximum potential of forestry biomass available under different feedstock scenarios.
PRIMES	Results from pre-existing runs of the PRIMES energy system model have been used in order to derive demand levels for bioenergy in stationary uses (power and heat generation and industry).
PRIMES-BIOMASS	The model transforms biomass feedstock from a. o. EFISCEN/EFI-GTM and CAPRI into bio-energy commodities – secondary or final form – which undergo further transformation in the energy system, e.g. as input into power plants or heating boilers, or as fuels for transportation. The model calculates the inputs, in terms of primary feedstock of biomass and waste, to satisfy a given demand for bio-energy commodities. The model further estimates the imports necessary and provides quantification of the amount of production capacity required. Furthermore, all the costs resulting from the production of bio-energy commodities and the resulting prices of the

Model	Linkages
	commodities are quantified.
PRIMES-TREMOVE	The PRIMES-TREMOVE energy and transport model has been used in order to determine bioenergy demand for mobile applications (road and non-road transport). The model has been run in all scenarios described in the report. The PRIMES Biomass model has provided the transport model with the bioenergy product prices for each scenario.
GEM-E3	The GEM-E3 model has been used in order to assess the socioeconomic impacts of certain scenarios. The model uses as input a variety of indicators coming from the PRIMES-Biomass model such as installed capacity per technology, types of feedstock used etc.

The Table 2 below provides in more detail the types of biomass commodities (feedstock), conversion pathways and end-use energy products which are included in the modelling suite. It shows how one type of feedstock or conversion technology can be part of various different conversion pathways from feedstock to end-use energy product, and how this is captured in the modelling.

Table 2 List of biomass to bioenergy pathways included in the PRIMES Biomass model

Feedstock	Conversion pathway	End-use energy products
Starch crops, Sugar crops	Fermentation	Ethanol
Woody Biomass[16]	Enzymatic Hydrolysis and Fermentation	Cellulosic Ethanol
Woody Biomass	Enzymatic Hydrolysis and Fermentation	Ethanol (advanced)
	HTU process, deoxygenation and upgrading	
	Pyrolysis, deoxygenation and upgrading	
	Pyrolysis, Gasification, FT and upgrading	
Woody Biomass, Black Liquor	Gasification, FT and upgrading	
Aquatic Biomass	Transesterification, Hydrogenation and Upgrading	
Oil crops, Non-agricultural oil and animal fats	Transesterification	Biodiesel
Starch crops, Sugar crops	Enzymatic Hydrolysis and deoxygenation	
Oil crops	Hydrotreatment and deoxygenation	Biodiesel (advanced)
Woody biomass, Black Liquor	Gasification and FT	
Aquatic Biomass	Transesterification and Hydrogenation	
Woody biomass	HTU process and deoxygenation	
	Pyrolysis and deoxygenation	
	Pyrolysis, Gasification and FT	
Woody biomass	Gasification and FT	Bio-kerosene
	HTU process and deoxygenation	
	Pyrolysis and deoxygenation	
	Pyrolysis, Gasification and FT	
Aquatic Biomass	Transesterification and Hydrogenation	
Woody biomass, Black Liquor	Gasification	Biogas/ Bio-methane

[16] Woody biomass refers to lignocellulosic input which could be derived from agriculture lignocellulosic crops, forestry stemwood, forestry residues, agricultural residues, wood waste etc.

Feedstock	Conversion pathway	End-use energy products
Organic Wastes, Starch	Anaerobic Digestion	
Woody biomass	Enzymatic Hydrolysis	
	Catalytic Hydrothermal Gasification	
Woody biomass	Hydrothermal Upgrading (HTU process)	Bio-liquids (for used in power generation, industry and shipping)
	Pyrolysis	
Non-agricultural oils and animal fats	Catalytic Upgrading of non-agricultural oils	
Landfill, Sewage Sludge	Landfill and sewage sludge	Waste Gas
Organic Wastes	Anaerobic Digestion	
Industrial Waste, Municipal Waste (solid)	RDF	Waste Solid
Woody biomass		Small Scale Solid
Woody biomass		Large Scale Solid

Note: Please note these are pathways included in the existing modelling suite. Some alternative pathways like for example directly ethanol (DEMA) and Carbon Capture and Utilisation (CCU) are not included. We assume that the impact of this omission is not significant, as we expect that the potential contribution of this pathway in the bioenergy system remains modest by 2030 and 2050.

Bio-CCU pathways, such as Power to Liquid, Power to Gas, Low Carbon Fossil Fuels (using exhaust or waste streams of fossil fuel industrial applications) and Artificial Photosynthesis technologies have been semi-quantitatively assessed in this study, but are not represented in the model exercise. Technologies for the production of synthetic fuels from CO_2 or industrial waste gas streams are currently in the research and demonstration stage and today's production volumes are negligible. Nevertheless, the potential of such fuels, along with the potential of all other advanced biofuels, might increase by 2030 and 2050.

The quantitative analysis, which takes the form of elaborating a number of scenarios, allows examining the contribution of advanced biofuels under different contexts. This includes factors and causes that are external to the biofuels sectors, e.g. long-term climate ambition and electrification of transport. The modelling tools have a good track record of being used for this purpose in previous studies (for more information see Text Box 2.1 below).

Text Box 2.1 Track record of modelling tools

Previous studies where the aforementioned modelling tools have been used include the construction of the EU Reference Scenario 2016[17] and the development of a variety of policy scenarios that constituted key input to the 2016 Impact Assessment work of the European Commission. The analysis of impacts of the latter was the input[18] to 1) the Effort Sharing Regulation Impact Assessment[19] and the Staff Working Document[20] accompanying the Communication on low-emission mobility strategy published in July 2016; 2) the Impact Assessment accompanying the proposal for recast of the Directive on the promotion of energy from renewable sources[21]; and 3) the Impact Assessment accompanying the proposal for revised Energy Efficiency Directive[22] published in November 2016.

17 Capros et al. (2016).

18 The scenario runs in this document are those used for the Effort Sharing Regulation Impact Assessment and the Impact Assessment accompanying the proposal for a revised Energy Efficiency Directive. Some minor technical changes were performed for sector-specific modelling in other analytical documents.

19 Carbon Market Watch (2014).

20 European Commission (2016a).

21 European Commission (2016b).

22 European Commission (2016c).

In a nutshell, the scenarios allow us to:

- investigate the different pathways that the energy system might head towards;
- assess quantitatively the R&I demand in several segments across the biomass-to-biofuels supply chain;
- assess quantitatively the importance of a number of factors that can influence the contributions of advanced biofuels in meeting the mid- and long-term energy and climate targets of the EU; and
- investigate the environmental and socio-economic impacts (employment, GDP, value added, trade) for each case.

Bibliometric analyses

We have mapped scientific efforts worldwide through bibliometric analysis in order to assess academic technological leadership, and the potential for technology transfer outside Europe.

A CWTS Citation Index system (CI-system) has been used for these analyses. The core of this system comprises an enhanced version of citation indexes by Clarivate Analytics (formerly Thomson-Reuters): Web-of-Science version of the Science Citation Index, Social Science Citation Index and Arts & Humanities Citation Index. These sources run back to the 1980s, are updated quarterly, and contain over 50 million publications. A combination of smart computer algorithms and manual data cleaning avoided problems with double entries of university and organisation names and addresses.

CWTS identified relevant publication clusters in the CWTS publication classification based on keywords. It also identified publications where these keywords appeared in the title or abstract in combination with the term “bio”. In addition, CWTS searched for all publications explicitly mentioning “biofuel”.

Literature review

A literature review has been conducted for the following purposes:

- Review of Research and Innovation options for improving feedstock production and conversion of feedstock to biofuels;
- Identification of major players in Research and Innovation in feedstock production and conversion;
- Updating databases on current feedstock production and biofuel production;
- Assessing the different renewable alternatives and advanced biofuel fuel options for the various transport modes.

We have made use of the following types of sources:

- Databases (national and international statistics, own data sets);
- Projects (research, innovation, demonstration, commercial projects; EU and national projects; international projects);
- Models (agricultural, forest, and waste models);
- Publications (literature, studies, papers, articles);
- Patents.

For more details on literature and data sources, we refer to the separate Deliverable 5. This deliverable is an Excel database outlining the various sources, including a description of how these sources have been used in the study.

Stakeholder engagement

We have engaged with stakeholders to validate findings and deepen our insights. This included interviews with academics, industry representatives, research institutes and public officials. In addition, we have organised a workshop with external stakeholders to discuss how to structure the scenarios, to critically review the elements and components of the identified R&I feedstock scenarios, and to discuss and validate the data to be used to run the different models to deliver the cost-supply curves for each biomass source sector. Experts involved in research and innovation within the biomass source sectors (which were mostly external to the project team) positively evaluated the proposed scenarios and made suggestions for further improvement.

In addition, a workshop was held at the 27th of June, where the results of the study have been presented. The aim of the workshop was to validate and enrich the conclusions and recommendations. The outcomes of the workshop have been used for the finalisation of the recommendations.

2.3 Scenario approach

2.3.1 Introduction

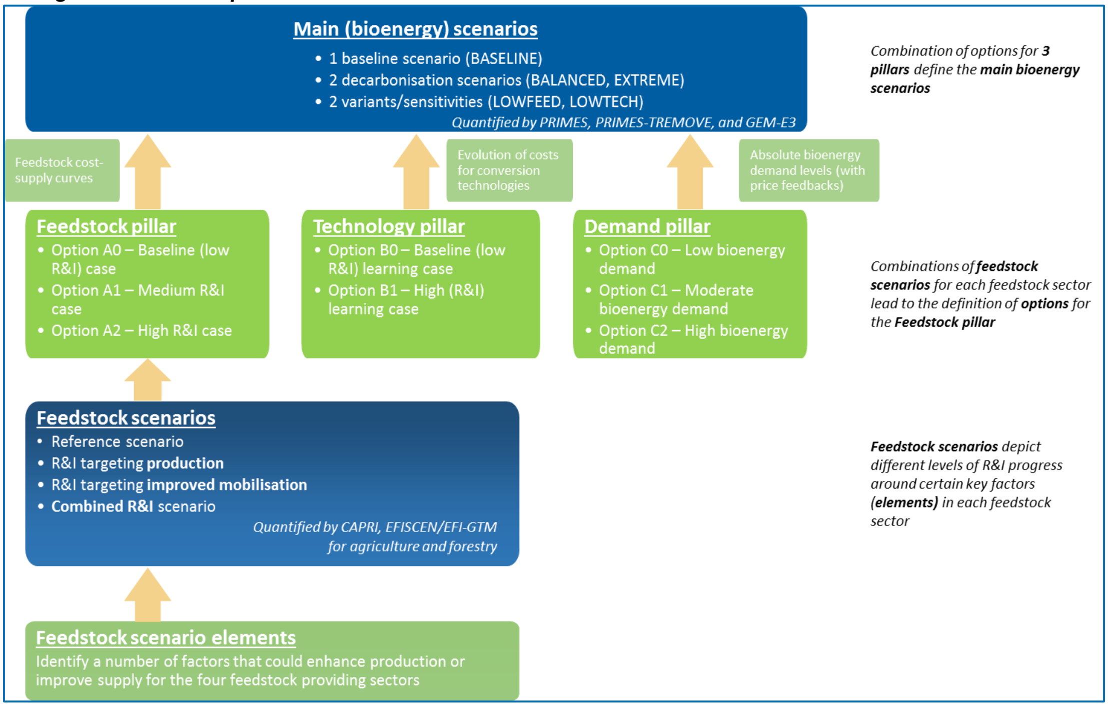
The quantitative part of the assessment included the design and construction of different scenarios and options, which have been developed using the different models. Generally speaking, the models used in the project can be classified, according to the main use of each one for this study, into the following categories:

- **Feedstock models**: Including *CAPRI* and *EFISCEN/EFI-GTM*; these have been used in order to evaluate the availability and cost of biomass from the agriculture and forestry sector, respectively, under different R&I assumptions;
- **Main bioenergy scenario models**: Including *PRIMES-Biomass* and *PRIMES-TREMOVE*; these have been used (in a closed-loop operation, where a price-demand feedback was established) in order to evaluate the demand for bioenergy and identify which feedstock types and conversion technologies shall be used for covering this demand for bioenergy. The feedstock models have provided key inputs to the PRIMES-Biomass model;
- **Macroeconomic models**: Including the *GEM-E3* model that has been used in order to evaluate the social and economic impacts of the main scenarios.

2.3.2 Overview of the approach

The scenario construction included the definition and categorization of different options/assumptions for each model. The steps undertaken for fulfilling the analysis are summarized in Figure 5. As in the figure, this included four discrete steps (as far as the feedstock sector is concerned), beginning with the definition of feedstock scenario elements and ending with the quantification of the main bioenergy scenarios.

Figure 5 Overview of the quantitative analysis: ***The blue boxes describe the two categories of scenarios— the main (bioenergy) scenarios and feedstock scenarios. The assumptions and options underlying the scenarios are presented in the green boxes. The feedstock scenarios feed into the bioenergy scenarios through the feedstock pillar***



Step 1 – Identification and construction of feedstock scenario elements (design)

For each of the four feedstock-providing sectors – agriculture, forestry, waste, and aquatic biomass – a number of factors has been identified that could lead to improved supply via the scaling-up of feedstock production or improving the mobilization of feedstock resources. For example, in the case of agriculture, the following elements have been identified (presented in Table 10):

- Yield increase of conventional (food/feed) crops due to breeding efforts. Breeding efforts to build up the resistance to biotic and abiotic stresses (drought, pests and diseases) are included. It will result in absolute increase of main crop biomass and crop residues and potentially providing more space for growing energy crops (if demand for food/feed can be satisfied with less land);
- Enhanced production by growing dedicated energy crops on un-used agricultural lands. Further expansion of energy crops on non-agricultural areas (marginal lands) is anticipated in the future. Expansion on marginal lands will be possible because of breeding efforts targeted to developing more robust plants, which are able to grow in less suitable conditions;
- Improved agricultural management practices (e.g. selection of varieties, crop rotation and intercropping, fertilization, water management, adoption of precision agriculture practices) to bridge the current gaps of yields among EU member states;
- Improved harvesting practices and machinery (development of new equipment for both – conventional and dedicated energy crop harvesting, improving harvesting practices, development of precision farming);
- Increased mobilisation of agricultural biomass by optimised supply chain logistics (mobilization of so far unexploited biomass by using cleaner, more efficient and more cost-effective technologies, technology transfer, streamlining biomass supply chains with existing practices, development of new supply chains for dedicated energy crops);Increased awareness and capacity of various actors involved in the biomass supply chain.

These scenario elements have been combined in three feedstock scenarios, which are explained in the table below.

Table 3 Feedstock scenario storylines

Scenario name	Description
Reference scenario	The *Reference scenario* illustrates a "business as usual" case, i.e. the policy and economic environment remain unchanged, resulting in limited additional developments in R&I for each sector.
R&I targeting increased supply of biomass through **enhanced production**	The *Enhanced production* scenario is based on the *Reference scenario*, but assumes R&I measures targeting an increased supply of biomass through enhancing biological production and improved management.
R&I targeting **improved** biomass **supply** through innovative harvesting, supply chain logistics and mobilization of potentials	The *Improved supply* scenario is based on the *Reference scenario*, but assumes R&I measures targeting an improved cost-efficiency of the biomass supply through innovative harvesting and supply chain logistics; measures targeting socio-economic innovations will result in enhanced mobilization of biomass potentials.
Combined R&I scenario with enhanced production and optimized biomass supply	This is a combined R&I scenario, with enhanced production as well as optimized harvesting, supply chain logistics, and mobilization of potentials.

The R&I potential for sustainable, low ILUC biomass assessed in this study builds on the biomass typology developed in the recent EU project S2Biom[23] (Panoutsou 2017). The S2BIOM Base potential has been used as a basis to construct the feedstock scenarios for agriculture, forestry and waste and can be characterised as the absolute maximum amount of lignocellulosic biomass potentially available for energy use, while considering agreed sustainability standards for agriculture, forestry and land management. The potentials for aquatic biomass can be characterised as technical potentials, which considers the absolute maximum amount of lignocellulosic biomass potentially available for energy use assuming the absolute minimum of technical constraints.

The feedstock scenarios and their elements are presented in detail in sections 3.2 and 3.3. later in this report.

Step 2 – Quantification of feedstock scenarios (modelling and literature review)

The next step involved the utilization of the CAPRI and the EFISCEN/EFI-GTM models, for the agriculture and forestry sectors respectively, in order to determine how much feedstock each sector could provide, as well as at what prices under the four different scenarios (reference, enhanced production, improved supply, and combined R&I effort). For the waste and aquatic biomass sectors, no feedstock supply model was available to the consortium in order to quantitatively assess the potential contribution of these two sectors. Literature reviews and expert judgement enabled undertaking a similar assessment as for agriculture and forestry also for these other two sectors. For more information, please refer to Sections 3.2 and 3.3.

[23] http://s2biom.alterra.wur.nl/web/guest/biomass-supply.

Step 3 – Definition of three pillars for defining the main bioenergy scenarios of the analysis (design)

The next step was the design of the main bioenergy scenarios that would be quantified by the models of the PRIMES family. The scenarios enable the assessment of the contribution of R&I in the fields of feedstock availability, cost-efficiency and biomass-to-bioenergy conversion technologies. The construction of the scenarios was based on three pillars:

- Pillar A: Feedstock;
- Pillar B: Conversion technology;
- Pillar C: Demand for bioenergy.

A number of options for each pillar were identified. The options can be seen as different levels of ambition regarding R&I effort, technological progress, etc. Regarding the feedstock sector, the three different options examined are essentially groups of the different feedstock scenario results obtained from the previous step.

Finally, a total of three main scenarios and two sensitivities were constructed with the aim to quantitatively assess the contribution of advanced biofuels in meeting the mid- and long-term EU energy and climate targets, while factoring in at the same time the effect of R&I in various stages across the biomass-to-bioenergy chain.

In addition, the scenario analysis and comparison allow for the assessment of the contribution of biofuels under different contexts, e.g. a reference case where the energy and transport systems are not foreseen to head towards a low carbon transformation, and various decarbonisation pathways that aim to meet the long-term energy objectives of the EU. Using sensitivities and more than one decarbonisation scenario increases the robustness of the analysis and provides a form of sensitivity analysis, analysing key uncertainties pertaining to the entire biomass-to-bioenergy system. For a more detailed description, please refer to Section 2.3.4.

Step 4 – Quantification of the main bioenergy scenarios (modelling)

The last step is the quantification of the three main scenarios and two sensitivities using the PRIMES-Biomass and the PRIMES-TREMOVE models. Inputs from the main PRIMES energy systems model were also used. The socio-economic impacts of the main scenarios were assessed using the GEM-E3 model. Section 4.3 and Chapters 5 and 6 present the outcomes of this quantitative assessment.

2.3.3 Description of the main bioenergy scenarios

The three pillars used for the scenario definition

For the quantitative assessment of the contribution of advanced biofuels to the EU climate targets, a number of scenarios have been constructed using a modular approach. Three areas/pillars have been identified and a number of options have been examined for each case as described in the previous section. The alternative options for Pillars A and B represent different levels of ambition regarding the impact of R&I. For Pillar C, options refer to different demand levels. Table 4 summarises the alternative options under each pillar. The grouping of the different options in scenarios is discussed later in this section.

Table 4 Summary of options identified for the three pillars

A - Biomass feedstock	B - Conversion technologies	C - Demand for bioenergy
Option A0 – Baseline case: • low R&I effort in all sectors.	Option B0 – Low learning rates for conversion technologies currently at low TRL.	Option C0 – Baseline: Low demand for biofuels. The EU doesn't meet decarbonisation objectives.
Option A1 – Medium R&I case: • Enhanced production for agriculture; • Improved supply for forestry; • Improved supply for waste; • Reference scenario for algae.	Option B1 – High learning rates for all technologies.	Options C1 – Moderate level demand for biofuel. EU decarbonisation objectives are met. High success for electro-mobility.
Option A2 – High R&I case: • Combined R&I for agriculture; • Combined R&I for forestry; • Improved supply for waste; • Enhanced production for algae.		Option C2 – High demand for biofuels. EU decarbonisation objectives are met. Moderate success for electro-mobility. Substantial improvement of internal combustion engines.

When combining the different options under each pillar, 18 distinct scenarios can in theory be obtained. However, some combinations are considered irrelevant or highly unlikely by the study team. For instance, a case with significant R&I effort progress in the feedstock sectors and biomass conversion technologies, but with limited demand for bioenergy, has not been considered.

The different options for each pillar have been combined so as to obtain a total of 5 scenarios. This allows the assessment of a variety of aspects, while keeping the number of scenarios manageable and without compromising the quality of the quantitative assessment. The options under each pillar are described in more detail in the following sub-sections.

Pillar A: Feedstock – description of the feedstock scenarios

To provide a quantified estimate of the biomass potential for energy up until 2050, a scenario approach was applied to cover each particular biomass source sector (agriculture, forestry, waste, and aquatic biomass). The scenarios included a set of feedstock scenarios, as well as a reference scenario to be able to assess the impacts of introducing R&I measures. The feedstock scenario storylines are described in Table 5.

Table 5 General *feedstock scenario* storylines and their relevance for each biomass sector

Scenario name	Description	Agri-culture	Forestry	Waste	Aquatic biomass
Reference scenario	The reference scenario illustrates a "business as usual" case, i.e. the policy and economic environment remain unchanged resulting in limited additional developments in R&I for each sector.	X	X	X	X
R&I targeting increased supply of biomass through **enhanced production**	This scenario is based on the reference scenario, but assumes R&I measures targeting increased supply of biomass through enhancing biological production and improved management.	X	X		X

Scenario name	Description	Agri-culture	Forestry	Waste	Aquatic biomass
R&I targeting **improved biomass supply** through innovative harvesting, supply chain logistics and mobilization of potentials	This scenario is based on the reference scenario, but assumes R&I measures targeting improved cost-efficiency of biomass supply through innovative harvesting and supply chain logistics; measures targeting socio-economic innovations will result in enhanced mobilization of biomass potentials.	X	X	X	
Combined R&I scenario with enhanced production and optimized biomass supply	Combined R&I scenario with enhanced production as well as optimized harvesting, supply chain logistics, and mobilization of potentials.	X	X		

These feedstock scenarios have been used to construct three different options for Pillar A of the bioenergy scenarios, which concerns the availability and cost of biomass feedstock. The options are the following:

- **Option A0** – no/limited R&I effort across all feedstock sectors;
- **Option A1** – moderate R&I case: most cost-effective feedstock scenario identified for agriculture and forestry, low R&I for algae, and enhanced availability of waste;
- **Option A2** – high R&I case: combined R&I for agriculture and forestry, improved supply of biomass, and enhanced availability of waste.

For more information on the design of each R&I scenario for each sector, please refer to section 3.2.

Options A0 and A2 have been defined using the scenario elements that utilise the low and upper parts of the ranges in terms of feedstock availability and costs, while Option A1 presents an intermediate situation where the most cost-effective options have been selected for each sector. The usefulness of this option can be seen in conjunction with the most optimistic case (Option A2) and allows for the formulation of quantitative conclusions about the significance of the first pillar in an EU energy system, which faces the transition towards a low-carbon economy.

Pillar B: (Conversion) Technology

The second pillar comprises the technologies used to convert biomass feedstock into biofuels and different assumptions regarding their techno-economic progress in order for their end products to become competitive with other energy carriers.

The technology progress in the PRIMES Biomass model is represented by two distinct mechanisms; learning-by-research and learning-by-doing. The *learning-by-research mechanism* simulates the cost reductions in a technology because of R&I efforts and development. It therefore represents autonomous progress. On the other hand, the *learning-by-doing mechanism* is an endogenous mechanism in the model, which resembles the progress and spill-over effects across all the EU MS, due to cumulative capacity additions of a certain technology in the EU.

Both options considered under Pillar B consider the learning-by-doing approach. The two options differ in the learning rate levels assumed, as follows:

- **Option B0 – Low learning rates for conversion technologies currently at low TRL;**

- **Option B1 – High learning learnings for all technologies.**

Option B0 assumes that all technologies follow low learning trajectories, with little progress shown from technologies at low TRL levels. On the contrary, Option B1 uses optimistic assumptions for all technologies. Normally, Option B0 is suitable for a baseline scenario, whereas the presence of coordination policies (enabling conditions) in decarbonisation scenarios would make the use of Option B1 necessary. Option B0 in a decarbonisation context is also useful as it enables the assessment of bottlenecks in the biomass-to-bioenergy chain and their importance.

The following tables includes the learning rates have been included in the quantitative analysis as far as some key technologies are concerned. The learning rates represent the effect of R&I in the learning-by-doing mechanism which influences the capital costs of the conversion technologies as capacity accumulates.

Table 6 Learning rates for selected conversion technologies in the options used for Pillar B

Conversion technology	Option B0	Option B1
Hydrolysis	-0,29	-0,35
Gasification	-0,19	-0,39
Hydrothermal upgrading	-0,25	-0,47
Pyrolysis	-0,19	-0,40
Hydrotreatment of vegetable oil	-0,25	-0,28

Pillar C: Bioenergy demand

The third pillar considers bioenergy demand for stationary and mobile applications. Mobile applications include energy demand from the transport sector while stationary applications include all remaining sectors.

Three different options are considered. The first serves as a baseline. It represents a context where the EU meets its 20/20/20 targets, but support policies are removed post 2020. The other two options serve well in scenarios where the EU aims to meet its mid- and long-term decarbonisation objectives. An important characteristic of these options is the inclusion of coordination policies/enabling conditions which are an indispensable part of an overall cost-effective pathway to meet long-term decarbonisation. For instance, positive consumer anticipation towards electric vehicles and large scale deployment of such technologies cannot be possible without the development of sufficient recharging infrastructure. The coordination policies included in the two decarbonisation options are listed in Table 7.

Table 7 Description of coordination policies

Enabling condition	Description
Reduction of battery and fuel cell costs	Maximum technological maturity and massive production of alternative vehicle powertrains. Increased R&D investments induce strong learning effects for the evolution of cost and performance of batteries, EV components and fuel cells – hydrogen to power fuel cells could also originate from bioenergy sources.
Availability of recharging/ refuelling infrastructure	Timely and adequate development of recharging and refuelling infrastructure poses no mobility constraints to the users of alternative powertrain vehicles.
Increased acceptance of new vehicle technologies by consumers	Increased assurance of consumers regarding costs, reliability and security on new vehicle technologies increases the market acceptance of such vehicles.
Commercialization of advanced biofuels	Market coordination for advanced fungible biofuels involve large-scale perennial energy crops, technological readiness of conversion processes. The success rate of this condition depends on the construction of the scenario.

The next paragraphs summarise the main characteristics of the three options under Pillar C:

- **Option C0:** serves as a baseline where the EU is not heading towards a decarbonised energy system and consequently, in the long term, the demand for biofuels is rather limited. It is based on the assumptions reflected in the modelling of the EU reference scenario 2016 - all policy measures are the ones already in place as of December 2014, and only specific policies adopted in 2015 (e.g. ILUC amendments to the RES and FQM directive) are included. No specific support post 2020 is assumed to be in place;
- **Option C1:** has a decarbonisation context and constitutes a scenario where a balanced transport system with the penetration of electric vehicles and advanced biofuels provides mobility with limited carbon emissions. Strong cost reductions in the case of low emissions vehicles are assumed, coupled with a rapid expansion of the recharging infrastructure network;
- **Option C2:** has a decarbonisation background similar to that of Option C1. The difference between Options C1 and C2 is that Option C2 assumes that the success in production and market diffusion of new generations of biofuels is also combined with a substantial improvement of internal combustion engines (ICEs). The diffusion is facilitated by the development of multiple fuel infrastructures and by technology progress allowing for high efficiency gains in conventional vehicle technologies, however mainly in ICEs. Thus this case assumes only a moderate success of electro-mobility, and thus only a moderate market penetration of electric vehicles. The use of conventional fuels for transport, and therefore the GHG emissions, can therefore only be limited through increased efforts from the (advanced) biofuels sector.

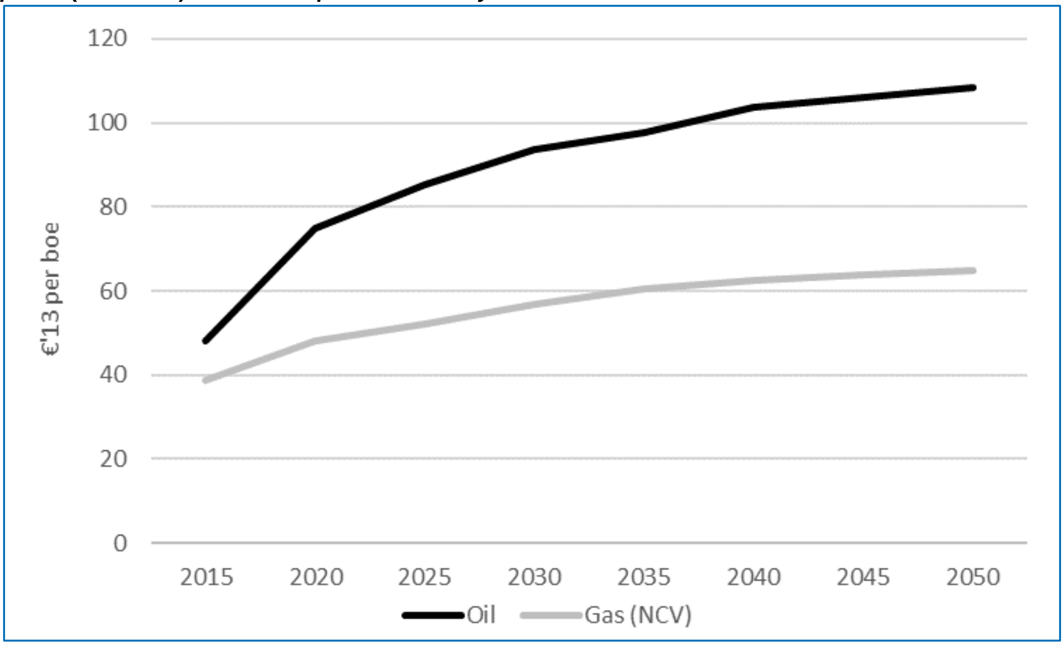
Options C1 and C2 have been designed so that they the same cumulative GHG emissions reductions, as compared to the baseline (Option C0), are achieved. The key assumptions for each option are summarised in Table 8.

Table 8 Options assessed for the third pillar - demand for bioenergy

Options	BASE	MEDIUM	HIGH
Demand for stationary uses – differentiated according to the context of the scenario (reference or decarbonisation).	Low	High	High
Technological development for EVs (refers to costs and performances of EV components such are costs and performance of batteries due to technological progress).	Low	High	Moderate
Refuelling infrastructure (limited, multiple or focused) – refers to electricity and non drop-in biofuels.	Limited	Focused (electricity only)	Multiple
Main policy driver (CO_2 emission regulation) – tight regulation of test cycle emission performance favour vehicles with lower emissions per km travelled such are electric vehicles, plug-in hybrids and fuel-cell powered ones. Such a regulation leaves less room for biofuels in the fuel mix of LDVs.	Relaxed	Strict	Moderate

The international fuel prices used for the quantitative analysis are common for all bioenergy scenario and are shown below.

Figure 6 International fuel prices: ***The figure shows the estimated development of international fuel prices*** **(2015-2050)** ***used in the quantitative analysis***



Source: Team analysis.

What the models can and cannot do

The PRIMES-TREMOVE and PRIMES-Biomass models combine micro-economic foundations with engineering at a fairly high level of detail, compatible with a long-term time scale and sectoral detail of available statistics for Europe. They are designed to provide long term energy system projections and system restructuring up to 2050 in the demand and the supply sides. The models are not econometric models and are not suitable for forecasting. They are to be used for scenario projection and comparisons between scenarios. In link with a macroeconomic model, such as GEM-E3, they can perform closed-loop energy-economy equilibrium analysis.

Although rich in sectoral disaggregation, PRIMES-TREMOVE is limited by the concept of representative consumer per transport sector, not fully capturing differences due to heterogeneity of consumer types and sizes (e.g. rich vs poor households). It lacks spatial information and representation of refuelling and recharging infrastructure at a level below the four stylised trip areas existing in the model (metropolitan, other-urban, motorways, other roads) and so it does not fully capture issues about retail infrastructure for fuels and electricity distribution at a more refined level.

PRIMES-TREMOVE, as well as PRIMES, differ from overall optimization energy models, qualified by some as bottom-up approaches. Such models formulate a single, overall mathematical programming problem, do not include explicit energy price formation and have no or simple aggregate representation of energy demand. PRIMES formulates separate objective functions per energy agent, simulates in detail the formation of energy prices and represents in detail energy demand, as well as energy supply.

PRIMES differ from econometric-type energy models. These models use reduced-form equations that relate in a direct way explanatory variables (such as prices, GDP etc.) on energy demand and supply. These models have weak representations of useful energy demand formation. They are usually poor in representing in detail capital vintages and technology deployment in energy supply sectors and lack engineering evidence, as for example the operation of interconnected grids and detailed dispatching.

The distinguishing feature of PRIMES is the representation of each sector separately – i.e. the transport sector represented by PRIMES-TREMOVE - by following microeconomic foundations of energy demand or supply behaviour and the representation of market clearing through energy prices. It is qualified as a hybrid model because it combine engineering-orientation with economic market-driven representations.

Description of the main bioenergy scenarios

The following subsections present the five scenarios that have been constructed by combining the Options under the three Pillars outlined above. Projections for all scenarios up until 2050 have been obtained by a combination of the PRIMES Biomass and PRIMES-TREMOVE models. The MEDIUM and HIGH scenarios have also been quantified with the GEM-E3 model in order to examine their socio-economic impacts, against the BASELINE scenario.

Apart from the BASELINE, all remaining scenarios are designed so as to meet the following targets, in order to ensure consistency with the mid- and long-term objectives of the EU:

- For 2030:
  - At least 40 % GHG emissions reduction (wrt 1990);
  - 43 % GHG emissions reduction in ETS sectors (wrt 2005);
  - 30 % GHG emissions reduction in effort sharing sectors (wrt 2005);
  - At least 27 % share of RES in final energy consumption;
  - 30 % primary energy consumption reduction as compared to the PRIMES 2007 baseline (1887 Mtoe in 2030).
- For 2050: Above 80 % GHG emissions reduction (wrt to 1990).

Table 9 Design of the *main scenarios* using options for the three construction pillars.

Scenario	Biomass feedstock	Conversion technologies	Demand for biofuels
BASE	Option A0 – Baseline case – low R&I effort in all sectors	Option B0 – Low learning rates for conversion technologies currently at low TRL	Option C0 – Baseline: Low demand for biofuels
MEDIUM	Option A2 – High R&I case	Option B1 – High learning learnings for all technologies	Options C1 – Moderate level demand for biofuel
HIGH	Option A2 – High R&I case	Option B1 – High learning learnings for all technologies	Option C2 – High demand for biofuels
LOWFEED	Option A1 – Medium R&I case	Option B1 – High learning learnings for all technologies	Options C1 – Moderate level demand for biofuel
LOWTECH	Option A2 – High R&I case	Option B0 – Low learning rates for conversion technologies currently at low TRL	Option C2 – High demand for biofuels

3 Research and innovation potential for sustainable biomass feedstock

3.1 Introduction

In order to define and quantify inputs for Pillar (A) - Production and delivery of biomass feedstock, the first task of this study consisted of the assessment of the research and innovation (R&I) potential towards sustainable and low cost biomass availability for bioenergy for the time horizons of up until 2030 and 2050. This chapter summarises the main outcomes of the qualitative and quantitative analyses of R&I activities. The aim of these analyses was to assess the impact of R&I on biomass feedstock availability and costs, and on the EU's competitiveness in 2030 and 2050 versus major players world-wide.

Within the study only these feedstocks were addressed, which comply with the sustainability requirements and are not competing with food production for the use of land. The main types of feedstocks included in the study are agricultural and forestry residues, energy crops (herbaceous and woody cellulosic crops and other low ILUC crops which can grow on marginal land), aquatic biomass (micro- and macro-algae) and wastes. Please note the used sustainability criteria presented in chapter 2.

The presentation of the feedstock assessment results is organised in the following sub-chapters:

- In Chapter 3.2, an overview of the research and innovation potential is presented separately for the fields of agriculture, forestry, waste, and aquatic biomass;
- In Chapter 3.3, an overview of the modelling results of R&I scenarios for the biomass potential (feedstock scenarios) is provided;
- In Chapter 3.4, the impact of feedstock-related R&I on the EU's competitive position is discussed.

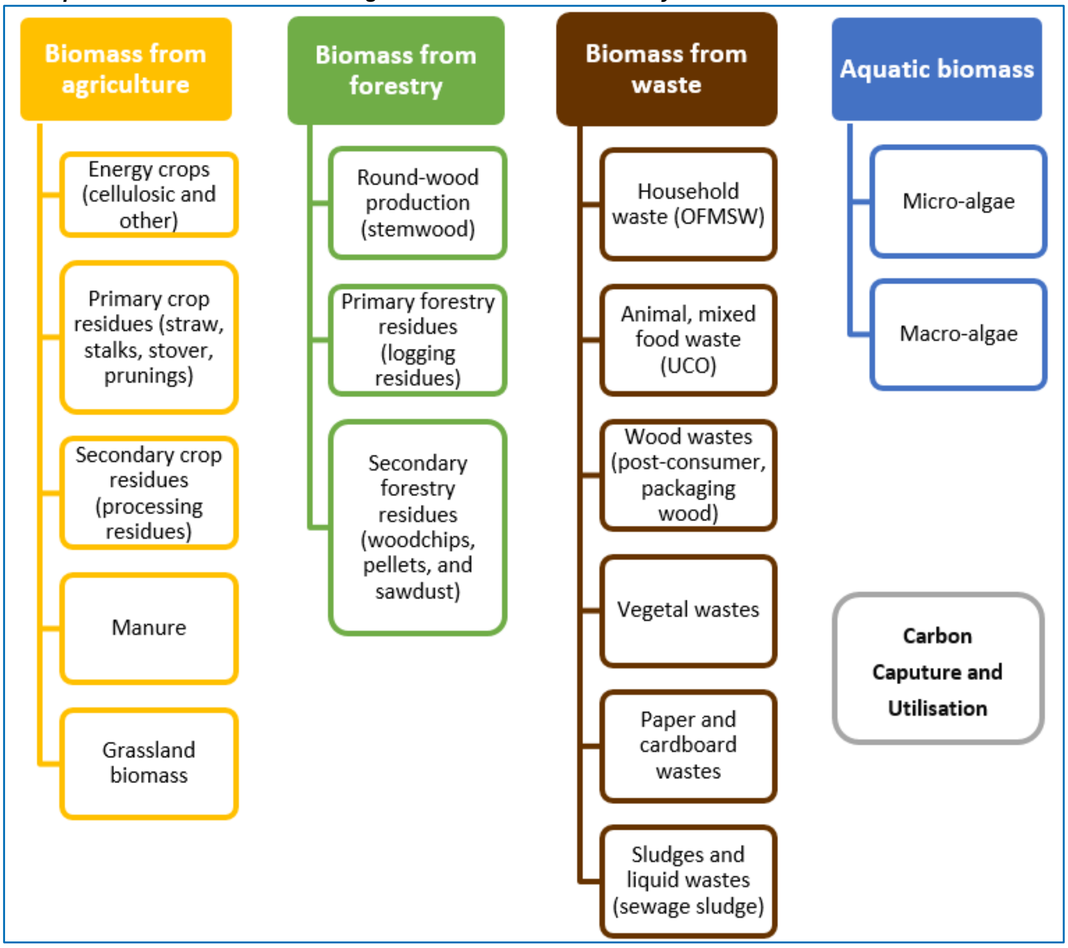
In addition, we have assessed the current feedstock availability from resides and waste with the use of biophysical model, which are presented in the box below.

Text Box 3.1 Current feedstock availability from resides and waste

When it comes to Europe as a whole, there is considerable potential for the availability of biomass feedstock for the future. Based on results from the BioBoost project, the total EU biomass technical potential, which can be dedicated for renewable energy in 2016, can be estimated at 416.3 Mt. The top five countries (with the highest biomass technical potential) are: (1) Germany, (2) France, (3) Spain, (4) Poland, (5) Italy. The most important biomass sources are: forest, straw and biodegradable municipal waste, which represent 37, 29, 18 % of total assessed biomass potentials. In case of manure and hay biomass, we can observe very high theoretical potential and a lack of technical potential in most of NUTS-2 region. This situation is due to the high demand for these resources in agriculture. However, this is a very beneficial effect of regional biomass utilization, which can be an additional advantage for the environment.

Figure 7 (below) presents the main agriculture, forestry, waste, and aquatic biomass feedstock categories that are addressed in this study. For the full list of feedstock categories, including the sub-types, please assess Deliverable 1.1 of the study.

Figure 7 Main feedstock categories addressed: ***The figure presents the main agriculture, forestry, waste, and aquatic biomass feedstock categories addressed in this study***

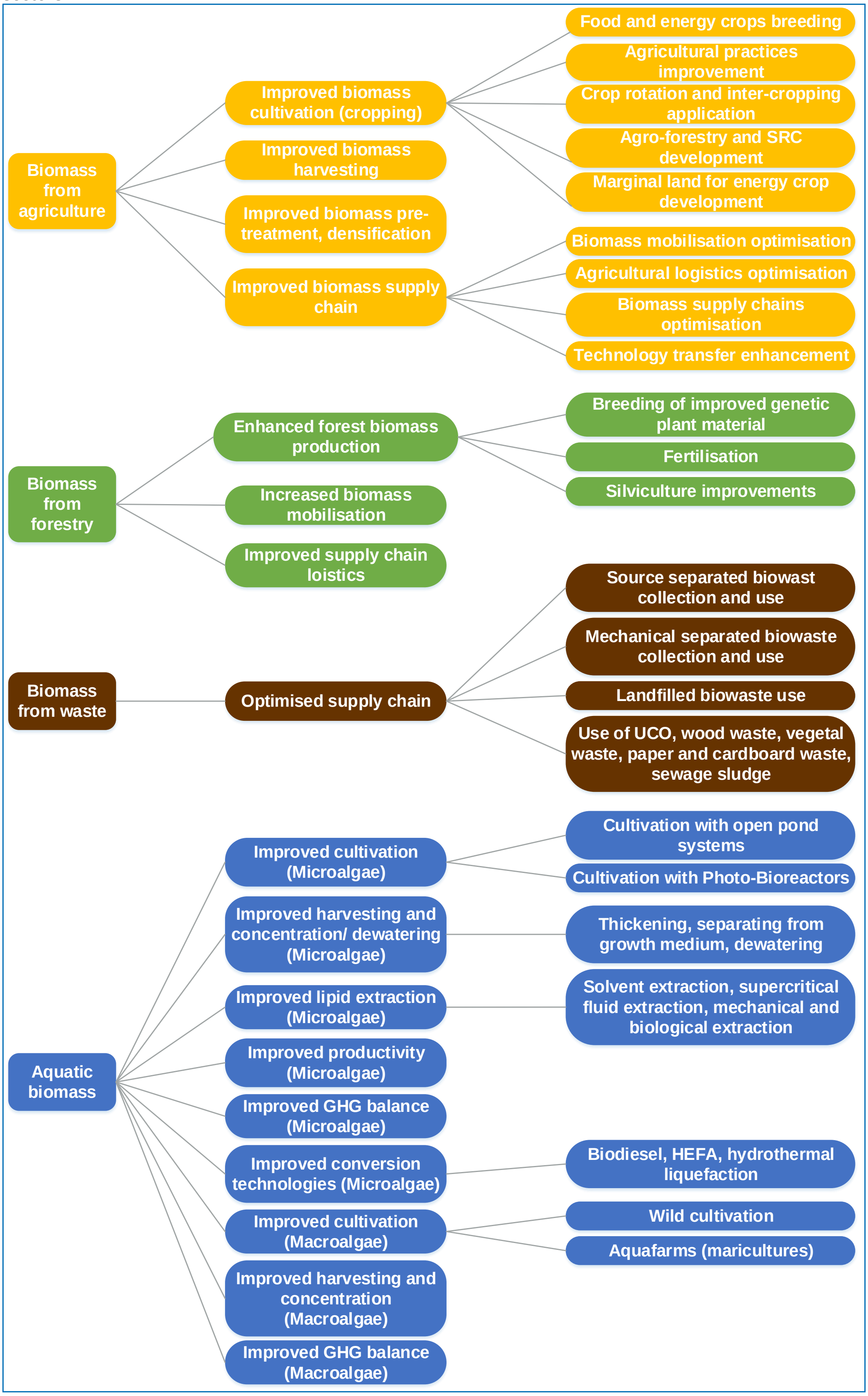


Source: Team analysis.

In the figure, Carbon Capture and Utilisation (CCU) is presented as a different category. CCU covers a variety of established and innovative industrial processes that utilise CO_2 as a source of carbon by transforming it into value added products such as synthetic fuels, chemical feedstocks or building materials. Thereby, carbon utilisation is regarded as complementary to CCS (Carbon capture and storage/sequestration) and often by definition does not include biological routes of transformation via aquatic biomass. At present it is difficult to predict the potential contribution of CCU technologies to the advanced (bio)fuel market in 2030 and 2050. The technology is also not part (yet) of the existing modelling suite. As a results CCU is not discussed here, but more details are provided in Deliverable 1.1.

Figure 8 (below) presents an overview of the main research & innovation fields - for agriculture, forestry, waste, and aquatic biomass - that are covered in this report.

Figure 8 R&I fields for agriculture, forestry, waste, and aquatic biomass: ***The figure presents the main R&I fields sorted by sector, which are relevant for enhancing biomass production in the four feedstock sectors***



Source: Team analysis.

3.2 Overview of the research and innovation potential of sustainable biomass production for transport fuels

Key Findings

- Primary crop residues and energy crops (both – woody and herbaceous cellulosic crops and new oil crops e.g. camelina and crambe) will likely be the most relevant future agricultural feedstock categories used for biofuels in Europe;
- Breeding of food crops in favour of energy dedicated ingredients (e.g. optimised straw/grain ratio) is developing; however, current scientific studies remain sceptical regarding actual contribution of those measures to increased availability of straw for energy use. The main criticism concerns increased management costs for farmers, increased risk of lodging (bending of stalks) and ethical debate concerning scarifying grain yield in favour of energy components;
- Breeding of better agricultural crop varieties (crops requiring lower water and fertiliser inputs, with increased resistance to pests and diseases) will have significant impact on increased availability of biomass for energy purposes. Better adopted crop varieties together with improved agricultural practices will allow closing existing yield gaps among European countries and can theoretically increase cereal yields by 30-75 % until 2020;
- Breeding efforts towards better adopted and more stress resistant energy crop varieties will extend the opportunities of growing crops on marginal lands, including polluted lands and fallow lands after recovery. In this study the availability and costs of energy crops have been modelled exclusively on the land areas which are released from other crops. Thus the obtained results reflect the potential and costs of growing energy crops on marginal/low quality land, avoiding competition with food crops;
- Genetically modified plants in recent studies produced 58 – 101 % more biomass yield compared with the non-transgenic control and allowed increasing biofuel yields by up to 38 % in conventional biomass fermentation processes. If research efforts in GM crops are intensified, our estimation is that attainable yield increases could exceed those of cereals for this reason by 33 %. However, the use of GM plants seems to be in conflict with current preferences of European citizens with few signs of more open attitudes. Therefore modelling scenarios in this study did not rely on the progress regarding the use of GM plants;
- Improved agricultural practices (crop rotation, intercropping and selection of better varieties) can increase the actual residue yields by at least 10-15 % for cereals and oil crops and by 20 % for vine prunings. Use of precision farming for better control of carbon stock in the soil, for optimal application of nutrients and water, is expected to amount to an additional 15 % increase on top of the cereal yield increase in the baseline scenario and will be important R&I contribution in the medium and long term – until 2030 and 2050;
- Improved harvesting machinery and methods as part of improved agricultural practices can increase the amount of currently collected crop residues by 35 % and with reduced cutting height additionally 50 % of crop residues (straw and stover) could theoretically become available;
- Measures targeting increased forest biomass production are estimated to have a realistic yield increase potential of around 30 %;
- Source-separated bio waste for biogas and UCO for biodiesel are waste feedstock categories with the highest potential.

3.2.1 R&I potential in the field of agriculture

Many previous research projects and studies, including the recently completed S2Biom project, acknowledge agriculture to be key for a substantial expansion of biomass supply in the future. There remains a high uncertainty, however, with regard to the amount of agricultural feedstock that can realistically be utilised for bioenergy production in a sustainable way and while still taking into account the demand from competing sectors.

Conventional energy crops used for the production of biofuels have been strongly criticised regarding their environmental impacts, primarily related to the concerns about indirect land use change (ILUC) impacts and associated emissions. Given these concerns, efforts in the agricultural sector have turned to a greater use of agricultural biomass residues (both primary and secondary), and energy crops (herbaceous and woody lignocellulosic crops as well as a new generation oil crops), which have high biomass yields, require less water and fertiliser inputs, and can be grown on marginal lands without interfering with food/feed production systems. Thus the work in this study focused on two main categories of agricultural feedstocks: i) crop residues and ii) dedicated energy crops. It should be noted that in the modelling of this study the envisaged areas to be used for growing energy crops are on below average quality land. Only the land that is released from other crops in a business as usual baseline has been used in the modelling for growing of energy crops.

An aim of this study is to identify research and innovation (R&I) activities in the agricultural sector which have the potential to increase the availability of agricultural feedstocks for advanced biofuels production in the future (in 2030 and 2050). Based on an extensive literature review and additional calculations of crop residue potentials, in the first step low ILUC and high potential agricultural biomass feedstocks have been selected as the most relevant at the EU level for the future bioenergy supply (see the overview in Deliverable 1.1).

Agricultural feedstock categories with the highest potential

Since many secondary crop residues have a limited potential to be used for bioenergy production due to their demand in competing sectors (mostly for animal feed production), the authors of the study decided to focus on the identification of R&I potential for increasing the availability of *primary crop residues* – straw, stalks and prunings. Regarding dedicated energy crops the modelling work focused on the main herbaceous and woody *cellulosic energy crops,* including miscanthus, giant reed, reed canary grass and SRC as willow, poplar and eucalyptus.

Text Box 3.2 Oil crops in this study

Besides cellulosic energy crops, this study estimated the potential supply of new generation oil crops in Europe for 2020, 2030 and 2050. Based on the state of the art of the current research in Europe, camelina (*Camelina sativa*) and crambe (*Crambe abyssinica*) have been identified as major candidates among currently researched oil crops for the future European bio-based economy. These findings are based on results of a recent EU funded Horizon 2020 Project COSMOS (Camelina and crambe Oil crops as Sources of Medium-chain Oils for Specialty oleochemicals). Both crops can be grown in a wide range of climatic and soil conditions, including saline and polluted soils, and are draught tolerant; however, they are frost sensitive and for achieving higher yields, milder temperatures are preferred.

Within this study potential oil yield of camelina and crambe in Europe has been calculated based on the following key assumptions:

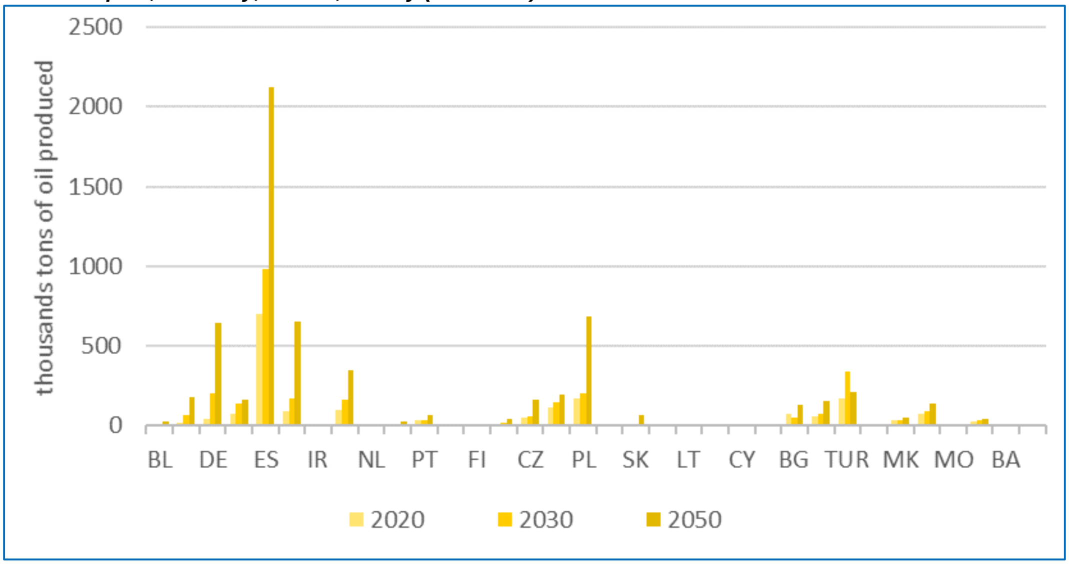
- Potential land areas were based on the same "base potential" used for modelling of the woody or herbaceous lignocellulosic crops;
- Potential areas were further limited to the territories with experiences and capacities of cultivating cereals, oil crops and pulses, since due to similar technology and management practices the probability

of adoption of new oil crops there is more likely than for instance in the areas dominated by fruits and vegetables, potatoes, olives and wine;
- Furthermore the areas which are affected by more than 5 days of frost of less than -5 degrees were excluded;
- Based on the literature, an average oil yield of 0,75 t/ha was assumed with annual yield increase of 2 %.

The above listed assumptions exclude several Northern countries – Finland, Estonia, Latvia and Lithuania, and some Balkan countries – Albania, Montenegro, Bosnia and Herzegovina and Kosovo completely from the potential areas of camelina and crambe cultivation.

The calculation results show potential availability of 1.86 million tons of oil in 2020, 2.82 million tons in 2030 and 6.13 million tons of oil could become available in 2050. Countries with the highest new oil crop cultivation potential are Spain, Germany, France, Turkey (until 2030) and Poland.

Figure 9 Oil crop production potential: ***Countries with the highest new oil crop cultivation potential in 2050 are Spain, Germany, France, Turkey (until 2030) and Poland***



Source: Team analysis.
Note: Since the same land areas as for lignocellulosic energy crops are assumed in this calculation, the result should not be considered as additional potential, but rather an alternative to lignocellulosic feedstocks.

The availability of agricultural biomass can generally be increased in two ways: through increased biomass production; and through optimised biomass harvesting, collection and supply.

Activities proposed for the short term (until 2020)

One of the conclusions from the expert validation workshop organised within this study was that R&I in breeding of energy crops is developing, but breeding itself is a complex, long term process and the effect of new energy crop breeding will not be visible in a short term perspective (until 2020). However, the agricultural feedstock availability can be increased in a short term by R&I measures in conventional food crop breeding and cultivation aiming to increase the amounts of available and collected primary crop residues.

To increase the absolute amounts of primary crop residues (straw and prunings) and make them available for energy purposes, first the existing yield gaps between European countries shall be closed.

The *selection of better crop varieties* is especially important in the short term, as well as *improved agricultural management practices* which, according to a recent study by Iqbal et al (2016) can theoretically increase cereal yields by 30-75 %. The relation between cereal grain and straw yield is not linear. There is a consensus in the recent scientific literature that straw yields can be further increased without compromising the yield of the main product. However, this does not mean that there would be no sacrifice of grain yields as these could have been higher without a specific focus on straw yield. Therefore this breeding goal is vulnerable to criticism from a global nutrition and sustainability perspective. It is considered in this study that grain yield is still the primary goal of cereal production, and increased straw yield should not bring along negative consequences such as increased susceptibility to lodging and diseases. Also, from a farmer's perspective, increased straw yield may increase fuel consumption, reduce the capacity of harvesting machinery as well as increase the demand for fertilisation, and these aspects must also be included in economic considerations (Iqbal et al., 2016). Therefore, the application of higher straw yielding varieties in practice will be limited and is not considered in future scenario modelling.

The authors further noted that the actual residue yield can be increased by 10-15 % for cereals and oil crops and by 20 % for vine prunings, when sustainability and technical limitations are respected and more advanced harvesting technologies are used. For instance, it is estimated that in future the improved harvesting machinery can increase the amount of collected crop residues by 35 % (calculated based on study of Iqbal et al. (2016)) and with reduced cutting rate (from >20 cm now to recommended 5 cm), additionally 50 % of crop residues (straw and stover) could become available. However, the given numbers are theoretical and in practice will be lower due to sustainability and economic feasibility limitations.

Influential R&I fields in middle and long term (until 2030 and 2050)

As mentioned above, in the middle and long term the R&I activities targeted to breeding and improved cultivation of next generation dedicated energy crops will provide the main contribution for increased agricultural feedstock availability for energy purposes.

Likely the most influential R&I activities for an optimised agricultural feedstock supply in the medium and long term include *breeding of dedicated energy crops* including lignocellulosic crops and new oil crops, and application of *precision farming*. It is expected that dedicated energy crop pre-breeding and breeding activities will be applied to develop more robust, biotic and abiotic stress-tolerant plants, which will be able to grow in less suitable soils (e.g. on marginal, less fertile land) and require fewer inputs in terms of water and fertilizers. Long term estimations and exact figures in the literature regarding potential increase of biomass availability with improved breeding activities (e.g. due to advanced breeding strategies, domestication of new energy plant species, optimised plant architecture or genetic modifications) are scarce. Some studies revealed that genetically modified plants produced 58 – 101 % more biomass yield compared with the non-transgenic control and increased ethanol yield by up to 38 % in conventional biomass fermentation processes. However, the use of GM plants seems to be in conflict with current preferences of European citizens with few signs of more open attitudes. This will constrain political acceptance and decision making to facilitate significant dissemination of GM plants such that our scenarios did not rely on progress regarding the use of GM plants. But even conventional breeding activities may be expected to have an above average yield increasing potential for new energy crops as these have not been intensively researched for decades as the main cereals. Attainable yield increases could exceed those of cereals for this reason by 33 %, if research efforts on new energy crops including herbaceous and SRC are intensified. This is a conservative estimate as there are several woody and herbaceous plants and research resources will be spread among them.

Application of precision farming methods and advanced information and communication technologies (ICT) will likely allow increasing the supply of both feedstock categories – crop residues and dedicated energy crops. Precision farming and advanced ICT will open new opportunities to increase crop residue removal rates without compromising soil fertility, and at the same time they will provide the overall increase of crop yields. The contribution of precision farming to increased yields is probably inferior to that of breeding because our current knowledge mainly relays on scientific trials with presumably good farm management. Therefore precision farming will be needed to ensure that high yields may also materialise under conditions of wider application but its yield increasing effect, including an optimised choice of future varieties, is expected to amount to an additional 15 % increase on top of the cereal yield increase rate which would bring us to a total mark up of 50 % for optimised farm management plus breeding gains.

Scenario development

Quantified information about potential yield developments and increased availability of crop residues due to advanced breeding efforts, the domestication of new species, optimised plant architecture or genetic plant engineering technologies in medium and long term is scarce. There are only a few studies providing a quantification of the yield increase. Although it has been measured that under laboratory conditions a genetically modified plant produced 58 – 101 % more biomass yield as compared to the non-transgenic control, low TRLs and the early advancements of R&I efforts in these fields do not yet allow reliable predictions regarding increase of biomass availability.

In order to facilitate the development of scenario storylines for the production and delivery of biomass feedstock (Pillar A of the modelled scenarios, as outlined in Chapter 2.3.2), several scenario elements have been identified for promising R&I activities in the fields of agriculture, forestry, waste, and aquatic biomass. The most relevant R&I activities for increased agricultural feedstock availability are summarised in Table 10 below, targeting either enhanced production of improved biomass supply.

Table 10 R&I scenario elements for increased availability of feedstock from agriculture

R&I scenario elements for enhanced production	R&I scenario elements for improved supply
• Yield increase of conventional (food/feed) crops due to breeding efforts. Breeding efforts to build up the resistance to biotic and abiotic stresses (drought, pests and diseases) as well as to increase residue to crop ratios (straw/grain ratio) are included. It will result in absolute increase of main crop biomass and crop residues and potentially providing more space for growing energy crops (if demand for food/feed can be satisfied with less land); • Enhanced production by growing dedicated energy crops on un-used agricultural lands. Further expansion of energy crops on non-agricultural areas (marginal lands) is anticipated in the future. Expansion on marginal lands will be possible because of breeding efforts targeted to developing more robust plants, which are able to grow in less suitable conditions; • Improved agricultural management practices (e.g. selection of varieties, crop rotation and intercropping, fertilization, water management, adoption of precision agriculture practices) to bridge the current gaps of	• Improved harvesting practices and machinery (development of new equipment for both – conventional and dedicated energy crop harvesting, improving harvesting practices, development of precision farming); • Increased mobilisation of agricultural biomass by optimised supply chain logistics (mobilization of so far unexploited biomass by using cleaner, more efficient and more cost-effective technologies, technology transfer, streamlining biomass supply chains with existing practices, development of new supply chains for dedicated energy crops); • Increased awareness and capacity of various actors involved in the biomass supply chain.

R&I scenario elements for enhanced production	R&I scenario elements for improved supply
yields among EU member states.	

The above described scenario elements were further used for the development of agricultural feedstock scenario narratives and assumptions to be used for the modelling with CAPRI. Table 11 below describes how the narratives have been implemented in the three scenarios.

Table 11 Implementation of R&I scenarios for increased availability of feedstock from agriculture

Scenario	Implementation of narratives
Reference scenario	• Yield data and regional distribution is based on aggregated data of S2BIOM; • Yield increase of energy crops in the reference scenario is assumed at equal rate as projections for yield increase of cereals in CAPRI.
Enhanced production scenario	• Yield increase of energy crops exceeds by 50 % the one for cereals in 2050 because of: - the development of hybrids of specific crops dedicated to energy; - development of more robust – stress resistant energy crops as a result of pre-breeding and breeding activities; and - domestication of new energy crop species. • In the long term the effects of development of genetic research are considered. Availability of straw and pruning residues is assumed to increase by 40 % until 2050 in a typical situation where current management only permits to remove 50 % of residues. This rests on improved agricultural management practices alleviating pressure on the carbon balance, including: - selection of higher residue yielding varieties; - adjusting of N fertilization rates to increase residue yield; - varying sowing time and rate; - optimized cropping systems with crop rotation, multi-cropping, catch and cover crops use; - selection of tillage system (e.g. studies show that only around 35 % of the maize residue is available in conventional tillage, but in the case of no till farming, 68–82 % of the maize residue can be available). • development and adoption of precision-agriculture practices in irrigation, fertilisation, seeding and crop protection, e.g., through increased water and nitrogen use efficiency and digital farming.
Improved supply scenario	• The use of improved harvesting technologies and practices leads to 20 % decline in labour and capital costs by 2050 because of: - development of new, more efficient equipment to collect agricultural residues from the field (collection of residues from primary crops results in no more than 40 % removal of stover or straw on average. Future residue collection technology with the potential of collecting up to 75 % of the residue is envisioned); - Reducing the cutting height (currently, the cutting height for cereals and oil crops is more than 20 cm depending on crop variety. If residue specific machinery is used, the residue harvest can be increased theoretically up to 50 % in case of straw from cereals and oil crops); - Development and wide application of new harvesting technologies specific for dedicated energy crops; - Application of precision agriculture practices in harvesting and farm logistics operations, e.g. by introduction of new machines which are able to provide high resolution information and with the capability of site specific agriculture management, determination of actual sustainable straw removal rates for each location. • Besides advances in harvesting machinery and methods, the cost reduction is affected as well by optimized supply chain logistics and increased awareness of actors involved in

Scenario	Implementation of narratives
	the biomass supply.

Key assumptions for agricultural feedstock scenario implementation

Groundwork for this study was performed under the S2BIOM project (see Dees *et al*., 2017) providing current costs and yields for energy crops as well as crop residues down to the NUTS3 level. The detailed S2BIOM information has been aggregated for use in the modelling suite of this study as shown in the table below:

Table 12 Matching of biomass categories between CAPRI and S2BIOM

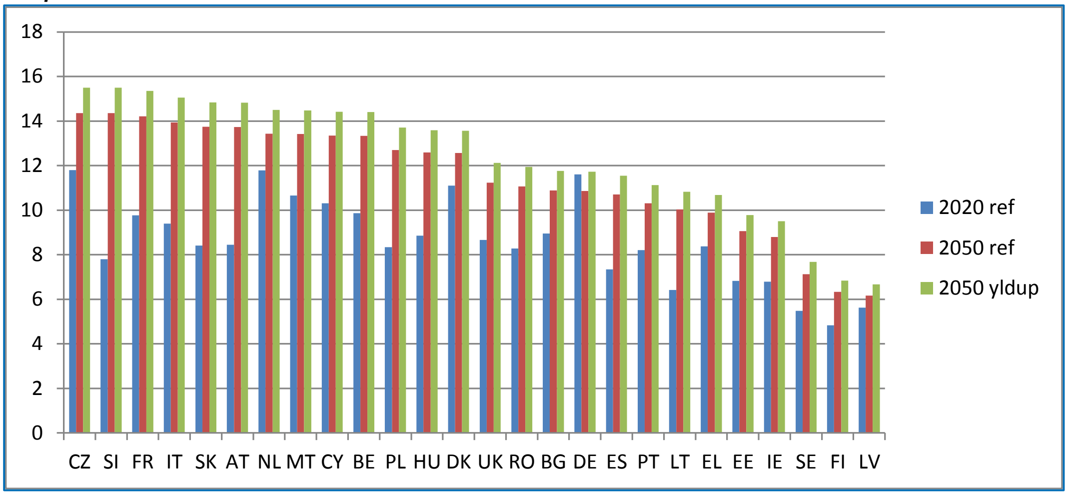
CAPRI biomass category	S2BIOM biomass types
Woody energy crops	Willow, poplar, eucalyptus
Herbaceous energy crops	Miscanthus, switch grass, reed canary grass, giant reed, and cardoon
Straw	Residues from wheat, barley, oats, rye, rice, maize, and other cereals
Pruning	Pruning residues from olive groves, vineyards, and fruit trees

In order to avoid the impacts related to indirect land use change (ILUC), the potential for dedicated energy crops has been defined assuming that they are only grown on fallow land or on land, which is released from agricultural production. Other areas in conflict with sustainability objectives have been excluded from the technical potential as well (Natura 2000 areas, High Nature Value farmland, wetlands, peatlands, and permanent grassland areas). For the use of straw and prunings, carbon balance related sustainability limits have been adopted from Miterra model estimates (see again the S2BIOM Deliverable 1.6 for details).

The yields of new energy crops have been assumed to increase similar as those of cereals in the *Reference* scenario. For the *Enhanced production* scenario it has been assumed that the combined effect of improved farm management practices (crop rotation and intercropping, fertilization, water management, adoption of precision agriculture practices) and of using better plant material (higher yielding, more resistant varieties) would permit to achieve yield increases that exceed those of cereals by 50 %.

Figure 10 shows that dry matter yields of woody energy crops in 2050 are expected to range from 6 (Latvia) to 14 (Czech Republic) tons DM per ha and would increase moderately in the “enhanced production” scenario (=”yldup” in the figure).

Figure 10 Variation of yields for woody energy crops across countries, time and two scenarios (reference and enhanced production)*: The yields increase in the enhance production scenario as compared to the reference scenario in 2050*

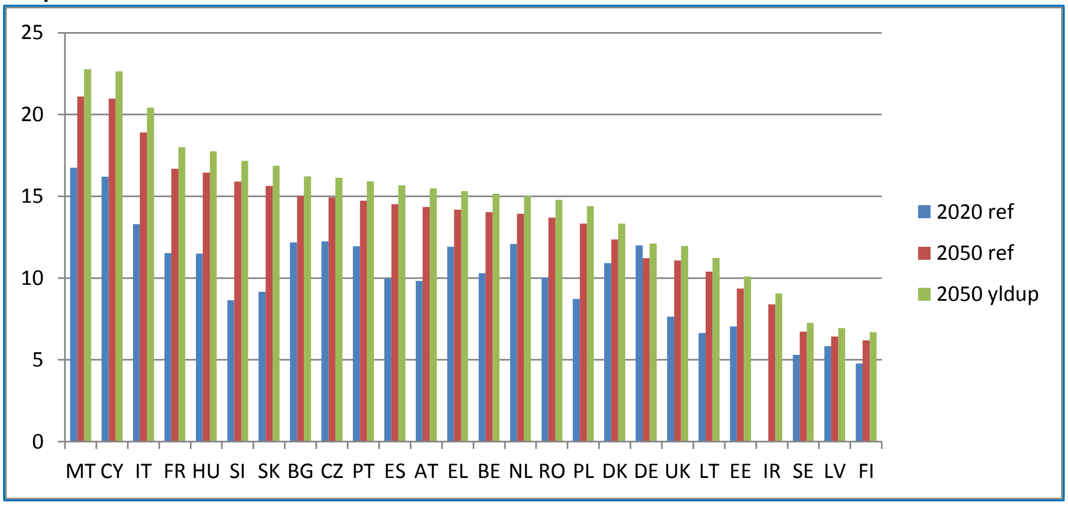


Source: CAPRI aggregations based on S2BIOM data. Country codes as used by Eurostat.

Over time the yield growth is non-uniform across countries.[24]

Figure 11 shows the corresponding range for herbaceous energy crops where highest yields of 21 tons per ha may be expected in Malta (based on irrigation at the illustrated point of full capacity use) that could increase to 23 tons under “enhanced production” (= “yldup”).

Figure 11 Variation of yields for herbaceous energy crops across countries, time and two scenarios (reference and enhanced production): *The yields increase in the enhanced production scenario as compared to the reference scenario in 2050*



Source: CAPRI aggregations based on S2BIOM data. Country codes as used by Eurostat.

For crop residues, straw yields have been linked to cereal yields according to functions adopted from the literature (and also used in S2BIOM; Dees *et al*., 2017), without a focus on the straw to grain ratio. However, it has been assumed that improved farm management practices in favour of increased carbon accumulation in soils allows to remove a larger fraction of crop residues as compared to the reference. Yields of straw and pruning residues are far lower than those of dedicated energy crops; yet, this is not surprising given that these are residues, secondary to the main harvest on these areas. However, under favourable conditions, 4 tons of DM from straw may be expected per ha.

R&I activities considered in the *Improved supply* scenario are assumed to reduce costs. Some cost elements have been linked to yield developments (fertiliser, fuel, plant protection, plant material, and irrigation). For labour and capital costs it has been assumed that productivity increases would exactly balance any price increase such that the costs would remain constant per ha. Based on the references collected in Task 1.1, harvesting technology improvements could achieve a cost reduction of 10-30 %. Therefore, it has been assumed in the improved supply scenario that a 20 % decline in labour and capital costs by 2050 is feasible whereas they would be constant in the *Reference* scenario.

[24] In Germany, there is apparently no yield growth at all. This is, however, purely due to regional aggregation effects as the new energy crop area is also increasing over time. Yields within each region, single crop (willow, poplar, eucalyptus) and land quality class are increasing but their weights change and produce the surprising outcome for Germany.

3.2.2 R&I potential in the field of forestry

Bioenergy generated from woody biomass is currently the largest renewable energy source in the EU. Although its relative share is slowly declining, woody biomass is expected to maintain a large role among bioenergy feedstocks. Felling rations in European forests vary regionally, ranging from 42 % in Southeast Europe to 79 % in Northern Europe, implying that in most European countries forest biomass utilisation could be intensified.

The S2BIOM project recently calculated up-to-date forest biomass resource potentials up to 2030 and indicated that high biomass mobilisation could increase the base potential by 15-20 %. The review of the scientific literature and analysis of ongoing or recently completed European research projects on forest biomass utilisation indicated that several measures exist that could enhance forest biomass production as well as that the utilisation of the existing biomass availability could be optimised.

The impacts of measures targeting increased forest biomass production

The impacts of measures to increase the mobilisation of biomass potentials are more difficult to quantify, because there is considerable uncertainty surrounding how social processes and societal preferences can be influenced in reality. Forest management is characterised by very long production cycles, therefore there are significant time lags before changes in forest productivity can result in enhanced biomass potentials. Major measures, such as planting improved genetic material, can only be implemented at the end of a management cycle and consequently only small shares of the total forest area are subject to possible changes each year. Nevertheless, measures targeting increased forest biomass production are estimated to have a *realistic yield increase potential of around 30 %*.

Scenario development

The most relevant R&I activities for increased forestry biomass feedstock availability are summarised in Table 13 below.

Table 13 R&I scenario elements for increased availability of feedstock from forestry

R&I scenario elements for enhanced production	R&I scenario elements for improved supply
• Use of more appropriate breeding material for main production tree species; • Use of new, more productive varieties for main production tree species through tree breeding; • Introduction of Douglas fir on sites when Norway spruce dominated stands are felled; • Fertilisation of forests growing on poor soils.	• Successful translation of recommendations on wood mobilisation and increased awareness of owners lead to an increased mobilisation of wood from forests. New forest owner associations or co-operations are established throughout Europe. Together with existing associations, these new associations lead to improved access of wood to markets; • Strong mechanisation is taking place across Europe; existing and new technologies are effectively shared between countries through improved information exchange, enhancing also the extraction of biomass from rugged terrain and water logged sites; • Trees are harvested more efficiently, which results in a reduction of harvest losses and thereby logging residues; • Biomass harvesting guidelines become less restricting, because technologies are developed that are less harmful for the environment. As a result, biomass from all tree compartments (stems, logging residues and stumps) are extracted; • Improved harvest machinery is applied, which reduces environmental impacts and thereby allows for increased forest biomass extraction;

R&I scenario elements for enhanced production	R&I scenario elements for improved supply
	• Innovative harvesting, supply-chain logistics and mobilisation is available resulting in more efficient felling, extraction and transport of woody biomass; • Application of fertilizer is permitted to limit detrimental effects of logging residue and stump extraction on the soil.

Key assumptions for forestry feedstock scenario implementation

The above described scenario elements were further used for the development of forestry feedstock scenario narratives and assumptions for the modelling. The EFISCEN and EFI-GTM models have been jointly applied to estimate available biomass from the forestry sector. First, EFISCEN simulated the maximum availability of stemwood, logging residues (stem tops, branches) and stumps from thinnings and final fellings by tree species for all uses (i.e. products, chemicals, energy, etc.) from forests available for wood supply (i.e. forest biomass potentials from strictly protected forests or other areas where harvest is not possible or allowed are not considered). EFI-GTM used this information to estimate how much biomass would potentially available at different costs levels for energy, taking into account demand and trade of forest products. Table 14 describes the narratives developed for the three scenarios as implemented in the two models.

Table 14 R&I scenario narratives for increased availability of feedstock from forestry

Reference scenario	Enhanced production scenario	Improved supply scenario
• Estimate theoretical biomass potentials based on current growth rates, tree species composition and management guidelines; • The effect of ownership structure on mobilisation is considered by linking size-classes of privately owned forest holdings with the maximum extraction rates per size-class. A non-linear relationship is assumed in which the maximum harvest level is 50 % in forest holdings, <1 ha, increasing to 85 % in forest holdings ≥5 ha and to 96 % in forest holdings ≥80 ha; • Constraints affecting the extraction of forest residues are considered with regards to site productivity, soil and water protection, biodiversity protection, recovery rate and soil bearing capacity. The quantification of these constraints is outlined in Annex III of D1.2); • Maximum potential availability	• Estimate theoretical biomass potentials based on modified practices to increase productivity: - Upon final felling, regenerate 50 % of forests dominated by species for which breeding programmes exits (Scots pine, Maritime pine, Norway spruce, Sitka spruce, Douglas fir, larch and poplar). These stands grow 25 % faster as compared to current varieties due to improved species-site selection, improved genotypes and optimised regeneration techniques; - Regenerate 25 % of the Norway spruce forests upon final felling with Douglas fir; - Fertilisation of forests growing on poor soils, excluding forests on peatlands. Fertilisation is implemented 20 years before the start of final fellings for conifers and	• Estimate theoretical biomass potentials based on modified practices to harvest, mobilise and transport forest biomass: - Fellings are carried out more efficiently and we assumed that the ratio between removals and fellings is increased by 5 %-points, i.e. there will be less harvest losses. This will result in more stemwood, but less stemwood residues; - Mobilisation of wood from private forest owners is raised by 5 %-points (with 100 % as maximum), as compared to the Reference scenario; - Improved technology and techniques are assumed resulting in less restrictive constraints on the extraction of forest residues with regards to site productivity, soil and water protection, biodiversity protection, recovery rate

Reference scenario	Enhanced production scenario	Improved supply scenario
of woody biomass based on the Reference scenario is taken from EFISCEN as main input on the wood supply assumptions in the EFI-GTM model; • Demand for forest products takes into account recent trends of declining graphic paper consumption and slow recovery of the wood products consumption; • Price elasticity of roundwood supply was set at 0,5.	long-lived broadleaves and 10 years in the case of short-living broadleaves. The expected growth increase is 10 % 5 years after fertilisation and 5 % 10 years after fertilisation. • Other assumptions for EFISCEN are the same as for the Reference scenario; • Maximum potential availability of woody biomass based on the Enhanced production scenario is taken from EFISCEN as main input on the wood supply assumptions in the EFI-GTM model; • Demand for forest products is assumed the same as under Reference scenario; • Price elasticity of roundwood supply same as under Reference scenario.	and soil bearing capacity assumptions on the extraction of forest residues, as compared to the reference scenario (see Annex III of D1.2 for details). • Other assumptions for EFISCEN are the same as for the Reference scenario; • Maximum potential availability of woody biomass based on the Improved supply scenario is taken from EFISCEN as main input on the wood supply assumptions in the EFI-GTM model; • Demand for forest products is assumed the same as under Reference scenario; • A reduction of the forest residues harvesting + forwarding + transport costs by 20 % in 2030 and 30 % in 2040; • Price elasticity of roundwood supply was set at 1 to reflects higher willingness of the forest owners to supply wood.

Feedstock availability from forests is estimated for the all scenarios using recent information on current forest structure growth rates, tree species composition and management guidelines, as well as constraints that limit the mobilisation of biomass from forests. These constraints include:

- Site productivity (limits residue extraction on poor soils);
- Soil and water protection (limits residue extraction to prevent erosion, soil compaction and water pollution);
- Biodiversity protection (reduces stemwood and residue extraction to prevent loss of biodiversity);
- Recovery rate (limits residue extraction level based on slope and machinery);
- Soil bearing capacity (limits mechanised harvesting of biomass on certain soil types);
- Ownership structure (reduces stemwood and residue extraction based on forest holdings the size of privately owned forests).

These constraints are quantified in the Reference scenario based on previous studies (Verkerk et al. 2011; Dees et al. 2017) (see Annex III of Deliverable 1.2). The Enhanced production scenario considers the same constraints, as well as the use of more appropriate breeding material, the use of new and more productive varieties for main production tree species through tree breeding, the introduction of Douglas fir on sites when Norway spruce dominated stands and fertilisation of forests growing on poor soils, as outlined in Table 12. The Improved supply scenario assumes improved mobilisation from privately owned forests and that fellings are carried out more efficiently.

Furthermore, techniques are assumed resulting in less restrictive constraints on the extraction of forest residues.

Supply costs of the roundwood are based on sawlogs and pulpwood prices in 2010 in the Reference and Enhanced production scenarios and include stumpage prices, harvesting, hauling, and transport costs to the mill gate. Forest residues supply costs are based on S2BIOM data on road side costs. In addition, €7/m^3 are added to take into account the average transports costs from a road side to a mill gate. Wood residues are by-products from sawmilling and their costs are therefore based on the shadow prices from the EFI-GTM model equilibrium solution. The Improved Supply scenario assumes a reduction of the forest residues harvesting + forwarding + transport costs by 20 % in 2030 and 30 % in 2040. Furthermore, the price elasticity of roundwood supply (indicating the responsiveness, or elasticity, of the roundwood quantity supplied to a change in its price) was set at 0,5 in the Reference and Enhanced Production scenarios, while it was set to 1 under the Improved Supply scenario. This reflects higher willingness of the forest owners to supply wood under Improved Supply scenario, which is in line with lower technical and social constrains set under Improved Supply scenario.

3.2.3 *R&I potential in the field of waste*

Efforts in research and innovation are ongoing in all parts of the European waste sector. However, in many Member States approved measures have not yet been implemented so as to make the best us of the bio-energetic potential of waste. A proper implementation of these measures shows the highest potential for enabling a significant increase in feedstock for sustainable bioenergy production.

Waste feedstock categories with the highest potential

The waste feedstock with highest potential for increasing biomass supply are considered to be source-separated bio waste for biogas, and UCO for biodiesel. It has been demonstrated that the best feedstock for biogas production out of bio waste can be provided when the waste is source-separated. Other measures can be taken into account when source-separation is not possible, however will normally result in lower quality feedstock for bioenergy production (the same goes for an increased collection of woody waste). Regarding the availability of UCO for biodiesel production, the separation (provision of suitable containers) and collection measures can have the best leverage effect. What these measures have in common, however, is that the active support of individuals is needed. Awareness about the topic should be raised, as the “human factor” is crucial for an increased availability of sustainable feedstock out of waste.

Scenario development

The most relevant R&I activities (scenario elements) for increased biomass feedstock availability from waste are following:

- Increasing availability of UCO/FOG by increasing collection yields due to extended application of separation and collection methods (from 2017), by:
    - Information campaigns in all EU countries (school level as well as for adults) where that has not been done yet (taking into account lessons learnt from conducted studies);
    - Development of efficient and accepted collection infrastructures;
- Increasing availability of the organic waste fraction (pre-sorted and out of commingled MSW) by mobilising at source separation, using most advanced separation technology and using suited AD plants for energy generation (from 2017), by:
    - Information campaigns directed at school and adult level for enhanced separation of biogenic fraction at source (i.e. home);

- Using of most modern industrial separation technologies for maximising organic waste yield out of commingled waste streams;
- Using of state of the art waste fermentation plants for the recovered organic fractions;
- Supporting schemes for extended construction of aforementioned plants in the EU in a decentral manner;

- Wider use of recent technology developments resulting in increased availability of organic waste.

The above identified scenario elements were further used for the development of scenario narratives and assumptions for the modelling of overall scenarios with PRIMES. Table 15 below describes the narratives developed for two of the scenarios.

Table 15 R&I scenario narratives for increased availability of feedstock from waste

Reference scenario	Improved supply scenario
No major changes in the use of organic waste fractions. The most actual data is used to show the status quo. The Baseline scenario from the S2BIOM project has been used as input for the relevant feedstock categories (MSW and post-consumer wood).	Considerably more organic waste feedstock will be used for energy generation. The assumptions go in line with studies conducted in this field. The “User defined potential” scenario from the S2BIOM project has been used for the feedstock categories for which it was available.

Key assumptions for waste feedstock scenario implementation

The quantification of information for further use in the modelling was based on a collection of studies, reports, and other scientific material. The analysis focused on the potential use of the organic fraction of municipal solid waste (OFMSW), used cooking oil (UCO), and the available post-consumer woody waste, as these could play a key role for the production of advanced biofuels.

For the modelling of the further development of available OFMSW, the actual separation rates were considered and moderately increased, taking into account the actual level of waste separation and the known efforts of the different Member States.

The potential availability of UCO for biofuel production is mostly dependent on collection measures. Results from a study on behalf of EWABA showed UCO collection best practice examples.

For post-consumer wood, data from the S2BIOM project has been used for 2020 and 2030. A linear increase per Member State, based on information from the PRIMES-BIOMASS model, was used to derive the potential for 2050.

The success factor for all measures is the active participation of the citizens. A better awareness concerning the chances of separated biowaste was assumed and led to the potentials as shown in Deliverable 1.2.

3.2.4 R&I potential in the field of aquatic biomass

Microalgae production takes place worldwide for food and feed products at a commercial scale, with an annual production volume of 9 200 tonnes. This aquatic biomass is primarily cultivated in open pond systems in regions with sufficient solar radiation and the corresponding, appropriate temperatures such as Israel, Australia, Asia, the United States and Southern Europe.

Progress in R&I in the field could lead to a shift in cultivation methods, from open pond systems to closed Photo-Bioreactors (PBRs), focussing on biofuel production. The operation of PBRs from pilot to demonstration scales (i.e. small commercial scale) could first take place in moderate temperatures in proximity to industrial facilities, with an ample CO_2 supply.

Focus will be placed on the further development of algae strains with high productivity rates and lipid content, such as *Chorella vulgaris*, *Chorella sp.* or *Dunaliella salina.*

The enhanced production of microalgae is expected to be realised by 2030-2050

Although an increase in the microalgae supply is expected within the medium to long term, the costs thereof are likely to remain high. It is anticipated that a microalgae technical production potential of 41 Mt/y in Europe at costs below 1 330 €/t can be realised by 2030, as well as a subsequent tripling of the microalgae production volume per decade and a decrease of production costs below 840 €/t by 2050.

Further R&I efforts will also lead to an implementation of harvesting methods that are already commercially available for the food and feed sector (such as flocculation, sedimentation, filtration as well as centrifugation) within the microalgae-to-biofuel value chains. Lipid extraction methods and the direct conversion of microalgae to biofuels via the HTL route will be economically viable at a pilot scale, and the production of the first batches of advanced microalgae-based biofuels with a GHG emission reduction potential of 30 % is expected by 2030.

Macroalgae (seaweeds) production is currently taking place at a much larger scale, with 80 % of the global annual production of approximately 23,8 million tonnes used for direct human consumption. The remaining 20 % are used for the production of cosmetic, nutritional, or chemical supplements, however not as yet for the production of biofuels such as bioethanol or biogas.

Macroalgae production is expected to double by 2030

Progress in R&I could focus on making use of macroalgal biomass for the production of biofuels, with about 10 % of the global production volume as an initial benchmark. However, no wildly harvested macroalgae should be used for biofuel production due to sustainability constraints, and all feedstock shall be produced in aquacultures. With increased R&I efforts in the field it is anticipated that aquaculture production volumes of macroalgae could double by 2030 as compared to current volumes, and a further tripling of macroalgae production is to be achieved every ten years after 2030. Furthermore, production costs are foreseen to decrease to 40 €/t (wet) by 2030, with a subsequent cost decrease of 20 % per decade until 2050, and beyond.

Scenario development

The most relevant R&I activities (scenario elements) for increased aquatic biomass feedstock availability within two scenarios, namely the reference and the enhanced production scenario, are briefly presented in the tables below.

Table 16 R&I scenario narratives for increased availability of feedstock from microalgae

Reference scenario	Enhanced production scenario
• Focus on microalgae in open pond systems (low biomass concentration of < 3 g/L); • Moderate cultivation of microalgal biomass in closed PBRs due to the high costs linked to cultivation, high energy requirements and generally high production costs; • Moderate R&I efforts on improvement of algae strains, harvesting methods and conversion technologies.	• Increased R&I efforts for the development of Photo-Bioreactor (PBR) systems; • Cultivation is shifted from open pond systems to closed PBRs with the aim of biofuel production; • Increased operation of PBRs at pilot to demonstration scale (i.e. small commercial scale) in moderate temperatures and in proximity to industrial facilities with ample CO_2 supply; • Targeted R&I efforts on algae strains with high productivity rate and lipid content such as chorella

Reference scenario	Enhanced production scenario
	vulgaris, chorella sp. or Dunaliella salina; • Adaption of harvesting methods that are commercially available for the food and feed sector such as flocculation, sedimentation, filtration as well as centrifugation to microalgae-to-biofuel value chains; • R&I efforts on direct conversion of microalgae to biofuels via the HTL route at pilot scale.

Table 17 R&I scenario narratives for increased availability of feedstock from macroalgae

Reference scenario	Enhanced production scenario
• European macroalgae relies on wild harvest, which is accompanied by a series of detrimental impacts on the marine ecosystem; • Moderate R&I efforts in the field of aquaculture production of macroalgae; • Moderate use of macroalgae for the production of biofuels such bioethanol or biogas.	• Increased R&I efforts in the field of aquaculture production of macroalgae while wild harvest of seaweeds is decreased; • Focus on making use of macroalgal biomass for the production of biofuels. 10 % of the global production volume could be an initial benchmark.

Key assumptions for aquatic biomass feedstock scenario implementation

In the reference scenario for microalgae, progress is expected to happen due to the continuation of on-going R&I activities. However, only those Member States where microalgae R&I activities are reportedly taking place at present have been considered to produce microalgae in the future. Most of the data for the year 2030 are based on the calculations by Skarka (2015) regarding the cost-based technical microalgae production potential. It has been assumed that the technical production potential stated by Skarka can be realized by 2030, under the assumption that current R&I activities are continued, but no enhanced efforts for the development of PBR technologies are taken. According to Skarka, this technical production potential of 41 Mt/y in Europe can be realized at averaged costs of 1 330 €/t. This value is used as the costs of producing 1 t of microalgal biomass in 2030. In the reference scenario it is assumed that the maximum supply remains constant between 2030 and 2050, but that price levels decrease by 20 % in the same period.

In the enhanced production scenario, it is assumed that due to increased (with respect to the reference scenario) R&I efforts to enhance aquatic biomass production potential the maximum supply triples every decade from 2030 onwards. Such R&I efforts include strain development and breeding on promising algae strains with high productivity rate and lipid content such as chorella vulgaris, chorella sp. or Dunaliella salina, improvement of harvesting and dewatering methods (e.g. flocculation, sedimentation, filtration entrifugation), efficiency increases of lipid extraction technologies as well as the further development of Photo-Bioreactor (PBR) systems. Future progress on the direct conversion of microalgae to biofuels via e.g. the HTL route will also require dedicated R %I efforts. Due to such increased R&I activities furthermore the production costs are assumed to decrease by 30 % per decade after 2030 in the enhanced production scenario.

In the reference scenario for macroalgae, progress is expected to happen due to the continuation of on-going R&I activities, but it is assumed that European macroalgae production almost completely relies on wild harvest. Macroalgae are thus only harvested and further processed in countries located by the sea. Therefore, only countries that meet this criterion are considered. It was assumed in the reference scenario that the production volumes stated by West et al. (2016) double until 2030 and remain constant until 2050.

For the enhanced production scenario, it was assumed that due to progress resulting from increased R&I activities, production volumes estimated for 2030 (based on West et al. 2016) triple every decade between 2030 and 2050. Such R&I efforts include productivity improvements of macroalgae strains in aquaculture systems though strain developmentand optimised algae growth conditions as well as improvements in harvesting and concentration technologies. Furthermore, R&I progress is expected on the conversion of macroalgae for the production of biofuels (e.g. via hydrothermal up-grading or pre-treatment and hydrolysis). It is further assumed that R&I efforts lead to a decrease of the price of macroalgae production to 40 € per tonne (wet) by 2030. In line with the approach taken for microalgal biomass, it is assumed that prices decrease by 30 % per decade while production volumes triple.

3.3 Research and innovation scenarios for biomass potential

Key Findings

Agriculture:

- Primary crop residues and cellulosic energy crops – the most relevant agricultural feedstock categories for biofuels in future;
- Selection of better adopted crop varieties and improved agricultural management practices – important short term (until 2020) activities to close existing yield gaps among European countries;
- Precision farming, breeding to achieve greater robustness of plants - the most influential R&I fields in mid- and long-term (until 2030 and 2050).

Forestry:

- Forest sector is estimated to be and remain the largest potential supplier of biomass;
- Measures related to improving supply have the strongest impact on availability and costs of woody biomass until 2050;
- Measures to enhance production appear to be less effective concerning availability and costs of woody biomass until 2050 due to long rotation cycles. These measures should nevertheless be considered already now to guarantee availability in the future.

Waste:

- Organic solid municipal waste and non-hazardous post-consumer wood represent sizeable feedstock available at no or very low costs;
- Used cooking oil represents a rather small potential.

Aquatic biomass:

- Biomass from microalgae is currently negligible but its theoretical potential is large: it has the potential to become the 2nd largest biomass feedstock sector by 2050;
- Yet, aquatic biomass from microalgae can only be supplied at very high costs, thus low competitiveness for bioenergy production is expected (low economic potential);
- Macro-algae will likely be produced in aquacultures, and production is expected to double by 2030, with a rapid cost decrease foreseen; yet, its usage might be too expensive for biofuels production;
- While there is great theoretical potential for growth in aquatic biomass up until 2030 and 2050, the predictions are rather uncertain due to the likelihood of continued high costs and sustainability constraints.

All:

- R&I measures are able to significantly increase availability of biomass by 2050;
- Full potentials can only be realized at very high cost.

3.3.1 *Feedstock scenario implementation*

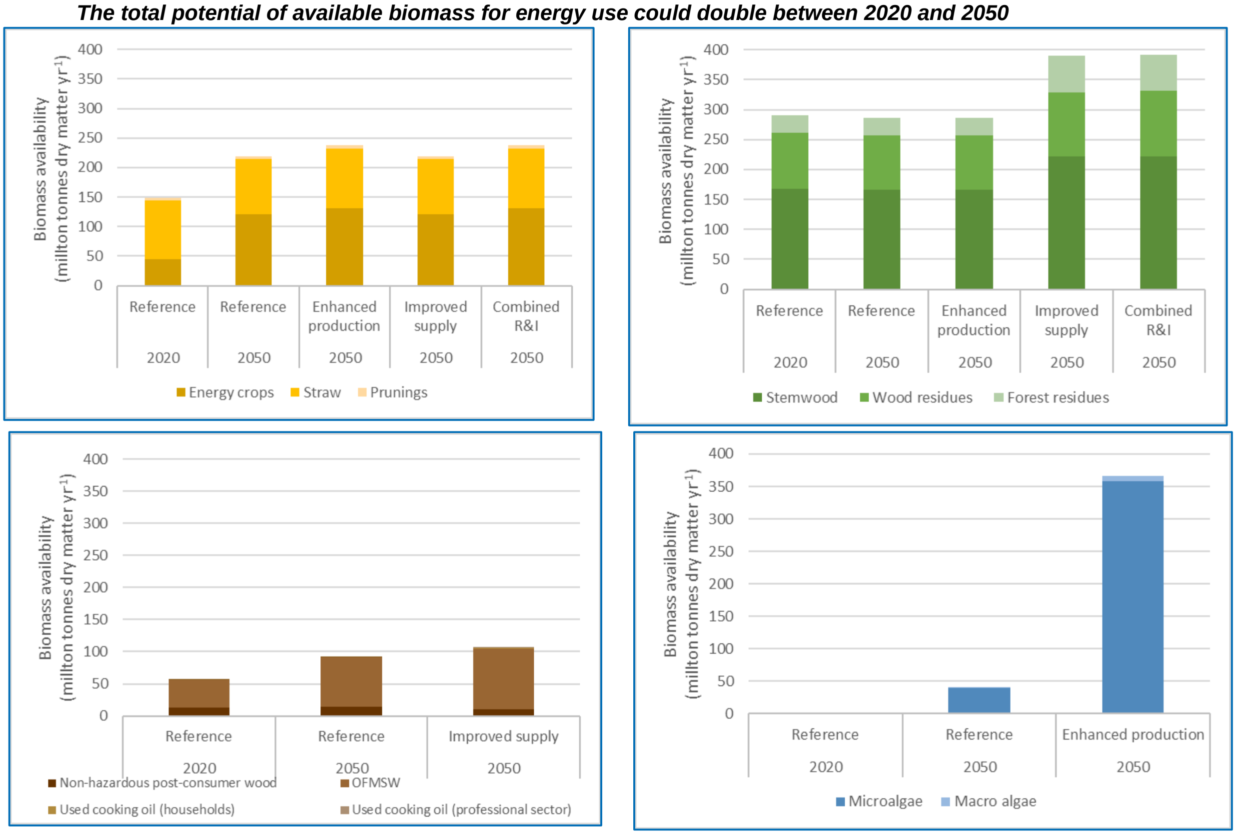
The general feedstock scenario storylines have been outlined in Section 2.3.2. Based on the identification of R&I measures, the feedstock scenarios have been elaborated and implemented as described in section 3.2. The potential of biomass for energy up until 2050 was then quantified for the three feedstock scenarios using models (CAPRI, EFISCEN, EFI-GTM) for the agricultural and forestry sectors and calculations based on literature and other data sources for the waste and aquatic biomass sectors. In the following sections, the main results for each of the feedstock scenarios are presented. The potentials that are estimated and presented are considered to be available for all energy uses. Biomass for other uses (e.g. stemwood biomass for material production) have been excluded. The use of these biomass potentials for advanced biofuels and other energy uses is considered in chapter 4.

3.3.2 *Potential availability of biomass for energy uses*

Total biomass availability for energy use could double between 2020 and 2050

According to the results for each sector, the total biomass availability for energy in 2020 is estimated at 497 million tonnes dry matter (DM) per year (Figure 12). The forestry sector is estimated to contribute 59 % of this potential availability, followed by agriculture (20 %) and waste (12 %). It should be noted this this is the total estimated biomass availability, and includes biomass that is already used. For example, fuelwood and wood residues are already used to a large extent to generate energy.

Figure 12 Summary of the estimated potential availability of biomass in the EU per sector and scenario: ***The total potential of available biomass for energy use could double between 2020 and 2050***

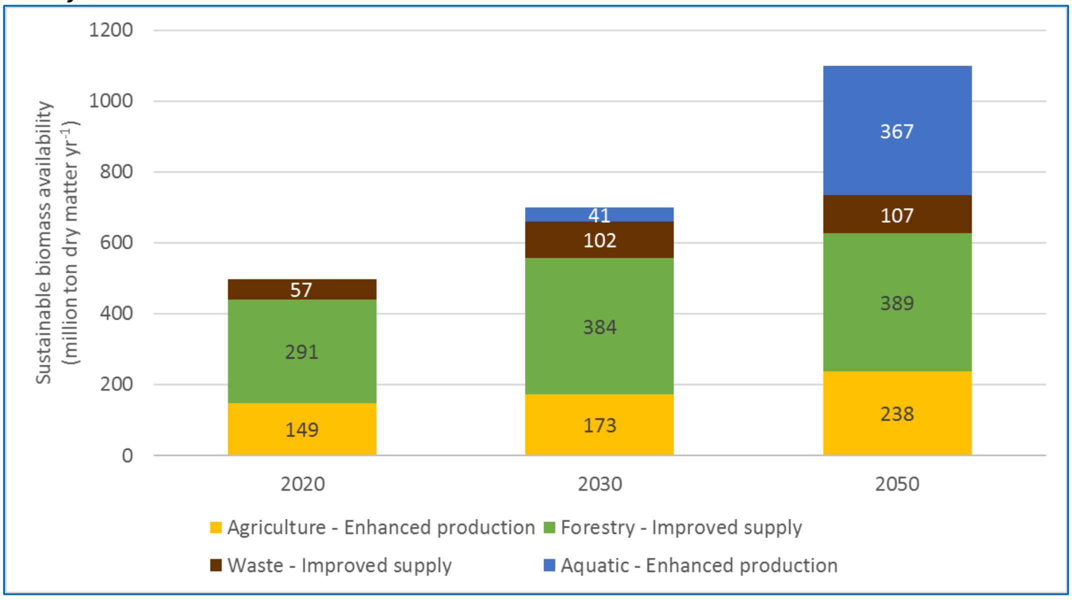


Source: Team analysis; Deliverable 1.2.

Note: Potential biomass availability has not been estimated for all scenarios for the waste and aquatic biomass sectors.

Based on the modelling and other calculations, the total biomass availability could increase to 638 million tonnes DM per year under reference conditions by 2050, which represents an increase of 28 % compared to 2020. R&I measures could significantly increase the estimated biomass availability to 1 101 million tonnes DM per year in 2050. This maximum availability could be achieved if R&I measures to *enhance production* in the agricultural and aquatic biomass sectors are combined with measures to *improve supply* for the forestry and waste sectors (Figure 13). Altogether, this increase represents more than a doubling of the total available biomass between 2020 and 2050, but critically depends on the increased production volumes of microalgae, which are assumed to have the potential to triple every decade between 2030 and 2050. By 2050, the forestry and aquatic biomass sectors come out as the two sectors that contribute most to potential biomass availability, with 35 % and 33 %, respectively. The agricultural sector could provide 22 % of the total biomass availability and the waste sector 10 %. Without the contribution of the aquatic biomass, R&I measures could increase total biomass availability by 48 % by 2050 as compared to 2020, or 23 % as compared to the development in the Reference scenario until 2050.

Figure 13 Maximum estimated potential availability of biomass for energy use in the EU: ***The maximum availability of biomass for energy use can be achieved if the R&I measures to enhance production in the agricultural and aquatic biomass sectors are combined with the measures to improve supply for the forestry and waste sectors***



Source: Team analysis.

Energy crops can become important to ensure biomass availability in the long term

For the agricultural sector, this study identified and investigated several promising measures to improve biomass availability for bioenergy production, while avoiding competition with food production. The agricultural biomass potential at the European level is estimated at 149 million tonnes DM in 2020 and increasing to 166 million tonnes in 2030 and 219 million tonnes in 2050. By using R&I measures focusing on enhanced production, the biomass potential could increase to 238 million tonnes by 2050. By 2030, almost two thirds of the potential comes from agricultural residues (straw and prunings), but in 2050 energy crops make up the main part of the potential comprising 55 % of the total. In the future, the largest agricultural feedstock potential is therefore in energy crops, thus support to R&I measures in energy crop breeding, cultivation, and supply chain optimisation will be essential.

The largest amounts of biomass expected to be provided by the forestry sector

The total potential availability of woody biomass from EU forests for energy use is estimated at 198 million tonnes DM in 2020 and is expected to remain relatively constant until 2050, in the absence of R&I measures. This potential excludes biomass from short-rotation coppice, which is accounted under agriculture. R&I measures focusing on improved woody biomass supply could increase the total potential availability from forests to 222 million tonnes dry matter by 2050. Harnessing this significant potential would imply rather drastic changes in current forest resource management in Europe. In addition to biomass from forests, 93 million tonnes DM would be available from forest industries as wood residues without R&I measures and 110 million tonnes with R&I measures. These potentials include biomass that is already used.

Within the coming decades, measures to enhance biological production from forests, as implemented in our modelling, appear to be less effective in increasing woody biomass availability as compared to measures to improve supply. This is because measures to enhance production need a long time to become effective and result in more biomass becoming available. These results do not mean that measures to enhance production are not meaningful. Instead, these results imply that measures to enhance production should be considered already now to guarantee availability in the future.

The availability of biomass from waste is significant, however determined by individuals' behaviour

The waste sector could provide over 100 million tonnes DM per year by 2050. Non-hazardous post-consumer wood and especially the organic fraction of solid municipal waste have been estimated in this study to represent sizeable feedstocks. Unlike the sectors where increased availability of biomass can be achieved through e.g. breeding or harvesting techniques, the main factor that affects the amount of feedstock to become available for the production of bioenergy from waste is the behaviour of the involved citizens and their willingness to support the increase of this feedstock.

The availability of aquatic biomass could rapidly increase between 2030 and 2050

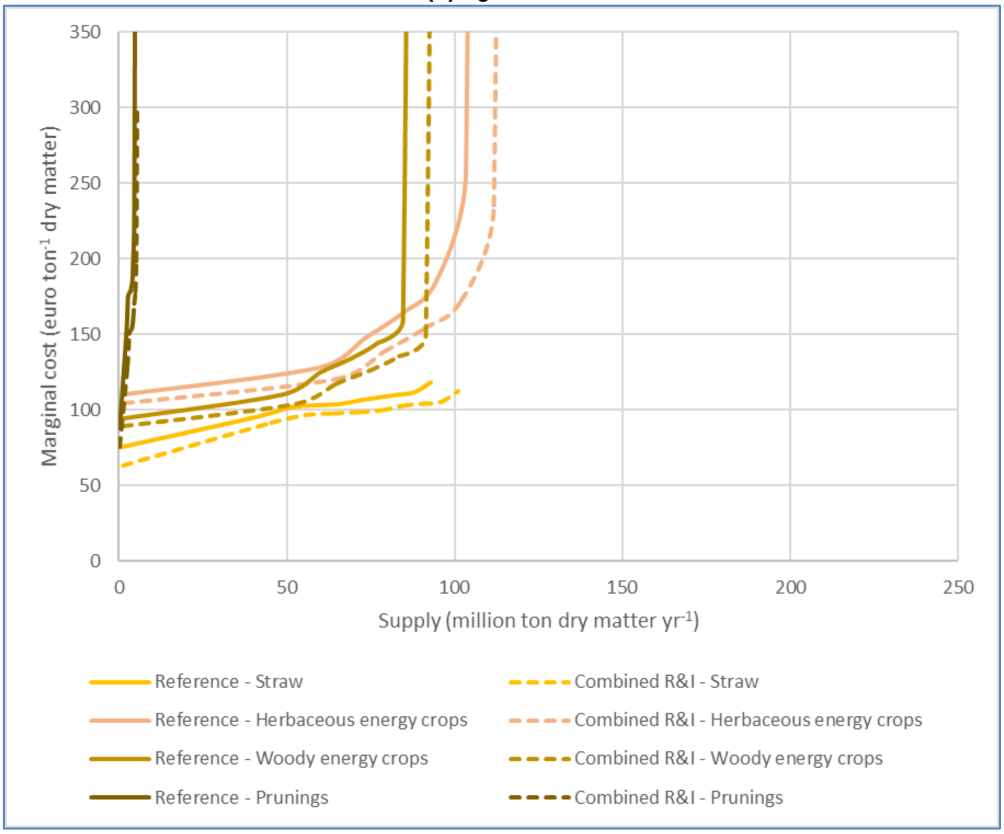
Based on literature, the availability of commercially available aquatic biomass is considered insignificant for 2020. However, the biomass available from this sector could rapidly increase to 38 million tonnes in 2030 and 344 million tonnes in 2050, which represents a tripling of the production volumes every decade. Only 12 out of the 28 EU Member States are identified as being able to provide the EU market with significant amounts of aquatic biomass. however. Out of these, only six are considered to be able to provide quantities of close to or more than 10 Mt DM of microalgae and macroalgae combined per year. Spain is estimated to have most significant potential, as the theoretical availability of Spanish algae is found to be almost 3 times larger than any of the other EU Member States.

3.3.3 Potential costs and supply of biomass for energy uses

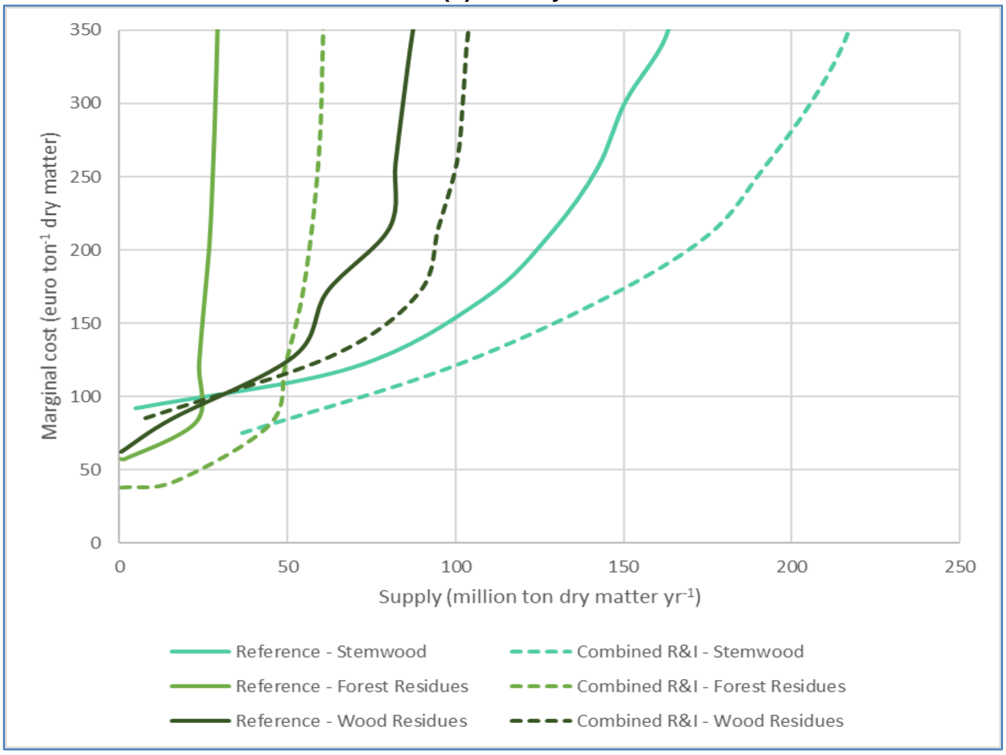
Biomass cost-supply curves for energy purposes have been estimated and are presented for feedstocks from agriculture and forestry. These curves are presented for the Reference and the Combined R&I scenarios in 2050 to illustrate the implications of R&I measures on biomass availability. In general, R&I measures are estimated to lead to more biomass being available from these two sectors at lower costs. Biomass cost-supply curves could not be estimated for feedstocks from the waste and aquatic biomass sectors. Instead, costs estimates have been derived from literature and are presented in the text following paragraphs.

Figure 14 Comparison of biomass cost-supply for energy for the Reference and the Combined R&I scenarios in 2050 for agriculture (A) and forestry (B): The figures below compare the costs at which different feedstock categories can be supplied, thereby giving insight to whether a feedstock is likely to be adopted as an economically viable feedstock in the future. Comparing the supply cost-curves between different scenarios, the effects of different R&I measures on the supply cost-curves of the specific feedstocks becomes apparent

(A) Agriculture



(B) Forestry



Source: Team analysis.

At medium price levels (120 €/ton), ca. 500 million tons of dry matter can be supplied in 2050, mostly available from the forestry sector and from energy crops

As shown in Figure 12 straw is a feedstock that could be supplied in amounts of up to 100 million tonnes DM per year, at a moderate price. For most other biomass types from agriculture and forestry, however, the total biomass availability can only be mobilised at very high prices, as the estimated marginal costs steeply increase when the maximum potentials are reached. For all scenarios and at medium price levels (e.g. 120 € per tonne DM of biomass), most biomass is available from the forestry sector in the form of stemwood and wood residues (sawdust, wood chips, bark), followed by herbaceous and woody energy crops from the agricultural sector and forest residues from the forestry sector.

For agricultural energy crops, the marginal costs increase steeply once the maximum availability approaches. This happens if irrigation is applied on top of other inputs, which may increase yields, in particular in Mediterranean countries. Irrigation is not a relevant option in all regions, but by construction of the marginal cost curve, the upper end reflects exactly those options which are the least cost effective. The increase in marginal cost is significant where, for example, only a single region is considered, or for woody energy crops, where only eucalyptus is considered.

By contrast, for straw there is no steep increase of marginal cost because expensive technical measures like irrigation have not been considered. As straw is a secondary product compared to the grain yield, the maximum potential to be harvested was treated as given. The moderate increase in the supply function stems mainly from regional variation within the countries and from the possibilities to harvest straw types that are less efficient than others (e.g. due to lower yields per ha).

In the case of the forestry sector, forest residues are initially supplied at the lowest costs due to absence of competition with forest industry for this feedstock. However, with the growing biomass for energy demand / prices, forest residues supply is quickly reaching the maximum availability. Wood residues initially face a limited competition with forest industries. However, larger quantities can only be supplied at high prices due to competition with the forest industry. Furthermore, the availability of wood residues is limited to certain extent by the amount of roundwood processed by forest industry. Finally, the steep increase in costs for stemwood is caused by the maximum about of biomass that can be produced sustainably, as well as increased competition with the wood products sector. As there are limits to trade in woody biomass, as described in Section 3.4, it cannot increase wood availability substantially.

Biomass from waste could be supplied at a low cost

From all the biomass feedstocks considered in this study, solid municipal waste and non-hazardous post-consumer wood represent sizeable feedstocks. Their availability can be enhanced by measures to improve supply, through supply chain logistics and mobilization of potentials. These feedstocks are considered to be available at no or very low costs for energy producers, because the costs of collection and processing are covered by households and the private and public bodies that are disposing their waste. This means that there are costs associated with this feedstock, but they are not covered by energy producers.

Relative to other feedstocks, used cooking oil represents a small potential

Used cooking oil represents a rather small potential. According to literature, restaurants could sell UCO for a maximum of 300 €/ton, small UCO collectors could charge up to 550 €/ton for filtered UCO and larger UCO collectors and melting plants would sell the purified UCO ready for biodiesel production for 800-900 €/ton. The supply costs of UCO are estimated to be significantly higher than the costs of most other feedstocks in this study. However, UCO requires less refining and has a much higher energy content, which makes a direct comparison with other biomass feedstocks covered in this study difficult.

Aquatic biomass is unlikely to become available at competitive prices

Biomass from microalgae could represent a significant feedstock by 2050, but can only be supplied at very high costs. Supply costs for 2030 are estimated at € 1 330/ton dry matter for microalgae and € 267- 333/t dry matter for macroalgae. Even if R&I measures focusing on enhanced production would reduce these costs, these supply costs would still be much higher than the costs of biomass available from the other sectors and would therefore not be competitive. However, a sensitivity analysis was conducted in order to assess the contribution of algae in the feedstock mix used for the production of bioenergy under more favourable conditions that would lead to lower costs than the ones used in our main scenarios. Results of this sensitivity analysis are presented in Chapter 4.

3.4 Impact of feedstock related research and innovation on the EU's competitive position

Key Findings
• Currently, only limited feedstock for the production of advanced biofuels is traded and much of the sustainable feedstock, such as waste biomass, is also not likely to be traded in the future. Only forest sector biomass, which is already traded in the form of pellets mostly for co-firing and electricity production, and possibly energy crops might be traded in the future. The commercialisation of the torrefaction process might make agricultural biomass transportable and hence tradable; • Australia, Brazil, Canada, China, India, Japan, Russia, Ukraine and the US are regarded to be the most important non-EU countries with respect to current and future feedstock production potential; • The EU feedstock potential is surpassed by the potential of other countries, such as Russia, Canada and the US. Also, feedstock production in the EU seems less competitive than production of agricultural and forestry biomass in the US, for instance; • Yet, European biomass is expected to face limited competition from other world regions due to limited mobilisation of feedstock from other world regions (Russia and the Ukraine), transportation costs (Brazil) and local feedstock demand (China, India, Japan, possibly Canada and the US), protecting the competitiveness of the EU's 'own' feedstock supply, even if on-site feedstock production costs are lower elsewhere.

We assess the impact of feedstock-related R&I on the EU's competitive position regarding sustainable feedstock production, and compare it with the competitive position of selected non-EU countries.[25] Based on this assessment, we try to draw conclusions about trade in sustainable feedstock in the future and the EU's future trading position.

Feedstock production in other world regions

Australia, Brazil, Canada, China, India, Japan, Russia, Ukraine and the US are regarded to be the most important non-EU countries with respect to feedstock production. These countries have been identified as relevant on the basis of their current and future feedstock production potentials, feedstock R&I and feedstock-related policies. They have been categorized in countries with high current and future potential, high current, but limited future potential, and low current, but high future potential.

[25] Competitiveness is defined as the ability to provide sustainable feedstock as or more effectively and efficiently than the relevant non-EU countries.

Currently, no feedstock for advanced biofuels production is traded worldwide, with the exception of feedstock for producing FAME.[26] In assessing the competitive position of the EU28, we focus on feedstocks originating from the agricultural and the forestry sector. In the agricultural sector, **energy crops constitute the most promising feedstock to be traded in the future**, as straw and other residues, such as prunings, are not yet suitable for transport due to their large volumes. Trade in wastes will probably also be difficult due to the low calorific value of waste and restrictions on trade. It is difficult to assess possible trade flows in aquatic biomass, as there is as yet no production or demand thereof in Europe. Generally, **forest biomass** is the most interesting feedstock for advanced biofuels to be traded, mostly in the form of pellets.

A possibly disruptive technology, which could make other agricultural residues, such as straw and prunings, suitable for transport and hence trade, is torrefaction. This process could also be used to pre-treat energy crops and all woody biomass. With the help of torrefaction, raw biomass feedstock can be densified and the vast potential of different types of biomass could be made tradable over long distances. Yet, as this process has not yet been applied on commercial scale, large uncertainties regarding the future market development of torrefied biomass and its effects on international biomass trade remain.

We focus on the effects of R&I on biomass availability and competitiveness in the agricultural and forestry sectors, as these categories of biomass have the potential to be torrefied, pelletized and traded.

Countries with advantageous current conditions and unclear prospects for the future

Russia possesses enormous biomass resources, in particular from **agricultural production** and **timber resources**: the estimates are 800 000 kton of timber and 250 000 kton of agricultural waste products per year.[27] Furthermore, there are major opportunities for the cultivation of energy crops. Already today, Russia is a major EU trading partner for wood pellets and wood chips due to some advances in its pellet production and export industry: in 2016, Russia exported 842 kton pellets to the EU, 189 kton sawdust and 1 692 kton wood chips.

Despite these positive current conditions, future potential seems limited: there are no specific policies or support schemes related to the production of sustainable feedstock or advanced biofuels, and no significant research activity appears to be done in Russia on sustainable feedstock. Russia's forests suffer from low productivity and much of the forests grow on the permafrost soils of Siberia and the Far East.

The situation in the **Ukraine** is similar to the one in Russia: although its feedstock potential is prospectively large and some of this biomass potential is already being used (e.g. wood residues to produce sawdust briquettes, pellets, fuel wood chips, etc.[28]), it is questionable whether the focus will be on producing sustainable feedstock. Furthermore, the current and future potential for feedstock exports is limited by the pellet mill capacity in the Ukraine.[29] Under optimistic assumptions[30], however, the entire export potential from the Ukraine could compete with the currently imported biomass of the EU (at a spot price of 179 €/ton or 10,1 €/GJ).[31]

[26] Biomass, such as wood pellets and wood chips, for instance, is traded for energy purposes (co-firing and CHP, for instance).

[27] Pristupa (2010), estimates from 2005.

[28] Around 80-85% of these produced solid biofuels are exported to the EU for electricity and heat production.

[29] The underlying optimistic assumption is that Ukrainian pellet mill capacity growth will mimic the pellet mill capacity growth in South-East of the US (it reached a four-fold increase between 2009-2016). The Business as Usual increase of pellet plant production, based on the years 2008 - 2012 will be assumed in the BAU scenario.

[30] These optimistic assumptions employed in the Bio Trade2020plus project (BioTrade2020plus, 2016) on the Ukraine encompass an increase of the sustainable agricultural feedstock and of the export potential due to higher use of fertilizers

Countries with disadvantageous current conditions and with significant future potential

Australia has relatively low current sustainable feedstock potential, but policies regarding drop-in fuels and research efforts on biofuels from different feedstocks are promising.[32]Australia's vast amount of marginal land, a considerable agricultural sector and good infrastructure imply huge potentials for energy and oil crops production. In recent years, Europe has been the main destination for exports of Australian oilseeds for use in the production of first-generation biofuels. These oilseeds need to be certified as sustainable and may also not be genetically modified. The availability and current potential of natural oils feedstock amount to 1 641 kton per year and costs range from 170 €/ton to 1 063 €/ton, with a median of 740 €/ton.[33] Naturally, natural oils feedstock for biofuels production are at the lower end of the presented price spectrum and expensive, premium quality natural oils are reserved for other uses. Furthermore, algae is receiving considerable attention as a possible source of biofuel in the future: there have been successful demonstrations of second-generation biofuels, such as energy crops and algae-based fuels, and there has been significant research effort by a number of research agencies in the development of first and second-generation biofuels.

Countries with advantageous current conditions and with significant future potential

Brazil has long had a focus on (advanced) biofuels. Its current potential in agriculture, forestry and waste-related sustainable feedstocks is considerable. Research into advanced biofuels feedstocks is stimulated. The sustainable agricultural feedstock and forestry residues potentials amount to 130 000 kton and 14 000 kton, respectively.[34] However, the availability of these potentials is constrained by domestic consumption. The estimates regarding the net sustainable surplus potential of agriculture and forestry residues in 2030 are much lower, even under optimistic assumptions in the BioTrade2020plus project, amounting to ca. 55 000 kton of agricultural waste and 6 800 kton forestry feedstock. The net export potential is even lower than the sustainable surplus potential as a result of limited pellet plant capacity: it equals 24 000 kton in the optimistic scenario in 2030. The current export costs range from 232 €/ton to 251 €/ton, depending on delivery costs.[35] In the 2030 optimistic scenario the potential takes off and the feedstock becomes relatively cheap, but the costs range still from 170 €/ton to 251 €/ton.[36]

Canada has large agriculture and forestry sustainable feedstock potential, with policies focused on agricultural feedstock and algae. Furthermore, it is one of the major scientific players regarding feedstock publications. Canada's current potential for sustainable agricultural feedstock amounts to 181 100 kton, for forestry to 160 000 kton and for waste to 25 330 kton per annum.[37] Canada is the

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and a higher pellet production capacity respectively. Yet, pellet production capacity is expected to remain a bottleneck even in this optimistic scenario.

31 The maximum potential in the high export scenario is about 220 PJ, equalling ca. 22,000 kton biomass to be exported, which is much lower than the sustainable surplus potential, which is around 600 PJ in 2030. The cheapest pellets could be delivered to the EU for 114$/ton (97 €/ton), the most expensive ones for 178$/ton (151 €/ton). The transportation costs to the Netherlands amount to 37.6$/ton (32 €/ton), to Italy to 60.3$/ton (50 €/ton) and to Austria to 64.44$/ton (54 €/ton).

32 Feedstocks such as lignocellulosic feedstocks, eucalyptus, mustard seeds, Ponamia pinnata trees, Moring oleifera and algae.

33 At current exchange rates (June 2017), this amounts to a price range of 252 AUD/tonne to 1,574 AUD/tonne, with a mean of about 1,100 AUD/tonne.

34 The residual potential is much higher, amounting to ca. 210 000 kton DM, whereas forestry residues account for 18,000 kton DM (IEA, 2010).

35 The fact that forest residues are more expensive than agricultural residues increases the prices for exported biomass since only wood pellets are produced in these scenarios. Transportation costs are calculated to Austria, Italy and the Netherlands.

36 The BioTrade2020 plus report (BioTrade2020plus, 2016) concludes that importing pellets from Brazil into Europe is not competitive at this time. Yet, a part of the biomass potential from Brazil in the future could compete with the higher range of historical spot prices. Cost reductions in Brazil, mainly through improvement of rail infrastructure could result in lower cost of pellets.

37 These numbers do not account for competing uses.

world’s third largest pellet producer with a production of 2 222 kton in 2015, out of which 1 440 kton were exported to Europe.

China has large feedstock potentials in the agricultural, forestry and waste sectors. Estimates amount to ca. 500 000 kton agricultural, 170 000 kton forestry and 170 000 kton waste feedstock per year.[38] Energy crops are an option regarding China’s marginal lands. Algae has been identified as a potential future feedstock and funding for research has been provided. Moreover, China is, next to the US, the second most important non-EU player with respect to scientific publications on sustainable feedstocks. As the government is concerned about food versus fuel competition, China’s attention is on advanced biofuels. The Chinese government has set a production target to produce 300 000 kton of advanced (cellulosic and non-grain) biofuels by 2020.[39]

India has large feedstock potentials in agriculture and waste. Political plans and measures aim at supporting sustainable feedstock production, and research support is given to technologies related to aquatic biomass. Moreover, India is one of the major players regarding publications in the field of feedstock R&I. Estimates of unused agricultural biomass amount to 400 000 kton per year, whereas there is only very little biomass from forestry with estimates varying between 5 500-15 000 kton. The total biodegradable fraction of waste is estimated at 130 000 kton. The Indian government has also been supportive of energy crops, especially the planting of Jatropha.

Japan has substantial feedstock potentials in agriculture and waste: agricultural biomass amounts to 102 000 kton, forestry to 25 400 kton and waste to 128 100 kton per year. The requirement that bioenergy production should not compete with food production has been in place since 2010. Japan belongs to the top 10 countries regarding publications on feedstock R&I. Research funding is also available for algae and joint research projects with both industry and academia are on the way.

The **USA** has the most advantageous current conditions and future potential: high current sustainable feedstock potential in agricultural, forestry and waste-related feedstocks, well-developed policies in support of sustainable feedstock production, and a dominant position regarding feedstock R&I. Current agricultural feedstock is estimated at 157 530 kton, forestry biomass at 192 000 kton, wastes at 30 000 kton and landfill gas at 280 000 kton per year.[40] Optimistic estimates for 2040 amount to 76 000 kton of forestry biomass, 200 000 kton agricultural residues, 736 000 kton energy crops and 142 000 waste resources per year, being available at $ 60 per dry tonne (50 €/ton) or less at the roadside or the farm-gate.[41]

Table 18 summarises the current and future biomass potential in non-EU countries. The figures reported have been obtained through an extensive desk research. Hence, the quality and comparability of the data varies: for some countries, up-to-date reports, publications, quantifications and projections could be found, whereas not much data was available for other countries. Similarly, for many studies it is unclear which feedstock definition the reported data pertains to, whether it represents the technical or the sustainable feedstock potential and whether other feedstock uses have already been accounted for.

38 These numbers are based on studies from the years 2010-2015.

39 IEA Bioenergy China (2016).

40 Currently used feedstock amounts to 154,000 kton DM for forestry resources, 144,000 kton for agricultural resources and 68,000 kton for waste resources according to the Billion ton report (2016) by the US Department of Energy.

41 In the base-case scenario these potentials amount to 151,000 kton of forestry resources, 320,000 kton of agricultural residues, 411,000 kton of energy crops and 142,000 kton of waste resource. These numbers can be found in the Billion ton report, 2016, US Department of Energy.

Table 18 Summary of current and future (agricultural and forestry) biomass potential in non-EU countries

Country	Feedstocks (kton) agriculture and forestry	Feedstock estimates (kton) 2030-2050
Russia	1 120,00[42]	
Ukraine	60 000[43]	775 000
Australia	59 981[44]	72 000 Possibility of aquatic biomass
Brazil	144 260[45]	61 800[46]
Canada	230 000[47]	Energy crops: 98 500 kton Aquatic biomass potential, 165 ktons
China	719 000 – 933 000[48]	Energy crops Aquatic biomass
India	430 000 – 440 000[49]	Energy crops Aquatic biomass
Japan	40 000[50]	Aquatic biomass
US	349 000[51]	1 000 000 (including energy crops) Aquatic biomass
EU	484 000	535 000 in the reference scenario 640 000 in the combined R&I scenario (agricultural and forestry biomass)

Source: Team analysis.

Impact of R&I on the EU's competitive position

Table 19 gives an overview over the biomass availability in the four scenarios in EU28.

Table 19 Biomass potential in the agricultural and forestry sectors in 2020, 2030 and 2050 for the four different scenarios and biomass from agricultural and forestry sectors as % of total potential (including algae and waste) as shown in Figure 56

Total biomass from agriculture and forest (in kton)		Reference scenario	Enhanced production	Improved supply	Combined R&I
2020	**Agriculture**	149 000	153 000	149 000	153 000
	Forestry	335 000	335 000	335 000	335 000
	Total	**484 000**	**488 000**	**484 000**	**488 000**
	% of total potential	**89,5 %**	**89,5 %**	**87,4 %**	**87,4 %**
2030	**Agriculture**	166 000	173 000	166 000	173 000
	Forestry	335 000	335 000	410 000	410 000
	Total	**501 000**	**508 000**	**576 000**	**583 000**
	% of total potential	**81,3 %**	**81,5 %**	**79,9 %**	**80 %**

42 This number not necessarily denotes the sustainable potential.
43 This number denotes the sustainable surplus potential, but export capacity is limted by pellet mill availability.
44 This number pertains to sustainable feedstock potential, but other uses are not accounted for.
45 This is the sustainable available potential.
46 This number denotes the export potential.
47 This number denotes the sustainable feedstock potential, competing uses have not been accounted for.
48 This figure is composed of the sustainable agricultural feedstock and the total forestry feedstock, without accounting for competitive uses.
49 This figure represents the sustainable available biomass.
50 This figure represents the sustainable available biomass.
51 This figure represents the sustainable available biomass.

Total biomass from agriculture and forest (in kton)		Reference scenario	Enhanced production	Improved supply	Combined R&I
2050	**Agriculture**	216 000	235 000	216 000	235 000
	Forestry	319 000	320 000	405 000	412 000
	Total	**535 000**	**555 000**	**621 000**	**640 000**
	% of total potential	**79,9 %**	**55,2 %**[52]	**80 %**	**57,7 %**

Source: Team analysis.

Biomass availability in the **enhanced production scenario** is mainly driven by improvements in the availability of **agricultural biomass**, especially energy crops. Whereas the potential of agricultural residues remains relatively stable over the years and even declines for straw from 2030 onwards due to a decline in agricultural land, the dedicated cropping potential for energy crops increases as unused land resources are expected to increase. Two types of measures for **enhancing production** contribute to this development. Firstly, measures, such as the development of specific crops dedicated to energy, the development of more robust and stress-resistant energy crops through breeding activities and the domestication of new energy crops species increase the yield of energy crops. Secondly, the availability of straw and pruning residues increases through the implementation of better agricultural management techniques allowing the removal of additional residues. These practices, which alleviate pressure on the carbon balance, include selecting higher residue yielding plant varieties, the adjustment of N fertilization rates to increase residue yield, variations in sowing time and rate, optimized cropping systems (crop rotation, multi-cropping etc.), tillage systems selection and the adoption of precision agriculture practices and digital farming. In the long run, the effects of genetic research and development are assumed to be effective.

Measures targeting **enhanced production in forests** are, in contrast, not very effective in the 2030 and 2050 horizon: forest regeneration upon final felling, optimised regeneration techniques and fertilisation of forests growing on poor soils can reach their effectivity only in the long term, resulting in a 3 % rise of available biomass in the 2100 horizon.

Measures to **enhance production** increase the total available biomass in 2050 by around 4 % as compared to the reference scenario. These measures affect agriculture in particular, increasing the theoretical potential by 8,8 %.

The **improved supply scenario**, on the other hand, is characterized by increases in the forestry biomass potential stemming from modified practices to harvest, mobilise and transport forest biomass. Examples of these measures are more efficient fellings resulting in less harvest losses, i.e., more stemwood, and the mobilisation of wood from private forest owners. The potential from the forestry sector increases with 27 % as compared to the reference scenario.

Overall, measures to **improve supply** increase the total available biomass in 2050 by around 16 % as compared to the reference scenario.

The **Combined R&I scenario** results in the highest available biomass from the agricultural and forestry sectors. The available biomass in 2050 is almost 20 % higher in the Combined R&I scenario as compared to the reference scenario.

52 The lower figure in the enhanced production and combined R&I scenarios are due to the very high technical potential of algal biomass in the long term (2050), resulting in a lower overall share of the agricultural and forestry biomass in total biomass.

Possible development of trade in sustainable biomass between the EU and non-EU countries

Currently, no feedstock for advanced biofuels production is traded, as mentioned before. Forest biomass is traded in form of wood pellets mostly for industrial use in power generation and CHPm, and is expected to remain the most interesting feedstock to be traded, also for advanced biofuels production. As mentioned before, this might change with the commercialization of torrefaction. Torrefaction could boost biomass trade by broadening the feedstock base to be traded and improving the transportation qualities of biomass: all feedstock types, agricultural residues, energy crops and woody biomass could be pre-treated using torrefaction and palletisation.

The production of advanced biofuels is expected to take off not only in the EU, but also in non-OECD countries, particularly in China and India.[53] China, India and Brazil have large biomass potential and are already producing biofuels. (Advanced) biofuels take a prominent place in their future energy strategies and these countries are among the world's top 10 countries regarding feedstock R&I.[54] It is likely that these countries, especially India and China, will focus on developing their own advanced biofuels sector and, given their size and population, will use the available feedstock for advanced biofuels production at home. Depending on their own and the worldwide decarbonisation paths, the biofuels produced in China, India and Brazil might be exported to the EU.

Japan also has ambitions in the field of advanced biofuels production and only little woody biomass. A possible exportable feedstock could be algae or the lipid extracted from microalgae. However, lipid extraction already involves a further processing step of the algae. The question is hence whether these lipids will be traded or whether it is preferable for algae producing countries to export the biofuel as end product. Furthermore, Japan is expected to become a main importer of biomass in the form of industrial wood pellets.[55]

In the EU, imported forestry residues amounted to 14 000 kton in 2016 in the form of wood chips and scraps, sawdust and wood pellets.[56] Being the world's largest pellet producer and accounting for about half of the worldwide pellet production, the EU consumes around 74 % of the world's pellets.[57] The US, Canada and Russia are already the EU's main trading partners in forest biomass. Export prices to Europe vary between 119 €/ton for pellets from Russia, 141 €/ton for pellets from Canada and ca. 170 €/ton for pellets from the US.[58] Given the prospect of future biomass potential, the US and Canada are expected to extend their shares of the EU's wood pellet imports, corresponding to the trend seen in the past.[59] The aforementioned problems, such as a

53 IEA (2010).

54 This is measured by the amount of top publications in the field of feedstock R&I.

55 WPAC (2017).

56 In 2016, 40% of the imports were wood chips and scraps, 56% were wood pellets, and 4% were sawdust. The three main exporters to Europe of wood chips and scraps were Russia, Switzerland and Norway, whereas 60% of the wood pellets came from the US, 21% from Canada and 10% from Russia. Prices for wood chips and scraps decreased from ca. 65 €/ton in 2010 to 47€/ton in 2016, prices for wood pellets increased from ca. 135 €/ton in 2010 to 155 €/ton in 2016, and prices for sawdust fluctuated around 80 €/ton, ranging from 45 €/ton to 100 €/ton.

57 The production amounted to 13,100 kton of wood pellets in 2014. The largest producers of wood pellets in the EU are Germany, Sweden, Lithuania and France. The EU imported an estimated 7,200 kton of wood pellets in 2015, 60% came from the US, 21% from Canada and 11% from Russia.

58 These costs are total wood pellet costs, including wood, labour, energy, depreciation plus interest, overhead, transportation to the port, loading, ocean freight, and other costs.

59 Yet, this also depends on domestic demand for wood pellets in these countries: whereas domestic consumption of wood pellets in the US was about 80% of total production, it was only 10% for Canada in 2008 (Sikkema et al. (2011): The European wood pellet markets: Current status and prospects for 2020, Society of Chemical Industry and John Wilely & Sons, Ltd.).

lack of sustainability considerations or pellet mill limitations, are expected to impede future trade with both Russia and the Ukraine.[60]
R&I measures, especially measures aiming at improving supply of forest biomass, increase European forest biomass availability and make it more competitive. The EU's trading position regarding forest biomass and the future development of pellets trade will depend, amongst others, on the development of domestic demand (in the EU, US and Canada[61]) and demand in other parts of the world (Japan, South Korea and China[62]),on the exchange rate between the euro and the dollar and on the development of transport costs. Demand within the EU for imported forest biomass might differ since there are additional transport costs within Europe.[63]

Whereas imported pellets are mostly low quality pellets for industrial use in power generation and CHP[64], high quality 'premium' pellets, which are predominantly used in the heating sector, are currently supplied by domestic production.[65] Pellet demand in the residential and commercial sector in the EU is expected to continue growing strongly.[66] Whereas international trade with pellets for industrial use is policy-driven (depending on subsidies, for instance), demand in the heating markets is driven by the comparative costs of heating fuels.[67] R&I can play a role to ensure that the future pellet demand for heating purposes can be met by domestic production in the EU and that the high quality pellets segment remains competitive as compared to other heating fuels available in the EU.

Regarding energy crops, the US has the highest potential to become a major trading partner to the EU: its available potential of herbaceous biomass available for less than 80 $/ton (67 €/ton) amounts to 508 000 kton in the base-case and to 812 000 kton in an optimistic scenario in 2040.[68] For forestry biomass these numbers are 97,000 kton for the base-case and 76 000 kton for the high-yield scenario.[69] Accounting for transportation costs, 550 000 kton can be delivered to the reactor for 120 $/ton (100 €/ton) and less in the base case. This is more cost-competitive than the available potential of 92 000 kton of woody biomass in the combined scenario for 150 €/ton and the available potential of 115 ,000 kton of herbaceous biomass for less than 200 €/ton. A possible

60 Pellet mill limitations can be alleviated by higher capacity growth, i.e. more investments in pellet mills, which would occur in favourable economic circumstances (high demand for biomass from Russia and the Ukraine additional to policies supporting sustainable feedstock production in these countries). The modelling results for the Ukraine already assume optimistic growth implying that one would need extraordinary high capacity growth to really annihilate the limitations posed by pellet mill capacity for export.

61 Canada has the potential to become a significant demander of industrial wood pellets. It has announced a national carbon pricing system. Whereas the US also has the potential to generate much pellet demand by 2030 if the Clean Power Plan is implemented. Yet, it is not sure whether the current administration will follow through with the CPP.

62 South Korea and Japan are already major demanders of industrial wood pellets and their demand is expected to increase even more in the coming years. The development of China's demand is uncertain.

63 Within the EU, most pellets are transported via truck with costs ranging from 12 €/ton to 18 €/ton in 2009.

64 The imported pellets are mainly for industrial use (Power plants and CHPs), with the UK being the world's largest industrial pellet consumer, before Denmark, Belgium, Sweden, Poland and the Netherlands.

65 Around 60% of the pellets produced in the EU are of high quality, suitable for small-scale (residential) combustion, whereas the other 40% were industrial pellets of lower quality. European demand for high quality pellets is covered by domestic production, while the use of industrial pellets depends partly on imports (WIP Renewable Energies (2009) Pellet market overview report Europe).

66 WPAC (2017).

67 WPAC (2017).

68 The base case scenario assumes an annual yield growth of 1% for energy crops genotypes, whereas the high yield scenario assumes a 3% annual yield improvement and high-yielding corn. R&I is not modelled explicitly, but the authors acknowledge that the realization of the potential described in their report is "contingent upon research, development, commercialization, and markets" (p. xxviii). With respect to energy crops, the report hints at underlying R&I leading to yield increase: it notes that the energy yield improvements are due to the identification of new high-yielding clones, fertilization and nitrogen addition, which enhance yields dramatically in some crops. Also improved agronomic practices are mentioned.

69 The baseline scenario assumes low growth in woody biomass demand for energy; moderate new plantation management intensity in the South; and moderate demand for conventional wood for housing, paper and paperboard, and exports. The high scenario assumes a high increase in demand both for conventional wood for housing, paper and paperboard, and exports and for woody biomass for energy.

explanation for the higher cost-competitiveness of energy crops grown in the US are lower land rental costs.[70]

For wood pellets, transportation costs are a large part of the total cost of wood pellets.[71] Yet, accounting for transport costs within the US, possible torrefaction and pelleting costs and similar freight costs as for wood pellets, energy crops from the US might still be able to compete with energy crops in the EU. Yet, as before, the EU's trade position in biomass from energy crops and the future development of this feedstock will depend, amongst others, on the development of domestic demand and hence the decarbonisation paths chosen in the EU and in the USA, on the exchange rate between the euro and the dollar and on the development of transport costs.

Concluding remarks

The EU feedstock potential is surpassed by the potential of other countries, such as Russia, Canada and the US. Also, feedstock production in the EU seems less competitive than production of agricultural and forestry biomass in the US, for instance, Yet, European biomass is expected to face limited competition from other world regions due to limited mobilisation of feedstock from other world regions (Russia and the Ukraine), transportation costs (Brazil and Australia) and local feedstock demand (China, India, possibly Canada and the US). This protects the competitiveness of the EU's 'own' feedstock supply, even if on-site feedstock production costs are lower elsewhere. The risk that R&I investments towards improving feedstock availability will become redundant due to competition from cheap imported feedstock is hence limited. With regard to the potentially important role of biomass feedstock for the EU's future bioenergy system and for the EU's compliance with its decarbonisation targets, R&I is needed to alleviate feedstock limitations and to mitigate possible dependence on imported biomass. Furthermore, with feedstock prices being the most important cost component of advanced biofuels, R&I can improve the EU's competitiveness in the advanced biofuels sector.

70 The baseline scenario in the Billion ton report does not consider land rental costs.

71 Freight costs between North America and the EU ranged from 27 €/ton to 69 €/ton between 2002 and 2010. According to Bloomberg New Energy Finance, transportation accounted for a quarter of the delivered price of wood pellets from the Southeast to the Netherlands in mid-2013, hence around 45 €/ton.

4 Potential contribution of Advanced Biofuels

4.1 Introduction

The second task of the study consisted of an assessment of the potential contribution of advanced biofuels for achieving the 2020 targets for renewable energy and reduced indirect land use (ILUC), as well as the 2030 Energy and Climate Package and other 2050 targets.[72]

For the 2020 situation, a review of installed and planned capacity of advanced biofuel production was conducted. For the 2030 and 2050 situations, the quantitative analysis has taken advantage of the modelling of the main scenarios, which have built on the results of the preceding chapter, notably by using the produced feedstock-supply curves. These curves indicate what volume of biomass feedstock is available to the market at what price. For the R&I potential of conversion technologies, extensive desk research and stakeholder engagement underpins the assumptions applied in the scenarios. Finally, A SWOT analysis was conducted to review the interest of Member States and major relevant non-EU countries, discussing the modelling results and the bibliometric analysis on technology leadership in a wider perspective.

The presentation of the feedstock assessment results is organised in the following sub-chapters:

- 4.2. Potential contribution of advanced biofuels for achieving the 2020 RED/ILUC targets;
- 4.3. Potential of advanced biofuels for achieving 2030 Energy and Climate Package and 2050 targets;
- 4.4. Evaluation of the advanced biofuels contribution to Europe's societal challenges and Energy Union vision and action points;
- 4.5 SWOT analysis of interests of Member States and major relevant nations.

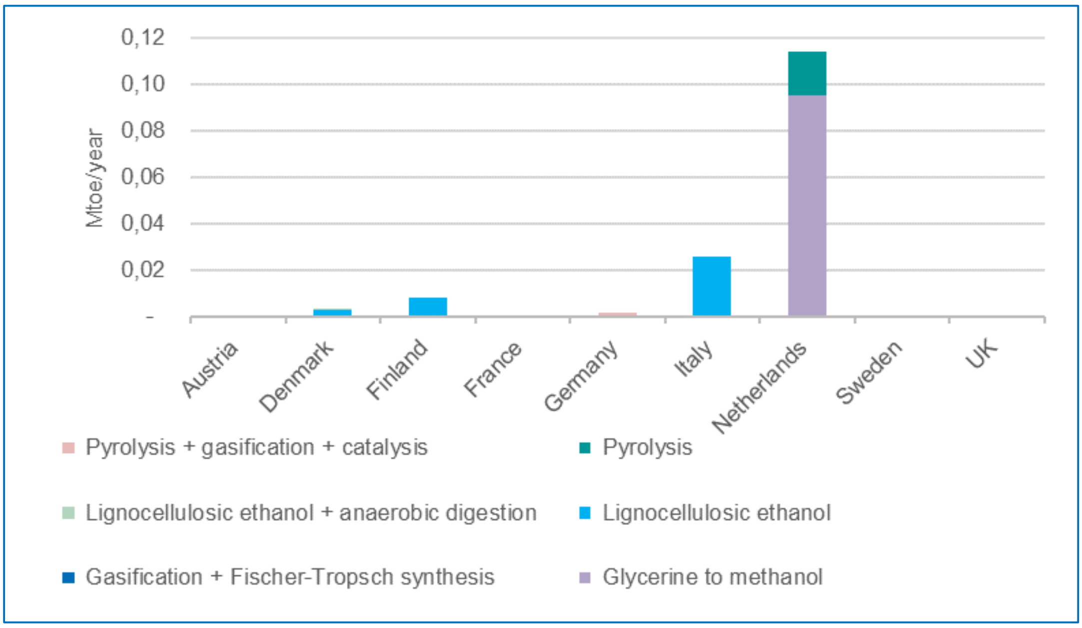
4.2 Potential contribution of advanced biofuels for achieving the 2020 RED/ILUC targets

Key Findings
• The current installed capacity for advanced biofuels in the EU is 0,15 Mtoe p.a; • If all planned projects continue, the additional capacity would be around 0,8 Mtoe p.a.; implementing such investments would cost between € 4.5-5 billion; • 1,5 Mtoe of biomass and waste feedstock is needed to produce roughly 0,8 Mtoe of advanced biofuels in 2020 (ratio: 1 to 0,53); • Estimated emissions from the production of advanced biofuels are 0,23 Mt CO_2, compared to 2,8 Mt CO_2 for the production and combustion of fossil fuels; • In 2020, the achievement of the 10 % target for the renewable energy used in the transport sector (RES-T target), will be assisted by the contribution of a 0,5 % from advanced biofuels, should the aforementioned investments materialise; • At the same time, advanced biofuels could provide 0,2 % of the GHG emissions savings needed to meet a 20 % reduction in GHG emissions compared to 1990.

[72] It is worth pointing out that since 2015 several actions towards the promotion of advanced biofuels have taken place, namely (i) the adoption of Directive 2015/1513, (ii) the Commission's Communication on "A European Strategy for Low-Emission Mobility" in July 2016 and (iii) the proposal for a revision of Directive 2009/28/EC, published as part of the November 2016 Clean Energy Package. Directive 2015/1513/EU (the ILUC Directive) sets a cap on the utilisation of crop based biofuels to 7% and an indicative target of 0.5% for advanced biofuels by 2020.

Figure 15 presents current installed capacity of advanced biofuel production in EU Member States. The existing sixteen facilities have a joint production capacity of 0,15 Mtoe of advanced biofuels per annum. Since most projects are still in the demonstration phase actual production may however be significantly lower than full production capacity.

Figure 15 Installed advanced biofuel production capacity per Member State: ***The majority of the EU's installed advanced biofuels production capacity can be found in the Netherlands, followed by Italy, Finland and Denmark***



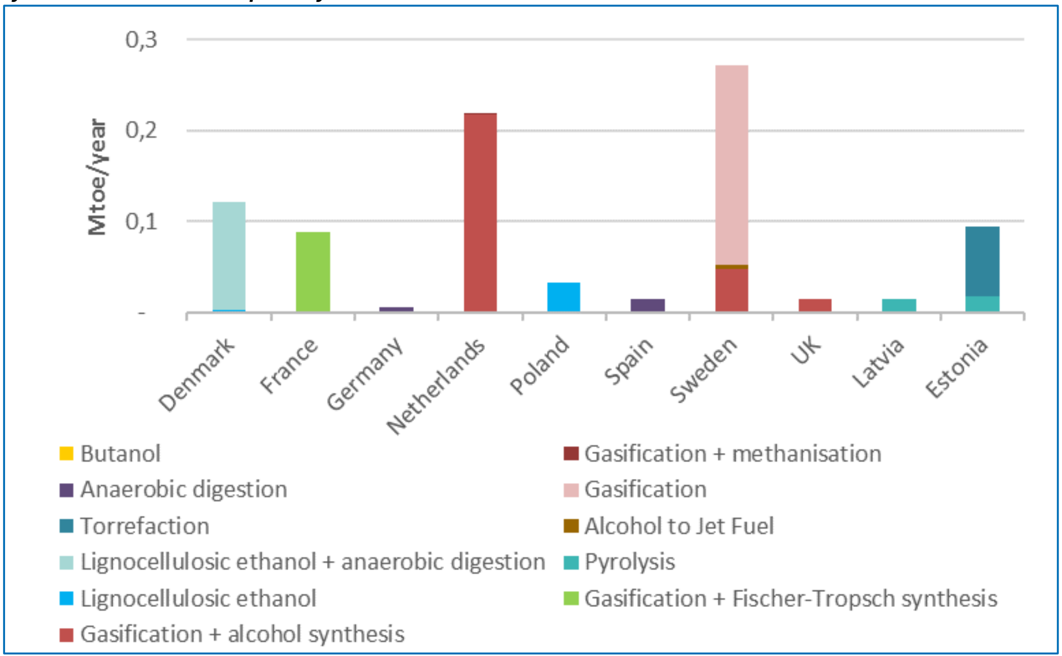
Source: Team analysis.

NB. Anaerobic Digestion capacities do not include plants for the production of non-upgraded biogas.

Planned capacity

Figure 16 presents planned advanced biofuel production capacity in EU Member States up to 2020. Production in most planned facilities are expected to begin between 2018 and 2020. Their joint production capacity is expected to be close to 0,8 Mtoe per year (35 PJ/year).

Figure 16 Planned advanced biofuel production capacity additions per Member State by 2020: ***The highest share of planned capacity in the EU can be found in Sweden, the Netherlands, Denmark, France and Estonia. The majority of the planned facilities will use gasification in combination with alcohol synthesis or Fischer-Tropsch synthesis***



Source: Team analysis.

Note: An overview of sources used to update the IRENA database is provided in the Deliverable report D2.1. The figures implicitly assume that all planned capacity will be realised in time, which is likely to represent an overestimation.

Investments needed

The next table presents the estimated capital investments needed to realise the planned capacities identified in the previous subsection. Total investment expenditures for the production of advanced biofuels are expected to be around € 4.5-5 billion by 2020.

Table 20 Investments on different technology processes (mln €)

	Lignocellulosic ethanol	Gasification & alcohol synthesis	Gasification & FT synthesis	Pyrolysis	Alcohol to Jet-Fuel	Torrefaction	Anaerobic digestion	Total
Total	**566**	**1 712**	**1 885**	**202**	**18**	**390**	**25**	**4 798**
Average investment per capacity in mln € per (ktoe/yr)	3,7	6,1	6,1	6,2	3,5	5,1	1,3	5,5

Source: Team analysis.

Feedstock required

To estimate the amount of feedstock required for the production of advanced biofuels in Europe by 2020, the volume of the existing and expected European capacities have been analysed. The analysis assumes an average utilisation rate for biomass used for advanced biofuels of 75 %, which is consistent with the capacity utilisation rates observed in recent years for the production of HVO (USDA, 2016). A selection of a higher utilisation rate could be proven unrealistic, as some downtime is expected from maintenance etc. The analysis reveals that, feedstock requirements for production of advanced biofuels will be approximately 1,5 Mtoe in 2020 (Table 21); this is less than 1 % of domestically produced feedstock requirements of the whole EU bioenergy sector. With such limited requirements, availability of the required feedstock quantities should pose little to no constraint in the short term. By 2020, the Netherlands is expected to be the largest user of feedstock for the production of advanced biofuels in Europe, followed by Sweden.

Table 21 Feedstock used for the production of advanced biofuels in Europe in 2020 (ktoe)

Agricultural residues	Wood waste	Other lignocellulosic feedstock	Other[1]	Total
290	419	640	142	1 491

1) includes MSW and glycerine.
Source: Team analysis.

Contribution to the energy mix

Advanced biofuels are expected to partially substitute a portion of fossil-based fuels used in the transport sector, replacing an estimated 0,8 Mtoe of fossil-based fuels by 2020 (see Table 22).

The quantity of gasoline replaced is expected to exceed that for diesel. This result is mainly driven by production in the Netherlands, which is expected to be the most important EU producer of advanced biofuels by 2020 and where most advanced biofuels will replace gasoline. As for kerosene, only very small quantities are expected to be substituted given that the level of maturity for producing kerosene is still rather low. The same holds for advanced biofuels substituting gas and coal, since these fuel sources face competition from other energy sources in for instance the power sector (e.g. Renewable Energy Sources).

Table 22 Advanced biofuels produced in 2020, per the respective conventional fuels they shall replace (ktoe)

(ktoe)	Gasoline substitution	Diesel substitution	Kerosene substitution	Natural gas substitution	Coal substitution	Total
Total	425	269	4	16	57	772

Source: Team analysis.

CO_2 emissions from the production of advanced biofuels

Having estimated the amounts of biofuels that can be produced from advanced conversion technologies, the CO_2 emissions from the overall advanced biofuels pathway can be calculated. Total CO_2 emissions from the production of advanced biofuels are estimated at 391kt of CO_2 in 2020, with the largest part coming from the gasification process. Direct emissions from the combustion of biofuels are zero, as any CO_2 emitted during the combustion has already been absorbed during the feedstock cultivation phase[73]. In the transport sector, advanced biofuels may substitute petroleum products from which overall well-to-wheel emissions are in the order of 2,8 Mt of CO_2. Hence, advanced biofuels may contribute to substantial net emissions savings.

[73] Any deviations from this balance are accounted as LULUCF emissions according to the IPCC guidelines for monitoring GHG emissions.

Table 23 Net emissions from the production of advanced biofuels in 2020 kt CO_2

Lignocellulosic ethanol	Gasification + alcohol synthesis	Gasification + FT synthesis	Pyrolysis	Alcohol to Jet-Fuel
88 %	81 %	83 %	81 %	65 %

Note: The analysis has included only the emissions from the transportation and transportation of biomass feedstock into advanced biofuels. GHG emisisons from the cultivation of agricultural crops and forestry are not included.
Source: Team analysis.

4.3 Potential of advanced biofuels for achieving 2030 Energy and Climate Package and 2050 targets

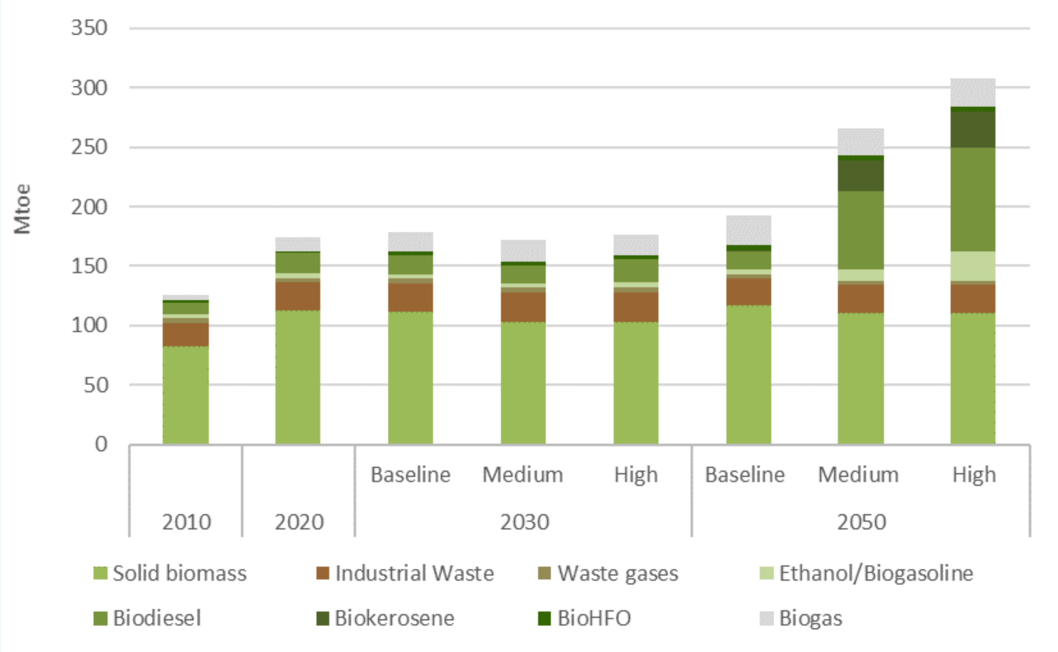
Key Findings

- Significant growth in the demand for advanced biofuels is expected in a decarbonisation context, which is led by the need to abate emissions in the transport sector (regardless of the degree of electrification in the transport system);
- Demand for liquid biofuels can reach close to 150 Mtoe by 2050, led by advanced biodiesel and biokerosene. Biodiesel is favored over ethanol/bio-gasoline as diesel engines present lower carbon emission per km and are favored by regulatory standards. Biokerosene is the only alternative available for the decarbonsiation of the aviation sector. Moreover, biofuels are one of the few viable options for long-distance road freight and maritime transportation;
- Close to 250 GW of conversion capacity for advanced biofuels could be built in the long term. In the mid-term (2030), the respective installations are estimated roughly at 30 GW and the installed capacities for conventional biofuels are larger than the installed capacities for advanced biofuels;
- Feedstock demand for the production of bioenergy is estimated around 180 Mtoe in 2030 and can reach more than 360 Mtoe by 2050 in a bioenergy system heavily relying on bioenergy; the role of forestry and new lignocellulosic crops for the production of advanced biofuels is amplified. Additional feedstock potential could be exploited through accelerated cost reductions;
- There are three factors that are driving the evolution of costs for advanced bio fuels: learning by research, learning by doing and the availability of feedstock;
- Advanced biofuels can cover almost 50 % of the EU transport sector's energy needs, using mainly domestic feedstock resources.

Biofuels demand

Demand for bio-energy at the EU level is shown in Figure 17. In all scenarios, demand for bioenergy is sluggish between 2020 and 2030. This result stems mainly from the significant efficiency improvements that are needed in order to meet the 2030 energy efficiency targets, which reduce energy demand in end-use sectors. An example of an energy efficiency target are the regulatory standards on CO_2 emissions from cars and vans post 2020 that lead to efficiency gains.

Figure 17 Bioenergy demand for EU-28 in the main Bioenergy scenarios: *Demand does not increase significantly between 2020 and 2030 due to efficiency improvements. There is, however, a significant increase in biofuels uptake up to 2050, especially regarding demand for biodiesel and bio-kerosene, due to the increasing role of the bioenergy sector in reaching the EU's long-term energy objectives*



Source: Team analysis.
Note: Biogas includes bio-methane (bioSNG).

In decarbonisation scenarios which aim to meet the long-term energy objectives of the EU, total bioenergy increases substantially towards the end of the projection period. As expected, demand in the HIGH scenario is significantly higher than the MEDIUM scenario, as the use of biofuels is the main driver of decarbonisation in the transport system, instead of the penetration of LEV. Demand for bioenergy exceeds 260 Mtoe by 2050 in the MEDIUM scenario and almost reaches 310 Mtoe in the HIGH scenario.

In terms of fuel shares, the bioenergy mix does not differ to a great extent by the end of the BASE projection period. By comparison, significant changes in fuel shares can be observed in the other two scenarios, as the decarbonisation of the transport system requires a significant transformation with great implications for the biofuels sector. In both cases, a clear majority of the incremental demand stems from the liquid biofuels sector, and in particular advanced biofuels.

There are certain characteristics of advanced biofuels that aid their market penetration in the long-term. Unlike 1st generation ethanol and FAME bio-diesel, most 2nd generation biofuels are fungible – interchangeable – with conventional petroleum derived fuels, as their chemical composition is identical. The fungibility of advanced biofuels, next to their lower quality feedstock requirements, constitutes an incredible advantage over first generation biofuels because there is no need for changes in current internal combustion engines. Due to increasing blending rates of biofuels, driven by more stringent targets to decarbonize the transport system, first generation biofuels will require changes to current internal combustion engines because the higher blending rates will exceed the tolerance limits from the engines (Kampman et al, 2013).

Further, 2nd generation biofuels present higher GHG emissions savings than 1st generation biofuels and hence they can tolerate stricter environmental criteria than the latter (IEA, 2017). The Fuel Quality Directive imposes sustainability criteria on the permitted bioenergy products that can be used in the EU, and these criteria could be further tightened in the future. The stricter the criteria become, the more the growth of conventional biofuels will be inhibited and the higher the need for advanced liquid biofuels will be to penetrate the EU market.

Unsurprisingly, the larger EU economies and consumers are the larger consumers of bioenergy in absolute terms – Germany, France, Italy, the United Kingdom and Spain – with the Nordic economies – Finland and Sweden – following, as the latter hold significant amounts of biomass feedstock resources. The same holds also true for Poland. Certain Member States that have large potential in terms of feedstock availability show low demand for bioenergy because of the size of their economies, which has significant implications for the trade of advanced biofuels between EU regions. On a per capita basis, the countries with important feedstock deposits are better performers, led by Finland, Sweden and Spain.

Potential conversion capacities

The PRIMES Biomass model includes a large variety of biomass to bioenergy conversion pathways, which, for presentation purposes, have been grouped together into the categories shown in Table 24. following the “main technology principle”.

Table 24 Grouping of main conversion technologies in the categories ‘conventional’ and ‘advanced’

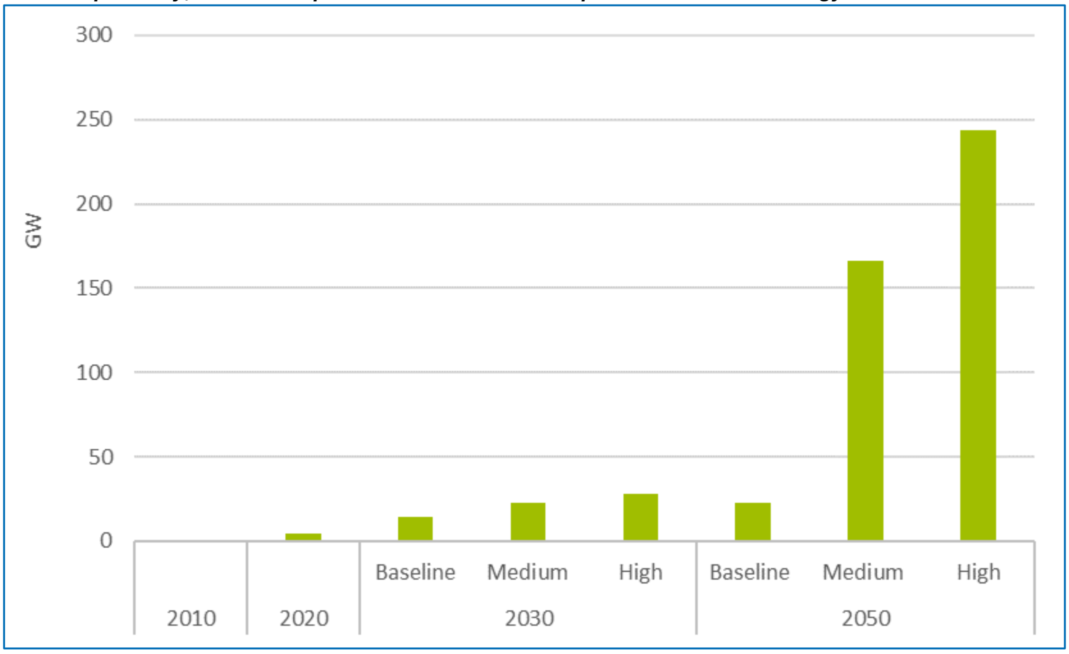
Conventional conversion technologies	Advanced conversion technologies
Fermentation	Enzymatic fermentation
Transesterification	Hydro-treatment of Vegetable Oil (HVO)
Anaerobic Digestion	Hydrolysis
	Gasification
	Pyrolysis
	Hydrothermal Upgrading

Regarding the presentation of end-use bioenergy products, the distinction between advanced and first-generation conventional biofuels is given. Should any exceptions apply, this is stated in the accompanying text.

The analysis of advanced biofuels and their contribution towards the EU energy and climate targets, should be coupled with an overview of the whole bioenergy sector (including the demand for first generation biofuels). Certain aspects that will drive the penetration of advanced biofuels in the EU energy mix are directly linked with development in other sectors of the energy system. For example, in many instances, the availability of feedstock for the production of advanced biofuels directly competes with the solid biomass requirements from the power generation sector. Therefore, in most cases, the presentation of results does not concentrate only on the sector of advanced biofuels, but they cover the wider bioenergy sector.

The conversion capacity needed to cover domestic production of advanced biofuels is shown in Figure 18. The required capacities by 2030 are only slightly higher than for 2020. The slight increases stem from the introduction of advanced biofuels in the European energy system, which are more pronounced in the HIGH scenario. In this scenario, the installed capacity of advanced technologies is 28 GW (i.e. when operating at full capacity, they can produce 21 Mtoe of advanced biofuels per year). In the same year, the capacities of conventional technologies stand at 62 GW (slightly less than 50 Mtoe per year) in all scenarios. By the end of the projection period the installed conversion capacity for advanced biofuels surpasses the installed capacity for traditional biofuels driven by an increased demand for advanced biofuels following their introduction into the EU energy mix. In the MEDIUM and HIGH scenarios the ratio of conventional to advanced biofuels conversion capacity reaches almost a factor of 5 and 8 respectively.

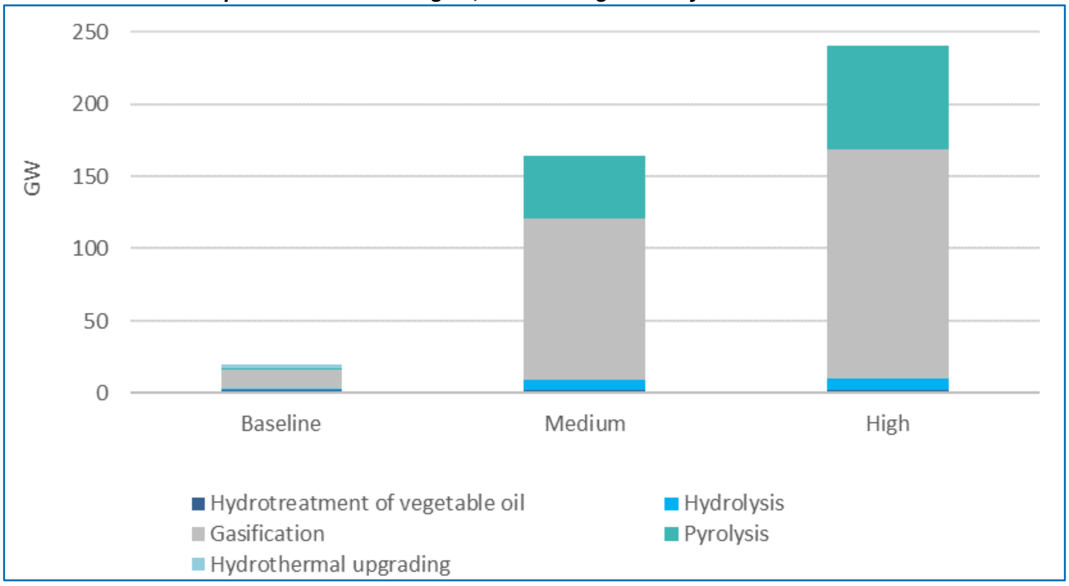
Figure 18 Production capacity of advanced conversion technologies in the main scenarios: ***The figure shows the production capacity needed to cover domestic production needs for advanced biofuels. The required capacities in 2030 are only slightly higher than for 2020. By 2050, the installed capacity of advanced biofuels increases significantly for both the MEDIUM and HIGH scenarios, by almost 5 and 8 times respectively, as a consequence of the increased importance of the bioenergy sector***



Source: Team analysis.

As far as advanced conversion technologies capacities are concerned, Pyrolysis and Gasification lead the way, producing mainly 2[nd] generation biodiesel (BtL). In 2030, the incremental biofuels demand in the HIGH, compared to the MEDIUM scenario is covered by the expansion of advanced conversion technologies. In all scenarios, small installations of HVO producing plants emerge.

Figure 19 Capacity of conversion technologies per main technology used in 2050: ***In contrast to the baseline scenario, production capacity using the gasification and the pyrolysis pathways, which are the most flexible biofuels production technologies, increase significantly***



Source: Team analysis.

Note: Anaerobic digestion is shown here under conventional technologies for illustration purposes. In reality, the technology can by categorised either as conventional or as advanced based i) the feedstock used as input (e.g. waste vs agricultural residues), ii) the post-treatment stages that results in different products (e.g. biogas vs bioSNG).

The flexibility of Gasification and Pyrolysis, in terms of the end-use fuels they can produce and the different feedstock categories they can utilise, are two key factors that allow these two technologies to hold such a large market share in the long-term. In the case of Gasification, for example, the intermediate product syn-gas can further be converted or upgraded to advanced biodiesel (BtL), bio-kerosene, biogas or biomethane (bioSNG). Other technologies such as Enzymatic Hydrolysis do not present such flexibility.

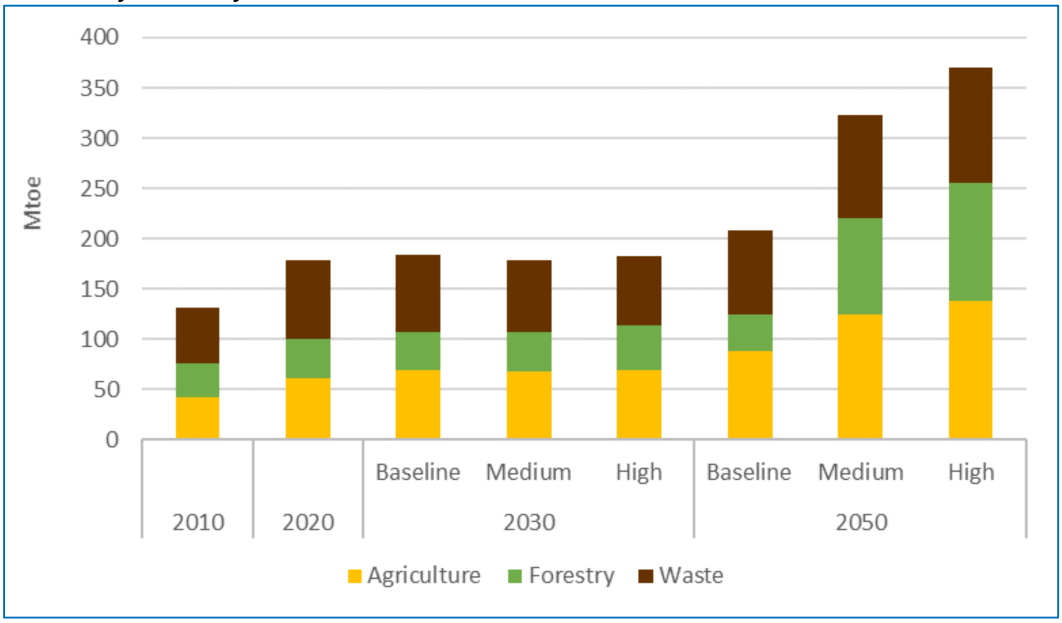
Feedstock used

This sub-section discusses feedstock requirements needed to cover bioenergy demand at the EU and MS levels, and how they differ by scenario and over time. Feedstock requirements are presented in energy units (Mtoe), so that the contribution of the different sectors can be combined.

In 2030, for all scenarios, feedstock requirements for the EU stand at around 180 Mtoe (Figure 20). In the MEDIUM scenario a more efficient energy system reduces the amount of indigenously produced feedstock required in 2030. In the HIGH scenario, the need to achieve more emissions abatement from the use of bioenergy in the transport sector increases the need for domestically produced feedstock. In the long term, the high ambition target for 2050 of reducing GHG emissions by more than 80 % compared to 1990 levels, implies feedstock requirements increase progressively in all scenarios. In 2050, the overall feedstock requirements of the EU bioenergy system exceed 350 Mtoe in the HIGH scenario.

The contribution of each sector under different scenarios and time periods is shown in Figure 20. In the mid-term, feedstock requirements from the waste sector remain relatively stable, while the demand for feedstock from the agricultural sector expands to different extents across scenarios. The forestry sector plays a balancing role, due to limited availability and more expensive supply. In decarbonisation scenarios, a high demand for advanced biofuels requires significant quantities of lignocellulosic feedstock, which can be provided mainly by the agriculture (lignocellulosic crops or agricultural residues), the forestry sector (logs or forestry residues), or imported solid biomass (i.e. more than 15 Mtoe in the HIGH scenario). Thus, in a context where the EU needs to meet its long-term energy objectives, the model findings highlight the intensified importance of lignocellulosic feedstock.

Figure 20 Split of feedstock used by the energy sector per main sector: *In the mid-term, the feedstock requirements are stable. In the long-term decarbonisation scenarios, the usage of feedstock from forestry increases substantially. Agriculture and waste feedstock usage also increases, but not as substantially as forestry*



Source: Team analysis.

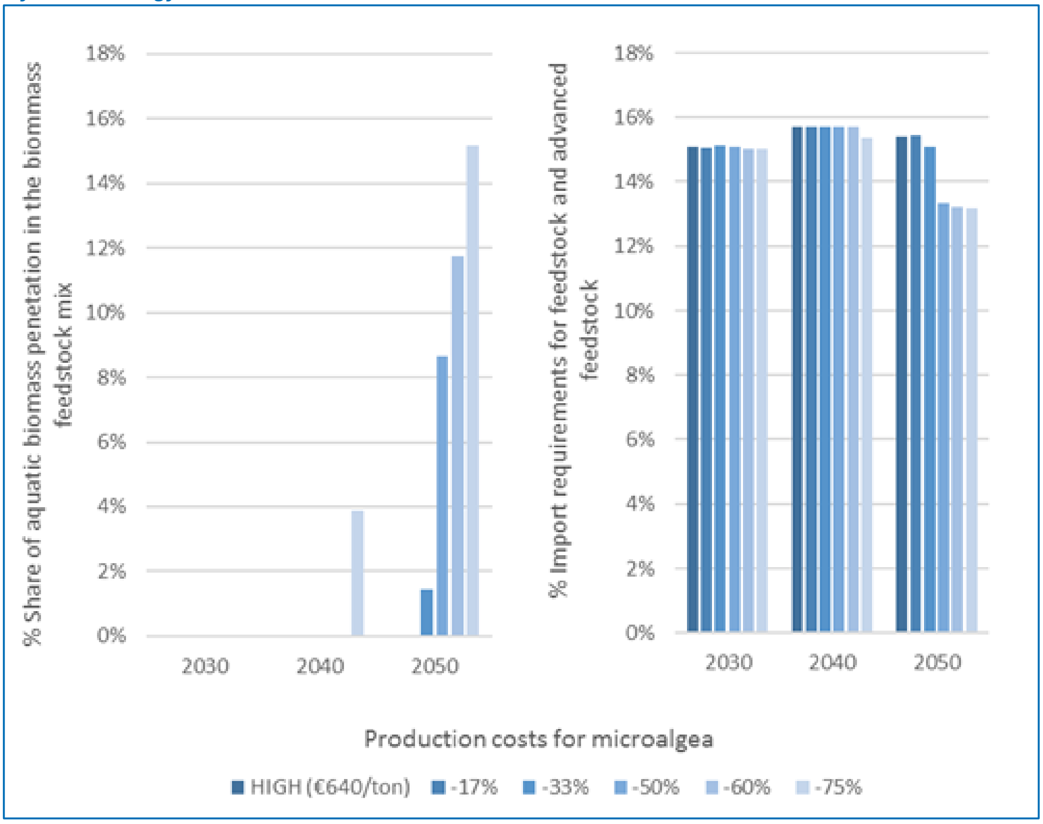
The modelling of HIGH reveals also significant highlights. In 2050, despite high R&I efforts assumed that lead to increase feedstock availability compared to the MEDIUM scenario, the EU biomass feedstock system is close to its maximum capacity in terms of feedstock production. This is reflected by the need to import 15 Mtoe (11 % of total feedstock requirements) of solid biomass to be used as feedstock by the EU biofuels sector, and additionally 31 Mtoe of end-use bio commodities (10 % of total bioenergy demand). By comparison, the total imports required in the other two scenarios (feedstock and products) are 20 Mtoe in the BASE and 29 Mtoe in MEDIUM (10 % and 11 % of total bioenergy demand respectively). Consequently, any further increases in the demand for bioenergy by the EU system is covered imported feedstock from non-EU regions or imported end-use bio-products. The quantitative analysis shows that aquatic biomass is not competitive against other feedstock types in any scenario, even in the case of high demand for biofuels. It should be highlighted though that more optimistic cost reductions in feedstock sectors (e.g. for the production costs of aquatic biomass), than the ones used for the modelling exercise, based on the findings of Task 1, could alter the feedstock mix, and make algae a domestic resources better placed to replace imports. However, there is high uncertainty around the future evolution of cost for both microalgae and the corresponding conversion technologies that could be used to produce advanced biofuels (see Text Box 4.1 for more details).

Text Box 4.1 Sensitivity analysis on the production costs of aquatic biomass

As with many technologies at currently low TRL, a lot of uncertainty surrounds the potential evolution of production costs for aquatic biomass. The qualitative analysis carried out in the early stages of the study has revealed that the technical potential of aquatic biomass produced domestically in the EU is significant (see Chapter 3). Nevertheless, the economic potential is quite limited due to the expected production costs, despite associated R&I efforts aiming at lowering the latter. However, the level of uncertainty behind those figures is important, hence a sensitivity analysis was conducted in order to assess the contribution of algae in the feedstock mix used for the production of bioenergy under more favourable conditions that would lead to lower costs than the ones used in our main analysis, i.e. breakthroughs in the production of algae). The sensitivity analysis has been based on the HIGH scenario which in turn already incorporates the Combined

R&I feedstock scenario, as it is more likely any further cost reductions than the ones used for the latter will come in a context where increased demand for advanced biofuels exists.

Figure 21 Share of aquatic biomass penetration in the biomass feedstock mix under different productions costs for microalgae (left) and associated import requirements for feedstock and advanced biofuels (right): *The costs for aquatic biomass need to drop significantly as compared to the costs used in the HIGH scenario to achieve a significant penetration of the feedstock mix used by the bioenergy sector in 2050*

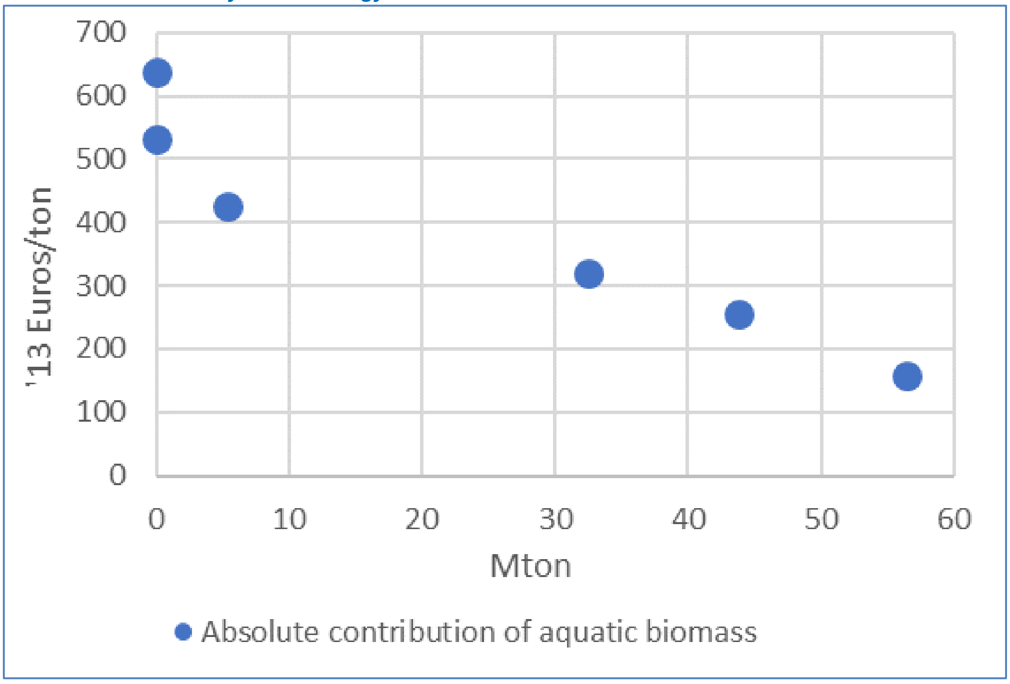


Source: Team analysis.

The sensitivity used conducted by performing additional runs of the PRIMES-Biomass model only starting from the costs of microalgae used initially in the HIGH scenario and lowering it up to 75 %. The analysis focused on microalgae, since earlier findings of the study indicated that its technical potential is much larger than the one for macroalgae. In total five additional runs were elaborated for this sensitivity analysis. The results indicate that aquatic biomass costs would need to drop significantly in order to achieve significant penetration in the feedstock mix used by the bioenergy sector (Figure 21 and Figure 22). In the context of the HIGH scenario, aquatic biomass start entering the feedstock mix when its production cost levels get lower than 450 € per ton, or 30 % below the costs in the HIGH scenario. With an important 75 % drop on the price used in the HIGH scenario (extreme case of the sensitivity), aquatic biomass holds a 15 % share in the feedstock mix. At the same time import savings for both feedstock and bioenergy of two percentage points relative to the HIGH scenario are achieved, indicating that the quantities of algae entering the mix displace mostly domestic feedstock production rather than imported feedstock or bioenergy.

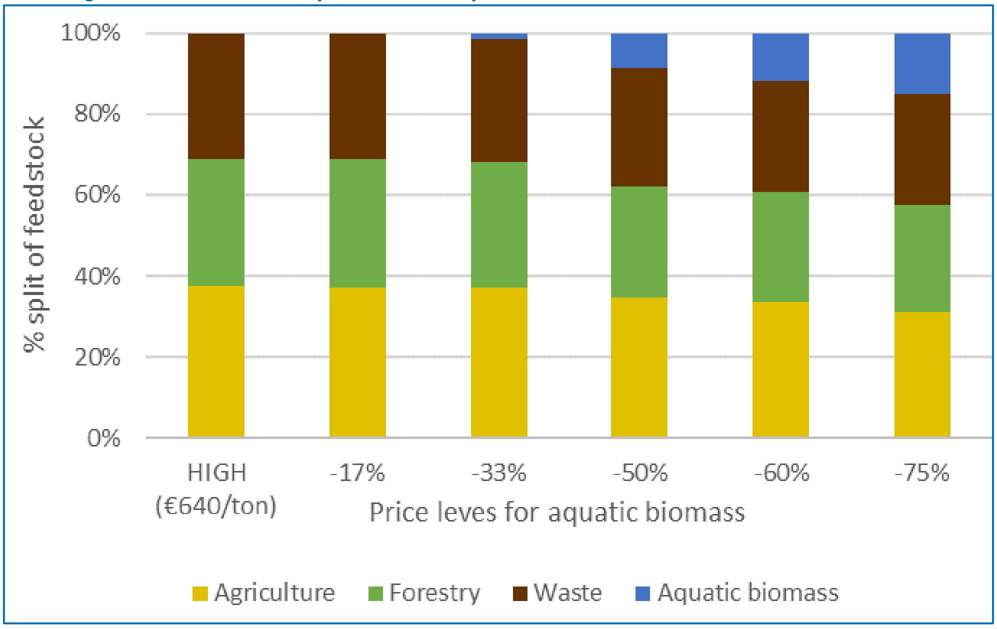
As far as the other main feedstock providing sectors are regarded, Figure 23 shows how they are affected by the increased penetration of aquatic biomass. All remaining sectors see their shares shrinking, with agriculture being the one affected the most (-6 pp in the 75 % case compared to the HIGH scenario) and forestry following (-5 pp). Within the aquatic biomass sector, woody energy crops (SRC) are the ones affected the most, due to their relatively higher costs.

Figure 22 Absolute contribution of aquatic biomass in the feedstock mix for different price levels examined for 2050: ***The costs for aquatic biomass need to drop significantly to contribute to the feedstock mix used by the bioenergy sector in 2050***



Source: Team analysis.

Figure 23 Shares of feedstock types used by the energy sector for different prices levels: The shares of the main feedstock types decrease with the increased penetration of aquatic biomass resulting from a decrease of aquatic biomass production costs



Source: Team analysis.

Feedstock requirements in the HIGH scenario are higher in countries with significant resources, which could either be directed to their domestic system (GE, FR, IT) or be exported in cases where their energy needs are low compared to their size in terms of land available for cultivation or forestry management (FI, SV).

As far as import requirements are concerned, the EU becomes increasingly dependent on bioenergy produced outside the EU in both decarbonisation scenarios (e.g. from 5 % in 2010 to 15 % in 2050 in the HIGH scenario), in contrast with the BASELINE where the import requirements remain stagnant between 2030 and 2050. However, the overall amount of biomass imports that would be available to the EU energy system is uncertain, thus requiring hypotheses to be made to enable quantitative estimates to be derived. Availability will depend on decarbonisation efforts outside the EU28; for example, in a context where the world heads towards achieving the goal to limit the global temperature increase below 2°C (compared to pre-industrial levels), it is questionable that significant feedstock will be available from the large non-EU biomass exporting regions – mainly North America and Russia. Alternatively, in other global contexts, it may be reasonable to assume that larger amounts feedstock could be imported by the EU. We have taken a cautious stance in our modelling inputs and assumed feedstock requirements will stay well below the import potentials found by the S2BIOM project (BTG, 2016).

Table 25 Import requirements across scenarios

	2030			2050		
(mtoe)	BASELINE	MEDIUM	HIGH	BASELINE	MEDIUM	HIGH
Solid biomass for feedstock	0	0	1	0	3	15
Solid biomass for combustion	17	16	16	17	18	23
Liquid biofuels	6	6	7	2	7	9
Total import requirements	**23**	**22**	**27**	**20**	**29**	**47**
% of total bioenergy demand	*13 %*	*13 %*	*15 %*	*10 %*	*11 %*	*15 %*

Source: Team analysis.
Note: Liquids biofuels include quantities of imported palm oil to be used as feedstock.

Text Box 4.2 Additional feedstock sources for the production of synthetic fuels

Besides the quantitative analysis via modelling, the study has also looked on the potential of several feedstock forms that were not covered by any of the models participating. This is the case for fuels produced via innovative Carbon Capture and Utilisation (CCU) technologies.

Carbon Capture and Utilisation (CCU) covers a variety of established and innovative industrial processes that utilise CO_2 as a source of carbon by transforming it into value added products, such as synthetic fuels, chemical feedstocks or building materials. Thereby, carbon utilisation is regarded as complementary to CCS (Carbon capture and storage/sequestration) and often by definition does not include biological routes of transformation via aquatic biomass. The following CCU technologies for synthetic fuel production were addressed in this study:

- e-Fuels, Power-to-Gas (PtG), Power-to-Liquids (PtL);
- Low Carbon Fossil Fuels;
- Artificial Photosynthesis.

Due to the current low TRL of existing Carbon Capture and Utilisation (CCU) technologies in the categories e-Fuels, Low Carbon Fossil Fuels, and Artificial Photosynthesis technologies, present production levels are negligible and will remain at a low level until 2020.

However, due to growing interest for CCU technologies among industrial players and on-going R&I initiatives such as pilot, demonstration and pre-commercial plants (mainly in Germany, Belgium, Denmark and Iceland) it is anticipated that advanced biofuels production via CCU technologies will increase in the coming decades. At present it is difficult to predict the potential contribution of CCU technologies to the advanced (bio)fuel market in 2030 and 2050. In its final report from March 2017 the Sub Group on Advanced Biofuels (SGAB) of the Sustainable Transport Forum estimates the potential contribution to 2030 transport fuel targets of e-fuels (i.e. advanced fuels from renewable electricity via electrolysis) and Low

Carbon Fossil Fuels (i.e. fuels from conversion of exhaust or waste streams via catalytic, chemical, biological or biochemical processes) to be 1.4-2 Mtoe (0,5 % of total EU energy for transport) and 2-3 Mtoe (0,7 %), respectively and depending on R&I ambition (SGAB 2017). For Artificial Photosynthesis technologies the production potential was analysed in Deliverable 6: Market potential and recommendations (Ecorys 2016b) in the framework of the study “Assessment of artificial photosynthesis“ performed for DG Research & Innovation. The findings regarding the potential of these feedstock sources are summarized in the following tables, however, the competitive position against the other feedstock sources has not been analyzed in via quantitative analysis.

Table 26: Estimated production potential of CCU technologies in 2030 and 2050

	Estimated production potential (Mtoe)			
	2030		2050	
	Reference	High R&I	Reference	High R&I
e-Fuels	1,4	2,0	2,0	10,0
Low Carbon Fossil Fuels	2,0	3,0	2,5	15,0
Artificial Photosynthesis technologies	0	0	1 8	5,8

Source: (Ecorys 2016): Deliverable 6: Market potential and recommendations, Study for European Commission, Directorate-General for Research & Innovation, 28 October 2016.

Costs

In general, the level of average costs for the production of bioenergy and, therefore, the overall costs of the bioenergy system are affected by the following:

- Demand level. Higher demand places pressure on the costs of advanced biofuels, as producers need to look for more expensive feedstock;
- Competition for feedstock. If more technologies and other sectors are competing for the same feedstock, biofuel costs and prices increase;
- Assumptions regarding the evolution of techno-economic costs (learning-by-research) and economies of scale (learning-by-doing). Capital, fixed and variable costs of technologies are decreasing over time and as economies of scale are achieved.

The total costs of the bioenergy production system for each scenario are given in Table 27. These costs include the overall cost for cultivating and transporting the appropriate feedstock, financing the necessary investment in advanced biofuels conversion capacities, operating the respective bio-refineries, transporting bio-commodities between Member States and importing feedstock or end-use products from outside the EU if necessary. To provide a better judgement of the cost-effectiveness of the biomass supply system, the simple indicator of total costs over amount of bioenergy provided to the energy sector is calculated.

Table 27 Cost of biomass supply

	2015	2030			2050		
	-	BASE	MEDIUM	HIGH	BASE	MEDIUM	HIGH
Total Cost of Biomass Supply (M€)	77 064	124 420	102 988	110 380	124 499	288 616	379 065
Total bioenergy demand (ktoe)	138 706	178 976	171 503	176 358	192 975	265 879	308 421
Total cost (‘000s €) / toe of bioenergy	0,56	0,70	0,60	0,63	0,65	1,09	1,23

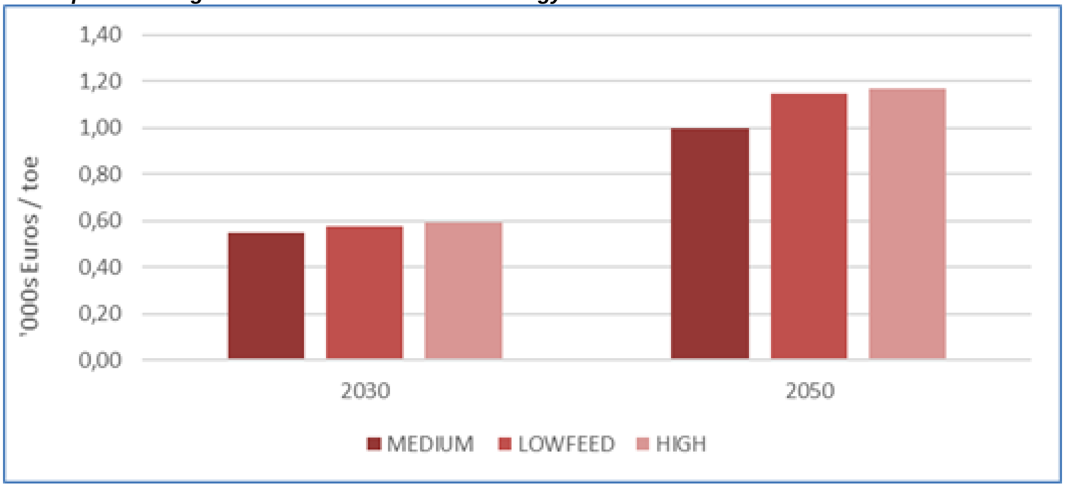
Source: Team analysis.

Note: the third row is an indicator of the average cost needed to produce one unit of bioenergy. It increases when higher demand shifts the costs towards the more expensive points on the feedstock cost supply curves (see also section 3.3.3).

In the mid-term, higher learning rates assumed for conversion technologies in scenarios MEDIUM and HIGH result in total system costs that are lower than in the case of the BASELINE scenario. Technological progress increases the cost-effectiveness of the biomass supply system, as the production of one unit of bioenergy costs less in the case of decarbonisation scenarios.

The two sensitivities run have enabled us to understand the implication of less optimistic R&I developments in the fields of biomass feedstock and techno-economic characteristic of conversion technologies.

Figure 24 Units costs of bioenergy production in the MEDIUM and LOWFEED scenarios (in 2013 euro): ***Despite progress in biofuels production, the unit costs rise significantly from 2030 to 2050 as a consequence of high biofuels demand in the bioenergy sector***



Source: Team analysis.

In the LOWFEED scenario, it has been assumed that despite R&I progress in the field of conversion technologies, there is only a targeted focus for research and innovation in the field of biomass feedstock. For agriculture, R&I is mainly targeting enhanced supply via improving the biological production and in the forestry sector, focus is given to improving feedstock mobilization. The same holds for the waste sector. No R&I efforts in the field of aquatic biomass are considered in the LOWFEED scenario, to reflect the situation where R&I efforts for this new feedstock source have no significant impact. Model findings reveal that in such a context, the cost to produce a unit of bioenergy increases by almost 20 % in the long run, as domestic feedstock supply from the EU is more limited and expensive (Figure 24). In particular, the average costs of the biomass supply in this case reach almost the ones of the HIGH scenario, a scenario in which they EU has move much closer to the upper part of the biomass cost supply curves (see Chapter 3).

Regarding the impact that limited R&I can induce to the techno-economic characteristics of the conversion technologies and the cost implications of such a case, a comparison of the investments costs needed to build conversion capacity between the HIGH and the LOWTECH is made. As presented in Table 28, limited learning-by-research and learning-by-doing can have detrimental effects on the capital needed to build the necessary conversion infrastructure in the long term. In the case of the LOWTECH scenario, such expenditures increase by 33 % on average annually.

Table 28 Average annual capital needed to build bioenergy conversion technology infrastructure[74], mln '13 €

Scenario	2021-2030	2031-2050	2021-2050
HIGH	4 520	20 215	14 983
LOWTECH	5 254	27 201	19 886
Difference (%)	16 %	35 %	33 %

Source: Team analysis.

Environmental impacts

As far as the environmental impacts due to the increased penetration of advanced biofuels in the EU energy system are concerned, the analysis focuses on the relative performance of the two decarbonisation scenarios against the BASELINE. This comparison addresses the key question whether a system with stronger reliance on biofuels leads to lower or higher emissions compared to a scenario depending more on electrification.

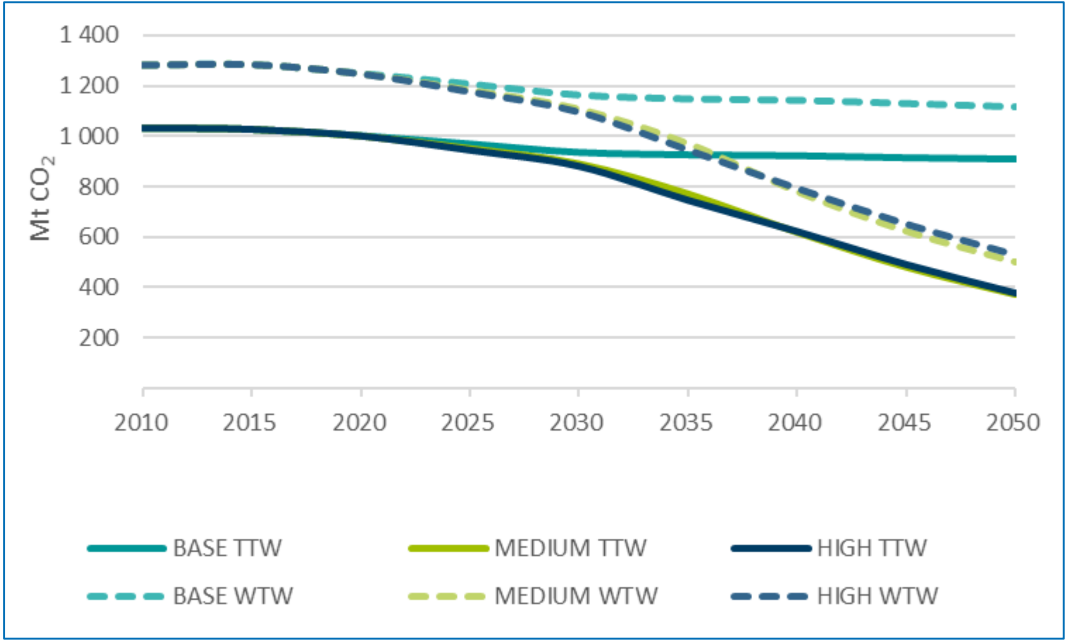
By assumption, the MEDIUM and the HIGH scenarios have been designed so as to achieve the same cumulative CO_2 emissions abatement, i.e. they used the same carbon budget in the horizon up to 2050. Therefore, no deviations between the two scenarios in terms of tailpipe emissions are observed. Both scenarios achieve roughly a 65 % reduction in the transport sector emissions compared to the 1990 level.

However, a more fair judgment should compare not only the direct emissions from fuel combustion, but also the lifecycle emissions (Well-To-Wheel). The reader can refer to Chapter 5 for more information. The HIGH scenario utilises less electricity and more biofuels for the decarbonisation of the transport sector. Since both carriers achieve zero emissions at the tailpipe, any differences in the lifecycle emissions stem from the following:

- Differences in the efficiency among powertrains. In general, electric motors achieve higher efficiency, therefore electric vehicles need less energy input than a conventional ICE powered vehicle running on petroleum products or advanced biofuels, for travelling the same distance;
- Efficiency of the feedstock to end-use energy carriers conversion. Higher losses imply not only higher feedstock (or primary energy) needs in order to produce equal amounts of outputs, but also higher own-use of energy within the conversion plants themselves. Therefore, less efficient conversion leads to higher emissions;
- Emissions in the extraction phase of the primary fuels or the cultivation of the feedstock.

[74] Includes both conventional and advanced technologies, as well as technologies for the transformation of feedstock to solid bioenergy used in stationary applications (e.g wood pellets).

Figure 25 Tailpipe and well-to-wheel emissions from the transport sector in the main scenarios, 2010-2050: ***Whereas both Tailpipe and Well-to-wheel emissions are highest in the baseline scenario, these costs decrease substantially for the MEDIUM and HIGH scenarios***



Source: Team analysis.

The scenario analysis reveals that in the long term, the HIGH scenario leads to higher CO_2 emissions (~30Mt more or 6 %) than the MEDIUM one, since the electricity used in the transport sector in the long-term is to a great extent generated via renewable energy sources (RES); the power sector is assumed to be decarbonised to a large extent by then. In the mid-term though, as the power sector still uses a significant amount of fossil fuels (mainly coal and gas) for electricity generation, emissions within the transport sector in the HIGH scenario are lower, although the differences between the two scenarios are rather small. It should be noted though that the analysis here has included only the upstream emissions for the production of electricity; any emissions from the manufacturing phase of RES, e.g. solar panels, have not been considered. Comparing WTW emissions across scenarios is a standard practice for comparing the performance of different energy pathways. We do not consider the non-inclusion of emissions from the construction of panels a flaw in the methodology.

In the case of the HIGH scenario, 330 Mt of GHG emissions can be abated by the use of advanced biofuels if it is assumed that they fully substitute petroleum products. This corresponds to 65 % of the required emission savings needed, compared to 1990 levels, in order to meet the target of reducing the transport sector's emissions by 60 %, as set in the White Paper for transport in 2011.

4.4 Evaluation of the advanced biofuels contribution to Europe's societal challenges and Energy Union vision and action points

Key Findings
• The wide penetration of advanced biofuels in the energy mix can enhance energy security by substituting the use of petroleum products for domestically produced advanced biofuels; • The use of advanced biofuels can lead to significant GHG emissions abatement.

Contribution to enhancing energy security

In both decarbonisation scenarios assessed (MEDIUM and HIGH), energy security indicators in all EU Member States improve from their reference levels in the BASELINE. In both mitigation scenarios the energy system transforms towards accelerated energy efficiency improvements and increased deployment of RES, which are to a large extent domestically produced. The level of improvement per Member State highly depends on the starting point, the energy system transformation effort in alternative scenarios and the energy supply mix.

Differences across scenarios are minimal by 2020 but they tend to increase non-linearly in the period after 2030. The figure below shows energy import dependence in all Member States in the HIGH scenario compared to the BASE in 2050. In the former, the EU energy import dependence improves by 0,02 % in 2020, 3,4 % in 2030 and 23 % in 2050, compared to the latter. The following table presents the change in import dependency by fuel in the HIGH scenario compared to the BASE scenario.

Table 29 Fuel dependency in the HIGH scenario

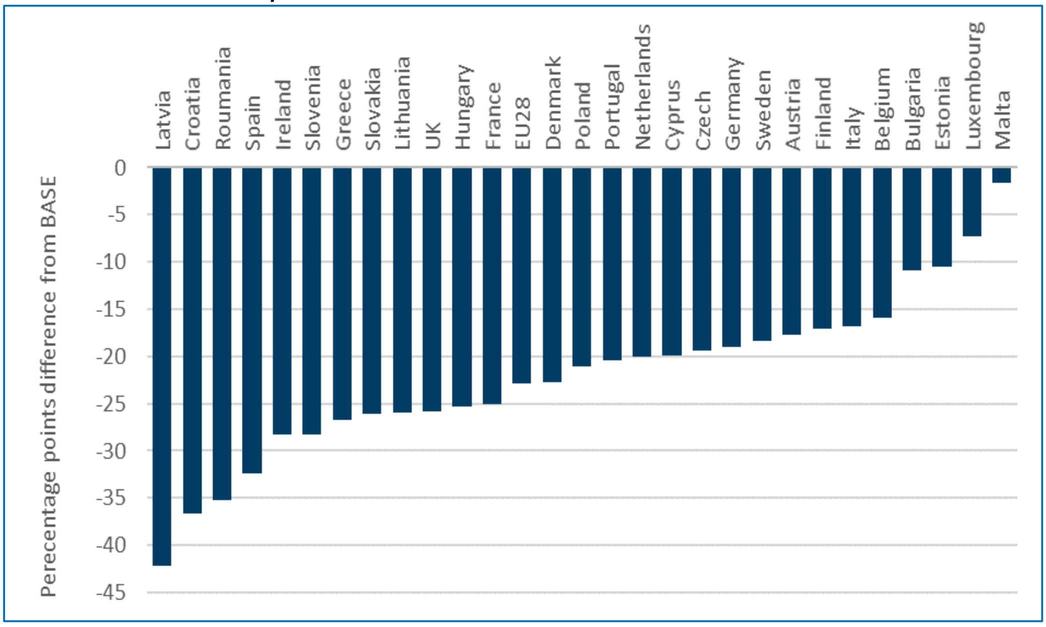
Fuel	2020	2030	2050
Oil	89 % (0 p.p.)	91 % (-1 p.p.)	96 % (-1 p.p.)
Gas	73 % (0 p.p.)	76 % (-3 p.p.)	72 % (-14 p.p.)
Bioenergy	-24 % (-1 p.p.)	13 % (-10 p.p.)	7 % (-13 p.p.)
Overall energy	55,4 % (0 p.p.)	53 % (-3 p.p.)	35 % (-23 p.p.)

Source: Team analysis.

Note: The figures in parentheses give the difference compared to the BASE scenario, in percentage points.

The highest improvements in import dependence indicator are registered for Latvia, Croatia and Romania, which are driven by energy savings and extensive substitution of (largely imported) fossil fuels by domestically produced renewable energy sources. The PRIMES-Biomass analysis projects that in the HIGH scenario, the above countries become net biofuel exporters leading to drastic reduction of their overall import dependence. On the other hand, positive impacts of HIGH are much lower in countries that remain largely dependent on fossil fuel imports.

Figure 26 Import dependence in Scenario HIGH per Member State in 2050: ***Whereas all EU country improve their import dependence indicator, there are large differences between the countries regarding how much the indicator improves***



Source: Team analysis.

In the HIGH, the successful penetration of advanced biofuels sustains the fleet of cars powered by ICE; the development of electric vehicles is constrained. This implies lower electricity production in all EU Member States relative to the MEDIUM scenario. The MS that produce electricity based on imported fossil fuels and are feedstock and biofuel producers are expected to be the ones that will present the higher improvement in energy security indicators (Latvia, Croatia and Slovenia). On the other hand, scenario impacts are expected to be minimal in countries that import a high share of their bioenergy needs. The scenario could even have negative energy security implications in case that a country produces electricity based on domestically produced RES, while it imports the majority of biofuels for its transport sector; this is the case for Austria and Luxembourg.

Contribution to EU climate goals

Contribution to the reduction of GHG emissions

Regarding the 2030 GHG abatement target (40 % reduction in GHG compared to 1990 levels), both decarbonisation scenarios respect the EU council target. In the case that advanced biofuels can be considered to substitute solely petroleum products, they would abate 13 Mt and 23 Mt of CO_2 in 2030 in the MEDIUM and in the HIGH scenario respectively.

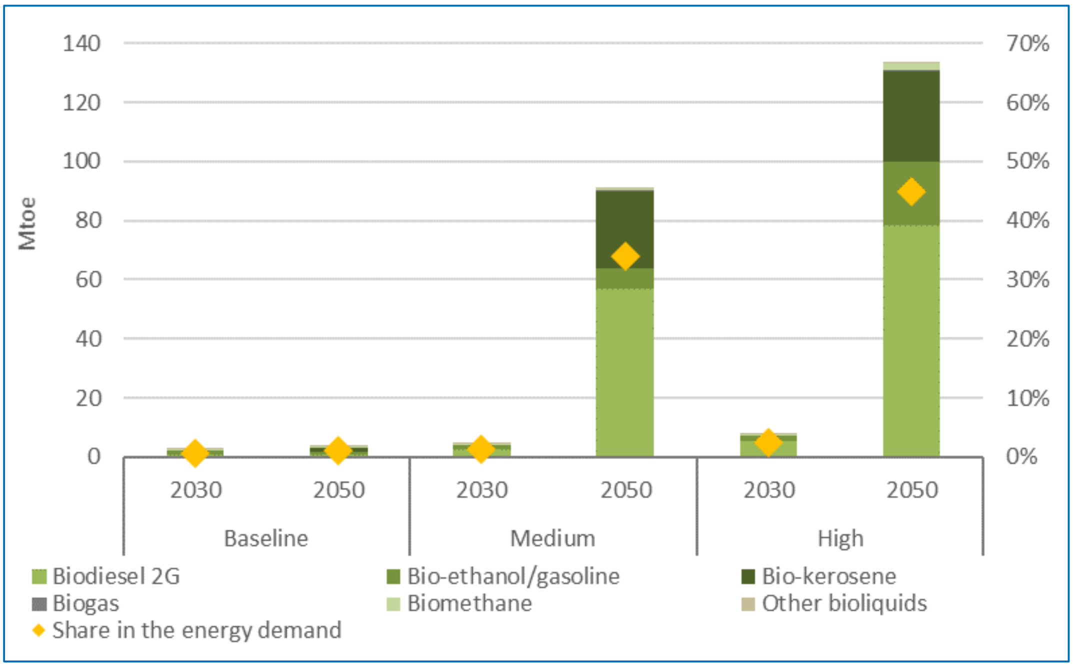
In addition, in the long term, both decarbonisation scenarios achieve a 57 % reduction in GHG emissions compared to the respective levels in 1990, which is broadly consistent with the long term goal as set in the White paper on Transport.

Contribution to the energy mix

The EU transport sector is considered to be the one that can be benefit from R&I efforts in advanced biofuels conversion technologies, as it currently relies heavily on petroleum derived products and alternative options are limited. Several options such as electrification are not viable for some transport modes like aviation, maritime and long-distance freight.

Total consumption of advanced biofuels in the overall transport sector by scenario are given in Figure 27. In a business-as-usual context, the contribution of advanced biofuels to the EU transport sector energy mix is minimal, both in the mid- and long-term. In the mid-term, the share of advanced biofuels increases but is still limited across all scenarios (less than 2 % of the energy sector's needs in the HIGH scenario). However, the scheme reverses towards the end of the projection period, as the ambitious GHG emission reduction targets, signals a significant transformation that needs to take place as far as both passenger and transport mobility is regarded.

Figure 27 Contribution of advanced biofuels in the transport sector: ***Whereas the sustainable biofuels' share in energy demand of the transport sector remains low in 2030 in all scenarios, it increases to ca. 35 % and ca. 45 % in the MEDIUM and HIGH scenario respectively. This is largely due increased biodiesel 2G and bio-kerosene demand***



Source: Team analysis.

4.5 SWOT analysis of interests of Member States and major relevant nations

Key Findings
• The EU is, together with the US, China, Brazil and Canada, one of the major current and future players in the advanced biofuels sector due to its sustainable feedstock potential, supporting policies and technology leadership. Yet, (future) policies will be crucial for realising this opportunity; • Finland, France, Germany, Italy, Spain, Sweden and the UK are the (potential future) leading countries in the advanced biofuels sector within the EU. Targeted policies are crucial to unlocking this potential and should address the substantial investments needed for the market transition to large-scale advanced biofuels production; • Increased R&I provides the opportunity for countries with otherwise little domestic feedstock to increase their potential and to build an own advanced biofuels sector.

The SWOT analysis assesses the strengths and weaknesses, opportunities and threats for the development of an advanced biofuels sector in the EU and in the most important non-EU countries.

Using quantitative modelling outputs on feedstock and biofuels production, policies supporting (advanced) biofuels and (sustainable) feedstock production in Member States, and indicators for technology leadership in the area of advanced biofuels and feedstock R&I[75], we group EU Member States into four clusters. The SWOT analyses are performed on cluster level. The information used for clustering is complemented by additional indicators from both quantitative and qualitative analyses. Table 30 summarises the quantitative and qualitative indicators feeding into the EU clustering and into the cluster SWOT analyses.

[75] We use by the number of top 10% publications in a country obtained from a bibliometric analysis as an indicator for technology leadership.

Table 30 SWOT criteria – EU cluster and EU28

Criterion	Explanation
Feedstock production and costs (current and in 2050) – BASE scenario and HIGH scenarios	Quantitative assessment of the amount of second generation feedstock produced in the BASE and HIGH scenarios, where relevant broken down by feedstock categories, MS and EU28 level.
Biofuel production and costs (current and in 2050) – BASE and HIGH scenarios	Quantitative assessment of the amount of advanced biofuels produced in the BASE and HIGH scenario, where relevant broken down by biofuel and/or conversion technology category, MS and EU28 level.
Feedstock imports/exports (current and in 2050) – BASE and HIGH scenarios	Quantitative assessment of the imports and exports of sustainable feedstock in the BASE and HIGH scenario, where relevant broken down by different feedstock categories, MS and EU28 level.
Biofuel imports/exports (current and in 2050) – BASE and HIGH scenarios	Quantitative assessment of the imports and exports of advanced biofuels in the BASE and HIGH scenario, where relevant broken down by different feedstock categories, MS and EU28 level.
GDP effects of advanced biofuels sector development –HIGH scenario	Quantitative assessment of the GDP effect of the development of an extensive advanced biofuels sector in the HIGH scenario as % change relative to the BASE scenario.
Employment effect of advanced biofuels sector development – HIGH scenario	Quantitative assessment of the employment effect of the development of an extensive advanced biofuels sector in the HIGH scenario as % change relative to the BASE scenario.
Effect on security of supply – HIGH scenario	Quantitative assessment of the % change of an indicator denoting energy import dependence relative to the BASE scenario.
Technology leadership – leading publications and leading companies	• Quantitative assessment of the amount of leading publications, where relevant broken down by cluster of research activity, MS and EU28 level; • Qualitative assessment of the prevalence of companies currently leading in technology development (where relevant), MS level.
Regulatory conditions and feedstock/biofuels policies	Qualitative assessment on the regulatory environment on MS level: to what extent is it supportive? Are there any clear (long-term) policy ambitions in place with respect to sustainable feedstock production? This indicates to which extent the institutional conditions currently and in the future are favourable/non favourable with respect to sustainable feedstock and advanced biofuels production in the specific country.

Source: Team analysis.

The EU28 SWOT analysis combines the four cluster SWOT's with additional EU-level information. enables us to obtain a clear picture of the implementation potential and best practices and can provide a basis on which room for improvement is assessed. 'Strengths' and 'weaknesses' pertain to the current or short-term positive or negative conditions in Member States and their clusters which might favour or impede the development of an advanced biofuels sector. These conditions are related to the Member States' geographical, political/institutional and other conditions (un)favourable to the development of an advanced biofuels sector.[76] 'Opportunities' and 'threats' denote future conditions and developments in Member States favouring or hampering the advanced biofuels sector.

Despite this amount of indicators, other important factors cannot be accounted for due to limitations in the modelling approach.[77] It is important to keep the limitations of the analysis in mind.

EU-cluster SWOTs

The clustering resulting from the analysis of some indicators as described above is presented in Figure 28. To correct for the bias towards large countries in assessing the sustainable feedstock and biofuels production potential, corrections pertaining to the size of a country have been accounted for.[78] Additionally to including these relative indicators, future prospects for some countries with low current potential in the advanced biofuels sector have changed due to increased R&I in the HIGH scenario. This is the case for Denmark and Hungary, for instance.

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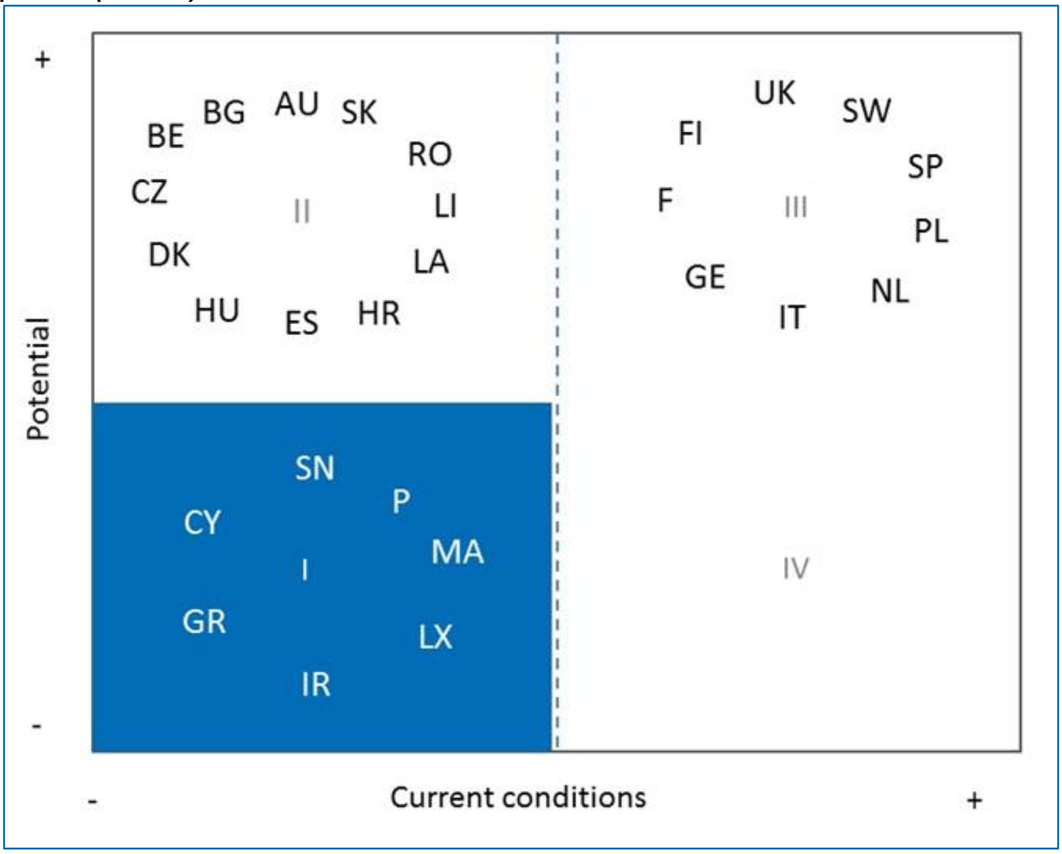
76 Examples of these conditions are the feedstock production potential, biofuels and feedstock policies, technology leadership of a country in the field of biofuels, and already installed or planned biofuel production capacity, for instance.

77 Examples of such factors are foreign investments in the advanced biofuels sector in the EU and European investments in non-EU countries, and technology transfer between the EU and non-EU countries.

78 This has been done by accounting for the ratio of feedstock production to country area and biofuels production to biofuels demand in a country. Consequently, geographically small countries with little absolute feedstock production can still be judged to have a large potential, if their feedstock production per ha land and/or their ability to cover domestic biofuels demand (produced biofuels/biofuels demand) are high or increase.

Figure 28 Clustering of EU28 countries in the HIGH scenario: ***There is a small group of countries leading with respect to advanced biofuels (cluster III) and another small group with limited current and future potential (cluster I), but most EU countries fall into the category of limited current, but high future potential (cluster II)***



Source: Team analysis.

Cluster I: Limited present and unclear future potential

Many small EU countries fall in this category: Cyprus, Greece, Ireland, Luxemburg, Malta, Portugal and Slovenia. In the BASE scenario, production of feedstock and advanced biofuels is very low in the short-term, which clearly is a weakness, as no substantial advanced biofuels sector develops in the short-term. Not only the absolute production is low – also the relative indicators are unfavourable: the countries' productivity per hectare is low and they do not produce enough feedstock to satisfy domestic demand. The lack of R&I in these countries implies that no significant improvement of the situation will be possible for the countries on their own (threat). By applying methods developed in other European countries and profiting from R&I done elsewhere, these countries could develop a (for their size) considerable feedstock and advanced biofuels sector: hence, most countries are able to considerably increase their future feedstock production by 2050 in the HIGH scenario. While no or little policies are in place targeting the development of sustainable feedstock, the design of future biofuel policies constitutes an opportunity needs to be strengthened.[79] Yet, these countries remain dependent on feedstock and biofuels imports in the short- and long-terms to meet their feedstock and biofuels demand, and R&I (HIGH scenario) does not alleviate this dependency.[80] Hence, although the energy import dependency indicator changes is positively for the EU in general, it is affected much less positively in countries remaining largely dependent on fossil fuel imports, also in the HIGH scenario. Nevertheless, R&I constitutes an opportunity for future biofuels production: three countries almost double their biofuels production in

79 In fact, these countries already employ some (advanced) biofuels supporting policies, which could be built upon.

80 There are some exceptions, however. Slovenia exports its feedstock in the BASE scenario in 2050, whereas Ireland becomes feedstock net exporter in the HIGH scenario in 2050 (opportunity).

the HIGH scenario as compared to the BASE. Overall, however, the effects of an advanced biofuels sector in the HIGH scenario are effect relative to the BASE scenario in terms of GDP growth.[81] In contrast, overall employment is affected somewhat positively, especially in Ireland, Luxemburg and Portugal. Unsurprisingly, almost all countries profit from an increase in the agriculture and biofuels production sectors due to the increased feedstock production, especially Luxemburg, Portugal and Slovenia, which is also mirrored in the employment numbers for these sectors.

Cluster II: Limited present, but higher future potential

This cluster consists of Austria, Belgium, Bulgaria, Czech Republic, Denmark, Estonia, Hungary, Croatia, Latvia, Lithuania, Romania and Slovakia. Although some of these countries have large (theoretical) current and future feedstock potentials (strength), this is not mirrored in their current and short-term production levels (weakness). Yet, installed/planned capacity, together with a number of operational and planned projects in advanced biofuels in these countries, indicate that there are opportunities in the future.[82] Most countries do not have to rely on feedstock and biofuels imports in the short-term, with the exception of Austria, Belgium and Denmark.[83] Overall, policies to support the production of (sustainable) feedstock or of (advanced) biofuels are in place.[84]

R&I can have a large positive impact on the production of both feedstock and advanced biofuels, almost doubling the feedstock production in the HIGH scenario as compared to the BASE scenario for 9 of the 12 countries.[85] R&I also renders the net importers of feedstock in 2050 (Austria and Belgium) into net exporters in the HIGH scenario. The indicator for energy import dependence improves most for Latvia, Croatia and Romania, driven by energy savings and extensive substitution of (largely imported) fossil fuels by domestically produced energy sources. Whereas current policies are predominantly a strength, opportunities could be enhanced by emphasizing the sustainability criterion of biofuel feedstocks more, or by implementing specific advanced biofuels provisions. The general lack of technology leadership is a clear threat to the innovative potential in the area of advanced biofuels (although there are some exceptions, such as Austria and Denmark, where academic research, biofuels production projects, and collaboration between academia and industry can be found). Another threat is the demand for biomass feedstock from other sectors, especially in Belgium.[86] Both threats might curb the installation of advanced biofuels production capacities in these Member States. Whereas the effects of R&I and the corresponding growth of the advanced biofuels sector have a negative effect on GDP, employment is positively affected for most countries.[87] The positive output change in the agriculture and biofuels production sectors in the HIGH scenario, ranging from 7 % - 21 %, is also mirrored by employment in these sectors, ranging from 3 % to 15,5. %.

[81] Only Ireland and Portugal slightly profit in terms of GDP in the HIGH scenario.

[82] Operational capacity for biofuels production exists in Austria and Denmark, whereas capacity is planned in Denmark, Estonia and Latvia.

[83] This is, however, due to their higher demand for biofuels. Czech Republic, Croatia and Slovakia export feedstocks, whereas Bulgaria and Hungary can export biofuels.

[84] Belgium scores high in terms of feedstock policies, whereas Bulgaria, Czech Republic and Denmark score high for biofuels policies. Estonia, Hungary, Lithuania, Romania and Slovakia are lagging behind regarding feedstock policies.

[85] The effect is large in absolute terms in Romania, Austria, Czech Republic and Hungary, and in relative terms in Bulgaria, Estonia, Latvia, Lithuania and Slovakia, for instance.

[86] This demand stems mostly from the energy sector, from co-firing of solid biomass, for instance.

[87] Only Croatia displays positive GDP changes of 3-3,5%. The highest employment increase is registered for Croatia and amounts to 1,75% more employment in the HIGH than in the BASE scenario. Employment is affected negatively only in Bulgaria, Czech Republic and Romania.

Cluster III: Advantageous current and high future potential

The current and future leaders regarding advanced biofuels are Finland, France, Germany, Italy, the Netherlands, Poland, Spain, Sweden and the UK. They are characterized by the highest feedstock and biofuels production in the short-term.[88] Other strengths encompass high demand for feedstock, biofuels production capacity[89], technology leadership, above average collaboration between academia and industry[90], and policies supporting (sustainable) feedstock and (advanced) biofuels production. The current dependence on both feedstock and biofuels imports is a weakness[91], just as the absence aquatic biomass production (despite a high theoretical potential).

R&I efforts increase future production of feedstock and advanced biofuels.[92] Increased R&I has very positive effects on the cost-competitiveness of agricultural biomass in Germany, Spain, France, Italy, Poland and the UK, whereas advantageous effects on forestry biomass are seen in Germany, Finland, France and Sweden. Continued high demand for bioenergy ensures a large market for bioenergy, resulting in economies of scale. Also, technology leadership and the experience and knowledge associated with the operation of production capacities leading to learning-by-doing effects can result in a competitive advantage for these Member States in advanced biofuels production. These effects can be amplified by continued high rates of capacity installation in these countries, especially in the HIGH scenario. Policies supportive of feedstock and biofuels production, but also of R&I development can enhance the opportunities. Also, future dependence on feedstock and advanced biofuels imports might become a threat, especially in the face of decarbonisation efforts outside the EU28.[93] Demand from other sectors such as the energy sector constitutes a threat especially in the Netherlands and Poland. Possible threats are related to the transformation into an energy system based on bioenergy: the success of this transformation is related to many interdependent factors, such as supporting policies and social acceptance. The bulk of the costs and investments is greatest for these Member States and needs to be born partly by consumers in these Member States.[94] This has negative effects on the GDP, especially in Germany, Finland, the UK and Poland. Nevertheless, the advanced biofuels sector has mildly positive effects on overall employment, which is largely due to an increase of employment and output in the agriculture and biomass sectors.[95]

Cluster IV: High present, but unclear future potential

No EU countries were identified which fall in this category.

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88 The Netherlands is an exception regarding feedstock production as it is relatively small and possesses only little feedstock potential.

89 Finland, France, Germany, Italy, the Netherlands, Sweden and the UK possess installed capacities for biofuels production, whereas capacity installation is planned in France, Germany, Poland, the Netherlands, Spain, Sweden and the UK.

90 An above average collaboration between academia and industry can be found in Sweden, Finland, Germany and the UK.

91 Only Germany is an exception by being a net exporter of feedstock in the short-term.

92 France, Germany, Poland, Spain and Sweden profit most in terms of feedstock production, whereas the Netherlands and the UK do not experience much effect.

93 In 2050, all countries, except France, are net importers for feedstock. In 2050, all countries, but France, Spain, Sweden and (in the HIGH scenario) also Finland, are net importers of biofuels.

94 The average costs per ktoe of biomass supply in these countries increase in 2050 in scenario 2 as compared to scenario 0 in all countries, apart from Sweden and Finland.

95 Only Poland has experiences slightly negative employment effects in 2050.

EU28 SWOT

The country cluster SWOT's provide a starting point for assessing the EU's potential. Various policy initiatives have taken on board the conclusions of several European studies which have already recognised that advanced biofuels are important constituents of a low-carbon transformation. This can be seen as an important strength as these policy initiatives provide the framework for (future) Member State policies and initiatives.[96] Although the technical potential for feedstock might be more abundant elsewhere than in the EU (weakness), the EU's global leadership in sustainable feedstock and advanced biofuels conversion technologies is an important strength.[97] A potential weakness translating into a future threat might be a lower involvement of academic research with industrial partners as compared to other non-EU countries[98], which might worsen the chances of fast technology application. Yet, due to its strong technical leadership, companies in the EU have a good starting position to establish themselves as a front-runner in the development and application of (advanced) biofuels conversion technologies, and to gain a comparative advantage due to early learning-by-doing effects. An appropriate EU-level policy design might enhance this opportunity.

Also, policy on EU level can significantly improve the opportunities for the development of the advanced biofuels sector: The fuel sustainability criteria of the Fuel Quality Directive could be tightened in the future, increasing the need for advanced liquid biofuels in the EU. Increased R&I efforts could lead to a 50 %-100 % increase in the EU's feedstock potential and to a decrease of capital expenditure for conversion technologies by 20 % on average.[99] Still, without policies directed at the demand-side of the market (quotas, blending mandates, fossil fuel taxes), advanced biofuels are unlikely to become adapted (threat).

The EU-level planned production capacity for 2020 is approximately sufficient to cover the projected biofuels demand. The required capacities are only slightly higher in 2030. Yet, by the end of the projection period, the required capacity increases dramatically, especially in the HIGH scenario, necessitating high additional investments. Also the total costs of entire bioenergy system are expected to increase by the end of the time horizon.[100] For the transition to succeed, policies need to be in place ensuring a long-term business case for investors in the advanced biofuels sector.

Despite the fact that there is substantial R&I regarding aquatic biomass in the EU, some major players in aquatic biomass R&I are located in the EU[101], no aquatic biomass sector exists or likely will exist in Europe. This is possibly a threat to the advanced biofuels sector, as one very promising feedstock, whose growth rate considerably surpasses the productivity rates of terrestrial feedstocks, is likely to not be produced economically in Europe.[102]

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96 These initiatives encompass Directive 2015/1513/EU, the Commission's Communication on "A European Strategy for Low-Emission Mobility" in July 2016 and the proposal for a revision of Directive 2009/28/EC, published as part of the November 2016 Clean Energy Package. The studies referred to are, among others, the "2030 energy and climate policy package", 2050 Energy Roadmap, Roadmap to Low Carbon Economy and the White Paper on Transport.

97 The EU is leading in all but one identified technology cluster, namely the cluster "biochemical conversion, glycerol as by-product of biofuel production".

98 Only 12% of the publications in Europe involved industrial partners, in contrast to 22% in Japan, 13% in the U.S. and Canada respectively.

99 These cost reductions are net of cost reductions induced by learning-by-doing effects.

100 The simple indicator of total costs over amount of bioenergy provided increases from 0.56 in 2015 to around 0.6 in 2030 and 1.23 in the HIGH scenario in 2050.

101 Some companies researching aquatic biomass are located in Germany, France, Belgium, Ireland, England, Scotland and the Netherlands. Furthermore, France and Germany are important countries regarding the count of patent fillings related to microalgae-related technologies, after China, the US, Japan and Korea. Finally, the EU is indeed the most important world region for the second filling of patents, ranking first before Australia, China and the US.

102 On the other hand, there is high uncertainty around the future evolution of costs for aquatic feedstock and the corresponding conversion technologies.

R&I improves the EU's competitiveness in terms of sustainable feedstock availability. Nevertheless, substantial feedstock potential is found in other non-EU countries at often lower production costs. Yet, the expected limited competition on biomass markets from other countries ensures that an advanced biofuels sector using domestic biomass can develop. Increased R&I in the EU does then not only ensure competitiveness, but also the availability of sufficient volumes of EU feedstock for domestic advanced biofuels production. Furthermore, R&I provides the opportunity to enhance competitiveness downstream as feedstock costs represent the largest cost item of biofuels costs.

Despite the R&I induced increase of available biomass in the HIGH scenario, the demand surpasses European supply in 2050; the EU biomass feedstock system is close to its maximum capacity in terms of feedstock production. A potential dependence from sustainable feedstock and from advanced biofuel imports could be a threat on the level of security of supply as it is impossible to predict the non-EU feedstock availability, advanced biofuels production and non-EU demand. Yet, the overall energy import dependence in the EU28 decreases by ca. 22 percentage points in the HIGH scenario relative to the BASE scenario; this is mostly due to energy savings and extensive substitution of (largely imported) fossil fuels by domestically produced renewable energy sources.

Whereas the impact on the EU's GDP growth is virtually zero over the period 2020-2050[103], 114 000 new jobs are created in 2020-2050 in the HIGH as compared to the BASE scenario, most of which in the biomass-to-biofuels conversion sector (68 %). The shift to more advanced biofuels improves the EU's overall energy security as it reduces the dependency on imported fossil fuels.

Relevant non-EU countries

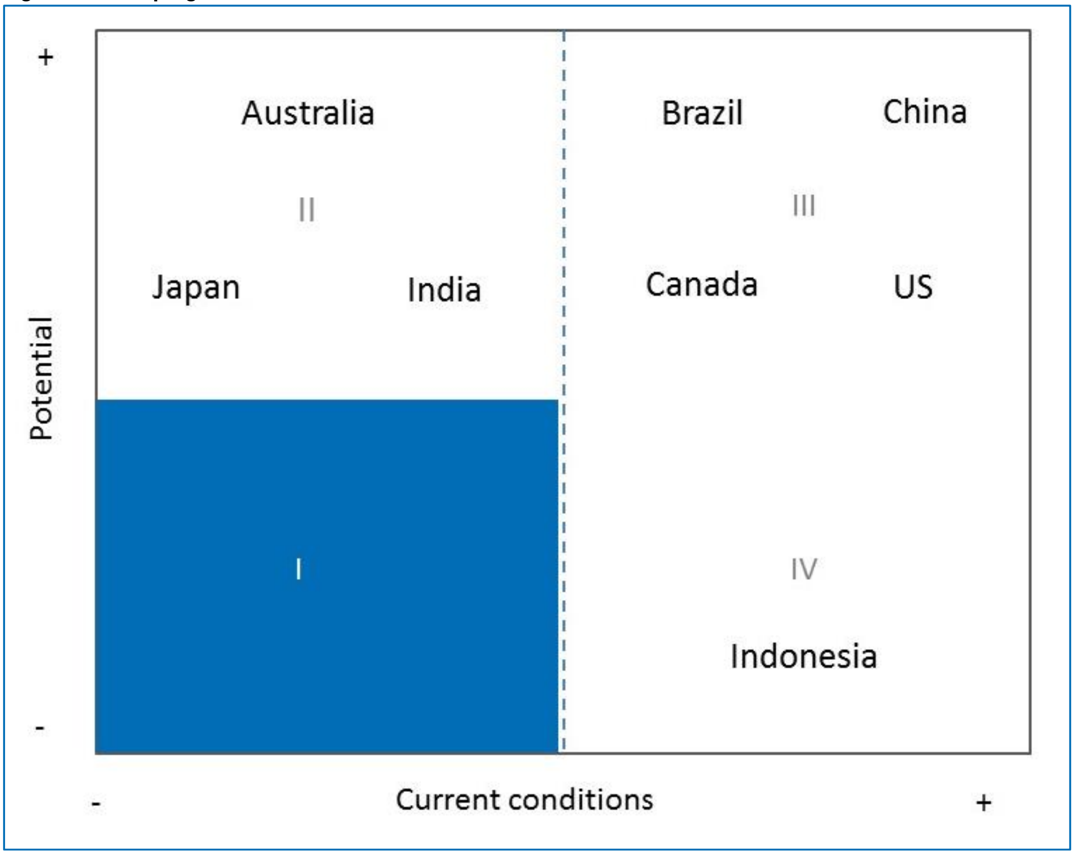
Similarly to the clustering of EU countries, non-EU countries have been grouped into three categories. The grouping accounts for the amount of sustainable feedstock and advanced biofuels produced both currently and in the future, current feedstock policies, scientific publications related to feedstock R&I and conversion technologies, relevant pilot projects, and patents related to the production of advanced biofuels. We focus on the following countries in the analysis (see also Figure 29):

- Countries with advantageous current and unclear prospects for the future[104]: Indonesia;
- Countries with disadvantageous current conditions and with significant future potential: Australia, India, Japan;
- Countries with advantageous current conditions and future potential: Brazil, Canada, China, US.

[103] The impact on GDP differs by MS, but, on EU-level, there are negative GDP effects in later periods (2030-2050) due to increased imports, exports and a decrease in household consumption, as compared to the BASELINE.

[104] Despite its high feedstock potential, Russia is not seen as a major player regarding advanced biofuels and sustainable feedstock: no advanced biofuels are produced and policies promoting sustainable feedstock and advanced biofuels production are limited. Furthermore, Russia has very limited current R&I potential regarding sustainable feedstocks or conversion technologies. Therefore, we consider it to have low current and a limited future potential. The same reasoning holds for the Ukraine. Other potential candidates would have been Malaysia (high feedstock potential and some first generation biofuels production), but no advanced biofuels production is taking place in this country. Also Argentina was a possible candidate, but due to the fact that no advanced biofuels are produced in the country, it has been dropped.

Figure 29 Grouping of non-EU countries



Source: Team analysis.

Non-EU country SWOTs – main conclusions

Countries with advantageous current and unclear prospects for the future

A major weakness is that an advanced biofuels industry is largely absent in Indonesia[105], although agricultural biomass is prevalent. The substantial theoretical potential of (sustainable) feedstock is a strength. Yet, substantial levels of undernourishment or food inadequacy and dependency on cereal imports require the prioritization of domestic production of food and feed in its agriculture, with little room for diversification to include non-food crops. Also, sustainability concerns constitute an important weakness, especially regarding the large biomass potential in the forestry sector. Deforestation and accessibility are major problems. Another strength is the production of a considerable amount of biofuels, but the lack of policies to stimulate the production of advanced biofuels and to provide incentives for future sustainable feedstock production pose a threat to the country's future sustainable feedstock and advanced biofuels production. Similarly, the lack of R&I efforts (academia, industry) poses a threat to the advanced biofuels sector in the future.

Countries with disadvantageous current conditions and with significant future potential

Whereas current sustainable feedstock and/or advanced biofuels production is relatively low in these countries (weakness), their future potential is likely to grow due to supporting policies, R&I regarding energy crops and algae, high agricultural and forestry feedstock potential and experience with conventional biofuels production. Australia's feedstock potential encompasses energy crops and algae, and India is experimenting with energy crops projects.[106] India and Japan have large potentials in agriculture and waste, as well as possibly aquatic biomass (opportunities). The

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105 There is significant conventional biofuels production, though; palm-oil based biodiesel and biogas are produced in Indonesia.

106 After the launching of this ambition in 2009, the viability of Jatropha as efficient energy crops has been contested in recent years.

recognition of sustainability requirements for biomass feedstock and policies supporting sustainable feedstock and advanced biofuels production are already in place and[107], just as their substantial R&I efforts regarding sustainable feedstock and conversion technologies, open up future opportunities for these countries.[108] Collaboration of research with industry is widespread especially in Japan. A possible threat, especially for India, is the traditional view of biomass as fuel for meeting rural energy needs.

Countries with advantageous current conditions and future potential

The strengths of these countries encompass production of sustainable feedstocks and advanced biofuels, while a large feedstock potential constitutes an important opportunity for the advanced biofuels sectors in these countries in the future. All countries have potential in the agriculture and forestry[109], while waste is important for the US, China and Brazil.

Text Box 4.3 The role of GMO in sustainable feedstock production

Whereas GMO is not specifically modelled in the feedstock models used for the EU in this study, GMO is regarded as one option to increase yields. Yet, as explicated in Chapter 3 of this report, the use of GMO plants seems to be in conflict with current preferences of Europeans, such that our scenarios did not rely on progress regarding the use of GMO plants.

In other parts of the world, such as in the US and in Latin American countries in particular, the attitude towards GMO is much more positive. GMO plants have been widely used in Latin America in the agricultural sector, contributing to the production of first-generation biofuels from soy beans and sugar cane, for instance. In addition to agricultural crops, GMO is starting to play a role in the forestry sector, too.[110] In 2015, the Brazilian government approved GMO eucalyptus trees.[111] In the US, there is a controversy whether these trees should be approved.

Although there is the theoretical potential that the development of GMO's will further enhance the sustainable feedstock potential of these countries, the deployment of GMOs is not part of the assumptions made in the Billion ton report, for instance. Naturally, specific genetic stocks with favourable characteristics are selected to improve the yields of forests and agricultural products, but genetic selection does not involve material which has been altered using genetic engineering techniques. Yet, some researchers see the role of biotechnology in a Sustainable Biofuel Future as indispensable (Sexton et al., 2009, http://www.agbioforum.org/v12n1/v12n1a12-zilberman.htm), as genetic modifications might reduce land-use changes associated with rising biofuel demand (although this is not relevant for second and third generation biofuels) and genetic modification might improve the efficiency of microalgae in biofuels production. In view of these findings, it might be the case that countries in which GMOs are allowed might have a **comparative advantage** regarding their sustainable feedstock production as more efficient feedstock types etc. might be developed. Yet, this potential has not been quantified yet.

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107 The recent change from policies focused on supply-side pushes to market-based incentives resulted in the introduction of modern biomass technologies in India.

108 In our publication analysis, all countries were identified as important players (Top 10) in the R&I fields concerning.

109 The countries vary in their management techniques: in Canada, there is a large uptake of sustainable forest management, whereas it is relatively low in the US. Also, low density of agricultural residue type feedstocks and their disperse availability might make them costly to trade.

110 The Guardian (2012).

111 GJEP (2015).

There is easy logistic access to highly forested areas in the US and Canada for trade with the EU and the rest of the world. Research in aquatic biomass constitutes an opportunity for China, the US and Canada. Technological leadership in the fields of sustainable feedstock and conversion technologies R&I creates[112], together with the amount and diversity of feedstock potential, the opportunity for these countries to become world leaders in the advanced biofuels sector. Collaboration of research with industry is present in the US and China, increasing the opportunities for application. The policy focus is on advanced biofuels; there are governmental (research) programs and market-based instruments introduce incentives for production.[113] In China, high regulation in the ethanol production section resulted in low participation of the private sector in this field, potentially hindering innovation and efficiency improvements (threat). Recently, the Chinese government opened market development resources to private industries, offering subsidies and partnerships with SOEs, resulting in partnerships of multinational biofuels leaders with Chinese SOEs and the opportunities for projects to shift from demonstration-stage to commercial scale projects. The presence of advanced biofuels industry in these countries can lead to competitive advantages by learning-by-doing effects.

Conclusions

Next to the EU, Brazil, Canada, China and the US display the most advantageous conditions for the development of an advanced biofuels sector. Although substantial feedstock potential is found in other non-EU countries at often lower on-site production costs, biomass trade is expected to remain limited. Increased R&I improves the EU's competitiveness and its ability to provide sufficient volumes of feedstock for advanced biofuels production by increasing the EU's feedstock potential by 50 %-100 % and decreasing the capital expenditure for conversion technologies by 20 %. This also enhances the EU's competitiveness downstream. Both in the EU, especially in countries of cluster III, and in the aforementioned non-EU countries, policies to support sustainable feedstock and advanced biofuels production, governmental research programs and technology support are in place. Yet, the EU has the global technology leadership in the field of advanced biofuels and sustainable feedstock R&I, surpassing China and the US in almost all feedstock and conversion technology R&I categories. This provides a good starting position for EU companies to establish themselves as front-runners in the advanced biofuels sector.

Overall the EU seems to be in an advantageous position for the development of an advanced biofuels sector. To retain and further develop this frontrunner position, policies should be implemented to support biofuels, sustainable feedstock production and advanced biofuels-related R&I, and to strengthen the demand side of the market, simultaneously ensuring a long-term business case for investors in the advanced biofuels sector.

[112] After Europe, the US has a dominant position in the fields of sustainable feedstock and conversion technologies R&I, according to our publication analysis. China is, after the US, the third biggest player regarding scientific publications.

[113] Only in China there is a lack of market-based incentives; most advanced biofuels companies are state owned.

5 Comparison of fuel options for transport up to 2030 and 2050

5.1 Introduction

The preceding chapters focused on the potential of research and innovation for the generation of biomass feedstock for energy in the 2030 and 2050 horizon (chapter 3), and the potential contribution of advanced biofuels for achieving various EU targets up to 2050 (chapter 4). However, the potential and position of advanced biofuels in the 2030 or 2050 fuel mix is not an isolated development and is influenced by various other factors, such as the uptake of electrification and/or fuel cells in the main transport sectors (road transport, maritime transport and aviation). Before presenting the results per transport sector (5.2-5.4), we briefly discuss some underlying issues with regard to the scope, societal life-cycle costs and consumer choices.

Scope - This chapter presents our assessment of the actual potential for advanced biofuels in the 2030 and 2050 transport fuel mix, taking into consideration other 'competing' fuel options that will also develop in the upcoming decades. Beside traditional fossil fuels (heavy fuel oil, gasoline, diesel and jet fuel) we identify four main alternative fuels: (advanced) biofuels, electrification, hydrogen, and natural gas. These are described in more detail in the following box.

Text Box 5.1 Alternative fuel options

Article 2 of the alternative fuel directive (Directive 2014/94/EU) defines six types of alternative fuels: electricity, hydrogen, biofuels, synthetic and paraffinic fuels, natural gas (CNG/LNG) and liquefied petroleum gas (LPG). In this study these are 'regrouped' into four main types of alternative fuels, which are briefly discussed here:[114]

- **Biofuels** – Biofuels refers to liquid or gaseous fuels produced from biomass and used for transportation. Within the transport sector the two most commonly used biofuels are ethanol and biodiesel. These are blended with conventional fuel or (under certain conditions) used in pure form. Various distinctions exist based on feedstock and conversion technology; see chapter 3 and 4 for more details. The 'synthetic and paraffinic fuels' are part of this group;
- **Electricity** – This technology involves producing electricity, storing the electricity in a battery and using the electricity in an electric motor. The electricity may originate from a variety of energy sources, such as fossil fuels, renewable energy (wind, solar, hydropower), nuclear energy and stored hydrogen (fuel cells);
- **Hydrogen** – Like electricity, hydrogen is an energy carrier that may originate from a wide variety of primary energy sources. This includes fossil fuels, hydrocarbons, and renewable sources. In transport, hydrogen is used via a fuel cell or directly burned in a combustion engine. In a fuel cell, hydrogen fuel combines with oxygen and the chemical energy is converted into electrical energy;
- **Natural gas and LPG** – Natural gas has various applications as a transport fuel. The most common application is in the form of liquefied natural gas (LNG), followed by compressed natural gas (CNG). Gas converted to liquid fuels (GTL) is gaining popularity, but the market size remains small. L[115]iquefied petroleum gas (LPG) has been a common fuel for decades in a number of Member States (e.g. France and the Netherlands).

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[114] The main reason for this distinction is to have a better fit with the definitionsin the equilibrium models used in this project (PRIMES-BIOMASS and PRIMES-TREMOVE). In these models the 'synthetic and paraffinic fuels' are combined with the 'biofuels', due to the overlap in conversion technologies.

[115] LPG is being manufactured during the refining of petroleum (crude oil), or extracted from petroleum or natural gas streams as they emerge from the ground. Mixes of LPG most commonly include propane and butane.

In the sections 5.2 – 5.4 we present the main outcomes of our analysis for the three main transport sectors (i.e. road, maritime and aviation). The analysis is primarily based on the scenarios for the period up to 2050, which are used for the projections in (i) the PRIMES-TREMOVE model, (ii) the PRIMES-Biomass model and the computable general equilibrium model (i.e. GEM-E3). Various aspects are covered in the models and scenarios including the maximum feedstock potential, biofuel conversion technologies, alternative fuel technologies and Member State specific characteristics like the infrastructure and future public investments and regulation.[116] The details of these scenarios are described in chapter 2.

The analysis shows that the penetration level of advanced biofuels will increase in the three sectors up to 2050. However, an increase in the penetration of advanced biofuels in the energy mix does not necessary drive any reduction in overall energy consumption. Advanced biofuels substitute petroleum products and have similar energy density and content. The amount of fuel consumed (petroleum products or advanced biofuels) depends on the efficiency of the vehicle's motor. On the other hand, electric vehicles generally are very efficient and use less energy input than combustion engines in order to cover the same kilometric distance. Therefore, it is expected that the MEDIUM scenario, in which electricity has a more prominent role in the decarbonisation of the transport system, performs better in terms of energy efficiency than the HIGH scenario.

Table 31 Total final energy demand in the transport sector (mtoe)

Scenario	2020	2030	2050
BASELINE	359	340	343
MEDIUM		326	268
HIGH		327	297

Source: Team analysis.

As shown in the table, the differences are minimal for 2030, indicating that there will be a small impact in the 2030 energy efficiency targets. However, in the long run, almost 30 Mtoe of energy can be avoided by using more efficient electric motors compared to conventional powertrains.

Societal life cycle costs assessment - Following a brief description of the current state of play, our analysis focusses on the comparison of the various fuel options in terms of the projected '*societal life-cycle costs*' in 2030 and 2050. The life-cycle costs comprise all social costs for society of the various fuel options, which accrue during the entire 'life span' of the fuel. This implies that besides the 'regular' costs for production and operation, negative externalities like polluting emissions and the depletion of scarce natural resources (e.g. rare earth material) are taken into account. The external costs, such as well-to-wheel emissions, air pollution and noise, are often not included in the cost-calculations, e.g. in case of buying a new vehicle. If all these costs are internalised and quantified (or monetized), a 'fair' comparison of the various fuel options can be made.

Although theoretically all societal costs can and should be incorporated in the analysis, in practice some limitations exist in terms of data availability, data comparability (across various technologies, Member States, etc.), and of the extent in which costs can be quantified and monetized. The PRIMES-TREMOVE model allows detailed quantification of both direct operating costs and other external costs such as emissions and noise (see table below). Other relevant societal costs are described in a qualitative way.

[116] The foundations for this can be found in the EU Reference Scenario of 2016 (Capros et al., 2016), which includes key (energy) policies and plans, macroeconomic and demographic assumptions and energy technology progress assumptions.

Text Box 5.2 Comparison of the societal life-cycle costs

The (partial) equilibrium models used to project the market developments up to 2050 make it possible to distinguish between three main types of life-cycle costs that cover the whole lifespan of a fuel. For road transport detailed projections can be made, while for maritime and aviation the projections are more aggregated.[117]

1. Internal (operating) costs – The internal costs represent the actual payable costs incurred by ordering and operating a vehicle (or a ship/airplane) of a certain powertrain and efficiency class for one km. The costs include true payments towards different stakeholders (automotive industry, fuel suppliers, maintenance crews, etc). Key cost categories in the model are:

- **Annuity payments for purchase of vehicles**; the annualized costs of purchasing transport equipment (e.g. vehicles) over its lifetime.[118] For each category, the vehicles are differentiated according to their powertrain technology. Some technologies may be able to use more than one fuel (e.g. plug-in hybrids);
- **Fixed costs**; expenses for maintenance, insurance and ownership taxes. These are independent of the annual mileage of the vehicles but they differ by powertrain;
- **(Variable) fuel costs**; actual (variable) fuel payments toward fuels suppliers. These costs include a markup for the build-up of the necessary recharging/refueling infrastructure in the case of new technologies (e.g. in case of electric vehicles; more indirect investments in the overall electricity grid, such as an extension of the electricity grid, are not included). The prices for fuels include the feedstock and technology costs, which depend on the size of the market, supply, etc. Please note that the fuel consumption in terms of energy units required to travel one unit of distance (e.g. km) differs between technologies (ICE, hybrids, plug-ins, electric) of a specific vehicle category (e.g. cars, trucks) and between technology classes of a specific powertrain. The cost-efficiency curves used in the model are based on an EC commissioned study;[119]
- **Other variable non-fuel costs**; all payments that are dependent on the annual vehicle mileage besides fuels costs, e.g. congestion fees, parking fees and toll payments. These are often independent of the powertrain. However, as part of specific policies, cases exist in which specific powertrains (i) are excluded and pay reduced rates (e.g. to promote electric vehicles), or (ii) are required to pay an additional fee (e.g. carbon pricing for vehicles operating on conventional fuels).

2. External costs – The external costs represent the monetary value of the damage ('negative externalities') incurred from the transport sector to other parts of the EU society. The following items are quantified, based on the 2012 Handbook on External Costs of Transport[120]:

- **Air pollution** - Costs resulting from air pollution caused by the emissions of different vehicle technologies (NOx, SO2, PM etc.);
- **Noise** - Certain vehicle powertrains cause more noise than others. E.g. electric engines are not as noisy as conventional ones;
- **Accidents** - When comparing transport modes, a higher use of private vehicles leads to higher number of accidents. Such cost do not differ by vehicle technology;

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117 The level of detail is related to the state of play of the various alternative technologies, which are well advanced for road transport and less for maritime and aviation.

118 A lifetime of 10 years is assumed for passenger cars, 12 years for LDVs and 15 years for HDVs. A user dependent discount factor is used for each type of vehicle in order to discount payments in future periods (11% for cars, 9.5% for LCVs and trucks).

119 Ricardo (2016). Differences in efficiency performance need to be 'compensated' via the payment of an excess amount to purchase the high performing vehicle. From a modeling perspective, the PRIMES-TREMOVE model fully incorporates such a mechanism (the purchasing costs of vehicles of the same powertrain increases with better efficiency performance), and distinguishes eight efficiency classes for each technology.

120 Ricardo-AEA (2014).

- **Congestion** - Costs associated with the additional time needed to travel a certain distance, when the number of vehicles increases. Similarly to the case of accidents, these are not technology dependent;
- **Well-to-wheel (WTW) carbon emissions** - As a measurement of the external costs[121] of the transport sector to the environment, this indicator takes into account the carbon emissions. These figures do not only cover emissions during the combustion of fuels, but also during their production/generation and transportation to consumers. Certain powertrains may achieve zero emissions at the tailpipe, while upstream emissions take place during production.

In addition to these external costs, other societal costs may be relevant. Examples are safety risks related to the production/generation, transport and use of fuels or technologies (e.g. risks for leakages and explosions) and the depletion of scarce natural resources. Although these costs are not quantified, they are assessed qualitatively in sections 5.2-5.4. Please note that for road transport it is not opportune to present EU-28 results due to country-specific circumstances (e.g. taxes and levies, infrastructure, etc.). In this chapter, we present the results for six EU Member States. For the maritime and aviation sectors EU-28 results are presented.

Consumer choices - Please note that besides cost considerations, other factors play a role in the final decision for a specific type of vehicle, vessel or aircraft. Important considerations to this extent are market acceptance, the availability of infrastructure and travelling range. The PRIMES-TREMOVE model takes into account such considerations by introducing a series of hidden, non-payable costs. The box provides more details about this.

Text Box 5.3 Consumer choices in the 2030 and 2050 projections

Market acceptance factors are used to simulate circumstances in which consumers display risk avert behaviours regarding new technologies in the early stages of market deployment. Perception of risk usually concerns technical performance, maintenance costs and operation convenience. When market penetration overcomes a certain threshold, consumers imitating each other change behaviour and increasingly accept the innovative technologies giving rise to rapid market diffusion. Both stages of market deployment are captured in the model through appropriate values of market acceptance factors. Therefore, the model can simulate reluctance to adopt new technologies in early stages of diffusion and rapid market penetration, often leading to market dominance, in later stages. The adoption pathway is kept constant across our policy scenarios.

The decision-making is also influenced by the availability of infrastructure and the range provided by each vehicle technology. These features are particularly important when new fuels or new technologies enter the market. In order to represent in a more refined manner the true effects of the range limitations of some vehicle technologies and the lack of adequate infrastructure of alternative fuels, the trip categories in the model are assumed to follow a frequency distribution of trip distances. The model assumes that decision makers compare the range possibilities of each vehicle technology and the availability of refueling/recharging infrastructure for all classes of trip types and trip distances and apply cost penalties in case of mismatches between range limitations or non-availability of refueling and trip types or trip distances. Thus, a vehicle or fuel type may not become competitive because of mismatches compared to other options, which do not present such limitations. This does not apply to conventional technologies, such as the internal combustion engines (ICEs), but is relevant for battery-electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), LNG, hydrogen and hybrid electric vehicles.

121 External costs of emissions are calculated in €/tonne of CO2. The figures used in the projections are based on the Updated Handbook on External Costs of Transport (Ricardo-AEA, 2014) and increase from € 90 per tonne in 2010 to € 157 per tonne in 2050.

5.2 Road transport

Key Findings

Scope and current fuel use:

- The road transport sector is dominated by fossil fuels like gasoline and diesel. Most new registrations for passenger cars in the EU are still diesel or gasoline based (>98 %) including biofuel blends, while the percentage for light- and heavy-duty vehicles (LDVs and HDVs) is even higher. The current use of alternatives (electrification, hydrogen, natural gas, and advanced biofuels) for road transport is limited. In electrification, passenger e-cares are the frontrunners, while the technology is immature for LDV and HDV. Hydrogen is still immature and natural gas uptake varies per country;
- Stimulation by the public authorities has been crucial for the uptake of alternative fuel vehicles, as they are not yet cost-competitive compared to fossil fueled vehicles. Government incentives vary per country and over time. Nevertheless, the market is showing signs of gradual change: new electric models are entering the market and sales of electric vehicles are increasing, while the density of the charging network has improved.

Setting the scene: the fuel mix in 2030 and 2050:

- In 2050, the share of fossil fuels in the overall road sector decreases from 85 % to 40 % and is substituted by electricity and especially advanced biofuels, which take a market share of 40-50 % depending on the scenario;
- For passenger transport, the projections show a substantial increase in the share of biomass (both scenarios) and also electricity, depending on the scenario. The projected share of natural gas and hydrogen is limited. For LDVs, the electricity potential is much lower, while it is almost nil for HDVs. For both light- and heavy-duty vehicles the main potential is in advanced biofuels (80-90 % of the market demand).

Comparison of the various fuel options (life-cycle costs):

- The societal life cycle costs depend on the national circumstances and as a result vary between the Member States. The projections show that the monetized externalities do not offset the internal operation costs.

5.2.1 Scope and current fuel use

The road transport sector is dominated by fossil fuels

The road transport sector can be divided in various vehicle categories. The most common typology distinguishes between four categories of road transport vehicles: (i) passenger cars, including taxis, (ii) light-duty vehicles (LDV), including cars and vans, (iii) heavy-duty vehicles (HDV), including medium trucks and heavy trucks and (iv) passenger road transport, including buses and coaches. In this study, we focus on the first three categories.[122] Each of the road transport categories may use different (engine) technologies and/or energy carriers.

Global road transport relies heavily on the use of fossil fuels, such as diesel and gasoline, which are mainly used by trucks (LDV-HDV) and passenger cars. Similarly, the European road transport sector is characterised by vehicles (trucks, passenger cars) which primarily use diesel and gasoline, but (small) changes are visible. According to Eurostat statistics, the majority of the new passenger cars (registrations) are still powered by diesel engines (2015: 52 %), followed by gasoline engines (46 %). With an EU market share of approximately 1 %, the annual number of new plug-in hybrid (PHEV) and battery-electric vehicles (BEV) is slowly increasing. For hydrogen fueled

[122] Some data sources combine the categories 1 and 2, as well as 3 and 4; leaving only LDV and HDV as the two main vehicle categories.

cars this percentage is even lower. In the next table we present an overview of the current state of the market.

Table 32 Overview state of play various fuel options

Fuel options	Remarks about the state of play
Biofuels	**Passenger cars and LDV/HDV:** Since 2007, EU regulation requires the blending of biofuels (ethanol and biodiesel) in all types of road transport vehicles.[123] As a result biofuels now account for 4.7 % of final energy consumption in EU-transport. The majority of biofuel used is still first generation.
Electrification	**Passenger cars:** Hybrid cars (HEV) entered the EU market around 2003/2004 and were followed by the entry of plug-in hybrid cars (PHEV). In more recent years full electric cars (BEV) were added to the mix. Compared to conventional fuels (diesel and gasoline), the uptake of electric vehicles is still relatively low: together PHEVs and BEVs now account for 1,1 % of all EU vehicle registrations. [124] However, the share is slowly increasing. National fiscal stimulation measures appear to be a strong driver for the choice for an electric car and, since 2013/2014, the number of charging points throughout the EU is gradually increasing. **LDV/HDV:** electrification is hardly relevant for light-duty vehicles (LDV) and heavy-duty vehicles (HDV) due to the short driving ranges. The total EU28 fleet of light commercial electric vehicles was (only) 43 000 by the end of 2016 (<1 % of total), with France (25k) and Germany (5 k) having the largest fleet.
Hydrogen / fuel cells	**Passenger cars and LDV/HDV:** Globally the number of hydrogen vehicles is limited, as they are (often) still part of demonstration projects and not commercially viable. This also applies for the EU: Germany and France are the frontrunners for passenger cars and light commercial vehicles, but the overall number of FHEVs (around 570 for the EU) is very small and the market is immature.[125] Apart from hydrogen, fuel cells can be fuelled with different fuel types, including biofuels.
Natural gas	**Passenger cars and LDV/HDV:** The market uptake of LNG and CNG vehicles is slow, even though more manufacturers are introducing new models. Over the last decade, sales of new CNG-vehicles (passenger cars) have fluctuated substantially. CNG is popular in Italy, which can be explained by a distribution network that has existed since the 1950s. In terms of new registrations (2016) Italy is followed by the Czech Republic, Sweden, and Belgium.

Source: Team analysis.

The uptake of alternative powered vehicles relies on government incentives

The uptake of vehicles powered by an alternative fuel, relies heavily on individual and mutual policy plans of Member States, as alternative fuel options cannot yet compete with regular fossil fuels in terms of (operating) costs. Member States have (or had) different incentives and encouragements to stimulate usage of alternative energy carriers. These incentives relate to regulatory measures (e.g. maximum emissions levels for CO_2), monetary measures (e.g. tax benefits, direct subsidies), access regulation (e.g. access to restricted traffic zones) and infrastructure measures (e.g. investments in the charging network). Due to these incentives, significant differences appear between Member States and from year to year. This reliance on incentives also applies for biofuels; in the EU (advanced) biofuels are mainly used as a drop-in to fossil fuels like gasoline and diesel. The blending of (advanced) biofuels is strongly related to the EU objective to ensure 10 % of

[123] In some Member States, there is a small market for pure biofuels, such as in Austria (100% biodiesel – B100).
[124] ICCT (2016).
[125] EAFO (2017).

transport fuels come from renewable sources, such as biofuels, by 2020. Further, the Fuel Quality Directive (FQD) set specific targets for emission reductions.[126]

The market is changing, but the outcome is still unclear

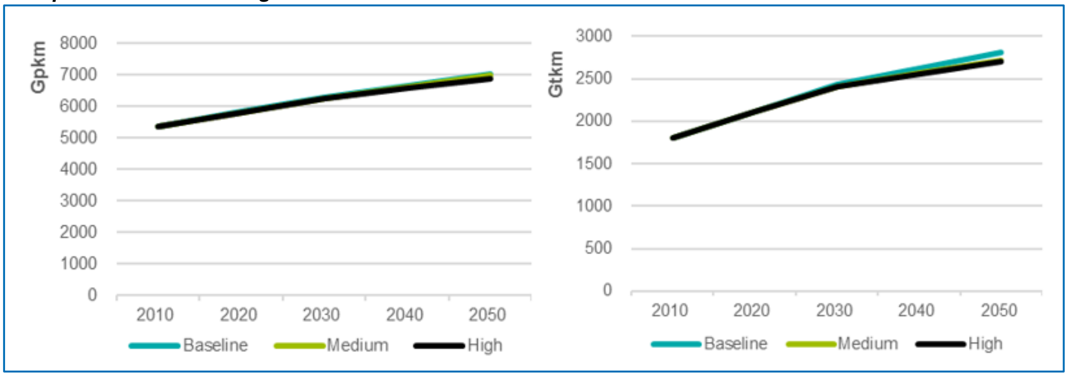
The market for road transport vehicles is clearly changing: within the supply chain for passenger cars (and to a lesser extent also for light-duty trucks), the various OEMs[127] anticipate technological developments and changing consumer demand. Especially for electric passenger cars, many new models have been launched or announced recently, with a clear emphasis on improved battery performance and extended drive range. At the same time, it is clear that the outcome in terms of the 'winning' alternative technology is still uncertain. Various interrelated factors will (continue to) influence the development and uptake of fuel alternatives. First, the outcome depends on the business strategy of the limited number of players (OEMs) which dominate the market.[128] If players realize a breakthrough or choose a certain technology ("*market push*"), this will change the end game. Secondly, consumer choices will be decisive; if demand shifts towards the alternative fuels, for example due to increased environmental consciousness, this will have a major impact on the market. Current consumer acceptance of alternative technological options is still low.[129] Finally, government regulations will influence outcomes. This relates, for example, to the direct stimulation of alternative fuels (fiscal measures), but also to the taxation of regular fossil fuels and regulation of polluting emissions.

5.2.2 Setting the scene: the fuel mix in 2030 and 2050

Transport activities will substantially grow until 2050

The future transport mix and needed energy supply for transport depends on the level of 'transport activity',[130] which is expected in 2030 or 2050. The projections for the various scenarios show that (in all three scenarios) the level of transport activities increase by approximately 30 % for passenger transport and 50 % for freight up to 2050, as shown in the next figure.

Figure 30 EU 28 Transport Activity: *The transport activity for both passenger (left) and freight (right) transport increases through 2050*



Source: Team analysis.

Note: Gpkm stands for giga passenger-kilometre (passenger transport); Gtkm stands for giga tonne-kilometre (freight transport).

[126] The Directive includes an obligation on fuel suppliers to reduce the greenhouse gas intensity of the fuel mix they supply by 6% in 2020 compared to 2010.

[127] OEM: original equipment manufacturers, like for example Toyota, Volkswagen or Renault.

[128] Limited number of players due to the high entry barriers. The production of vehicles is very capital intensive, requires high-tech knowledge and benefits from economies of scale. These factors make it difficult (but not impossible) to enter the market.

[129] Low customer acceptance has various reasons, ranging from the (cheap) costs of diesel and gasoline to the lack of vehicle choices and uncertainty about the battery performance.

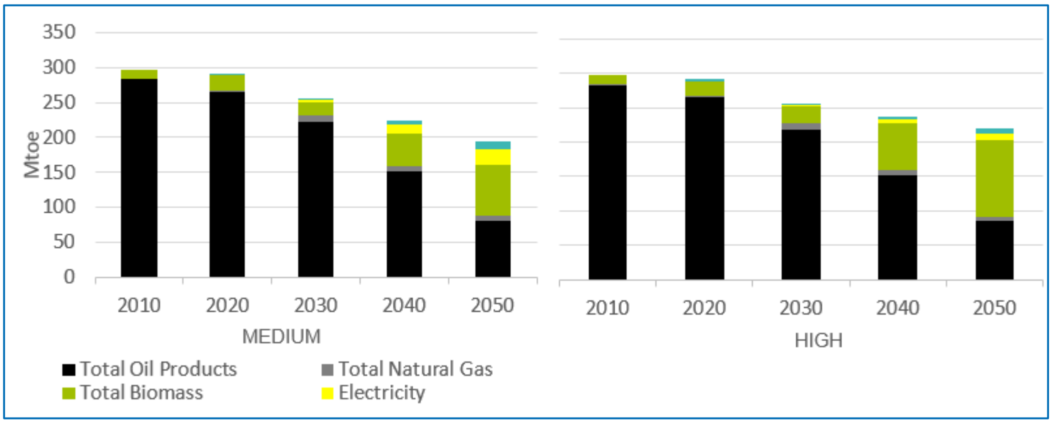
[130] The transport activities refer to the number of kilometers passengers or freight 'travel' per year. Within the PRIMES-TREMOVE model, the transport activity is econometrically estimated based in particular on trends of GDP, population, and fuel prices.

Scenarios: stimulation measures pay off in less energy use

Despite the projected increase in transport activities, the level of total energy demand (expressed in tonnes of oil-equivalents) is expected to decline up to 2050.[131] The main reasons for this are twofold. First, technological development increases 'fuel efficiency': over time less energy is needed for each kilometre of travel.[132] The second reason is the expected substitution from fossil fuels to alternative fuels: higher use of electric vehicles results in reduced use of fossil fuels. Under the BASELINE-scenario, projected energy demand will decline by approximately 12 % (from 297 to 262 mtoe), but fossil fuels will still be the dominant type of fuel.[133]

The next two figures present the results of the energy demand projections for the total road transport sector (including passenger, LDV and HDV sub-sectors) under the MEDIUM and HIGH scenarios. The figures show that under the MEDIUM-scenario (with both electrification and biofuel contributing to the EU's goals of decarbonisation), the decrease in energy demand is the highest: a decrease of 35 % (from 297 to 194 mtoe). The fuel alternatives of electricity and biofuels (biomass) significantly increase their growth after 2030: respectively, electricity and biofuels attain a 12 % and 38 % market share, compared to 41 % for oil products. Under the HIGH-scenario, the decline in energy demand is smaller (-26 %, from 297 to 220 mtoe), but the share of biofuels (50 %) is higher and outstrips oil products (41 %). The developments per type of road sector are described in more detail in the next paragraphs.

Figure 31 EU 28 Road Transport Energy Demand: ***Energy demand decreases in both scenarios. The decrease is higher in the MEDIUM scenario. The share of biofuels increases both in the MEDIUM and HIGH scenario***



Source: Team analysis. Note: although a full phase-out of first generation (food-based) biofuels is not assumed in the modelling per se, the further penetration in the energy mix is constrained by the European sustainability criteria that are modelled. Therefore, the importance of first generation biofuels as an energy carrier in the future energy mix decreases.

These EU-28 results are also broken down to the level of individual Member States, presented in the next figure. It shows that the share of Advanced Biofuel varies across Member States, which can be explained by the cross-EU28 variety in policy making, infrastructure development, etc.

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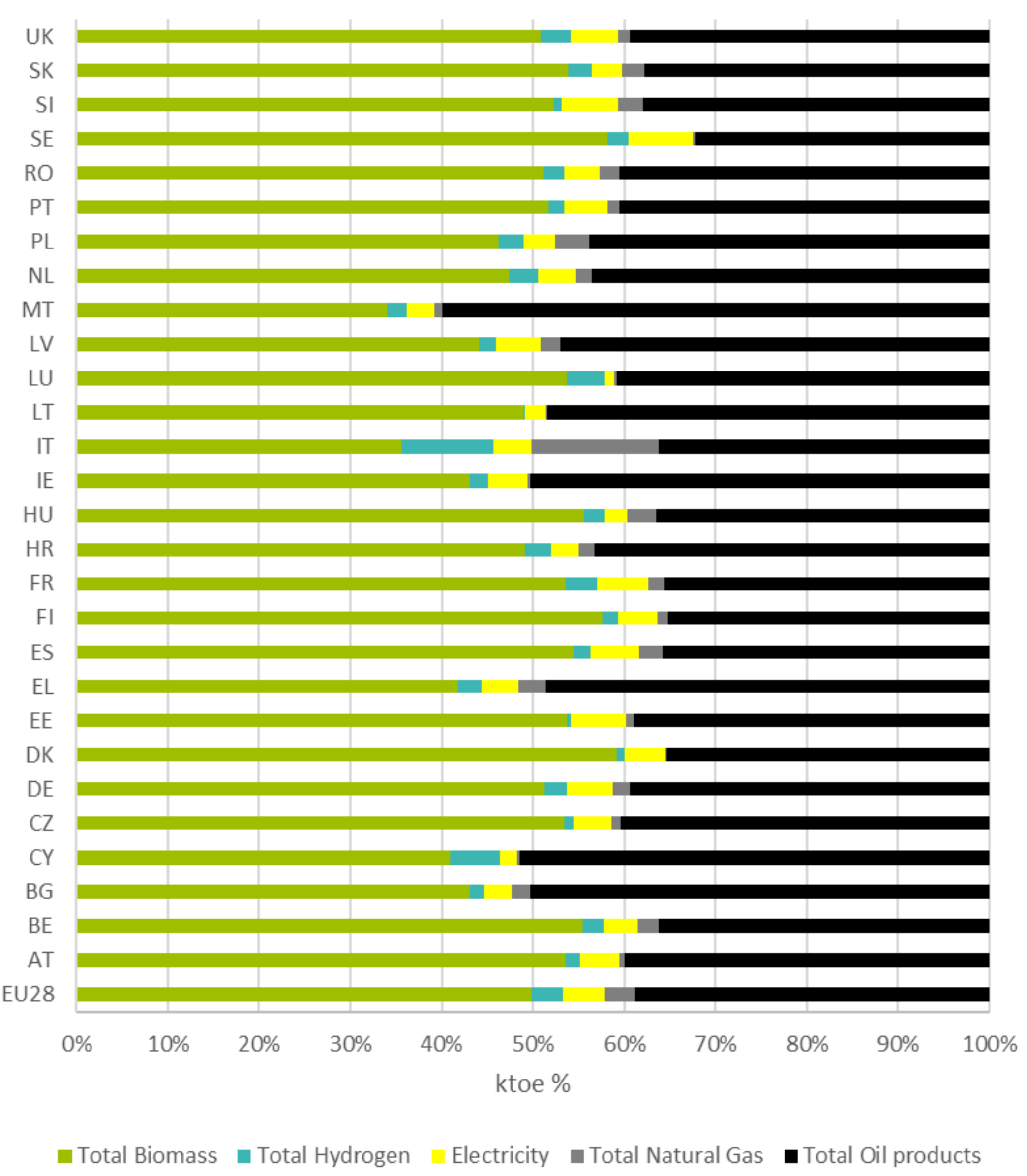
131 Previous research showed that this 'decoupling' between activities and demand started around 2005.

132 In the same report (E3M-Lab, IISA & EuroCare (2013), p. 59-60)) the projections by E3M-Lab indicates that in the period 2010-2030 the energy efficiency of vehicles will improve by 30%, mainly due to regulation requirements.

133 The projections show that in 2050 approximately 84% of the energy demand is oil-based (221 mtoe), followed by natural gas (4%) and electricity (3%).

Figure 32 Fuel mix for total road transport sector in EU MS in 2050 (High Scenario): ***The fuel mix in the MS is similar in all MS. By 2050 in the High Scenario, the share of biofuels in all EU 28 MS will be between 40-60 %***



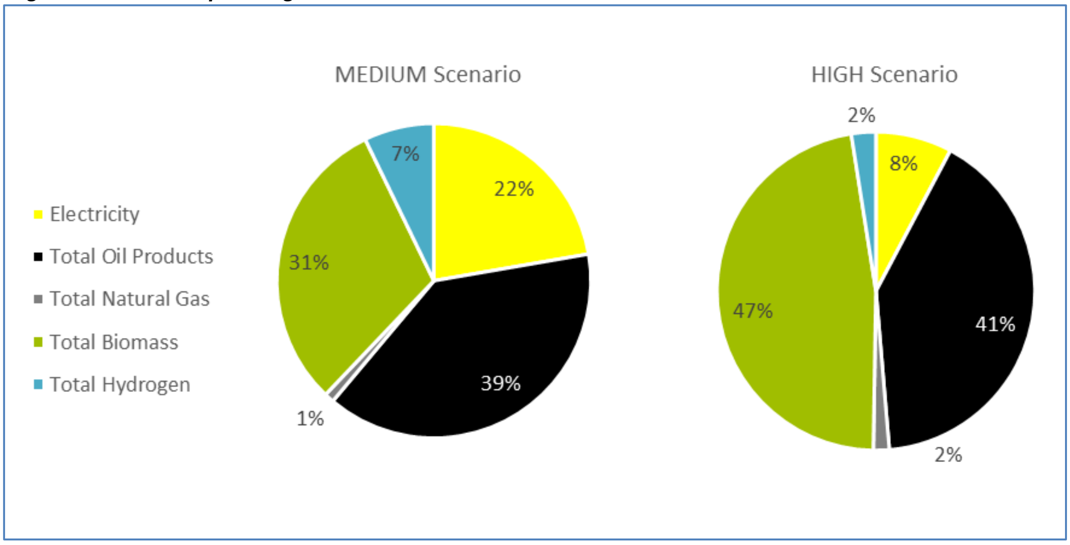
Source: Team analysis.

Passenger cars: projected shift towards biofuels and electricity in 2050

The projected changes in the total energy demand in 2050 relate to the type of (alternative) fuels used by passenger cars. As indicated above, this segment is dominated by vehicles which use conventional fuels, mainly diesel and gasoline. Under both the MEDIUM and HIGH scenario, the share of fossil fuels drops from 95 % to approximately 40 % in 2050. At the same time, the projections show a substantial increase in the share of biomass[134] (in both scenarios) and also electricity (particularly under the MEDIUM scenario). The projected share of hydrogen and natural gas is relatively limited in 2050 (see Figure 33).

[134] Share of biomass consists mainly of bio diesel and bio gasoline.

Figure 33 Fuel mix passenger cars in 2050: *The combination of biomass and oil products will have the largest share on the passenger car market*



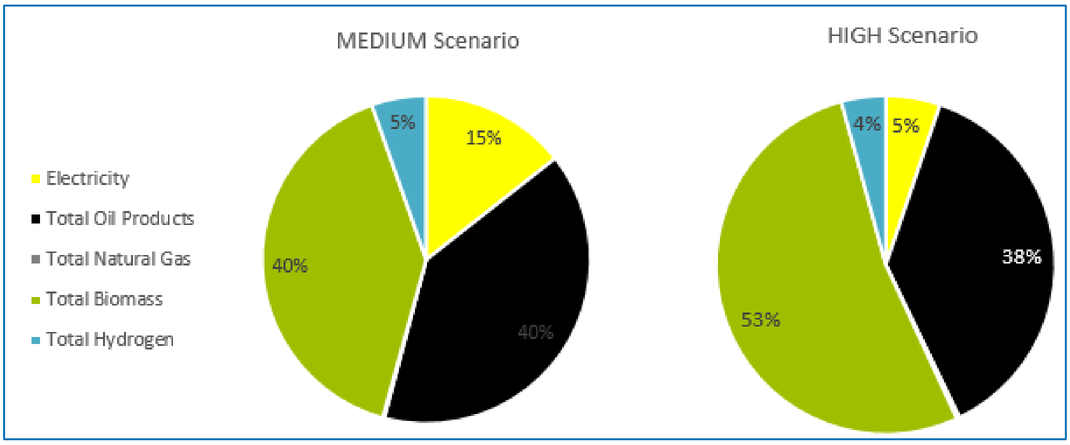
Source: Team analysis.

Note: In the MEDIUM scenario the total energy demand for passenger cars decreases from 184 mtoe to 87 mtoe; In the HIGH scenario the demand drops from 184 mtoe to 112 mtoe.

Light- and heavy-duty vehicles: substitution towards more biofuels

The main pattern in fuel mix for passenger can also be observed regarding light- and heavy-duty vehicles. Light- and heavy-duty vehicles are dominated by fossil fuels (diesel), but the projections show a significant substitution towards the use of biofuels (biodiesel). The next figure presents the projected fuel mix for the **light-duty vehicles**. It shows that (in both scenarios) the combination of biomass and oil products will dominate the market. More specifically regular diesel and biodiesel will cover approximately 80 % of the market for both scenarios. Additionally, there is some room for electric vehicles; particularly, the assumptions of the MEDIUM scenario favour electric vehicles (15 % versus 5 %). Both scenarios leave some room for hydrogen-powered vehicles.

Figure 34 Fuel mix light-duty vehicles in 2050: *The combination of biomass and oil products will dominate the LDV market*

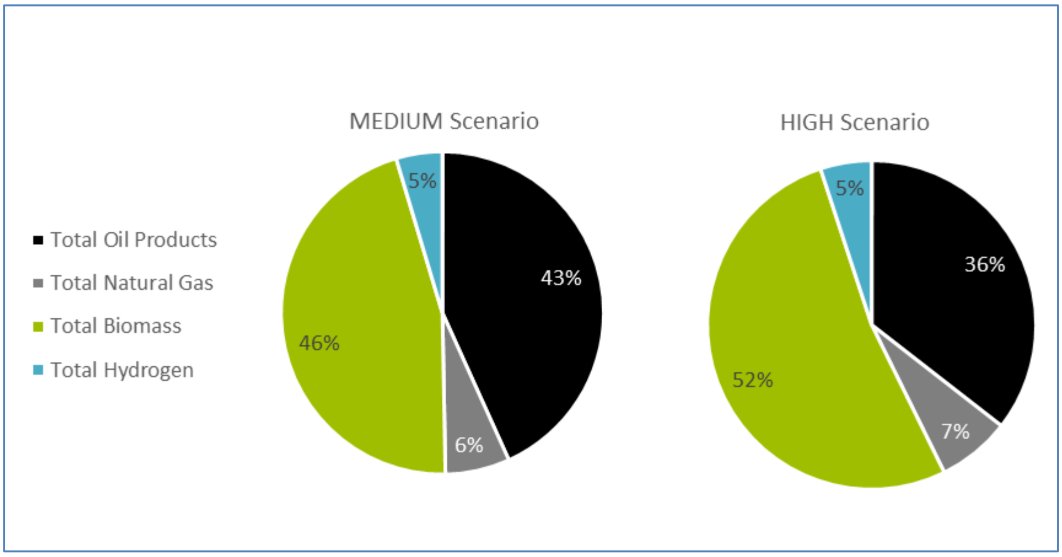


Source: Team analysis.

Notes: (i) within the MEDIUM scenario the total energy demand for light-truck vehicles decreases from 37 mtoe to 21 mtoe; within the HIGH scenario the demand drops from 37 mtoe to 25 mtoe; (ii) natural Gas is not 0 % for both scenario 1 and 2. For scenario 1, it has 0,17 % of the fuel mix. For scenario 2, it has 0.28 % of the fuel mix.

For **heavy-duty vehicles**, the projections show clearly that electricity will play a marginal role and that (again) the combination of regular diesel and biodiesel will cover most of energy demand (close to 90 % in both scenarios). The remaining 10-12 % is covered by hydrogen and natural gas. It should be noted that the clear differences in terms of fuel potential due to the key characteristics of use: electricity is still not an option for long range (heavy) truck work, even by 2050.

Figure 35 Fuel mix heavy-duty vehicles 2050 - ***The combination of biomass and oil products will dominate the HDV market***



Source: Team analysis.
Note: Electricity is not 0 % for MEDIUM and HIGH scenario. For the MEDIUM scenario, it has 0,03 % of the fuel mix. For the HIGH scenario, it has 0,02 %.

5.2.3 Comparison of the societal life cycle costs (LCC) of the various fuel options

The potential for alternative fuels in the 2050 fuel mix for road transport will, to a large extent, be determined by the actuals costs of using the alternative fuel. As described above, most alternative fuels cannot currently compete with the regular fuels (diesel, gasoline) in terms of cost. So far, due to strong regulatory incentives, only electricity-based passenger cars are a (upcoming) substitute for regular vehicles. In addition, the current blending of biofuels has a strong regulatory incentive. In this section, we present the results of the projections in terms of the societal life cycle costs (LCC) of the various fuel options in 2050: *can the alternative fuels compete with the fossil fuels when taking into account all relevant costs*?[135]

Some methodological notes: the powertrains as starting point

Details on the different cost elements and the assumptions are presented in Text Box 5.2 (see section 5.1). In addition to the literature review, our LCC assessment is based on data for six Member States.[136] The analysis in the following sections compares the different costs per km travelled, including both internal and external costs.[137] The comparison is made across powertrains,

[135] As explained, a distinction is made between three types of life-cycle costs, which in principle cover the whole lifespan of a fuel: (1) internal (operating) costs, (2) external costs related to well-to-wheel emissions and (3) external costs related to air pollution and noise.

[136] This small selection includes some of the largest European Member States (DE, FR), as well as a geographical spread across the EU (SE, NL, PL, HU). At the same time the selection also shows some variety in the size of the own feedstock production (e.g. very limited in NL).

[137] With regard to road transport some specific assumptions are made: (i) annuity payments for purchase of vehicles: A lifetime of 10 years is assumed for passenger cars, 12 years for LDVs and 15 years for HDVs. A user dependent discount factor is used for each type of vehicle in order to discount payments in future periods (11% for cars, 9,5% for LCVs and trucks).

i.e. compression ignition (CI) engines running on diesel and biodiesel, and spark ignition (SI) engines running on gasoline and ethanol/bio gasoline, electric, etc. As a result, advanced biofuels do not appear in the figures as a separate category, as they constitute a fuel, not a technology choice. The effect of the advanced biofuels (or bioenergy) is captured in the way they influence the costs per km of the respective technology. This can be fully understood by comparing the performance of a specific powertrain across scenarios, as the main element differentiating the scenarios is the level of bioenergy penetration in the energy mix of each transport sector.

Within this context it is important to note that, as most advanced biofuels categories will be able to substitute conventional petroleum-based fuels, any efficiency progress made by conventional engines will also benefit the position of advanced biofuels: it will make advanced biofuels more attractive for final consumers. A comparison of different scenarios, with different levels of advanced biofuels penetration in the energy mix of the transport sector, allows us to examine, how much the costs differ when higher levels of advanced biofuels are utilized. This is illustrated when comparing the HIGH scenario to the MEDIUM scenario. In this way, the LLC of advanced biofuels are assessed indirectly.

Passenger cars: The combination diesel/advanced biofuel is the cheapest option in 2050

Literature taking into account all societal life cycle costs (in a comparable way) appears to be limited. For **electric vehicles** publications suggest that the break-even point for internal operating costs may be reached around 2030, when the battery costs are low enough. [138] With regard to the external costs, some publications indicate that, although there are some environmental advantages, these costs do not differ significantly between regular ICEs and electric vehicles if the upstream (electricity) supply chain is not sustainable as well.[139] The safety risks of electric vehicles differ from regular ICEs, as the battery contains chemical substances and high voltage components. So far, the safety risks seem manageable and not significantly higher than regular cars.[140] Given the immature market status of **hydrogen**, also the literature shows uncertainty about the societal costs. A 2015 LCC-study for the German market concludes that fuel cell electric vehicles (FCEV) become a 'socially beneficial alternative for decarbonizing' around 2050, despite avoided CO_2 emissions.[141] Other studies project that the costs of fuel cells may reach the point of break-even under certain conditions earlier, for example around 2030. With regard to other externalities, literature suggests that safety risks due to the compressed pressure are limited, i.e. the use of these vehicles is not significantly more dangerous than ICE vehicles.[142] The cost-competitiveness of **natural gas** is close to fossil fuels, which is illustrated in countries with a strong infrastructure deployment like Italy. Negative externalities are mainly related to safety risks for transportation and for filling and bunkering stations. Investments in an up to date infrastructure will reduce these risks.[143]

Our model projections, as described in the previous section, indicate (under the MEDIUM and HIGH scenarios) a shift towards biofuels and electricity in 2050, but still with a substantial position (40 %) for the regular fossil fuels. In the BASELINE scenario this shift is much smaller. These

[138] See for example: IEA (2017). The study assess that in Europe the electric vehicles (BEVs and PHEVs) will become cost-competitive with internal combustion engines (ICEs) in 2030. The vehicle costs for BEVs decrease in this period from $8,000 (2015) to $6,000 in 2030. This reduction is mainly caused by lower battery costs (which cover 70% of all costs). NB: The costs are calculated over a 3.5 year period.

[139] See for example: Jochem et al. (2016). The study concludes that "*only for climate change, local air pollutants in congested inner-cities, and noise some advantageous effects can be observed for EV. The advantages depend strongly on the national electricity power plant portfolio and potentially also on the charging strategy*."

[140] NHTSA (2015). The paper states that "ten years of crash testing electric/hybrid vehicles by ANCAP and IIHS, covering a wide range of crash conditions, indicates the variation in crashworthiness performance of hybrid/electrical drive vehicles is comparable with the variation observed with conventionally powered vehicles".

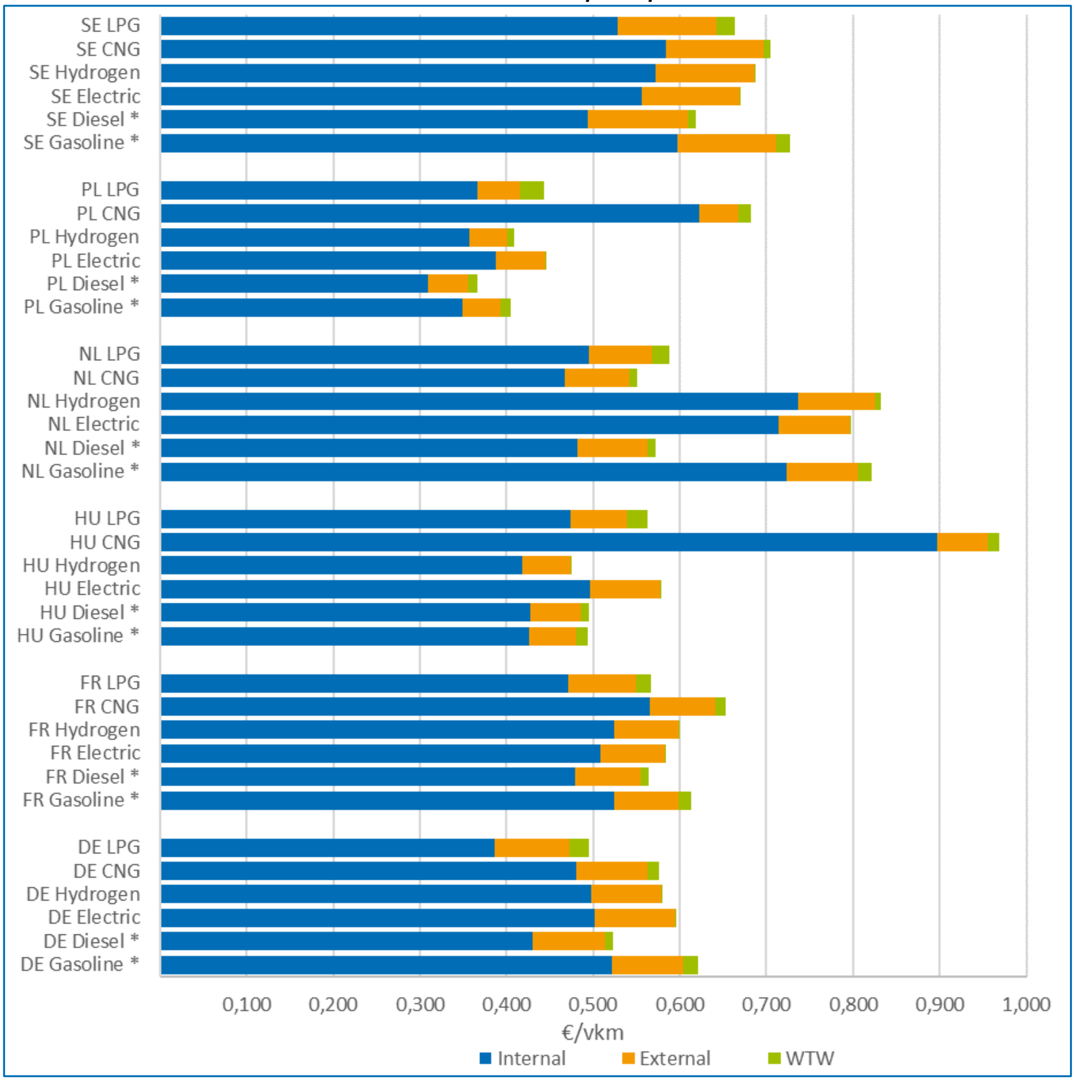
[141] Creti et al. (2015).

[142] Schoettle and Sivak (2016). They refer to Flamberg et al. (2010).

[143] Osorio-Tejada et al. (2017).

outcomes are reflected in the comparison of the societal life cycle costs (LCC) of the various fuel options. In the BASELINE scenario the alternative fuels are (often) more costly than regular fuels, while under favourable conditions the (cost) position of alternative fuels will improve. The next figure presents the projected societal life cycle costs (LCC) of six types of fuel in 2050 under the most favourable conditions (the HIGH scenario). For the overall societal lifecycle costs the figure shows that, even when monetizing negative externalities like CO_2 emissions, the combination of advanced biofuels and regular diesel (and sometimes gasoline, see Poland and Hungary) is often still the cheapest fuel in 2050. The main explanation for this is that the internal operating costs of (especially) diesel are low compared to the other fuel options. Both the monetized external costs for air pollution/noise and well-to-wheel emissions cannot offset this difference. Note that, beside these life-cycle costs other factors play an important role in the decision for a type of vehicle. As mentioned in the introduction this mainly relates to market acceptance, the availability of infrastructure and travelling range.

Figure 36 Passenger cars - societal life cycle costs 2050 (HIGH scenario, in €/vkm): ***In 2050, the combination of diesel/advanced biofuels is often the cheapest option***

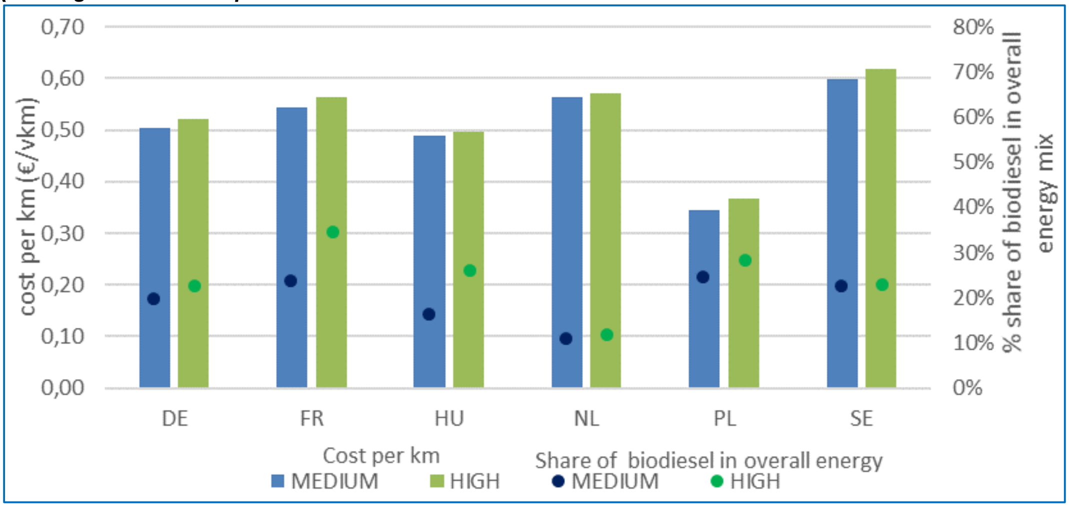


Source: Team analysis.

Note: (*) the diesel and gasoline categories include also advanced (drop-in) biofuels that can substitute gasoline or diesel in conventional ICE engines, as well as blended biofuels. The overall share of biofuel (both drop-in and blended) within gasoline and diesel differs per country: Sweden (respectively: 52 % and 60 %), Poland (55 % and 60 %), The Netherlands (45 % and 57 %), Hungary (57 % and 60 %), France (52 % and 60 %) and Germany (53 % and 60 %). In the case of blended biofuels current legal or technical constraints for blending rates are respected. LNG is not relevant for passenger cars.

With regard to advanced biofuels (compared to the other alternative fuels) it is important to assess in more detail the future role of advanced biofuels in the projected fuel mix.[144] The following two figures present a comparison of the LLC for SI and CI engines across scenarios.[145] The analysis indicates that for the passenger cars segment, a higher share of advanced biofuels would result in a marginal increase in the LLC for both CI and SI (*i.e running on mixes of petroleum fuels and advanced biofuels*). The learning effects both on the production side for advanced biofuels and on the efficiency performance of ICEs, are not enough to cancel out the higher prices for bioenergy (see chapter 4), especially for a segment for which other alternatives constitute strong competition because of their characteristics (higher efficiency, lower WTW emissions, zero pollutant emissions and etc.).

Figure 37 Passenger cars – comparison of LLC for CI powertrains across scenarios, 2050 (in €/vkm): *A higher share of advanced biofuels used in the sector would bring marginal increases in the LCC for CI (running on a mixes of petroleum fuels and advanced biofuels*

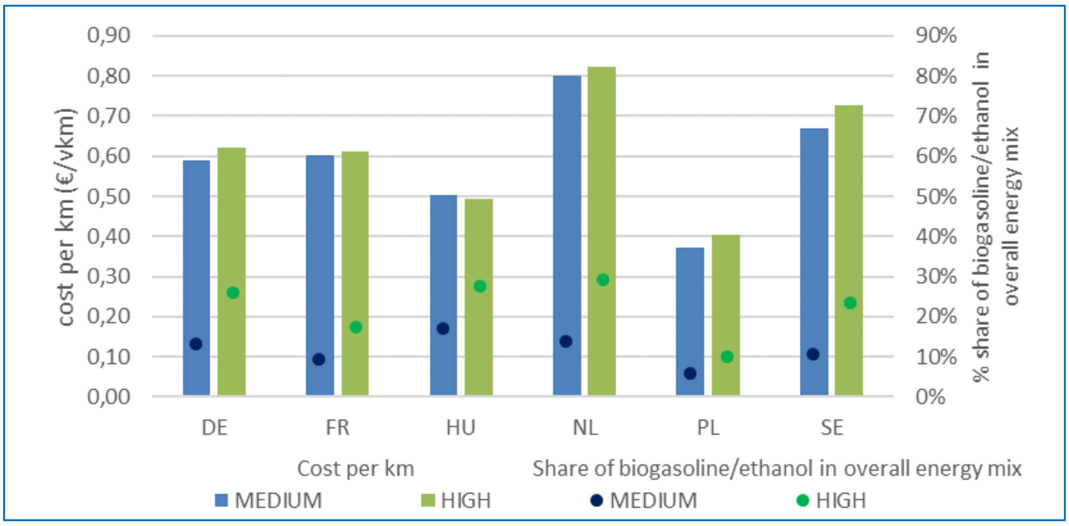


Source: Team analysis.

Figure 38 Passenger cars – comparison of LLC for SI powertrains across scenarios, 2050 (in €/vkm): *A higher share of advanced biofuels used in the sector would bring marginal increases in the LCC for SI (running on a mixes of petroleum fuels and advanced biofuels*

144 Please note the analysis of the projected costs of advanced biofuels in chapter 4.

145 Differences between scenarios stem from three main factors: (i) different efficiency improvement by 2050 for CI and SI engines across scenarios, (ii) different fuel prices for advanced biofuels across scenarios (see chapter 4) and (iii) the share or bioenergy over the total fuel mix used by vehicles with CI/SI engines. With regard to the latter, it is important to note that this is about the overall energy mix for passenger cars in a country. It makes no difference if a vehicles runs only on advanced (renewable) biodiesel, petroleum-based diesel or a mix of those, as in practical terms these consist of the same molecules.



Source: Team analysis.

Light- and heavy-duty vehicles: the combination diesel/advanced biofuels is cost-effective

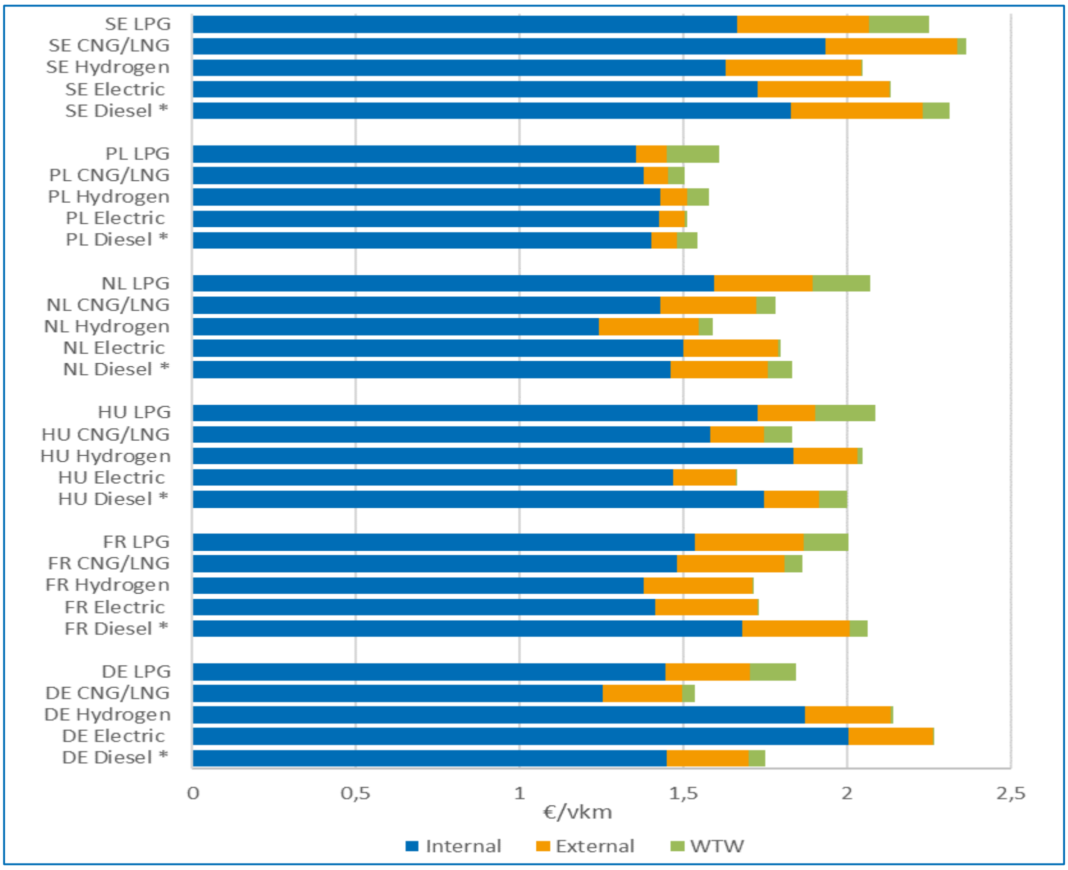
At the moment, the segments of light- and heavy-duty vehicles are dominated by the use of diesel. The projections show that in 2050, both light- and heavy duty vehicles mainly use a combination of regular diesel and biodiesel, while there is also some room for electric and hydrogen powered (light-duty) vehicles. As for the passenger cars, the literature on the societal life cycle costs of alternative fuels for LDVs and HDVs is fragmented. In a recent publication, the environmental impacts of various types of alternative fuels were assessed. It showed that, due to the importance of the (non-sustainable) upstream power supply, the environmental impacts of electric LDVs are (often) comparable to alternative fuel options.[146] In addition, publications show that, due to the practical purpose of the LDVs and HDVs, the internal costs of electric transport solutions are often not cost effective. Only under certain conditions (e.g. urban delivery), the LLC for light duty electric vehicles is better than regular diesel trucks.[147] Other negative externalities, like safety risks, are often not included in the LCC analysis; these risks are in line with the risks described for passenger cars.

Our model-based analysis of the societal-life cycle costs shows that there are substantial differences between the Member States (see table below).

Figure 39 Heavy-duty vehicles - societal life cycle costs 2050 (HIGH scenario, in €/vkm): ***the combination of diesel and advanced biofuels is in 2050 not always the cheapest option in terms of LCC***

[146] Zhao et al. (2016a).

[147] Lee et al. (2013). See also: Zhao et al. (2016).

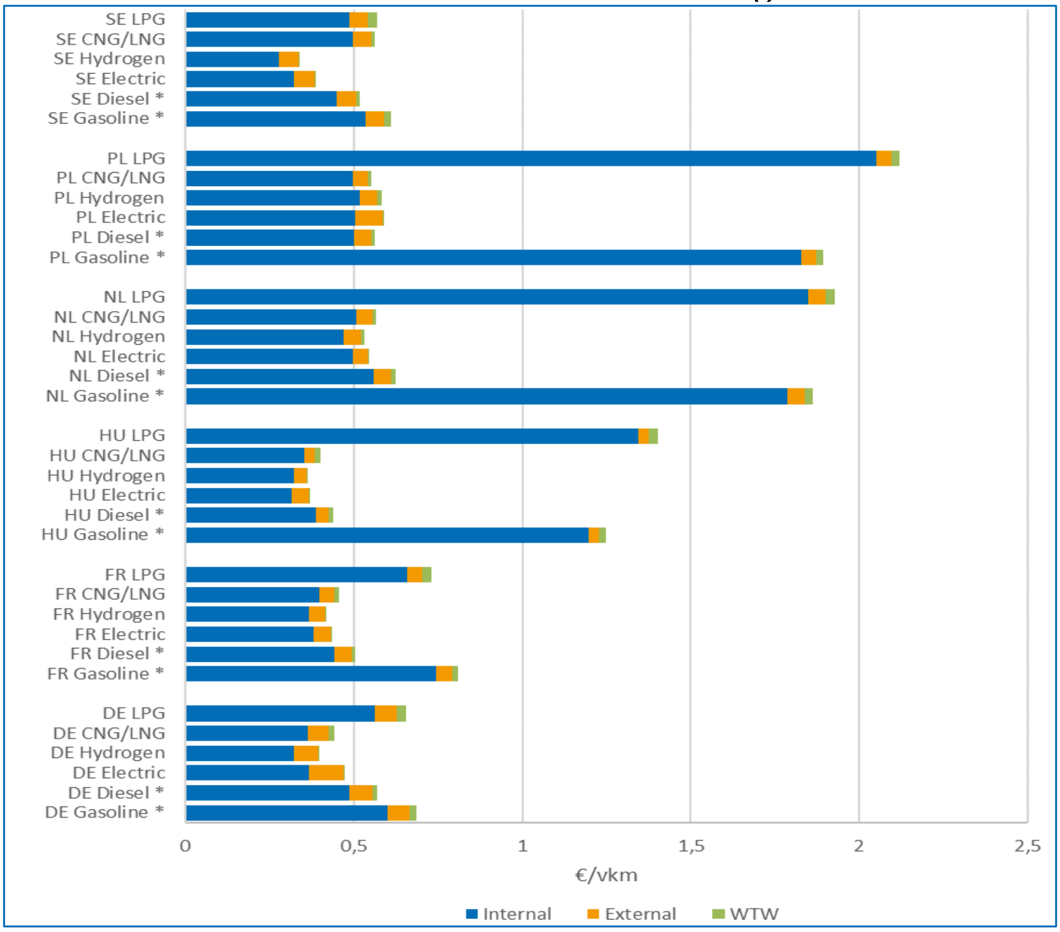


Source: Team analysis.

Note: gasoline is left out, due to the high costs. The diesel contains advanced biofuels (*). The share of biofuel within the diesel is projected to be 40-60 % per country. In the case of blended biofuels current legal or technical constraints for blending rates are respected. Within the model CNG and LNG are assessed in an aggregated way; the output variables show that it is mainly LNG for HDVs.

With regard to heavy-duty vehicles (see figure above), the projections show that in some countries (e.g. in Germany and the Netherlands, which both have large truck fleets) the **internal operational costs** in 2050 still favour diesel. To some extent but not entirely, this difference is offset by the monetization of well-to-wheel emissions. The results also show that, in 2050, the alternative fuels (hydrogen, electric) can compete with diesel, however this does not materialize in the actual demand. The main reasons relate to practical considerations: limitations in infrastructure and travelling range (see also the introduction to this chapter). The same considerations apply for the light-duty vehicles (see figure below). Despite the fact that the societal life cycle costs of certain technologies (e.g. electric and hydrogen) may be the lowest, other factors play a role in the final decision for a vehicle.

Figure 40 Light-duty vehicles - societal life cycle costs 2050 (HIGH scenario, in €/km): ***In 2050 electric and fuel cell solutions are often a cost-effective alternative for fossil fuels (*)***

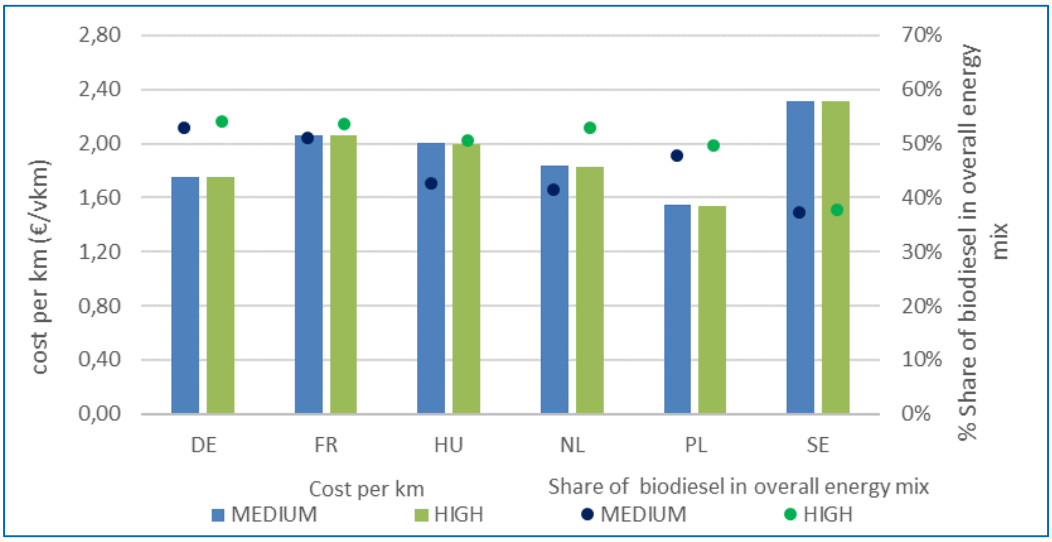


Source: Team analysis.

Note: The diesel and gasoline contain advanced biofuels (*) The share of biofuel within the diesel is projected to be 40-60 % per country. In the case of blended biofuels current legal or technical constraints for blending rates are respected. Within the model CNG and LNG are assessed in an aggregated way; the output variables show that LNG is the most important category.

In chapter 4 we discussed the costs developments of advanced biofuels. Unlike the case of passenger cars, the LLC costs for CI-engined heavy duty vehicles (i.e running on mixes of petroleum fuels and advanced biofuels) do not change significantly across the MEDIUM and the HIGH scenarios, which is shown in the next figure. This is due to the fact that engines need to be well developed for the decarbonisation of this transport segment. There are still some efficiency gains that can be exploited that can cancel out any increases in the cost of bioenergy.

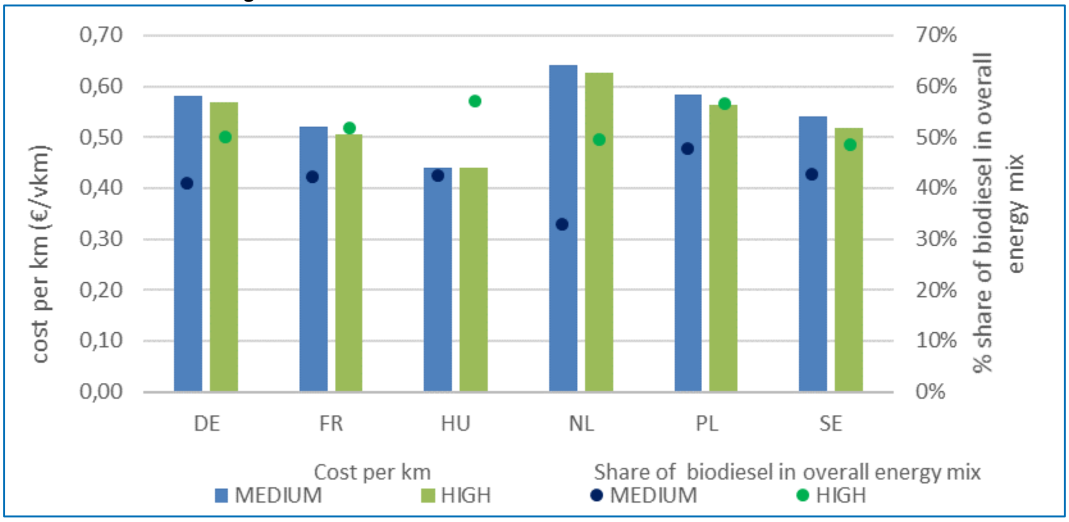
Figure 41 Heavy-duty vehicles - comparison of LLC for CI powertrains across scenarios, 2050 (in €/vkm): *The LCC costs for CI of heavy duty vehicles do not change significantly across the MEDIUM and HIGH scenarios*



Source: Team analysis.

More or less the same observations can be made for the LDVs. Like the HDVs, the LLC costs for CI-engined light duty vehicles do not increase between the MEDIUM and the HIGH scenario. The main reason is that there are still some efficiency gains that can be exploited, which cancel out any increases in the cost of bioenergy. On the contrary, marginally lower costs are observed for most of the six Member States.

Figure 42 Light-duty vehicles - comparison of LLC for CI powertrains across scenarios, 2050 (in €/vkm): *The LCC costs for CI-engined LDVs are lower across the MEDIUM and HIGH scenarios*



Source: Team analysis.

5.3 Maritime transport

Key Findings
Scope and current fuel use: • Low- quality residual fuel followed by diesel are the main fuel sources for global maritime transport. The scattered international regulation, in combination with the capital intensive nature and long investment cycles of the industry, result in a high use of low quality fuels; • The regulation on emissions pushes for higher quality fuels (Emission Control Areas), scale, and use of biofuels in shipping sectors is still limited (but promising); • The current use of alternative fuels in the maritime transport sector is very limited. While the number of LNG-powered ships is increasing slowly, the other technologies (hydrogen, electricity) are still in an immature market stage. Also, the use of biofuels in the sector is still limited. **Setting the scene: the fuel mix in 2030 and 2050:** • The projections up to 2050 show that there will be hardly any potential for hydrogen or electricity as an alternative fuel. There is potential for biomass-based fuels as a substitute for diesel: 45-55 % of the fuel demand is projected to be biomass (bio diesel) under the favourable scenarios. The potential for LNG is around 7 %. **Comparison of the various fuel options (life-cycle costs):** • The combination of regular diesel / fuel oil with biofuels is the main credible option for the future fuel mix. The internal operational costs over time and between the scenarios are stable (among MS), but well-to-wheel emissions (small) differences over time (among MS).

5.3.1 *Scope and current fuel use*

Low-quality residual fuel is the main fuel source for global maritime transport

Maritime transport is commonly divided into three different modes according to the transport distance: (i) inland navigation, (ii) short-sea and (iii) maritime or deep-sea transport. A typical categorization of inland navigation vessels can be made between passenger ships (ferries, cruise boats), non-passenger vessels (e.g. freight vessels, tug boats and special ships like police and customs) and recreational crafts. For short-sea shipping a distinction can be made among general/bulk cargo vessels and passenger ferries. Deep-sea transport mainly includes oil tankers, general/bulk cargo vessels, container vessels and project (maintenance) vessels.

The annual fuel consumption of the global merchant fleet is approximately 11 % of total global energy demand for transport.[148] Global fuel use amounts to 330 million tonnes, most of which (around 80-85 %) is low-quality residual fuel[149] with a high sulphur content used in deep-sea shipping (dry bulk carriers, oil tankers, container ships, etc.). This fuel use implies that the maritime fleet is dominated by fossil fuel engines. The current market position of alternative fuels, such as biofuels, hydrogen or electric propulsion, is far from maturity. Only in the case of LNG has the market found ways for cost-effective operations. This is summarised in the next table.

[148] IEA (2016).

[149] Like for example residual fuel oil (HFO) and marine diesel oil (MDO).

Table 33 Overview state of play various fuel options

Fuel options	Remarks about the state of play
Biofuels	In principle, drop-in biofuels can used as direct substitution for current conventional fossil fuels. So far, the scale and use of biofuels in shipping sectors is still limited, but for the long-run a substantial role for biofuels is expected, also propelled by regulation on sulphur emissions, for instance, as (advanced) biofuels are sulphur-free.
Electrification	The technological maturity for electricity in maritime transport is low. As a result, the fleet of fully electric or hybrid ships is currently limited; all of the existing fleet operates short-distance or is used for in-port operations. Examples of fully electric or hybrid ships can mainly be found in short-distance passenger shipping and in the pleasure crafts sector (encompassing motor or sailing yachts, etc.).
Hydrogen / LNG/ fuel cells	The only commercial vessel using fuel cell technology is the Viking Lady, an offshore supply vessel deployed in the North Sea. The vessel's engine uses the molten carbonate fuel cell and LNG to produce all energy requirements. Yet, the technology has been developed to also work with hydrogen gas, methanol, biofuels, and landfill gas. There have been suggestions to combine fuel cells with hybrid battery systems in the near future.
Natural gas	Although the global LNG carrier fleet is growing, the number of LNG-fueled ships in the global fleet remains very limited: 77 LNG fueled ships in operation worldwide in 2016, plus 85 confirmed orders.[150] So far, the market for LNG has mainly developed through the use of dual fuel systems, i.e. engines burning diesel and methane. Due to its low energetic value per volume, CNG does not have any commercial prospect for powering maritime vessels. The fact that LNG is a relatively clean fuel as compared to conventional maritime fuels, such as heavy fuel oil (HFO) and marine gas oil (MGO), makes it a relatively sustainable option for maritime transport.

Source: Team analysis.

Regulation on emissions pushes for higher quality fuels

In the last two decades, several initiatives were launched to reduce the use of low-quality residual fuel with a high sulphur content. The international and cross-border character of maritime transports makes it necessary that this is regulated on a supranational level. An agreement via the International Maritime Organization (IMO) sets limits on the emissions of sulphur oxides and nitrogen oxides in specially defined Emission Control Areas (ECAs) which, for example, include the North Sea, the Baltic zone and the North American coast.[151] The scope of the ECAs may be extended in the future, but this is uncertain. Further, the IMO agreed upon progressively higher NOx emission standards (since 2000) and technical measures limiting GHG emissions from ships (since 2011). Also, on an EU level, there have been multiple regulatory activities, driven by the EU decarbonisation goals. For example, irrespective of the developments concerning ECAs, the EU aims to mandate a sulphur limit of 0,5 % in EU waters from 2020 on.

Alternative fuels: substantial shifts are not expected before 2030

The maritime transport sector is characterised by its capital intensity and long investment cycles (>20 years), which results in slow changes in terms of technological developments (e.g. on design, fuels, engines, etc.). In addition, scattered international regulations limit the enforcement of strict rules on emissions and technical standards. As a result, the use of 'traditional' low-quality residual fuel is still very high and significant shifts are not foreseen. It is expected that in the medium run

150 Most existing and ordered LNG vessels are car/passenger ferries and platform support vessels, with only a few container ships, gas and oil/chemical carriers, making the share of LNG fuelled ships in the global fleet as measured by global deadweight tonnage negligible.

151 Annex VI of the 1997 MARPOL Convention came into effect in 2005. In 2010 and 2015 sulphur emission limits were tightened further to 1% and 0.1% respectively.

(2030) low sulphur alternatives (MDO/MGO or LSHFO) will replace part of the high sulphur fuels. A substantial uptake of LNG or hydrogen is only expected under favourable conditions[152], although certain niche markets may pick up earlier.[153]

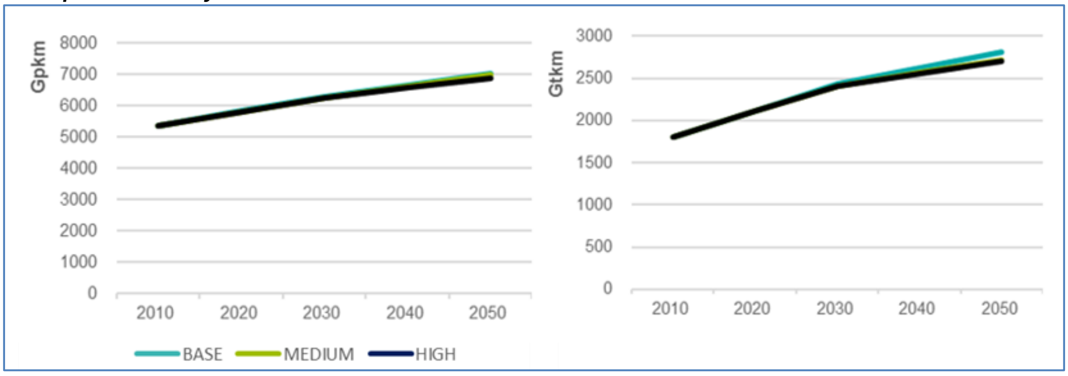
5.3.2 Setting the scene: the fuel mix in 2030 and 2050

The PRIMES-TREMOVE model used for the 2030 and 2050 projections covers 'inland waterway navigation'. This implies that the deep-sea transport is not included in the model set-up and/or the presented projections.

Maritime transport activities are projected to grow until 2050

The model results show an increase in the level of 'transport activity'. The projections for the three scenarios show that the level of maritime transport activity for passengers is estimated to grow by around 20 %. Also, the level of activity for freight transport is expected to increase by around 20 %, see the next figure.

Figure 43 Transport Activity by Passenger and Freight Transport: ***Transport activity for both passenger and freight transport increases, the transport activity in the MEDIUM scenario almost completely overlaps with activity in the HIGH scenario***



Source: Team analysis.

Note: Gpkm stands for giga passenger-kilometre (passenger transport); Gtkm stands for giga tonne-kilometre (freight transport).

Scenarios: significant potential for bio diesel as substitute in 2050

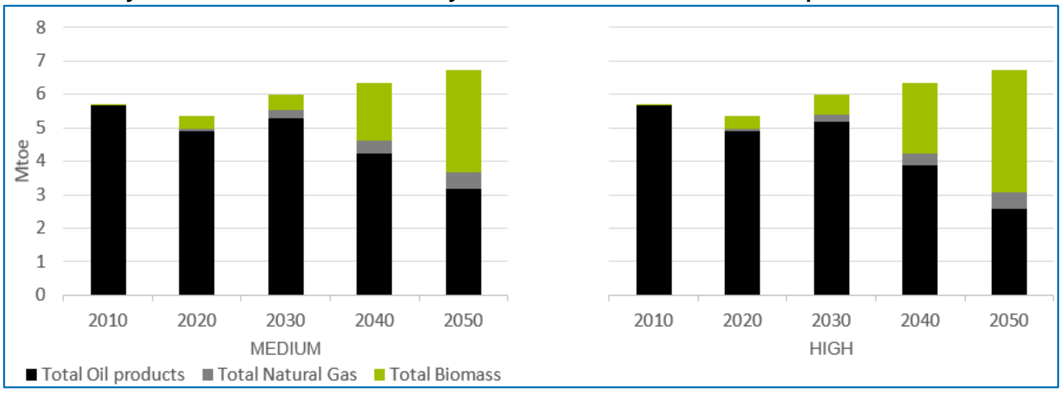
Along with the projected increase in the level of maritime transport activity, the level of total energy demand is expected to increase up to 2050 across all three scenarios. Under the BASELINE scenario, projected energy demand will increase by around 13 % (from 5,7 to 6,5 mtoe). Nearly all energy demand comes from (fossil) oil products. In 2050, 85 % of the fuel mix is oil products, 7 % is natural gas, and 7 % is total biomass.

The figure below presents the projections of energy demand for the MEDIUM and HIGH scenarios. These scenarios project similar results for energy demand, with an increase of around 15 % by 2050 (from 5,7 to 6,7 mtoe). Oil products dominate the fuel mix until 2030. Only after 2030 does biomass start to substantially enter the fuel mix. In the MEDIUM scenario in 2050 the fuel mix is: 47 % oil products, 45 % biomass, and 7 % natural gas. In the HIGH scenario, the 2050 fuel mix is similar: 38 % oil products, 54 % biomass and 7 % natural gas.

152 Lloyd's Register and UCL (2014).

153 CE Delft/TNO (2015). The projections show that even under unfavorable assumptions some ships switch to LNG (e.g. roll-on-roll-off vessels, ferries, offshore and service vessels; these vessels typically stay close to EU ports).

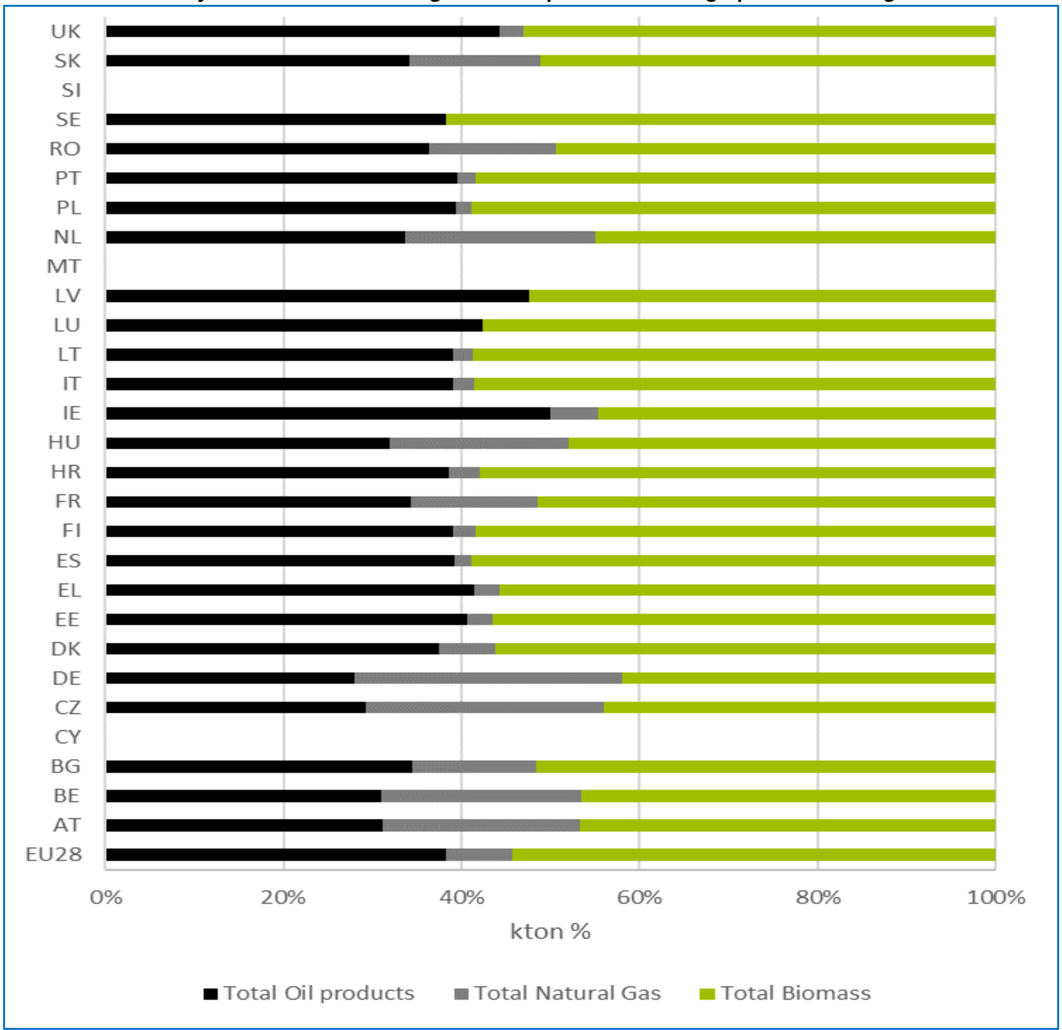
Figure 44 Energy Demand by Fuel Type: ***Energy demand will increase in both MEDIUM and HIGH scenarios. By 2050 the fuel mix will be mainly a combination of biofuels and oil products***



Source: Team analysis. Note: although a full phase-out of first generation (food-based) biofuels is not assumed in the modelling per se, the further penetration in the energy mix is constrained by the European sustainability criteria that are modelled. Therefore, the importance of first generation biofuels as an energy carrier in the future energy mix decreases.

The projections show that the majority (85-90 %) of the biomass-based fuel will consist of bio diesel, which replaces (or is blended with) regular diesel. Besides that, there is potential for 'bio heavy' which serves as a substitute for heavy residual oil. In the next figure we present, besides the average fuel mix for the EU-28, the fuel mix projections per Member State. Especially with regard to natural gas the figures shows quite some variation; the highest levels can be found in countries along the big European rivers (e.g. The Netherlands, Belgium, Germany, Austria, Hungary, etc.).

Figure 45 Fuel mix of inland navigation sector under the HIGH scenario (kton %): ***In 2050, the fuel mix will be dominated by biofuels with natural gas and oil products making up the remaining share***



Source: Team analysis.

5.3.3 Comparison of the societal life cycle costs (LCC) of the various fuel options

Fuel mix options for maritime transport in 2050 are limited, i.e. regular fossil fuels combined with biofuels and (to a lesser extent also) LNG. As explained before, alternative fuel options like electrification and hydrogen are still immature and are not seen as viable solutions for most vessel types before 2050.

Due to the various market stages, the literature on LCC for maritime vessels mainly covers regular fuels (in combination with advanced biofuels) and LNG. In 2015 an extensive study[154] was published on the development of LNG-fueled **(inland) ships** in Europe, which also assessed the LCC (i. c. the 'total cost of ownership') of the various vessel types. The study shows that the level of cost-effectiveness (in 2025) depends strongly on the price of regular fossil fuels, like HFO and MGO: only if HFO and MGO prices are 10-20 % below the LNG prices, LNG breaks even (which is currently not the case). The study also assessed in a number of case studies[155] the environmental impacts and concludes that the environmental benefits are potentially high, especially in cases where LNG use is compared with HFO (with scrubber). For **short-sea shipping**, the uptake of LNG

[154] CE Delft/TNO (2015).

[155] These case studies cover for example cruise ships and container vessels, mainly for inland waterways.

is limited by very practical issues like space, strength and stability of the vessels.[156] Investments in the conversion to LNG are only viable for large vessels, which have the capacity to install large and special LNG tank sections. At the same time, the extra investments need a stable çost gap' between LNG and MGO/HFO to be profitable. With the current market prices the total cost of ownership (TCO) is in favor of MGO/HFO, with a pay-back time for LNG-investments of 10-15 years, which is seen as too high. With regard to **deep-sea shipping** the internal operating costs are still too high compared to MGO/HFO. It is expected that an uptake only takes place after 2025 under favourable conditions. The total cost of ownership (i.e. the internal operating costs) will only be favourable in case of a price reduction of LNG bunker fuel by 25 % and/or a price raise for MGO/HFO.[157]

Concerning the societal life cycle costs for the combination of **regular diesel/heavy oil and biofuels**, our model projections show that the internal operational costs among selected European countries is more or less the same over time and between the scenarios (the higher share of advanced biofuels slightly increases the internal costs). The model projections also show some (small) differences over time for the monetized well-to-wheel emissions. Please note that the projects only show the costs for regular fossil fuels and advanced biofuels (not LNG). In the next table, we briefly present the results.

Table 34 Overview LCC for inland freight shipping in 2050 (in €): ***the projections show small variations in the LCC costs in 2050 in the HIGH scenario***

Countries / scenario	Internal costs Baseline	Internal costs High	WTW-costs Baseline	WTW-costs High
Germany	0,166	0,169	0,002	0,001
France	0,153	0,156	0,003	0,002
Hungary	0,143	0,145	0,001	0,000
Netherlands	0,122	0,125	0,002	0,001
Poland	0,174	0,176	0,003	0,002
Sweden	0,135	0,137	0,002	0,001

Source: Team analysis.

Note: in the overall fuels mix a substantial share is covered by advanced biofuels, see previous section.

The following table provides some insight on the relative the LCC of ships running on LNG compared to a blend of liquid petroleum and biofuels. For all countries the LCC of LNG is greater than liquid petroleum and biofuel blends. The higher costs can be contributed to (1) higher capital costs for LNG ships compared to conventional liquid ones operating with petroleum and bio-blends, relative to the gains in efficiency, (2) the relative prices for gas/oil in each MS, and (3) lower blending of advanced biomethane in LNG ships, leading to higher external costs for WTW.

Table 35 LCC costs- gas compared to liquids in 2050 for the HIGH scenario (in %): the projections show the difference between the LCC for ships running on liquid petroleum/bio blends and LNG for the 6 MS included in the LC analysis

Member States	LLC costs - LNG compared to liquids
Germany	+5 %
France	+3 %
Hungary	+5 %
Netherlands	+2 %
Poland	+10 %

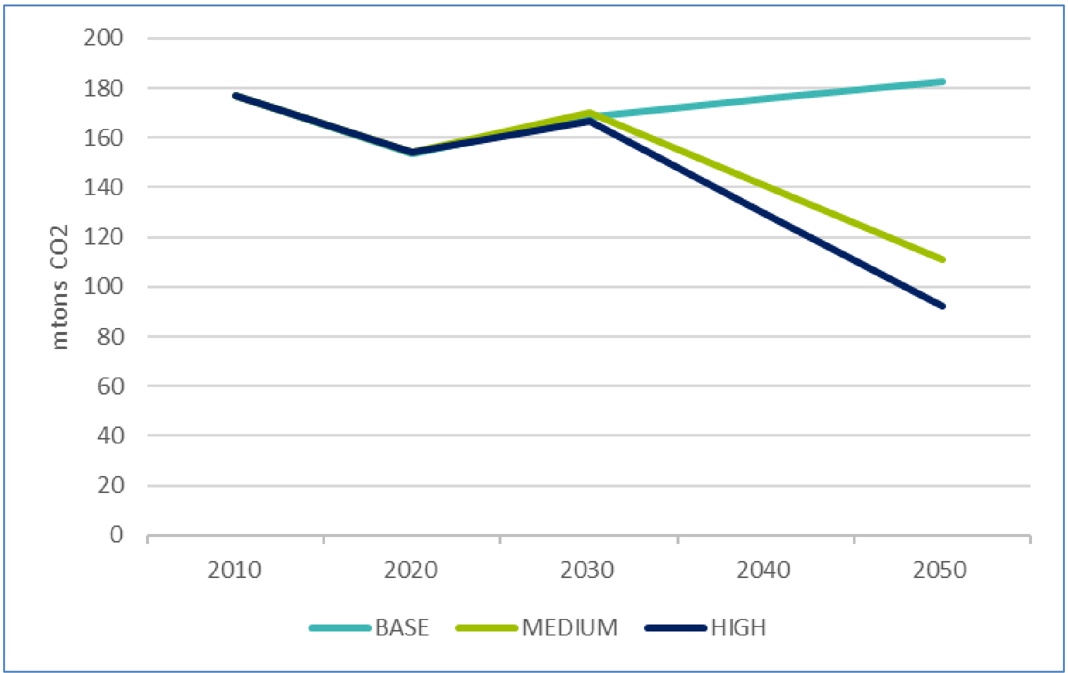
156 Koers & Vaart (2015).

157 Lloyd's Register (2012).

Member States	LLC costs - LNG compared to liquids
Sweden	+3 %

The projected developments in CO_2 emissions for inland navigation are shown in the next graph. It shows that the uptake of advanced biofuels after 2030 can have a substantial impact on the level of avoided emissions as compared to the BASE scenario.

Figure 46 CO_2 emissions for inland navigation (in mton CO_2): ***In the MEDIUM and HIGH scenario the CO_2 emissions decreases***



Source: Team analysis.

5.4 Aviation transport

Key Findings
Scope and current fuel use: • Fossil fuels dominate the aviation transport sector (global and EU). The aviation sector faces slow technology uptake due to high barriers to entry including long investment cycles, capital intensive nature, and high fuel certification standards; • Compared to other transport sectors, alternatives to fossil fuels are limited. Bio-kerosene is the only option in the short and medium-term, due to its potential as a 'drop-in' fuel. Electrification and hydrogen are considered as long-term alternative (commercialization after 2050). **Setting the scene: the fuel mix in 2030 and 2050:** • The projections show that there will be a major shift form conventional kerosene to a blend of bio kerosene and conventional kerosene. The share of fossil fuels drops in both scenarios due to blending of bio kerosene with conventional kerosene. **Comparison of the various fuel options (life-cycle costs):** • For the aviation sector, the number of credible fuel options for 2050 is limited to only the combination of conventional kerosene and bio-kerosene. The model projections show a slight increase in internal operational costs (from € 0,18 in 2010 to € 0,19 in 2050 per km). The projections also show (small) differences over time for the monetized well-to-wheel emissions.

5.4.1 *Scope and current fuel use*

The aviation transport sector is dominated by fossil fuels

The aviation sector[158] accounts for about 10-15 % of global energy demand and emits around 650 million metric tons of carbon pollution annually.[159] Currently, the global market for aviation jet fuel is dominated by fossil fuels, with few existing fuel alternatives. In recent years, the sector has focused on technology developments that increase the efficiency of airplanes in order to reduce its emissions. In the long-term, however, efficiency gains will not be enough to meet the emission targets.

Alternative fuels such as hydrogen and electric powered planes are still in the development phase and will be suitable for aviation only in the longer term (2050 or after 2050). The only viable option in short and medium term is biofuels. This is summarised in the next table.

Table 36 Overview state of play various fuel options

Fuel options	Remarks about the state of play
Biofuels	Biofuels are seen as the only fuel alternative in the short and medium term. They are considered a “drop-in” fuel and thus minimal adjustments have to be made to the infrastructure and the planes. Partnerships with airlines and biofuel suppliers already exist, and commercial flights with bio-kerosene have taken place.
Electrification	Electrification is considered a long-term alternative for most medium to large commercial aircrafts. Yet, it requires that not only the airplane engine, but also the entire aircraft is designed and constructed anew. Also the refueling infrastructure would need to change completely. There are, however, developments in technology, but adoption will be gradual: first from small niche markets and smaller planes, to larger hybrids, to finally large commercial aircrafts. Currently, there are already small one to two seater electric planes. This niche segment may further develop up to 2050.
Hydrogen / fuel cells	Hydrogen is considered a long-term alternative. Fuel cell powered planes would use electric propulsion. Many of the issues facing electrification apply to fuel cells as well. In aviation, liquid hydrogen fueled planes have been explored and technology advancements have been made but neither the technology nor the infrastructure is sufficiently developed. Hybrids are likely to appear on the market before a fully powered hydrogen plane.
Natural gas	Natural gas is not considered a viable alternative, due to its lack of suitability and furthermore, because it is not considered sustainable.

Source: Team analysis.

Slow technology uptake due to capital intensive nature and long investment cycles

The aviation transport sector is characterised by its capital intensity and long investment cycles (>25 years), which result in slow technological developments (e.g. on design, fuels, engines, etc.). Furthermore, a few large OEMs dominate the aviation sector, most notably Airbus and Boeing. Both these OEMs have global supply chains with many suppliers. Furthermore, there are high market barriers for alternative fuel options (such as hydrogen and electric powered airplanes). Firstly, the technologies are still in the development phase and are not mature enough for commercial use. Even though, there are many partnerships, funds, and other efforts in research and innovation to develop these technologies (e.g. CleanSky); so far, most applications are limited to one to two

[158] In the aviation sector, various typologies are used by different sector publications and statistical data sources. Distinctions can be made on the basis of range distance, number of seats, type of flight, etc. Here we will mainly distinguish between passenger/freight flight, domestic/international flights and the type of plane (large commercial aircraft, regional aircraft, business jet, freighter aircraft).

[159] IRENA (2017).

passenger planes. The addition of an electric motor and its storage capabilities (either batteries or fuel cells) changes the configuration of the entire plane, which will (slowly) affect existing suppliers and result in more suppliers being added down the supply chain. Secondly, once these technologies are mature, there will be a long uptake period due to the long lifetime of a commercial aircraft. Thirdly, the infrastructure adjustments needed for refueling infrastructures are significant. Since the aviation sector is global in nature, these infrastructure investments must be made at many airports for planes to refuel conveniently. This will require substantial cooperation between a variety of stakeholders (e.g. airlines, airports, biofuel suppliers, government agencies, petroleum companies, etc.). Fourthly, alternative fuels have to meet high fuel certification standards because of the adverse conditions. Due to these market barriers, many alternative fuels such as hydrogen and electric powered planes are still in the development phase and will only become suitable for aviation in the long term (2050 or after 2050).

Focus to find a sustainable "drop-in" fuel

The only viable option for short-term, mid-term, and most likely the near long-term is the use of drop-in fuels, which do not require adaptation to the aircraft or infrastructure. The most sustainable drop-in fuels are those generated from renewable resources such as biomass. To date, there are production pathways in place that are technically certified, and commercial flights have already flown on bio jet fuel (bio-kerosene). However, especially the certification is (due to the safety need) a delicate and time-consuming process. Further cooperation between a variety of stakeholders (airlines, OEMs, suppliers, airports, governments, biofuel suppliers, etc.) is needed due to the global nature of aviation.

Supranational organisations are taking a leading role in the industry's fuel mix shift

Due to the international nature of the aviation sector, supranational organisations are taking a leading role in the industry's shift to alternative fuels. The Air Transport Action Group (ATAG) set ambitious environmental targets; which the International Civil Aviation Organisation (ICAO)[160] supports through identifying a basket of measures to meet these targets.[161] The basket of measures includes aircraft technology standards, operational improvements, sustainable alternative fuels, and a global market-based measure scheme. To reach the industry's environmental target, EU Member States have agreed to use the ICAO's basket of measures. Furthermore, the aviation sector is included in the EU Emissions Trading System (EU ETS).

5.4.2 Setting the scene: the fuel mix in 2030 and 2050

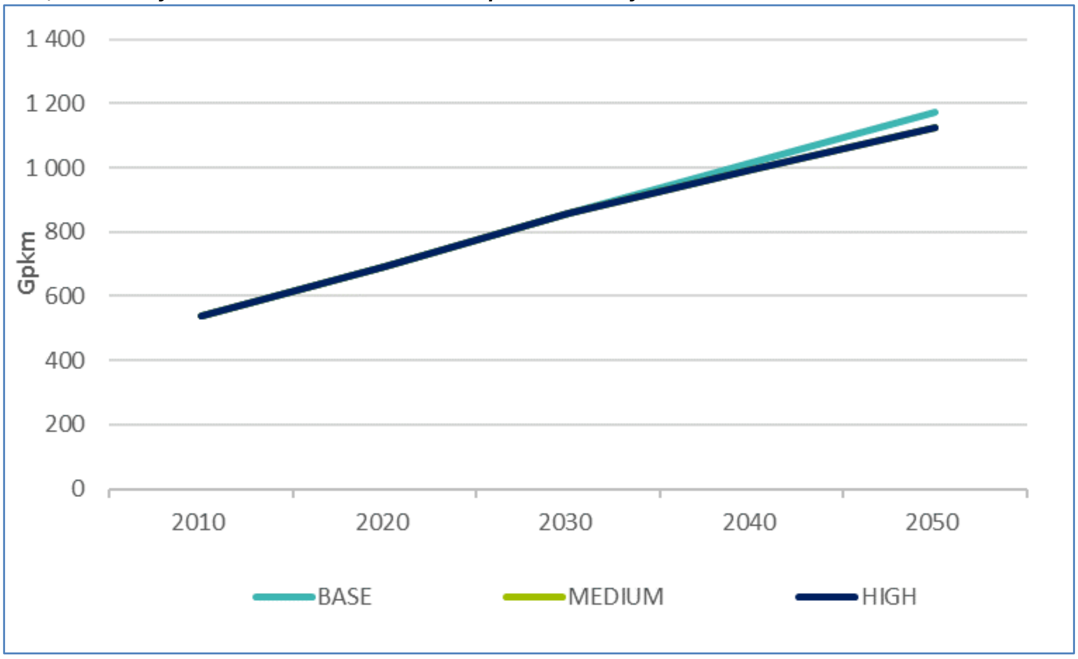
Transport activities will substantially grow until 2050

As in the other transport sectors, the level of 'transport activity' is expected to increase substantially. The projections for the three scenarios show that the level of aviation transport activity is estimated to increase by approximately 50 % by 2050, see the figure below.

[160] ICAO is a specialized agency of the UN, that works with Member States and industry groups to reach consensus on international civil aviation Standards and Recommended Practices (SARPs) and policies to foster a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector.

[161] See: ATAG (n.d.), and ICAO (2016).

Figure 47 Aviation Transport Activity (Gpkm): ***The aviation passenger transport activity increases until 2050, the activity in the MEDIUM scenario overlaps with activity in the HIGH scenario***



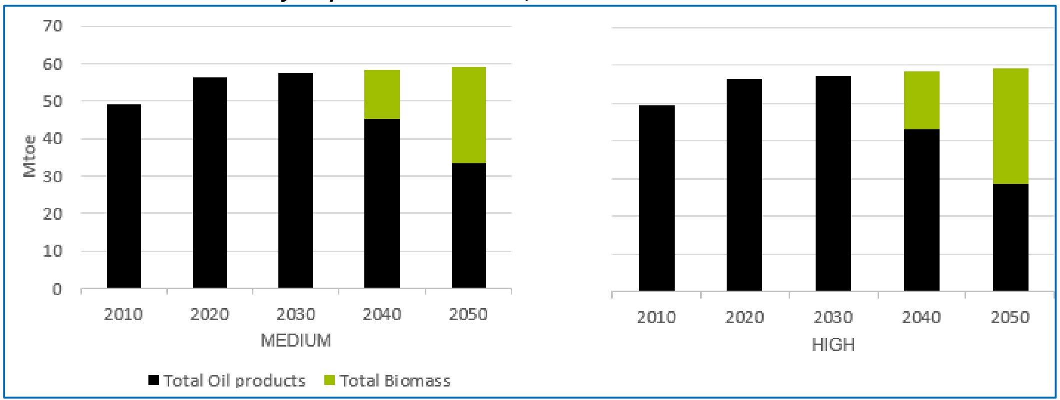
Source: Team analysis.

Energy demand increase and uptake of bio-kerosene after 2030

Along with the projected increase in the level of aviation transport activity, the level of total energy demand is expected to increase up to 2050 under all three scenarios. The growth rate of energy demand is expected, however, to be lower than rate of increase in activity. This difference occurs due to technological developments that increase fuel efficiency of aircrafts. Under the BASELINE scenario, projected energy demand will increase by around 33 % (from 49,2 to 65,4 mtoe). Nearly all energy demand is covered by oil products, with only around 1 % from biomass in 2040 and 2 % in 2050.

The next figure presents the projections of energy demand for the MEDIUM and HIGH scenarios. As electrification of airplanes is not covered by the model, as it is not seen as a plausible mature technology in 2050, the MEDIUM and HIGH scenarios project similar results for aviation energy demand. The scenarios project that energy demand will increase by around 20 % by 2050 (49,2 to 59,2 mtoe). Oil products dominate the fuel mix until after 2030, when biomass starts to substantially enter the fuel mix. In the MEDIUM scenario, bio-kerosene accounts for around 44 % of the fuel mix by 2050. The HIGH scenario projects a similar increased demand for bio-kerosene, which accounts for around 52 % of fuel mix by 2050.

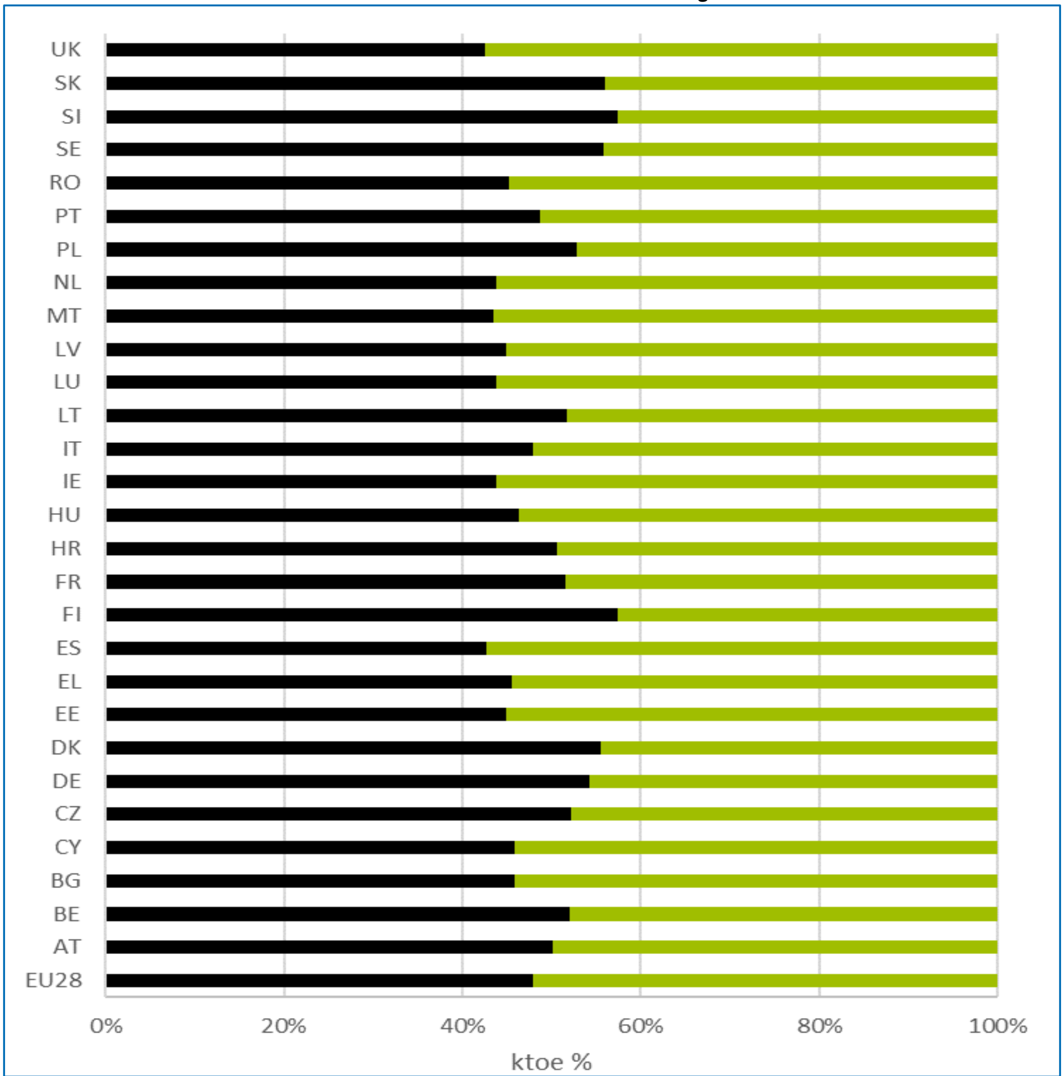
Figure 48 Energy Demand by Fuel Type: ***There is a significant increase in energy demand until 2020. The fuel mix is dominated by oil products until 2030, after 2030 biofuels enter the fuel mix***



Source: Team analysis. Note: although a full phase-out of first generation (food-based) biofuels is not assumed in the modelling per se, the further penetration in the energy mix is constrained by the European sustainability criteria that are modelled. Therefore, the importance of first generation biofuels as an energy carrier in the future energy mix decreases.

The figure below shows the fuel mix in 2050 under the HIGH scenario for each of the MS. The fuel mix for each MS is expected to be around 40-50 % biofuels and the rest conventional kerosene.

Figure 49 Fuel mix for total aviation transport sector in EU MS in 2050 (HIGH): ***In 2050, the fuel mix in all EU MS will consist of around 40-50 % bio-kerosene with the rest being conventional kerosene***



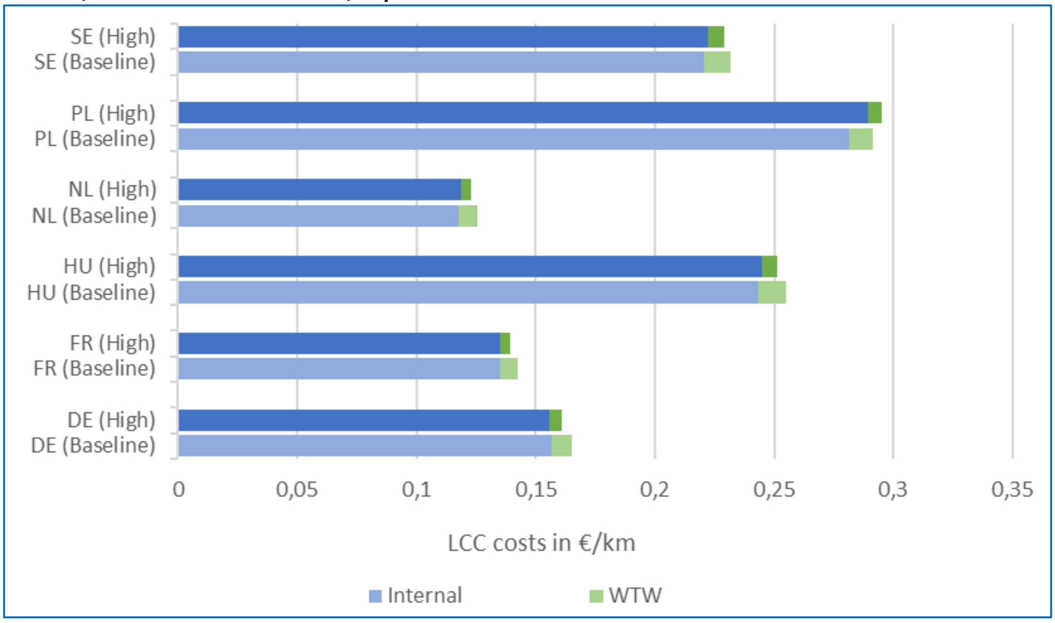
Source: Team analysis.

5.4.3 Comparison of the societal life cycle costs (LCC) of the various fuel options

As with the maritime sector, there is a limited number of credible fuel options for the aviation sector by 2050; i.e. only the combination of conventional kerosene and bio-kerosene. Other alternative fuel options, like electricity and hydrogen, are technologically immature and not expected to materialize before 2050. IATA, ICAO, and other industry organisations take the view that electric aircrafts will not be commercially viable before 2050.[162]Only specific niche markets like small airplanes (mainly for personal use) may become cost-effective. This makes the comparison of the societal life cycle costs (LCC) not very useful.

Our model projections show that the average internal operational costs increase slightly over time from € 0,18 (2010) to € 0,19 (2050) per kilometre, with little difference between scenarios. For well-to-wheel emissions, some small differences are visible over time, as the share of biofuels increases under the medium and high scenario. This increasing share hardly influences the internal operating costs. The results per country are shown in the next figure.

Figure 50 Overview LCC for EU aviation in 2050 (High scenario): *Due to the increased use of advanced biofuels, the WTW-costs decrease; impact on internal costs is limited*



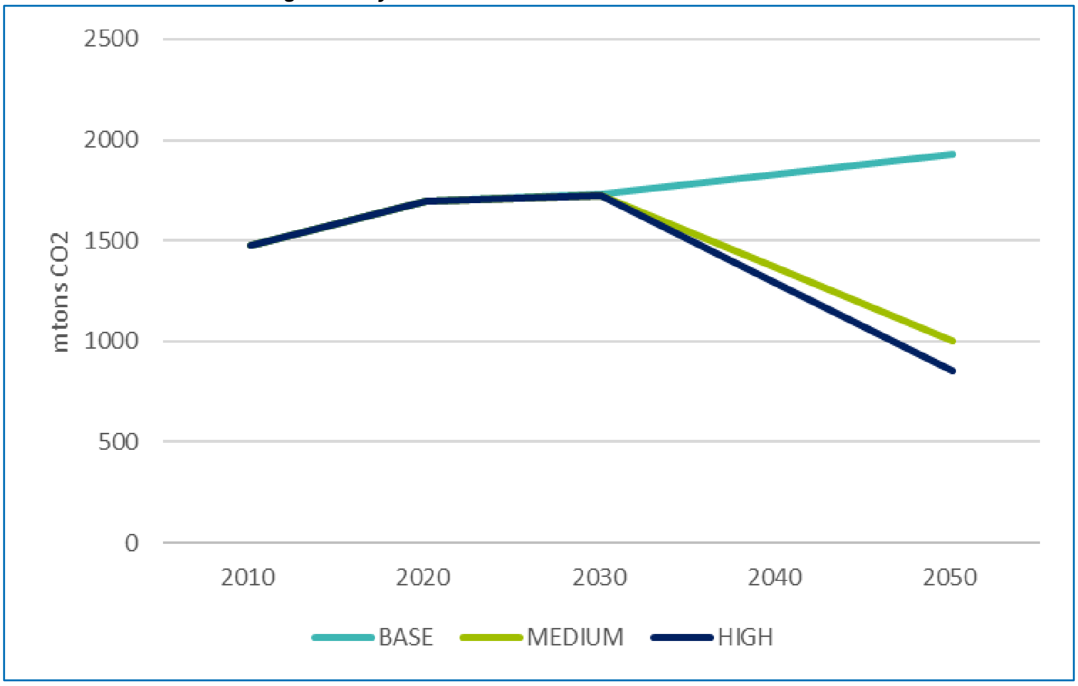
Source: Team analysis.

Note: in the overall fuels mix a substantial share is covered by advanced biofuels, see previous section.

The projected developments in CO_2 emissions for aviation are shown in the next graph. The graph shows that the increased share of advanced biofuels after 2030 results in a significant drop in CO_2 emissions.

162 IATA (2016) & ICAO (2016).

Figure 51 CO_2 emissions for aviation (in mtons CO_2): *After 2030 in the Medium and High scenarios the CO_2 emissions decreases significantly*



Source: Team analysis.

6 Assessment of key social-economic impacts for the EU

6.1 Introduction

The European Commission stipulated various objectives with regard to the societal challenges the European Union is facing. In the Europe 2020 strategy for example, the European Commission formulated the key targets for the European Union, which (amongst others) include the creation of growth and jobs, as well as mitigating climate change.[163] With regard to energy and climate change, a 2030 Energy Strategy was launched, which emphasises the need to move towards a low-carbon EU economy.[164]

In the previous chapters we assessed some of the impacts which are related to the future development of Advanced Biofuels, like the impact on the security of supply, the EU climate goals and the EU energy efficiency targets (see section 4.4). In this chapter we focus in more detail on key social-economic impacts, i.e. the impact on the **GDP-level** for the EU, as well as the impact on **employment**. As part of this analysis we also present the impact on knowledge spill-overs.

6.2 Assessment of key social-economic impacts

Key Findings
• Despite high investments and higher energy system costs, the transition to a bio-based energy system does not affect the EU's GDP negatively over the period 2020-2050. Moreover, the biofuels industry grows substantially. This implies that the MEDIUM and HIGH scenarios do not result in less growth compared to the BASE scenario; • The projections show that some bioeconomy related sectors are positively affected: those that deliver the services, equipment and biofuels for the transition to the low carbon economy (construction, agriculture, electric vehicles); • New jobs will arise due to the shift towards low carbon transport. In the EU economy, the net positive effect in employment is 108 thousand new jobs in the period 2020 – 2050 or a 0,05 % increase from the MEDIUM scenario total employment levels; • The increased deployment of advanced biofuels leads to knowledge spill-overs in bioeconomy related sectors. The knowledge created as a result of R&I leads to production costs reduction, creation of new products and to improved production processes of higher quality. In addition, knowledge is transferred and absorbed by other sectors contributing to general economic growth.

No significant negative? impact on economic growth in 2050 with achieving at the same time decarbonisation?

Based on the main future scenarios, the impacts on the European economy were assessed. The projections show that the EU market for biofuels increases to ~365 billion € in 2050 in the HIGH and to 260 bn € in the MEDIUM scenario, which accounts to 1,6 % of the total EU GDP in 2050. However, the cumulative impacts on EU GDP over the period 2020-2050 are virtually zero (Table 37). At the aggregate EU level the net changes on GDP are marginal between the MEDIUM and HIGH scenarios, as the lower capital and fixed costs for purchasing transport equipment in the

[163] European Commission (2010).
[164] European Commission (2014).

latter are counterbalanced by higher fuel costs due the accelerated penetration of advanced biofuels in the energy mix of the transport sector.

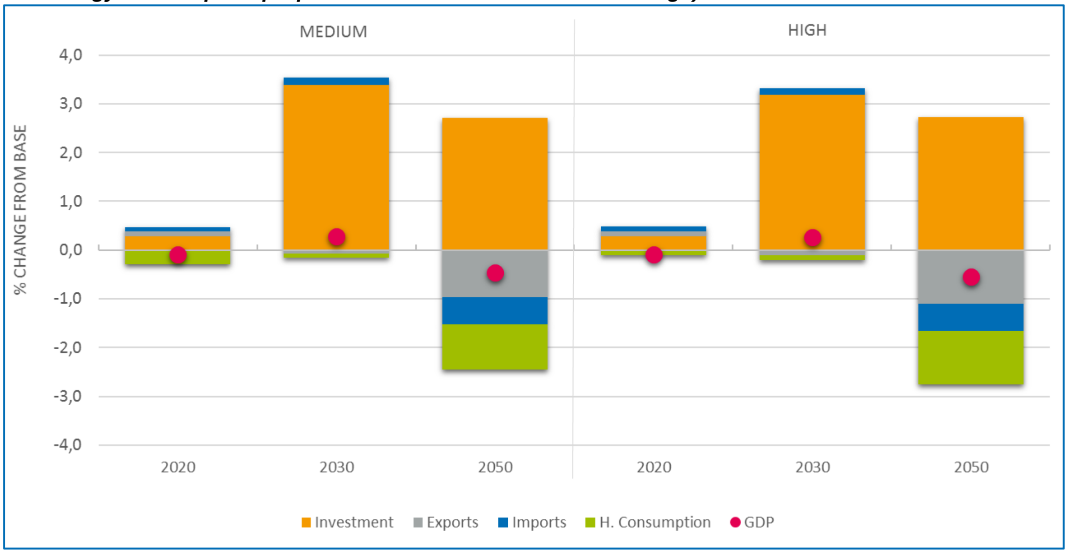
Table 37 Projections EU28 GDP

Scenario	Annual % changes		
	2020-2030	2030-2050	2020 - 2050
BASELINE	1,38 %	1,51 %	1,47 %
MEDIUM	1,42 %	1,47 %	1,45 %
HIGH	1,42 %	1,47 %	1,45 %

Source: Team analysis.

The decomposition of the impacts on GDP (Figure 52) shows that in both scenarios examined investments increase from the baseline levels in the BASELINE, as a result of the increased domestic demand for equipment and services to reduce GHG emissions and energy consumption. The temporal adjustment of household consumption differs among the two scenarios. This impact to households mainly reflects the additional savings that need to be made in order to finance investments (i.e. households postpone their consumption to future driven by high current energy prices).

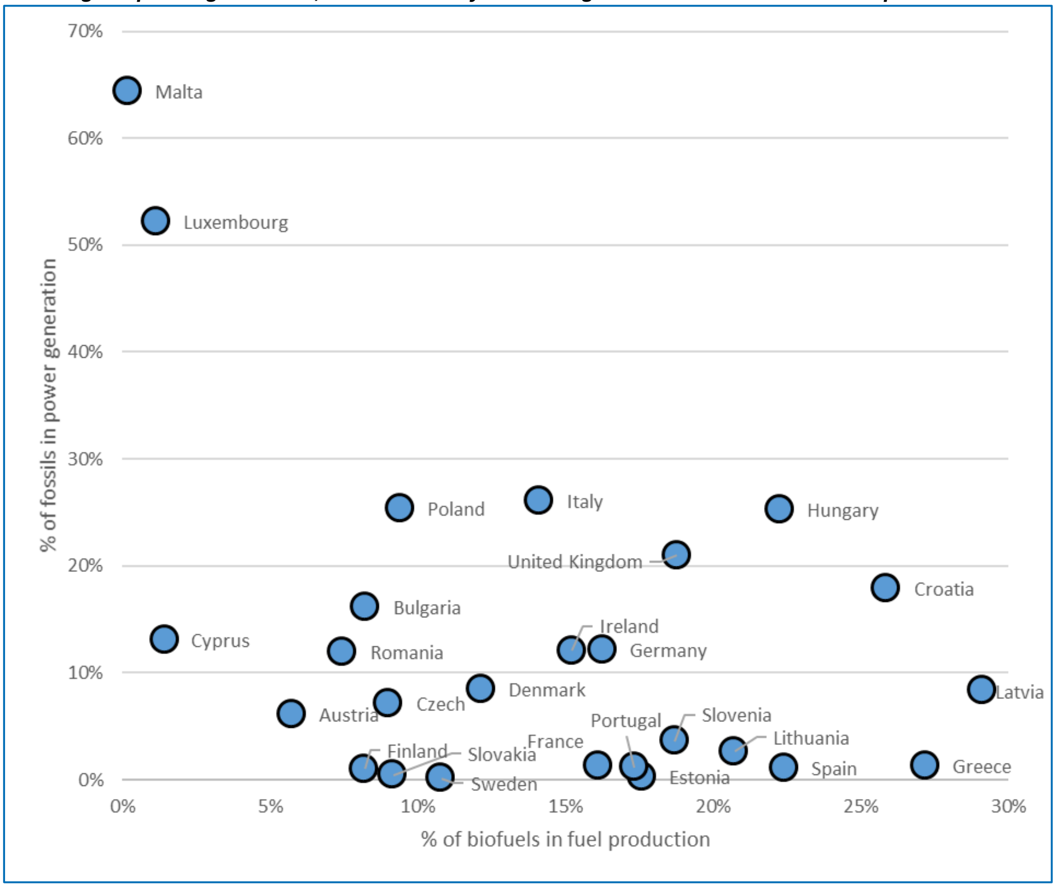
Figure 52 Decomposition of GDP impact- EU28: ***In both scenarios the GDP effect is positive relative to the baseline due to additional investment in 2030. The long-term effect (2050) is negative on GDP, mainly driven by lower household consumption (higher energy prices reduce the disposable income for non-energy consumption purposes and drive an increase in savings)***



Source: Team analysis.

The impact on GDP differs by MS depending on a multitude of factors. An important factor determining the economic adjustment of the member states is whether countries are biofuels/feedstock producers and their power generation mix was dominated by fossil fuels (Figure 53). In the HIGH scenario, demand for electric cars and subsequently for electricity is reduced as compared to the MEDIUM scenario. Countries which have been dependent on imported fossil fuels to generate electricity and which now become biofuels producers benefit.

Figure 53 Biofuels and fossil dependence in power generation (2050): ***Most EU countries reduce fossil fuel usage in power generation, simultaneously increasing the share of biofuels in fuel production***



Source: Team analysis.

The sectors that are positively affected are those that deliver the services, equipment and biofuels for the transition to the low carbon economy (construction, agriculture, electric vehicles). The increase in the cost of energy services affects mainly the sectors that are energy intensive and at the same time exposed to foreign trade. Metals and paper industries which are both energy intensive and trade exposed sectors lose market share in international markets as their production cost increases. Increasing demand for domestically produced vehicles is not enough to sustain metals production to reference levels. Agriculture increases its output from the baseline as a result of the increased demand for advanced biofuels and consequently lignocellulosic feedstock from the agricultural sector. Construction is a key sector to energy efficiency improvement projects and as a result increases its production in almost all cases examined. Transport equipment is a key sector which increases its production driven by the increasing use of electric vehicles in the MEDIUM scenario and the successful penetration of advanced biofuels in the HIGH scenario.

New jobs will arise due to the shift towards low carbon transport

Total employment is driven by economic activity, employment multiplier effects and interactions between sectors acting throughout the EU economy and put in motion under the different transformations of the energy system. In general, the net effect on employment depends on:

- the impact of the policies on economic activity;
- the labour intensity of the sectors that deliver inputs to low carbon projects as opposed to the energy sectors (whose production is reduced); and
- the share of domestically produced inputs to total inputs used in the production process.

The net impact on employment in the HIGH scenario is positive compared to the MEDIUM scenario. Employment is driven from the sectoral activity as certain sectors, which are related to the production of advanced biofuels production, benefit from the increased contribution of advanced biofuels in the EU's climate goals.

In the EU economy, the net positive effect in employment is 108 thousand new jobs in the period 2020 – 2050 or a 0.05 % increase from the MEDIUM scenario total employment levels. The biomass-to-biofuels conversion sector is the main contributor to this positive impact with a share of 45 % of the incremental new jobs (49000 new jobs). Employment in power generation technologies is reduced due to the lower electricity production in the HIGH scenario. In Table 6.2 the percentage change in employment by sector for the period 2020 – 2050 is presented.

Table 38 Employment by sector in the HIGH scenario

Sector	% change from MEDIUM (2020 – 2050)
Agriculture (non - biofuels)	0,12 %
Biofuels	26,15 %
Basic Metals	-0,01 %
Other Energy Intensive Industries	0,.02 %
Construction	0,02 %
Transport Equipment	0,00 %
Other Equipment Goods	-0,05 %
Consumer Goods Industries	0,09 %
Services	0,04 %
Energy	-0,61 %
Total	**0,054 %**

Source: Team analysis.

Different biofuel processes have different employment requirements, which results in differences in job creation among the various biofuel technologies.

Table 39 Employment by different biofuels technologies in the HIGH scenario (1000s)

Sectors	Change from MEDIUM (2020 – 2050)
Biofuels	48,59
Conventional biofuels	0,28
Enzymatic hydrolysis	0,97
Gasification	26,57
Pyrolysis	22,33
Production of HVO	0,00
Gaseous biofuels	-0,15
Solid biomass	-2,29

Source: Team analysis.

Increased production of biofuels which are using used cooking oil (UCO) and animal fats as feedstock results in an increase in conventional biofuels. Other bioenergy sectors such as the production and transformation of solid biomass used in stationary applications (industrial thermal uses and power and heat generation) are affected negatively, as demand for electricity is reduced. In Table 39 the results for each biofuel technology are presented.

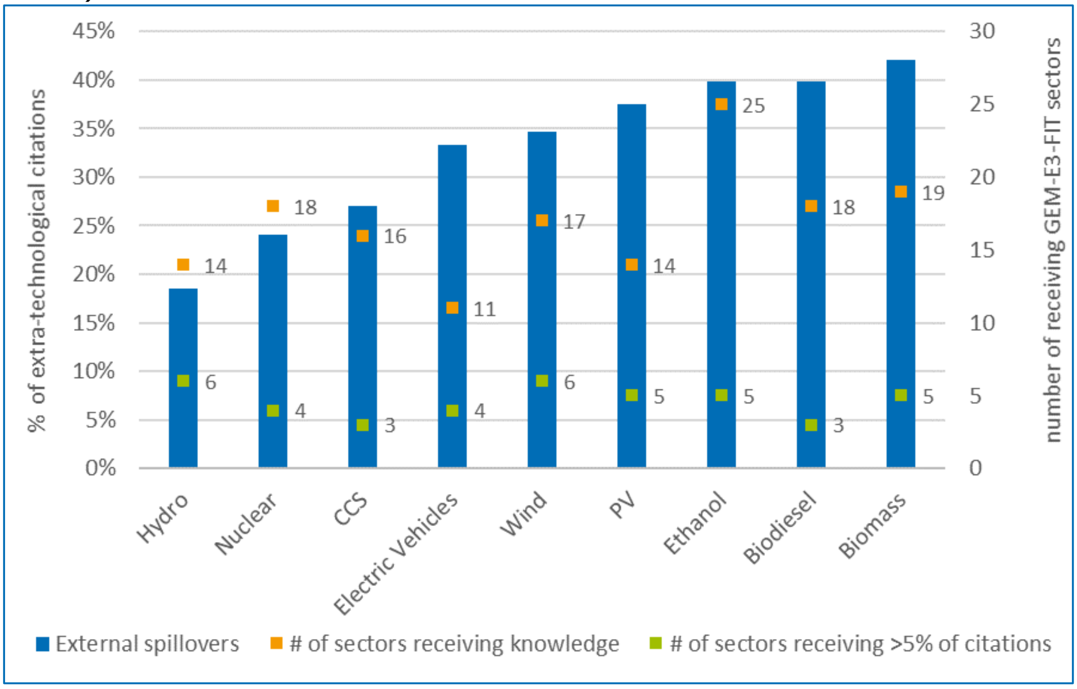
Increased deployment of advanced biofuels leads to knowledge spill-overs

The EU market size allows effective economies of scale whereas the increased deployment of biofuels has positive technology spill-over impacts in a number of sectors outside agriculture and forestry. The transition to a low carbon energy system is a capital and R&I intensive process. The development and adoption of low or zero carbon technologies implies the intensification of R&I towards these technologies. The knowledge created as a result of R&I does not only lead to production costs reduction, creation of new products and to improved production processes of higher quality, but it is also transferred and absorbed by other sectors. That is, knowledge spill-overs take place within the industry but also across different industries and sometimes are essential components of overall economic growth.

The most commonly used methodology to capture knowledge spill-overs is through technology transfer matrices which are differentiated by sector and by country. The methodology was developed by Johnson for the OECD (Johnson, 2002). "*This consists of identifying, for every patent registered at the European Office, the sectors producing and using the innovation described in the patent. This is then used to determine the proportion in which the knowledge accumulated in a sector will benefit others, by calculating knowledge transfer coefficients, the knowledge being, by assumption, borne by the patents*" Zagame et al (2010).

Paroussos et al (2017) has constructed such a knowledge transfer matrix based on the most recent patent citations data on RES technologies. Biofuels have been found to exhibit the highest technology spill-overs (Figure 54) as measured by i) how many citations of a patent are outside the primary industry and ii) how many different industries make the citations. This knowledge transfer matrix has been used in the quantification of the scenarios with the GEM-E3 model.

Figure 54 Technology Spillover: ***Compared with other technologies, such as hydro, nuclear, wind energy or PV, bioenergy-related technologies (biodiesel, biomass) have the highest external spillovers. They hence can be said to contribute most of the energy technologies displayed to technology transfer. Furthermore, the knowledge is transferred to a broad range of sectors (18 sectors for biodiesel, 19 for biomass)***



Source: Paroussos et al (2017).

7 Strategic R&I outlook, conclusions and recommendations

This final chapter combines all the results presented in the previous chapters. In Section 7.1 we present a strategic outlook, in which we answer four key questions that together answer the main overarching question for this study: *What is the research and innovation perspective of the mid-and long-term potential for advanced biofuels in Europe?* In Section 7.2, we present very briefly the main conclusions and related recommendations.

7.1 Discussion and strategic R&I outlook

7.1.1 Key question 1: What is the R&I-driven potential of Advanced Biofuels in the European landscape?

Despite the current unattractive production costs of advanced biofuels as compared to that of regular fuels, the uptake of advanced biofuels as a relevant low-carbon alternative in the 2030 or 2050 transport fuel mix is not yet evident and depends on multiple factors. The analysis shows that ongoing R&I efforts will be crucial in shaping the role biofuels will play in the future fuel mix.

The potential of Advanced Biofuels depends on multiple factors

The position of Advanced Biofuels in the future transport fuel mix depends on various factors, which are both exogenous and endogenous to the biofuel industry. Typical exogenous factors relate, for example, to the price development of crude oil and refined fuel products (diesel, gasoline, jet fuel), as well as the market 'success' of upcoming alternative 'rival' technologies, such as electricity and hydrogen. If these competing fuel options outperform advanced biofuels in terms of costs, reliability, and user-friendliness, the chances for market success of advanced biofuels will be drastically reduced. Endogenous factors concern the extent to which the biofuel industry is able to optimize the overall process from feedstock generation to biofuel production, such that advanced biofuels become a cost-competitive alternative for end-users in the different sectors (aviation, maritime, and road).

Research & Innovation plays an essential role in increasing sustainable feedstock production

The current cost-competitive position of advanced biofuels is weak, resulting in limited production and end-use. In order to improve the cost-competitiveness of advanced biofuels it is important that both feedstock supply and production processes are simultaneously strengthened. Several types of potential R&I gains were identified, mainly targeting the improved supply and enhanced production of biomass feedstock, but also the production cost of conversion from feedstock to advanced biofuels. If R&I efforts targeting feedstock supply and production processes are successful in increasing the cost-competitiveness of advanced biofuels, then the analysis finds significant (market) potential for biomass feedstock and advanced biofuel production in the EU. The increased potential availability applies across all biomass feedstock segments (agriculture, forestry, waste, and aquatic) and can result in a doubling of the available feedstocks[165] if all R&I efforts 'pay off' to a maximum. However, this maximum situation can only be realised against very high costs (especially for aquatic biomass) which in a market situation are unrealistic. A 40-50 % increase in

[165] The projections show that the maximum estimated potential availability of biomass for energy use is approximately 1.101 Mt in 2050 (and 497 Mt in 2020). The biggest contribution comes from forestry (35% of total biomass availability), followed by aquatic (33%), agriculture (22%) and waste (10%). However, this maximum situation can only be realized against very high costs (especially for aquatic biomass) which are unrealistic in a market situation.

feedstock availability, which excludes algae, is therefore considered to be more plausible. This is significant, considering that this figure excludes potential increases due to potential R&I progress in Genetically Modified Crops and new breeding techniques. In addition to that we also assumed that energy crops are only grown on fallow land or on land released from agricultural production. The increase of feedstock for energy use can therefore be even higher.

There is significant potential for Research & Innovation to drive down conversion costs

Results from desk research and stakeholder consultations indicate that R&I can drive down the costs of conversion technologies significantly. Excluding cost reductions driven by economies of scale and learning-by-doing, capital expenditure for conversion technologies is expected to decrease by some 20 % on average if R&I is successful. The largest cost reductions (40 to 60 %) are expected for the following three conversion types: gasification in combination with the Fischer-Tropsch process, pyrolysis, and enzymatic hydrolysis.

Advanced Biofuels require demand-side incentives to scale up and penetrate the market

Within the context of R&I-driven improvements, maximizing the cost competitiveness of advanced biofuels will also require achieving production levels sufficient to (fully) realise economies of scale and scope. In other words: the existence of economies of scale and scope are an important pre-condition for reaching optimal production levels (cost-wise). This condition is currently not met, but can be achieved through (a combination of) various public policy measures, like incentives on the use of Advanced Biofuels (e.g. subsidies, minimum use requirements), incentives on investments in production capacity (e.g. tax reliefs), and/or incentives for public or private investments in supporting infrastructure or fiscal measures (e.g. taxation on carbon).

Meeting mid- and long-term goals requires short term investment in Advanced Biofuels

Although small, the contribution of Advanced Biofuels to the energy mix of 2020 should not be seen as insignificant. As most advanced biofuels conversion technologies are commercially immature and feedstock production need to be scaled up significantly in the medium and long term in order to assist in meeting the EU’s 2030 and 2050 climate objectives, it would require policy makers to set in motion appropriate measures and incentives in order to boost investors’ confidence in the short term. Essentially, the advanced biofuels sector needs to move from demonstration scale plants towards larger plants and scales of operation. The same holds true for the agricultural and forestry sectors, which will need to mobilise lignocellulosic feedstock quantities at scales which have not been seen before.

The “push” for Advanced Biofuels could significantly affect supply and demand balances of biomass feedstocks

It is important to note that, despite these significant benefits of R&I, there is another side of the coin: the cost of feedstock supply. Our analysis shows that the prices of feedstocks for most of the assessed sectors are expected to increase as a result of an increasing demand for advanced biofuels. This demand growth induced price increases can furthermore not be fully offset by cost improvements stemming from R&I (e.g. technological progress and economies of scale). As a result, a sharp increase in the demand for bioenergy will likely lead to higher overall system costs. In the case of **agriculture** and **forestry**, the marginal costs of the feedstock will steeply increase when maximum levels of feedstock are needed (with the exception of the marginal costs of straw). **Waste-related** feedstock, like municipal waste and (non-hazardous) post-consumer wood waste, are expected to be available at low costs, even with increased demand. For used cooking oil the overall potential is limited, however.[166] For **aquatic biomass** more significant R&I developments

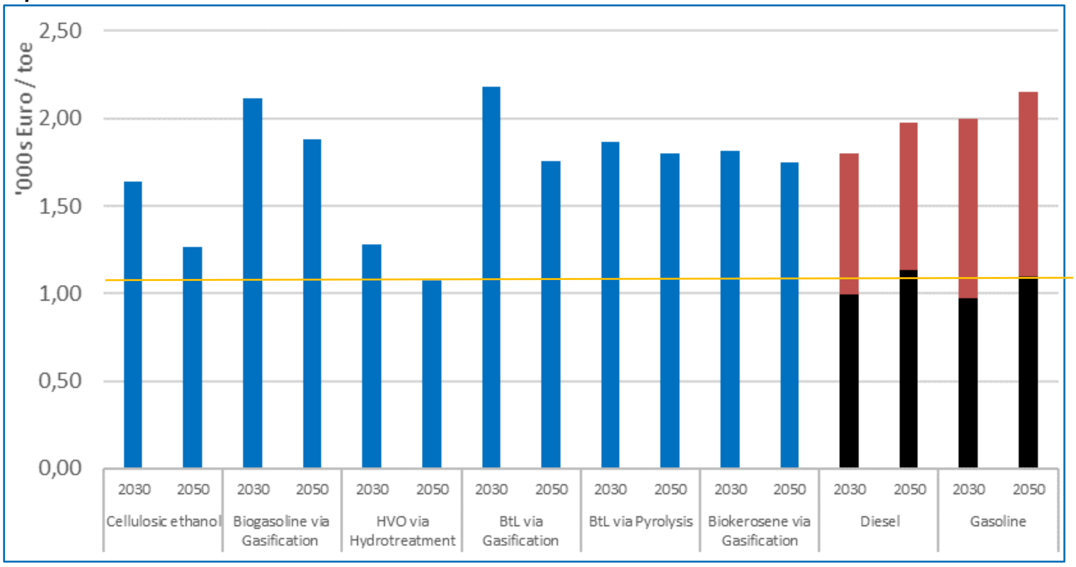
[166] This is mainly related to the fact that this is a ‘by-product’: improvement of their ‘cultivation’ is not possible. In essence, R&I efforts need to focus on methods to extract more from the current supply.

are needed (than the ones foreseen) in order to provide cost-competitive microalgae and macro algae for energy purposes. These observations imply that, if the advanced biofuels "push" becomes a reality, the costs of the entire bioenergy system are expected to increase due to knock-on effects. The projections show that, under the heavy biofuel scenario (HIGH), advanced biofuels can cover 40-50 % of the total fuel demand in the transport system, however this comes at increased costs. Compared to the MEDIUM scenario, the cost of bioenergy production (in toe) increases by 17 %.

Economies of scale and R&I can reduce the 'gap' with regular fossil fuels (but not close it)

The actual production costs of biofuel are the result of the interplay between the demand for feedstock, costs of available feedstock, and the actual production costs. The latter refers to capital, fixed, and variable costs of the various technologies, which relate to economies of scale and R&I gains. The scenario projections show that, in the case of R&I-driven improvements, higher demand, and higher economies of scale, the production costs of advanced biofuels are expected to decrease, however not close the 'gap' with regular fossil fuels entirely. The next figure shows the projected average production costs of different types of advanced biofuels in 2030 and 2050 in comparison to those for diesel and gasoline. It shows that throughout the projection period production costs of advanced biofuels remain (for most types) higher than the costs of conventional biofuels, and, consequently, higher than the costs of fossil fuel based products. On average, production costs for advanced biodiesel remain 50 - 60 % higher than the price evolution assumed for petroleum diesel (without taxation). If the taxation of fossil fuels (red bar) is taken into account, the picture changes: in the absence of taxation on advanced biofuels and maintaining the same tax levels for fossil fuels, most advanced biofuels types become a cost-competitive alternative to conventional fossil fuels.

Figure 55 Average production costs of advanced biofuels (scenario HIGH): *Most advanced biofuel types become a cost-competitive alternative to conventional fossil fuels if the tax levels for fossil fuels remain in place and advanced biofuels are untaxed*



Source: Team analysis.

Notes: (i) the red part of the bar for diesel and gasoline represents the current tax levels across EU Member States, (ii) this result is applicable under the assumptions of the HIGH scenario.

The projected high demand for advanced biofuels leads to improved production efficiency, however, by driving up the demand for feedstock and hence feedstock prices, the overall costs of the energy system are expected to increase. In other words: the projections show that the increase of marginal costs for feedstock outweighs the learning-induced cost reductions due to the higher demand. In essence, this emphasises that in 2050 there is not enough ("cheap") feedstock available to, in an open market, serve the (hypothetical) demand for Advanced Biofuels to reach the EU's climate goals.

The conditions in the EU are advantageous to R&I and the development of an advanced biofuels sector

Currently, the EU seems to be in an advantageous position for the development of an advanced biofuels sector. To retain and further develop this frontrunner position, policies should be implemented to support biofuels, sustainable feedstock production and advanced biofuels-related R&I, and to strengthen the demand side of the market, simultaneously ensuring a long-term business case for investors in the advanced biofuels sector.

7.1.2 Key question 2: What is the contribution of Advanced Biofuels to the EU's energy objectives?

In the Europe 2020 strategy, the European Commission formulated the key targets for the European Union, which (amongst others) include the creation of growth and jobs, as well as mitigating climate change.[167] With regard to energy and climate change, a 2030 Energy Strategy was launched, which emphasises the need to move towards a low-carbon EU economy.[168] The contribution of Advanced Biofuels up to 2050 is mainly related to the improvement of the energy security of the EU, as well as the reduction in carbon emissions.

No significant negative impact on EU growth, yet positive effects on employment, in 2050

Under the scenario assumptions, the projections for 2050 show an increase in the total size of the EU market from biofuels: € 260 billion under the MEDIUM scenario, which amounts to 1.6 % of the GDP of the European Union. However, compared to the BASELINE scenario, the cumulative impacts on EU GDP over the period 2020-2050 are virtually zero. At the aggregate EU level, the net changes on GDP are marginal between the MEDIUM and HIGH scenarios, as the lower capital and fixed costs for purchasing transport equipment in the latter scenario are counterbalanced by higher fuel costs due to the accelerated penetration of advanced biofuels in the energy mix of the transport sector. Both scenarios result in a net positive effect on employment. The HIGH biomass scenario, however, results for the period 2020 – 2050 in 108 thousand new jobs *more* than the MEDIUM scenario. These new jobs are mainly created in the biomass-to-biofuels conversion sector, while employment in power generation technologies is reduced.

Shift towards Advanced Biofuels can significantly improve energy security of the EU

A shift towards the use of more advanced biofuels will improve overall energy security[169] for the European Union. This transition means that fossil fuels are substituted by other alternative fuels, which results in lower imports from outside the EU. In the BASELINE scenario, the energy security of the EU deteriorates slightly between 2015 and 2050, mainly as a result of the decline in domestic production of oil and natural gas in almost all Member States. The scenario projections show that in both decarbonisation scenarios (MEDIUM and HIGH), the energy security indicators in all EU Member States improve significantly in the period 2020-2050. In the HIGH scenario, the EU energy import dependence improves by 0,02 % in 2020, 3,4 % in 2030 and 23 % in 2050, compared to the BASE scenario.

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[167] European Commission (2010).

[168] European Commission (2014).

[169] The IEA defines security of energy supply "as the uninterrupted availability of energy sources at an affordable price".

7.1.3 *Key question 3: How are Advanced Biofuels positioned as a Renewable Alternative Fuel?*

Advanced Biofuels are not the only alternative fuel option for achieving low-carbon and renewable transport. Electrification, hydrogen, LNG, and natural gas are other so-called 'Renewable Alternative Fuels'. Whereas LNG and natural gas are fossil fuels, hydrogen and electrification are partially fossil. From an R&I perspective, it is relevant to see (i) how Advanced Biofuels 'perform' compared to these alternative fuels and (ii) to what extent Advanced Biofuels compete with these fuel options, to avoid a doubling of R&I efforts, while ensuring that climate goals are met.

There are various angles to compare the fuel options, with different outcomes

First, in terms of cost-competitiveness and market maturity, most of the alternative fuel options currently face difficulties competing with regular diesel and gasoline, which are still the dominant fuels in all sectors. In the long run, the position of electricity is expected to improve for passenger cars, but for hydrogen this is still uncertain. Secondly, the assessment of the life-cycle costs shows that hydrogen and electricity perform better in terms of well-to-wheel emissions than natural gas or advanced biofuels. Thirdly, the analysis showed that especially the use of electricity and advanced biofuels will have a positive impact on the EU's energy security, as less fossil fuel would need to be imported.

Advanced Biofuels are mainly complementary to other alternative fuel options

The projections shows that the share of alternative fuels in the 2050 fuel mix for is rather low for all transport sectors (primarily shipping, aviation and heavy-duty vehicles). This implies that the number of alternatives for fossil fuel use, besides advanced biofuels, is limited for these sectors. For the road sector (especially passenger cars), however, there are more options besides advanced biofuels.

Although this differs per transport sector, the overall share of hydrogen, LNG, and natural gas in 2050 is more or less the same in all scenarios. This implies that the share of these fuel options only marginally depends on the development of advanced biofuels, which is low in the BASE scenario and high in the HIGH scenario. We therefore conclude that R&I investments in these fuel options will mostly be complementary to those for Advanced Biofuels, with a limited risk of displacing advanced biofuels in the fuel mix. A different picture emerges for electrification, for which the potential share can both be bigger than that for the other renewable alternative fuels and compete with advanced biofuels in the fuel mix. This is the case for passenger cars and light duty vehicles, while other transport sectors do not face this competition. Nevertheless, we highlight that even under the HIGH scenario, electrification will still have a significant share in the fuel mix.

7.1.4 *Key question 4: What are the implications for R&I policy ambitions, for:*

A) Different types of feedstock technologies?

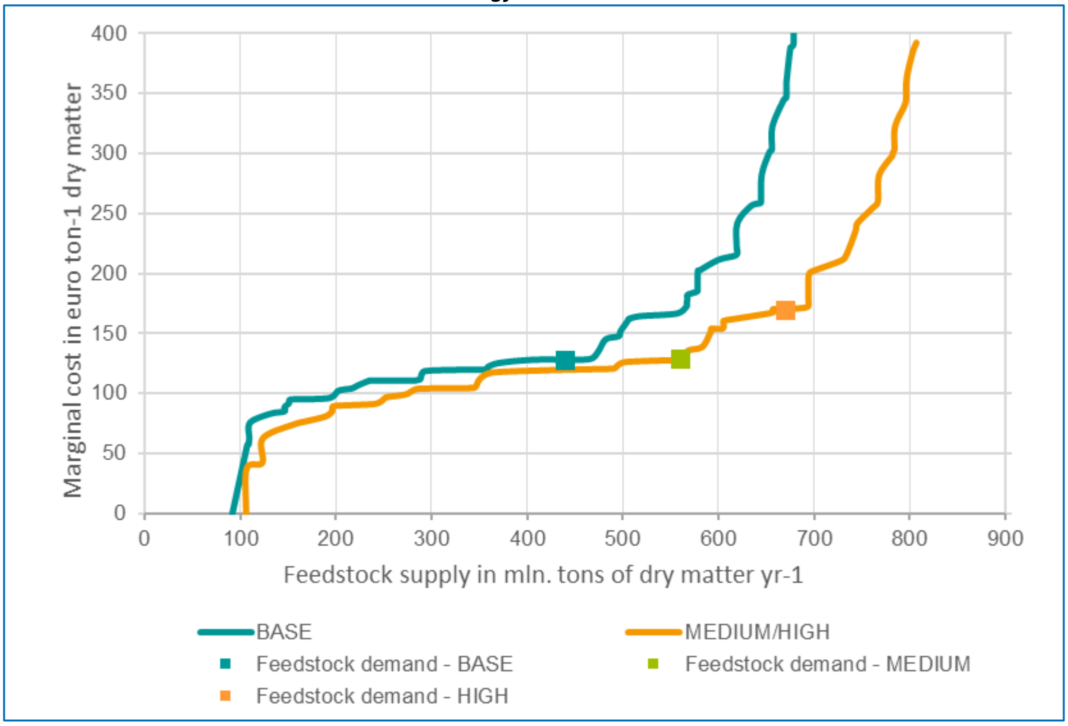
EU feedstock availability faces limitations as demand increases

The figure below presents the aggregated cost-supply curve for feedstock sources for 2050 byscenario. The cost-supply feedstock availability curves show that the marginal price increase for one additional unit of these feedstock stabilises at a level of roughly 100 euros per ton of dry matter. In the HIGH scenario, the marginal cost per unit of feedstock mobilised increases beyond a supply of 350 mln. Tons of dry matter per year, with sharp increases beyond 560 mln. tons of dry matter per year, and reaching the realistic limit of European feedstock supply at 700 to 800 mln. tons of dry matter per year. Mobilisation of feedstock beyond these levels would require very significant feedstock price increases. The results, which show that 670 mln. tons of dry matter from feedstock sources can be used in the production of advanced biofuels in the HIGH scenario, suggest that there are (economic) limitations to the mobilisation of European feedstock.

R&I efforts in feedstock supply offer significant benefits in the decarbonisation scenarios

When comparing the BASE and HIGH scenario, we observe that the R&I impacts depend on the de-carbonisation scenario. With feedstock demand in a no-decarbonisation context, the cost reduction of feedstock is limited with some 8 %, although feedstock supply at the same price level would increase feedstock mobilisation by some 27 %. R&I impacts are more pronounced under the decarbonisation scenarios. With feedstock demand under the MEDIUM and HIGH scenarios, R&I impacts reduce feedstock costs by some 30 to 104 %, respectively. Or put differently, under the demand of the MEDIUM and HIGH scenarios, R&I in feedstock supply increases the availability of feedstock by 100 to 120 Mt of dry matter per year.

Figure 56 Aggregated cost-supply curve for feedstock that can be used in the production of advanced biofuels (excluding algae) by scenario, 2050: ***Mobilisation of feedstock becomes more expensive as demand goes up. Under feedstock demand needed for decarbonisation, the price of feedstock sharply decreases because of R&I in feedstock technology***



Source: Team analysis. Note: given the common assumptions for R&I on feedstock (see chapter 2), the MEDIUM and HIGH scenario have the same cost curve. Please note that the effects of economies of scale are modelled for the conversion technologies, not for feedstock supply.

Feedstock production will face limited competition from other world regions

At the same time, the mobilisation of feedstock from other world regions is expected to be limited. Importing feedstock from other world regions is limited by both transportation costs and local feedstock demand. This indirectly protects the competitiveness of the EU's 'own' feedstock supply, even if the on-site production costs of feedstock are lower elsewhere.

R&I investments to increase feedstock availability have no-regret characteristics

This limited competition will reduce the risk of R&I investments towards improving feedstock availability becoming redundant due to competition with cheap feedstock imported from other world regions. Moreover, under the assumption that decarbonisation targets are met, feedstock limitations are a bigger barrier than lack of demand. Bearing in mind the important role of biomass feedstock in both the future bioenergy system and circular economy, R&I investments in enhanced feedstock availability have strong no-regret characteristics.

R&I in feedstock availability will facilitate price reduction in conversion technologies
Enhanced feedstock availability results in scale-driven cost reduction through learning-by-doing, as well as in lowering the market price of feedstock in a high feedstock demand context. As such, R&I efforts to ensure the availability of sufficient volumes of EU feedstock are key to drive down (or at least reduce) the costs for the entire bioenergy system.

Feedstock availability will have downstream competitiveness implications
Competition can emerge further downstream at the level of (intermediary) advanced biofuels, as these commodities are easier to transport. In addition, changes in advanced biofuels costs can have competitiveness implications as they affect (cost) competitiveness of EU transport systems, and in turn the users of these systems. R&I efforts to increase the availability of biomass feedstock are thus key from a competitiveness perspective, bearing in mind that a successfully developed and scaled up advanced biofuels industry can destabilise the market for biomass feedstocks, with knock-on effects throughout the bioenergy system.

R&I investments in feedstock availability and conversion technologies are complementary
This suggests that added value optimisation of R&I investment in conversion technologies requires R&I investment in feedstock availability, and vice versa. We note that feedstock demand for other purposes than advanced biofuels, e.g. biomass co-firing, can in fact also facilitate the development of advanced biofuels, as a supply chain for the provision of feedstock can mature.

B) Different types of conversion technologies?
It is highly uncertain what type of dominant conversion pathway(s) will emerge
Conversion pathways from feedstock to fuel are intertwined, which means that one conversion process can be applied for a range of pathways, using different feedstock types and producing different final commodities. This suggests that individual advanced conversion technologies can be complementary. It is therefore unwise to put all our eggs in one basket, also given the high uncertainty concerning whether, and if so, what conversion pathways will emerge as dominant, which is of course inherent to R&I.

R&I support for one fuel technology can also benefit other technologies
Many advanced biofuels conversion technologies, but also conventional fossil and conventional biofuel technologies, are interrelated and show synergies. They can share knowledge and skills requirements (human capacity), upstream infrastructure (logistics of feedstock streams), feedstock (lignin for one process, cellulose for another), and downstream infrastructure (processing, but also changes in the transport infrastructure).

In the transition towards advanced biofuels, competing concepts can be complementary from an R&I perspective
In light of these interrelations and synergies, Advanced Biofuels can, as a drop-in solution, benefit from an existing and already mature value chain. First generation biofuels can also pave the way in this respect, helping advanced biofuels scale up after first generation biofuels have. Similarly, biorefinery concepts producing higher added value biochemical as co-products can improve the advanced biofuels business case. This suggests that concepts, which will compete in the long run, can in fact start out as complementary. From a commercialisation and scaling up perspective, support to first generation biofuels can facilitate Advanced Biofuels development.

Conversely, focusing scale-driven cost reductions can improve cost-performance of Advanced Biofuels
The study results show that the average costs of the bioenergy system go up, as R&I and scale-driven cost reductions do not outpace higher feedstock costs. This suggests that more attention is

needed in order to avoid ‘wasting’ capacity and learning (cost reductions) by extending support across too many different technologies. This argument contrasts the earlier points made on ‘diversifying’ support, implying that a more restricted focus needs to be applied as conversion technologies enter the full scale pre-commercial phase of development.

Feedstock availability, feedstock flexibility, and fuel versatility are key

Several transversal themes emerged from the inventory of research challenges specifically for advanced biofuel conversion technologies: a manageable and scaled-up feedstock stream, feedstock flexibility for the conversion process, and fuel flexibility for processing intermediate products into fuel end-uses. Taking note of the importance of scale-driven learning and cost reductions, dominant conversion pathways in the medium and long term may well include conversion technologies which can handle a wide range of feedstock and can produce a diverse set of fuels, including conversion technologies such as pyrolysis and gasification.

Relevant R&I considerations are the ‘field to fuel’ value chain distribution and EU technology leadership

R&I investment can take an industrialisation perspective. Relevant considerations are therefore EU technology leadership and ‘field to fuel’ value chain distributions, which should provide insight into what part of the value chain can materialise in Europe. The study results suggest that EU academic leadership can emerge in a wide range of research clusters, with the exception of biochemical conversion technology, where the USA is clearly leading. For gasification research, Asian countries have a strong (non-leading) position.

C) Different transport sectors?

Strategic R&I choices are important for the mid-term transport horizon

The limitations of feedstock availability at a competitive price indicate that it will not be possible to supply all transport sectors with advanced biofuels without driving up the cost of the bioenergy system. This suggests that from a mid- to long-term perspective, choices need to be made whether or not advanced biofuels should still be available for all transport sectors. This relates not only to the question of whether advanced biofuels should be used in the aviation and maritime sector instead of passenger road transport, but also to the question of whether the choice for advanced biofuels is efficient from a societal perspective (i.e. *is the cost of decarbonisation via advanced biofuels still an efficient choice?*). Within this context it is also key to consider the relative or comparative impacts of using advanced biofuels instead of the substituted fuel type. In other words, what would the fuel mix be without advanced biofuels? The study results show that, especially in aviation, shipping and heavy-duty vehicle road transport, the alternatives are limited, and advanced biofuels are the main substitute for conventional fossil fuels.

Facilitating the complementarity between electrification and Advanced Biofuels

Whether competition should be avoided between electrification and advanced biofuels is a complex issue. We note that in the process of scaling up, R&I in advanced biofuels can benefit from serving (niche) markets in the passenger car and light duty vehicles segments. Moreover, serving parallel transport sectors does not account for industrialisation considerations, for example differences in the global value chain distribution of electric vehicles vis-à-vis conventional vehicles with drop-in fuels. Overall, we argue that advanced biofuels can facilitate the complementarity of the various fuel options. In the mid- to long-term horizon, when technologies and supply chains have become more mature, a change of focus of advanced biofuels towards heavy duty vehicles, shipping, and aviation might be necessary for further decarbonisation. R&I has a central role to play here, as it can help bring about economic incentives to make this change.

7.2 Conclusions and recommendations

This study assesses the highly complex global interactions of R&I developments in feedstock production and conversion to biofuels, as well as the demand for these and other fuels within the EU transport sector. This complexity of these interactions is driven by a strong heterogeneity in the potential of advanced biofuels from a geographic, technological, and market perspective. Actual R&I progress is difficult to predict, especially considering the 'chicken-and-egg' issues regarding technology push and market pull mechanisms. Nonetheless, it is crucial to analyse the R&I potential and to produce quantitative estimates even under high uncertainty, as they enable us to obtain a glimpse of the possible future market potential. The study findings suggest a rationale for investments in R&I linked to the advanced biofuels sector, whether through measures concerning the development of feedstock supply, conversion technologies, or stimulating advanced biofuels demand.

Overall, enabling the development of advanced biofuels requires R&I instruments on several fronts:

- R&I can improve the supply of biomass feedstock. The study results show that in the 2050 horizon, total sustainable feedstock availability can increase by some 50 % for agricultural, forestry and waste biomass feedstock. Should algae biomass emerge, the feedstock availability would increase by 120 % instead of 50 %, although we expect algae feedstock would not be available at a competitive price;
- R&I can improve advanced biofuels production processes to reduce conversion costs. It is difficult to predict which conversion technologies will dominate, and not only one conversion pathway may prevail. Feedstock availability, feedstock flexibility, and fuel versatility will be the key characteristics of a successful conversion technology. R&I synergies between various conversion technologies, with conventional (bio)fuel sectors and with biochemical co-production can be exploited;
- A stable demand outlook for advanced biofuels is needed to establish a market and to spur development. Maximising the cost-competitiveness of biofuels will require production levels sufficient to achieve economies of scale, which may rely on public policy instruments to stimulate market demand.

If successfully developed, the contribution of advanced biofuels to achieving EU targets can be significant. The share of advanced biofuels in the overall transport sector energy mix can reach almost 50 % by 2050. By substituting imported fossil fuels with domestically produced biofuels, energy security would improve significantly. When comparing with a Reference case (BASE scenario), energy security for oil improves by 1 percentage point for oil – with much lower demand though, implying a significant reduction in absolute imports – and 13 percentage points for bioenergy. Overall energy security improves by 23 percentage points. The absolute market volume could reach € 365 billion (1,6 % of EU's GDP), although net GDP growth is negligible. The net employment impacts amount to a net increase of 108 000 extra jobs, taking into account a reallocation of employment from other sectors.

However, even with significant R&I developments and resulting cost reductions, achieving the levels of biofuel production needed to reach EU targets may require continuous support to allow advanced biofuels to compete with conventional fuels. The high cost of biofuels would be structural by nature, as high demand levels risk destabilising the market for biomass feedstock. Destabilisation would push prices up and have knock-on effects throughout the bioenergy and transport systems. Thus, the levels of biofuel production, as assessed in our scenarios, is probably in the upper range of future possibilities.

Feedstock limitations suggest that R&I investments should steer towards the long-term use of advanced biofuels, complementary with renewable alternative fuels. The R&I focus would then be to facilitate the market penetration of advanced biofuels in the transport sectors with limited fuel alternatives, such as aviation and shipping. The successful diffusion of advanced biofuels in the EU energy mix depends on the right market transformation and coordination between various stakeholders, which cannot be considered guaranteed. Immense efforts are needed by farmers and forestry owners, who enhance biomass production and invest in the cultivation of new lignocellulosic crops. Their efforts need to be supported by innovators and industrial investors, who develop advanced conversion technology capacities. Consumers, especially in the transportation sector, need to become aware that the use of biofuels in their vehicles is safe and that it is cost-effective to fully adopt advanced biofuels. However, even if the aforementioned actions are followed by all stakeholders, scaling up towards a substantial advanced biofuels sector in the EU will take time – the transition period may last more than 15-20 years.

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