ADVANCEFUEL

# Total system costs of RESfuel scenarios and the employment impacts of biofuel production

## D6.3 Socio-economic assessment

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## *ADVANCEFUEL at a glance*

ADVANCEFUEL (www.ADVANCEFUEL.eu) aims to facilitate the commercialisation of renewable transport fuels by providing market stakeholders with new knowledge, tools, standards and recommendations to help remove barriers to their uptake. The project will look into liquid advanced biofuels – defined as liquid fuels produced from lignocellulosic feedstocks from agriculture, forestry and waste – and liquid renewable alternative fuels produced from renewable hydrogen and $CO_2$ streams.

In order to support commercial development of these fuels, the project will firstly develop a framework to monitor the current status, and future perspectives, of renewable fuels in Europe in order to better understand how to overcome barriers to their market roll-out. Following this, it will investigate individual barriers and advance new solutions for overcoming them.

The project will examine the challenges of biomass availability for second-generation biofuels, looking at non-food crops and residues, and how to improve supply chains from providers to converters. New and innovative conversion technologies will also be explored in order to see how they can be integrated into energy infrastructure.

Sustainability is a major concern for renewable fuels and ADVANCEFUEL will look at socio-economic and environmental sustainability across the entire value chain, providing sustainability criteria and policy-recommendations for ensuring that renewable fuels are truly sustainable fuels. A decision support tool will be created for policymakers to enable a full value chain assessment of renewable fuels, as well as useful scenarios and sensitivity analysis on the future of these fuels.

Stakeholders will be addressed throughout the project to involve them in a dialogue on the future of renewable fuels and receive feedback on ADVANCEFUEL developments to ensure applicability to the end audience, validate results and ensure successful transfer and uptake of the project results. In this way, ADVANCEFUEL will contribute to the development of new transport fuel value chains that can contribute to the achievement of the EU's renewable energy targets and reduce carbon emissions in the transport sector to 2030 and beyond.

To stay up to date with ADVANCEFUEL's stakeholder activities, sign up at:
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# Executive Summary

## *Aim and approach*

One of the main aims of this report is to provide information regarding the economic aspects of the two scenarios Road ZERO and Transport BIO, presented in detail in Uslu *et al.* (2020) "*D6.2 Role of renewable fuels in transport sector up to 2050"* of the ADVANCEFUEL project. The total system cost refers to the total costs needed to employ renewable fuels in the transport sector (road, rail, aviation, inland navigation and maritime). It covers all costs, including the fuel supply costs, capital expenditures (CAPEX) and operating expenditures (OPEX) of the conversion technologies related to transport sector. The additional costs needed for the engine adaptations or replacement of the existing vehicle fleet are also included to the total system costs. Next to the total system costs, average energy costs are calculated to reflect the total cost of one unit of energy supplied to the transport sector according to the two different scenarios.

Another aim of this report is to assess the employment effects of biofuel deployment in each scenario. The employment effects are estimated by allocating the money spent on investments in new biofuel production capacities, operation and maintenances (O&M) and feedstocks to different sectors in the EU member states and using economic statistics to estimate how many jobs can be supported from the amount spent in each sector. The methodology was adapted from that developed for the EurObserv'ER project[1]. Results include gross employment effects of biofuels production in the EU. Employment in electricity, hydrogen or power-to-X fuels used in the transport sector are not considered in the assessment, nor is employment from vehicle manufacturing. The assessment considers direct employment in the construction and operation of biofuel production plants as well as indirect employment in feedstock supply, equipment manufacturing, transport and storage. Induced employment effects, the broader impact on the economy due to reinvestment of worker's wages, are not considered. Displaced jobs in the fossil fuel, agricultural, or forestry sectors are not considered. The difference in results between the two scenarios are therefore a reflection of the differences in installed capacities per member state for the scenarios (both the quantity and the type). For biomass feedstock supply employment, the proportion of domestic production to imports from outside the EU also influence the results.

In D6.2 two scenarios are constructed using the RESolve-Biomass model. Two main factors – technology development and the availability of renewable electricity – have set the scenario framework. Firstly, the Transport BIO scenario reflects a significant technology development in the production of advanced biofuels; whereas the Road ZERO scenario assumes a technology breakthrough in zero emission vehicles as well as low electricity prices. The ultimate aim of both scenarios is to reduce GHG emissions in the transport sector (which includes road and rail transport, inland shipping and aviation, but excludes international shipping) by 85% in 2050 compared to 1990. They also aim to reduce the GHG emission in international shipping by 50% compared to 2008. These scenarios are built upon PRIMES (2018) baseline scenario. RESolve-Biomass determines the least-cost configuration of the entire biobased production chain (including biofuels in transport, bioelectricity, bioheat and biobased products). In addition to biofuels, the model includes other zero-emission fuels and vehicles.

[1] See ECN (2017).

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## Results-total system costs

The analysis shows that the total system costs of the renewable energy supply options in 2050 comprise around 2-3,5% of the EU28 GDP[2]. Both the total system cost and average energy cost of the Road ZERO scenario are significantly lower than the Transport BIO scenario. However, such a comparison should not led to a conclusion that one scenario can be preferred above the other. The total system costs consist of different cost categories that will affect the stakeholders differently. For instance, in case of direct electrification the majority of the costs relate to the batter electric vehicles (BEVs) followed by the electricity prices, whereas in case of biofuels the major cost component relates to the biomass-to-biofuels conversion stage. Besides, both scenarios describe worlds with different external factors, which result in a different energy mix for the transport sector. The electricity prices and the costs of electrical vehicles have a very large impact on the energy mix of the transport sector and the framework set for Road ZERO favours electrification through lower electricity prices and vehicle costs. The results show that the major cost component relates to the costs of BEVs, followed by the electricity costs in direct electrification, whereas it is the other way around with hydrogen ($H_2$) use in the transport sector. The engine costs are the highest followed by the $H_2$ energy carrier cost. As e-fuels can be directly used in existing vehicles, the total costs relate to energy carrier costs only.

Even though the direct electrification total system cost per GJ energy consumed in the transport sector are much higher than biofuels, the model favours direct electrification. This relates to the fact that direct electrification has a much higher efficiency converting the 'energy carrier' to the wheels. In principle, a better indicator to compare the attractiveness among the different renewable fuel supply options considered here, would be to compare the average costs per km driven.

In 2030, the total system costs of biofuels are dominated by feedstock costs in both scenarios. This is because first generation and used cooking oil-based biofuels have a large share in the total system costs, representing 64% and 24% for Road ZERO and Transport BIO, respectively. This changes in 2050 and feedstock costs make up a less dominant portion of the total costs related to biofuel deployment. Around 30% and 24% of the biofuel total system costs relate to feedstock in Road ZERO and Transport BIO respectively. The costs related to the conversion technologies become the major cost component, comprising around 40% and 50% of the total system costs for Road ZERO and Transport BIO. Transportation costs of feedstocks and biofuels also become an important cost component in 2050 as more feedstocks need to be mobilised from remote locations. Vehicle adaptation cost and additional cost for distribution make up a small fraction.

When the energy system costs per GJ biofuel are considered it becomes clear that biofuels are, on, average significantly cheaper than e-fuels. So, the deployment of e-fuels relate to the limited availability of feedstocks in Transport BIO scenario and the mismatch between demand for renewable fuels and outlet of biofuel options in Road ZERO. The average biofuel cost per GJ is lower in Transport BIO than Road ZERO in 2030. It increases significantly after 2030 in Transport BIO, becoming around 50% higher as compared to Road ZERO. Such a strong increase in average biofuel cost can be attributed to several factors. First, a large part of the biomass potential is used in this scenario, which means that the more expensive biomass feedstocks have to be utilized. Second, demand for biofuels is low in certain market segments, in particular in passenger cars. The conversion processes that produce biofuels to other segments, such as aviation,

[2] In 2019, the EU28 GDP is stated as 16452 billion €.

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are in general more expensive. Third, since the biomass potential is a limiting factor, biofuel conversion technologies that have a high conversion efficiency are favoured. These technologies are, as well, more expensive.

## Results-employment effects

The modelling results show an estimated 116 (Road ZERO) and 440 thousand (Transport BIO) *job years*[3] can be created in sectors related to the construction of new advanced biofuel production capacity. Over the period 2018-2050, these increase to 1,1 and 3,4 million job years according to the scenarios Road ZERO and Transport BIO, respectively. These include jobs in the project planning, construction, equipment manufacturing and related services. Employment in operation and maintenance of advanced biofuel production plants and feedstock supply are estimated to be around 56 thousand FTE in Road ZERO and 251 thousand FTE in Transport BIO in 2030. This increases to 350 thousand and 1016 thousand FTE in 2050 according to Road ZERO and Transport BIO, respectively. Employments related to feedstock supply comprise more than 70% of the total FTEs. Employment estimates for the Transport BIO scenario are higher than for the Road ZERO scenario because of higher levels of advanced biofuel capacity and production. In both scenarios, employment is highest from the thermochemical routes such as bio dimethyl ether (Bio-DME), bio Fischer Tropsch (bio-FT) process, hydrothermal liquefaction (HTL) and pyrolysis. The biochemical routes, advanced bioethanol and alcohol-to-fuels, are the second largest contributor to employment.

Comparisons to other studies show that there is a significant range in the estimates for employment effects, due to (amongst other things) scope, modelling approach and input assumptions. Differences in formats for reporting employment estimates also complicates comparison to other studies.

[3] A job year refers to 1 FTE job for the duration of 1 year. It is used here as an indicator of total employment over a period.

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# Contents



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# 1. Introduction

The overarching goal of the ADVANCEFUEL project is to facilitate the market roll-out of advanced liquid biofuels (produced from lignocellulosic feedstocks) and other liquid renewable fuels (further jointly addressed as "RESfuels") in the transportation sector in 2030, with an outlook to 2050. To contribute to this goal and as part of this project a scenario-based analysis has been conducted. These scenarios and the results are presented in detail in Uslu *et al.* (2020) "*D6.2 Role of renewable fuels in transport sector up to 2050*".

This report is complementary to D6.2. In this report the total system costs of the scenarios and the possible employment impacts are presented. Chapter 2 recaps the main assumptions behind the scenario analysis, introduces the modelling tool and presents some of the results. In chapter 3, the scenario modelling related total system costs are presented. This is followed by chapter 4, where the possible employment effects of the two scenarios are illustrated. This chapter starts with a comprehensive presentation of the methodology, followed by the employment analysis results. Chapter 5 presents the main conclusion of the preceding two chapters.

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# 2. Scenario modelling

The possible future role of RESfuels, including the role of advanced biofuels in relation to the possible developments in other renewable fuel options are analysed in *D6.2 Role of renewable fuels in transport sector up to 2050*, through scenario modelling. Two different scenarios are modelled for this purpose. These scenarios are based on the uncertainties related to the future developments regarding zero emission vehicles (ZEVs), the technology developments in the time frame 2020-2050, and the availability of renewable electricity supply.

Figure 1 illustrates the scenario construction based on the uncertainties stated above.

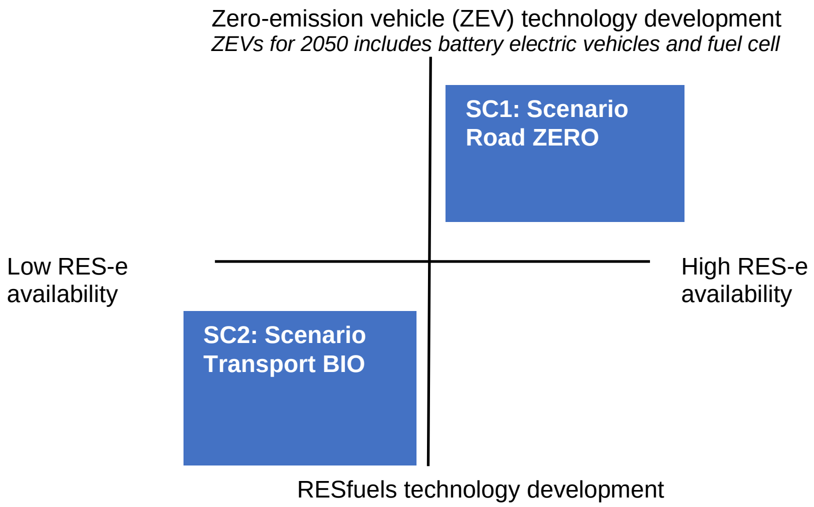


*Figure 1. Scenario construction based on the above stated uncertainties*

Scenario Road ZERO assumes a Technology breakthrough in zero-emission vehicles (ZEVs) such as electric vehicles with batteries (BEVs), and fuel cell vehicles (FCVs). These zero emission vehicles play the major role to meet the climate objectives in the transport sector through higher efficiency and reduced costs over time. The availability and price of renewable electricity also play key role in the future deployment of electric vehicles. Therefore, a relatively low renewable electricity price is assumed in this scenario – 45€/MWh in 2030, reducing to 40 €/MWh in 2050. In this scenario there is limited technological developments in biofuel conversion technologies in terms of efficiency and cost-competitiveness for commercialization that result in a relatively slow implementation of advanced biofuels in the transport sector. In scenario Transport BIO there is a strong growth of biofuels and a breakthrough of advanced biofuels in the transport sector. In this scenario diffusion of electric vehicles and thus, electrification in vehicles is slower.

More details of the scenarios and the modelling results regarding the contribution of renewable fuels to reduce GHG emissions are presented in Uslu *et al.* (2020) "*D6.2 Role of renewable fuels in transport sector up to 2050*". Main scenario assumptions are presented in Table 1.

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*Table 1. Main assumptions regarding model input data as implemented in D6.2 (Uslu et al. 2020)*

<table>
<tr><th></th><th>Reference</th><th>Scenario Road ZERO</th><th>Scenario Transport BIO</th></tr>
<tr><td>Electricity price</td><td>65 €/MWh in 2030<br>60 €/MWh in 2050</td><td>45 €/MWh in 2030<br>40 €/MWh in 2050</td><td>65 €/MWh in 2030<br>60 €/MWh in 2050</td></tr>
<tr><td>Bioelectricity demand</td><td colspan="3">1161 PJ in 2030<br>964 PJ in 2050</td></tr>
<tr><td>Bioheat demand</td><td colspan="3">2694 PJ 2030<br>2412 PJ in 2050</td></tr>
<tr><td>Assumptions regarding 1st gen biofuels</td><td colspan="3">• Palm oil import for energy purposes is set to zero in 2030 and 2050.<br>• Biodiesel import potentials of 1st generation is kept the same as 2020 potential in 2030 and 2050 (total 132 PJ)<br>• Cap on 1st generation and UCO also beyond 2030</td></tr>
<tr><td>Domestic biomass supply</td><td>• Lignocellulosic biomass supply from Biomass Policies & S2Biom study<br>• Other non-ligno. biomass supply from Biomass Policies</td><td>25% reduced reference potential for forestry (roundwood);</td><td>Same as reference</td></tr>
<tr><td>Biomass import</td><td>• BioTrade2020 project BASELINE Import for wood pellets and agricultural residues<br>• Biomass Policies for import of biofuels<br>• Spöttle et al (2013) for import of UCO</td><td>• BioTrade2020 project BASELINE Import for wood pellets and agricultural residues<br>• Biomass Policies for import of biofuels<br>• Spöttle et al (2013) for import of UCO</td><td>• BioTrade2020 High import scenario for wood pellets and agricultural residues<br>• Biomass Policies for import of biofuels<br>• Spöttle et al (2013) for import of UCO</td></tr>
<tr><td>Assumptions regarding electric vehicles (EVs)</td><td>• Same as Transport BIO</td><td colspan="2">• EV capital expenditures are lower in Road ZERO compared to Transport BIO</td></tr>
<tr><td>Power to liquid options</td><td colspan="3">• These value chains consider $CO_2$ via direct air capture</td></tr>
<tr><td>Multipliers</td><td colspan="3">No multipliers beyond 2030</td></tr>
<tr><td>Biofuel blending</td><td colspan="3">B7 in 2030 and 2050<br>E10 applied to all MSs by 2025<br>By 2030, E20 introduced in all MSs</td></tr>
<tr><td>Introduction of $CO_2$ targets to the model</td><td colspan="3">In the model one common $CO_2$ target for road, rail, inland navigation and aviation for the years 2030 and 2050 have been specified and interpolation of these $CO_2$ targets for the intermediate years has been applied. For the maritime sector similarly $CO_2$ targets have been applied for the years 2030 and 2050 and interpolation for intermediate years. $CO_2$ emission calculations are based on the tank-to-wheel emissions. This means that emissions related to mining, transport of the fuel, land use change emissions for biomass and emissions of the grey part of electricity are excluded.</td></tr>
</table>

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## 2.1. RESolve-Biomass model

The TNO model "RESolve-Biomass" is employed to conduct the scenario analysis. RESolve-Biomass determines the least-cost configuration of the entire biobased production chain. This is based on the demand projections for biofuels, bioelectricity, bioheat and biobased products. It takes into account the cost-supply curves of various biomass feedstocks and conversion technologies (including technological progress), under several possible conditions and constraints. The optimization is myopic, starting from base-year 2005, up to 2050. Each year is optimized individually, but years are linked since a vintage approach is applied for biomass conversion technologies. An overview of the current model characteristics is provided in Figure 2.

**RESolve-Biomass Model**

| System component | Exogenous model components (input) | Endogenous model components (output) |
|---|---|---|
| **Biomass supply** | • Domestic and imported cost supply potential<br>• Key constrain: feedstock mobilization rate | • Feedstock portfolio deployed |
| **Energy system** | • Conversion technologies<br>  • Techno-economic data<br>  • Technological learning and introduction year<br>• Road transport<br>  • Vehicle fleet techno-economic data<br>• Additional infrastructure costs (compared to existing conventional infra)<br>• Key constraint: Technology deployment rate | • Technology portfolio deployed (for heating, electricity, chemical sector, maritime & aviation<br>• Road transport vehicle fleet portfolio<br>• System costs<br>• Final energy demand in road transport<br>• RESfuel portfolio deployed in road transport |
| **Biomass demand Renewable electricity demand from transport sector** | • Energy demand for<br>  • bio-based electricity, heat, chemical sector, maritime and aviation<br>• Passenger-kilometers for<br>  • public and private transport)<br>• Tons-kilometers for freight transport<br>• Regulatory framework (targets, caps and multipliers) | • Biomass use in electricity heat, electricity, chemical sector and transport sector<br>• Renewable fuel use in road transport, maritime and aviation |

*updated from de Jong 2018.

*Figure 2. Exogenous and endogenous model components of RESolve-Biomass*

As Figure 2 shows, demand for bio-based electricity, heat, chemical sector is an exogenous component of RESolve-Biomass. Demand for transport fuels for maritime and aviation sectors is also exogenously provided in *final energy*.

For the purpose of this project, the RESolve-Biomass model is expanded for road transport so that the competition of different types of vehicles meeting different service demands in the transport sector can be mimicked. In this new version, final energy demand for biofuels in the road transport sector becomes an endogenous parameter optimized by the model. In contrast, end-use demand driving this final energy consumption is exogenous, provided either in passenger-kilometers (for public and private transport) or in ton-kilometers (for freight transport).

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Figure 3 shows the expansion in RESolve-Biomass (lined in red) within the complete scheme considered in the model. Worth mentioning is that for biofuels there is an entire chain from raw biomass to distribution (filling station), but for the other energy carriers (fossil fuels, electricity, e-fuels and hydrogen), they enter the system via External Fuels nodes. This means that the all cost component of these energy carriers before distribution are aggregated in the External fuel nodes. For example for fossil diesel the costs for refining are not explicitly included. The price is derived from the oil price assumed and multiplication derived from an historical time series. Similarly the price of e-fuels is derived from techno-economic parameters directly relating the price of electricity to the price of e-fuels.

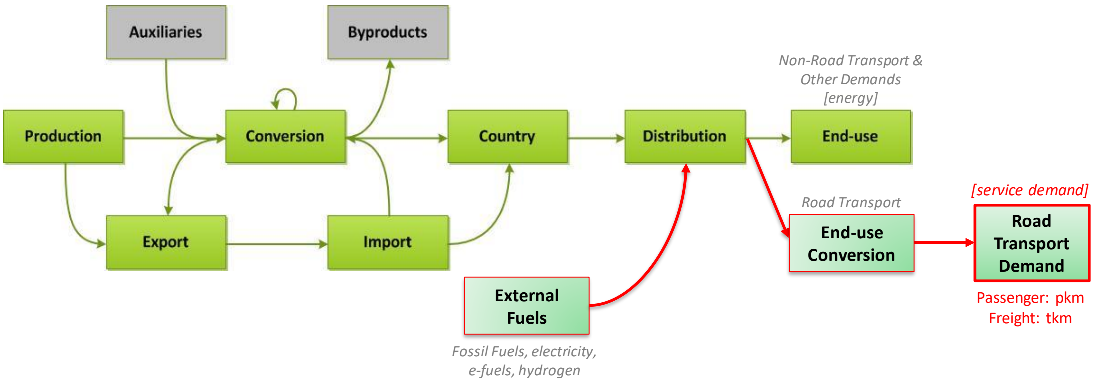


*Figure 3. Diagram with energy flows considered in RESolve-Biomass*

## 2.2. Main modelling results regarding the fuel mix

Figure 4 summarizes the modelling results regarding the transport sector fuel mix to meet the Green House Gas (GHG) emission reduction targets according to the two scenarios. The transport sector refers to road and rail transport, inland shipping, aviation with international extra-EU flights and EU international maritime transport. According to the results, fossil fuels continue to dominate the total fuel mix in transport sector. The role of both direct electrification of road transport via electric vehicles (EVs) and biofuels are very limited in 2030. In 2050, next to the direct electrification and biofuels, power-to-fuel options, including $H_2$ and e-fuels[4], appear to be necessary to help reducing GHG emissions in transport sector. According to the modelling, around 95% of the vehicle fleet in road transport consist of electric vehicles, whereas this is around 85% in Transport BIO in 2050. The low electricity prices assumed in Road ZERO results in higher deployment of e-fuel to be used mainly in aviation, maritime and also heavy-duty vehicles (HDVs). Biofuels in this scenario are also mainly supplied to maritime and aviation sectors as the road transport mainly consists of EVs. In Transport BIO, biofuels play the major role in reducing $CO_2$ emissions in the transport sector. Around 65% of the biofuels are supplied to the road transport in 2050, according to Transport BIO. The total biofuels amount around 4700 PJ in 2050. In both scenarios, more than 70% of the total biofuels consist of advanced biofuels produced from lignocellulosic feedstocks. More details regarding the scenario modelling results can be found in Uslu *et al.* (2020) "*D6.2 Role of renewable fuels in transport sector up to 2050*".

[4] E-fuels: synthetic fuels, created using $CO_2$ and $H_2$.

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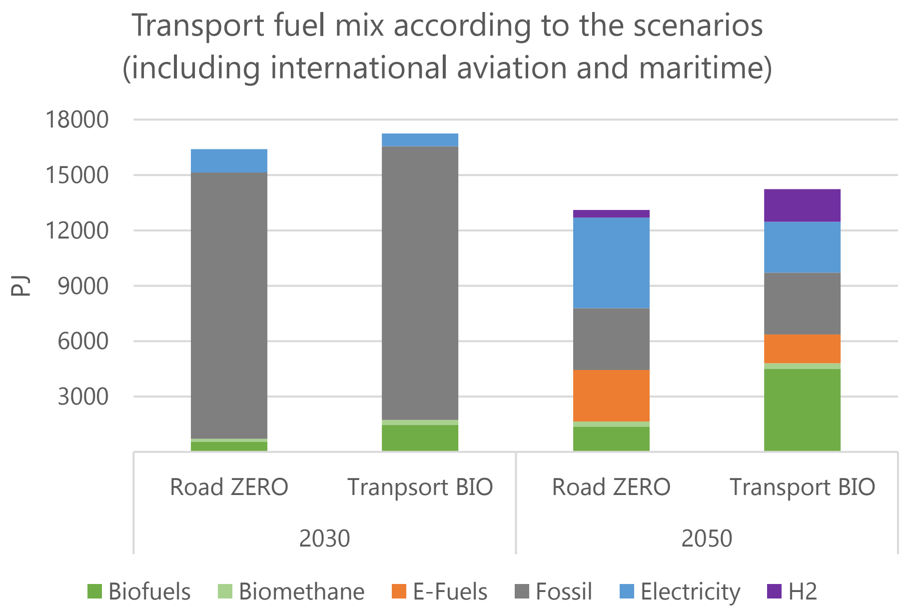


*Figure 4. Fuel mix according to the scenarios Road ZERO and Transport BIO in 2030 and 2050.*

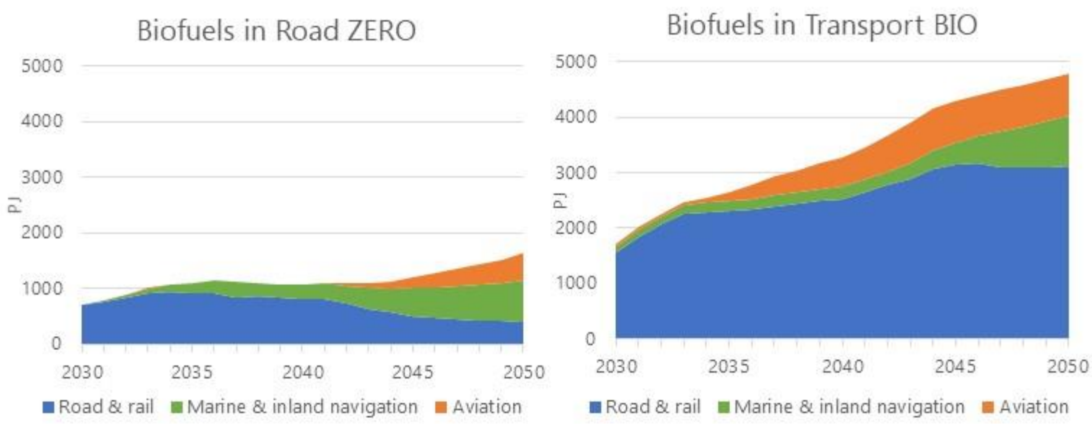


*Figure 5. Contribution of biofuels to different segments of the transport sector.*

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# 3. Total system costs

In this chapter total system cost of the two main scenarios introduced in Chapter 2 are presented. RESolve-Biomass minimizes the total cost of the bio energy, biomaterials and transport system. It also gives annual cost for this system. Since in this project the focus is on transport, the cost related to power and heat generation from biomass resources and also biomaterials production are not presented in this section. The total system cost considered in this section refers to the costs related to transport sector and includes fuel supply costs, capital expenditures (CAPEX) and operation expenditures (OPEX) of the related conversion technologies. The transport sector corresponds to road, rail, aviation, inland navigation and maritime. The additional costs needed for the engine adaptations or replacement of existing internal combusting engines are also included to the total system costs. Important to mention is that the total system costs in this report are annual cost and all costs are expressed in Billion €$_{2018}$. The total system cost should be considered from a macro-economic perspective, therefore taxes, levies, subsidies, etc. are excluded.

Below equation summarises the total system cost:

Total System Cost = ΔEngine Cost + Energy Carrier Cost + Energy Carrier Conversion Cost + Transportation Cost + ΔDistribution Cost

***ΔEngine Cost*:** Represents the difference in engine cost[5] as compared to the fossil reference (i.e. the adaptation costs of existing engines, if for instance Bio-DME is to be used). Next to that the additional costs are needed when existing vehicles are to be replaced with electric vehicles (EVs) or fuel cell electric vehicles (FCEVs). These costs are part of this delta engine costs. Differences in engine cost are used, to present the additional costs needed to the already existing car fleet and to fine tune to be able to adopt those technologies. Assumed techno-economic characteristics can be found in the Annex of Uslu *et al.* (2020).

***Energy Carrier Cost:*** This relates to the total cost of fossil fuels, electricity, e-fuels and hydrogen energy carriers, since RESolve-Biomass does not include the entire production chain for these carriers, but covers their aggregated cost via External Fuel nodes, see section 2.1. For biofuels, only the cost of the raw biomass are covered under this cost component. The cost of biofuels that are imported from outside the EU, are fully assigned to this cost component.

***Energy Carrier Conversion:*** This step includes costs related to the conversion of raw biomass to biofuels. It includes annualized investment costs based on the technical lifetime of the conversion processes and the operational and maintenance cost. A discount rate of 7% has been used for the annualized investment costs.

***Transportation Cost:*** This includes the cost for transporting (including transhipment) biomass commodities: raw biomass, intermediate products and biofuels. This concerns national and international transport (including extra EU). This cost component is only considered for biofuels.

***Δ Distribution Cost:*** represents the additional cost that are needed in the distribution chain (from factory to fuel station) as compared to fossil reference fuels, such as Bio-DME, which is assumed to have similar distribution costs as LPG. These are higher than the distribution cost

[5] More specifically, changes in drive train cost, including both annualized investment costs and operational and maintenance costs

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for fossil diesel. Another clear example is the charging of electrical vehicles: distribution cost for electricity and charging of vehicles (excluding the wholesale electricity price), is much more expensive than the distribution of liquid fuels.

The total system costs, decomposed by type of energy carrier, is presented in Figure 6 for the Road ZERO and Transport BIO scenarios for 2030 and 2050. It is necessary to remind that the two scenarios are very different from each other regarding several assumptions, including the electricity prices, costs of electric vehicles and also the CAPEX and OPEX of different advanced biofuel conversion technologies. Therefore, it does not mean that the scenario with the lower total system cost is 'preferred' over the other scenario.

The analysis shows that the total system costs of the renewable energy supply options in 2050 comprise around 2-3,5% of the EU28 GDP[6].The total system costs of Transport BIO appear higher than Road ZERO in 2030 and 2050. One of the main reasons relates to the direct electrification. Even though the direct electrification of road transport is lower in Transport BIO, the related total system costs are higher. In Road ZERO, around 70% of the road transport fuel mix is directly electrified in 2050. In Transport BIO, this is 35%. These high costs relate to the scenario assumptions. First, the electricity prices are assumed to be much higher in Transport BIO (reaching 60 €/MWh in Transport BIO and 40 €/MWh in Road ZERO by 2050, see Table 1). Second, the CAPEX of electric vehicles are considered to be lower in Road ZERO (i.e. BEVs become around 20% cheaper compared to Transport BIO). Another reason behind the higher total costs of Transport BIO scenario is the high deployment of advanced biofuels.

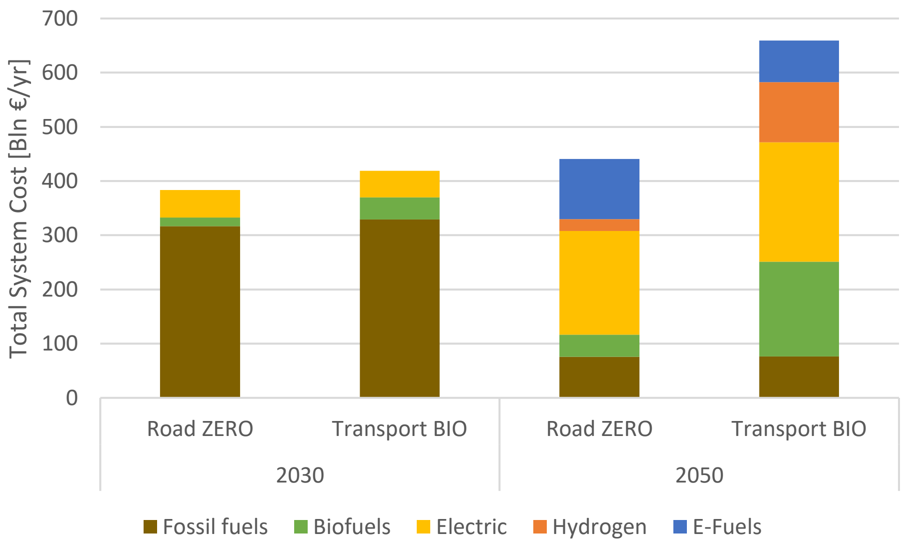


*Figure 6. Total system cost of the transport sector[7] split by type of energy carrier. Cost are given in Bln € per year.*

According to the modelling results, the contribution of fossil fuels will continue to be dominant in 2030, in both Road ZERO and Transport BIO. They become much smaller in 2050. Direct electrification of the transport sector makes the largest contribution to the total system costs in 2050. This relates to the very high deployment of electrical vehicles (EVs) in both scenarios.

[6] In 2019, the EU28 GDP is stated as 16452 billion €.

[7] Road, rail, aviation, inland navigation and maritime.

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A further decomposition of the total system cost of the non-fossil part of the transport sector is given in sections 3.1 and 3.2.

## 3.1. Total systems costs of direct electrification, $H_2$ and e-fuels

The total system costs related to the direct electrification for both scenario's in 2030 are given in Figure 7. From this graph it is immediately clear that the additional costs for the vehicles (Δ Engine) represent the largest contribution to the total costs related to direct electrification. In the transport BIO scenario, the contribution of electrical vehicles to the total transport activity is only 55-56% of the total activity of electrical vehicles in Road ZERO in 2030. However, the total system cost of electrical vehicles (including the electricity price) in absolute terms is only slightly higher in Road ZERO (2,5%) than in Transport BIO. Again, this is very much related to the scenario assumption: much higher electricity prices and higher cost for electrical vehicles in Transport BIO.

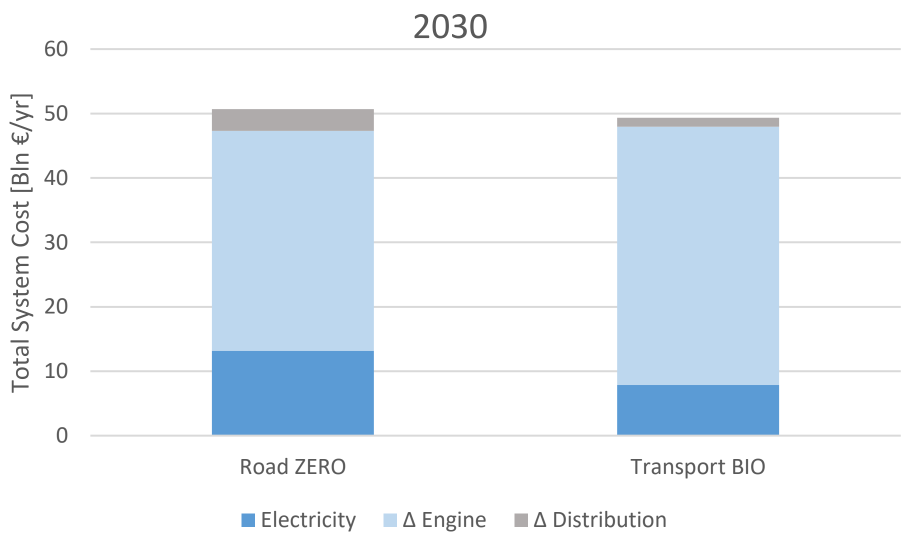


*Figure 7. Total system cost of the direct electrification part of the transport sector split in subcomponents in 2030. Direct electrification only corresponds to road transport.*

In 2050, around 95% of the road transport vehicle fleet consists of battery electric vehicles (BEVs) in Road ZERO and 85% in Transport BIO. The role of BEVs is lower in Transport BIO, but the total system cost is higher than in the Road ZERO scenario, see Figure 8. This indicates that the assumed cost for electrical vehicles and cost of electricity have a very large impact on the way emission reductions are achieved in the transport sector.

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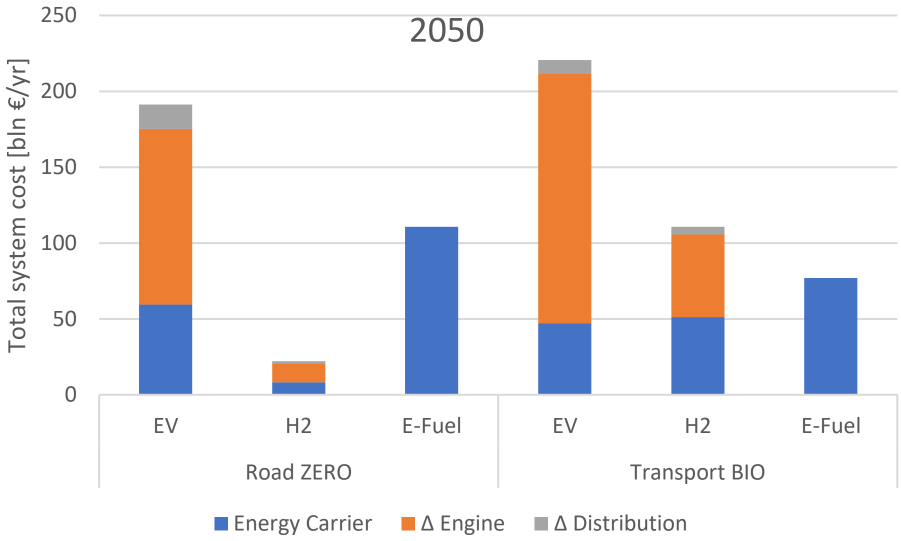


*Figure 8. Total system cost of the direct electrification, $H_2$ and e-fuels part of the transport sector split by type of energy carrier and subcomponents in 2050.*

## 3.2. Total systems costs of biofuels

In 2030, the total system cost of biofuels is dominated by feedstock costs, see Figure 9. The reason for this is that first generation and used cooking oil-based biofuels have a large share in the total amount of biofuels (64% and 43% for Road ZERO and Transport BIO, respectively). The cost of both types of biofuels can for a large fraction be attributed to feedstock cost.

In 2050 (see Figure 10), feedstock costs make up a less dominant portion of the total biofuel cost, although with 30% and 24% of the biofuel total system cost, the contribution remains large. In 2050 the share of advanced biofuels (incl. biomethane) has increased to 85% and 94% of the total biofuel market for Road ZERO and Transport BIO, respectively. This is reflected in the larger contribution of conversion cost to the total biofuel cost, since for advanced biofuels conversion make up a larger share of the total cost. The contribution of conversion costs to the total system costs is around 40% and 50% for Road ZERO and Transport BIO, respectively in 2050. Transportation cost of biomass commodities also makes up a larger share of the total cost in 2050 than in 2030. The reason is that biomass needs to be sourced more from remote locations, since a large fraction of the biomass potential is utilized. Since the markets of all EU countries needs to be served it simply means more transfer of intermediate products or biofuels.

Figure 11 indicates the total cost distribution in 2050 for Transport BIO. As can be seen, both feedstock, conversion and transportation cost, represent the bulk of the cost. Vehicle adaptation cost and additional cost for distribution make up a small fraction.

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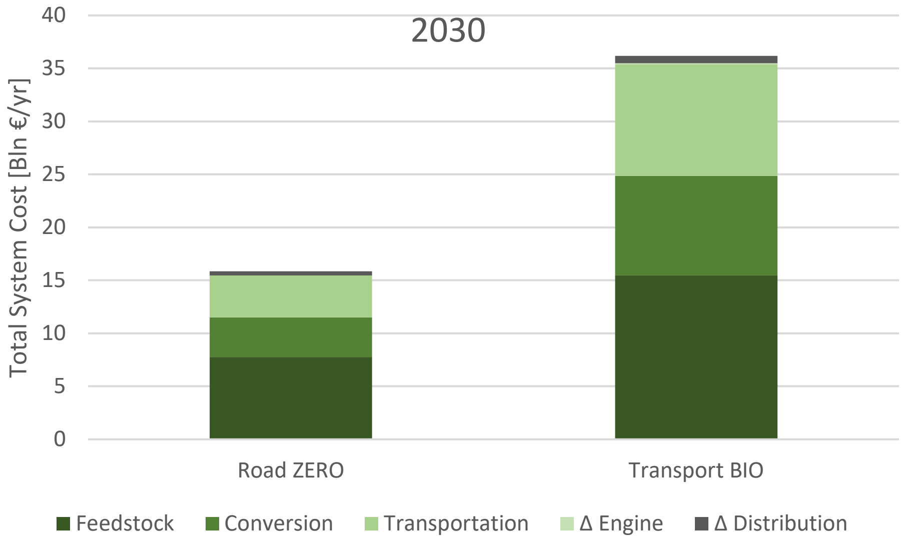


*Figure 9. Total system cost of the biofuel part of the transport sector in 2030.*

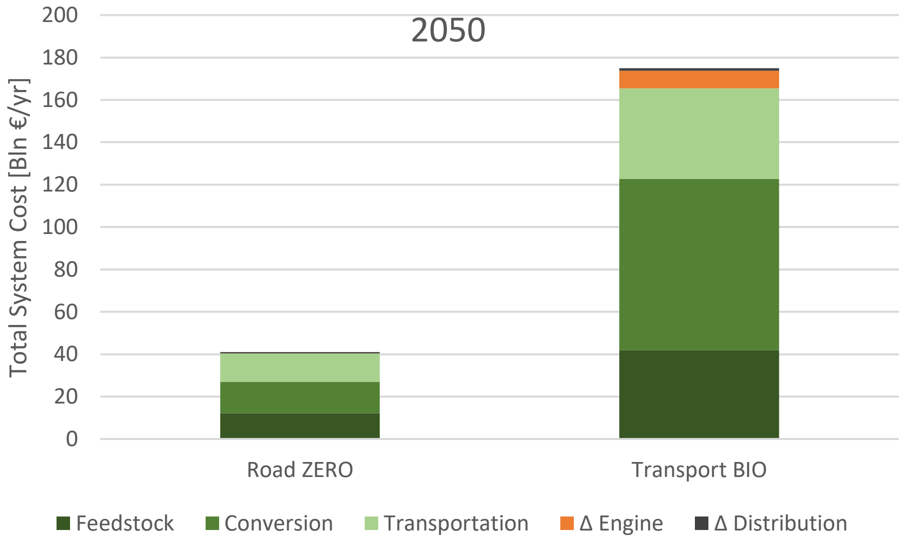


*Figure 10. Total system cost of the biofuel part of the transport sector in 2050.*

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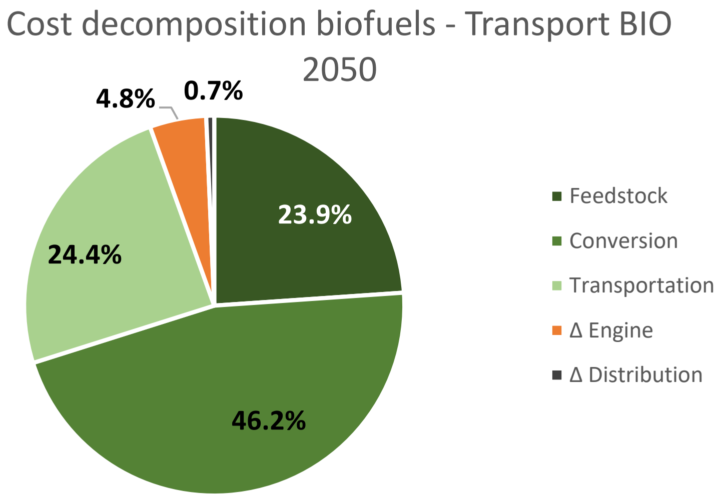


*Figure 11. Decomposition of the total system cost of the biofuel part of the transport sector for Transport BIO in 2050.*

## 3.3. Average system cost intensities

In Figure 12 the average energy system costs per GJ (renewable) fuel are presented. The average energy system costs of direct electrification and hydrogen are presented in Figure 13. The average energy system costs per GJ refers to the above introduced total energy system cost of different renewable fuel options divided by the total amount of each renewable fuel. Not surprisingly, the fuel cost of fossil fuels remains the lowest, as the total costs of fossil fuels do not include the external costs, including climate change effects, of these fuels. Biofuels are, on average, significantly cheaper than E-fuels. The reason why E-fuels still appear in Transport BIO is that almost all of the total biomass potentials are utilized in 2050. Before 2050 the mobilization of biomass is not fast enough to allow for more biofuel production (it takes time to be able to utilize the entire potential). In the Road ZERO scenario the use of E-fuels is almost solely for marine and in aviation. Biofuels do not play a major role in this scenario. This relates to the multi-product structure of refineries. Refineries produce biofuels suitable for road transport, aviation and also maritime. High electrification of road transport results in lower demand for biofuels produced for road transport. This makes the biorefineries less preferable in the modelling analysis. For example, a large fraction of the biofuel from pyrolysis biofuel processes is bio gasoline. Since all passenger cars shift almost completely towards electrification, there are no possibilities to use the bio gasoline and therefore pyrolysis biofuel processes become a non-preferred option according to the modelling analysis

Figure 13 illustrate the direct electrification related total system costs divided by total electrification for the two scenarios. As can be seen, direct electrification is much more attractive in Road ZERO than in Transport BIO: the cost difference between the two scenarios is very large. Even though the direct electrification total system cost is much higher than biofuels the model favours direct electrification. This relates to the fact that direct electrification has a much higher efficiency converted the 'energy carrier' to the wheels. In principle, a better indicator to compare the attractiveness among the five different renewable fuel supply options considered here, would be to compare the average cost per km. Unfortunately, that information is not possible to extract from the total system cost. The reason is that, except from road transport, distances are not used.

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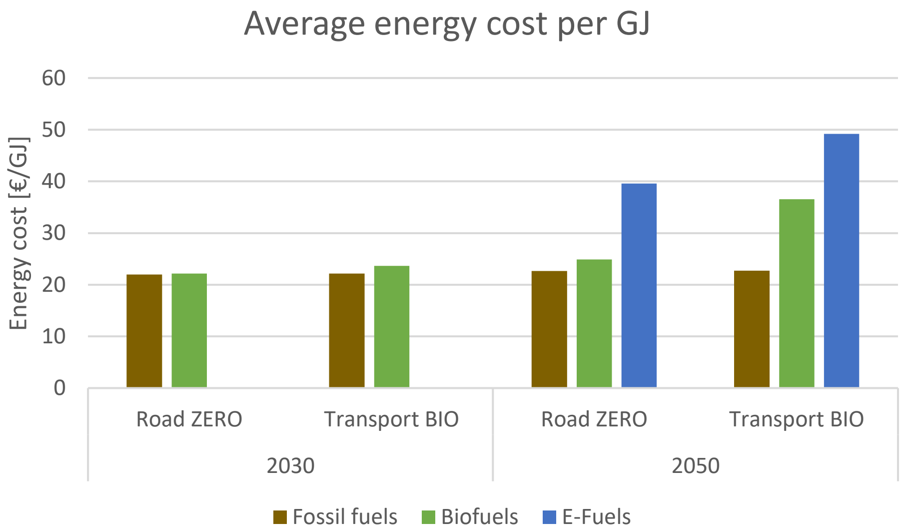


*Figure 12. Average transport energy cost for fuels [€/GJ] for both scenario's in 2030 and 2050*

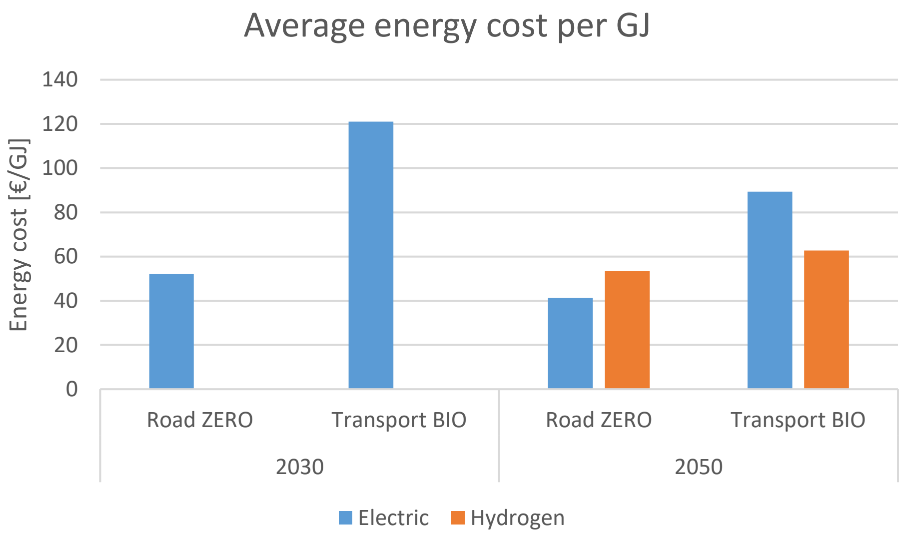


*Figure 13. Average transport energy cost [€/GJ] for direct electrification and hydrogen for both scenarios in 2030 and 2050.*

A presentation of the average biofuel cost split in components can be found in Figure 14. It is clear from this graph that the average cost of biofuels increases from 2030 to 2050, in particular for Transport BIO in 2050. This increase can mainly be attributed to a stronger shift towards advanced biofuels. Remarkably, the average cost of biofuels in 2050 is higher for Transport BIO than for Road ZERO, considering that the biofuel conversion CAPEX are higher in Road ZERO. The figures for the different cost components in 2050 are given in Table 2. The average biofuel system cost in Transport BIO are almost 50% higher than the biofuel system cost for Road ZERO in 2050. The difference in cost components can be explained as follows:

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- **Feedstock cost:** the difference in feedstock cost can be attributed to the fact that a much larger share of the biomass potential needs to be utilized in Transport BIO. This means that also more expensive parts of the biomass potentials are used. Note that this effect is larger than reflected in the relatively small difference given in Table 2, since imported biofuels are placed under this cost component and the use of biofuels based on used cooking oil (relatively high feedstock cost), have a relatively much larger role in Road ZERO.
- **Conversion cost:** this cost component causes the main cost difference between the two scenarios. The difference can be attributed to the large role that Bio-DME plays in the biofuel distribution in Transport BIO (almost 42% of the total biofuel volume in 2050). Bio-DME has a rather high conversion cost per GJ of output. It still appears as the largest biofuel, since the fuel efficiency of this value chain is relatively high, so it makes effective use of the limited amount of biomass. Additionally, it is assumed that Bio-DME can replace diesel (in contrast to many other processes) with some minor modifications to the diesel engines. Furthermore, in some conversion processes electricity plays an important role as input (in particular for alcohol-to-fuels and HTL), and the electricity price is significantly higher in Transport BIO. This is also reflected in the higher conversion cost.
- **Transportation:** the total contribution of transportation costs are high, but the difference between the two scenarios is modest. The difference between the two scenarios can be attributed to the larger fraction of the biomass potential that is utilized in Transport BIO. This means that more transportation is needed in Transport BIO.
- **Δ Engine:** this difference can be attributed to Bio-DME. As mentioned above Bio-DME has a very large market share in Transport BIO, however, to be able to use Bio-DME in trucks a more costly engine needs to be utilized.

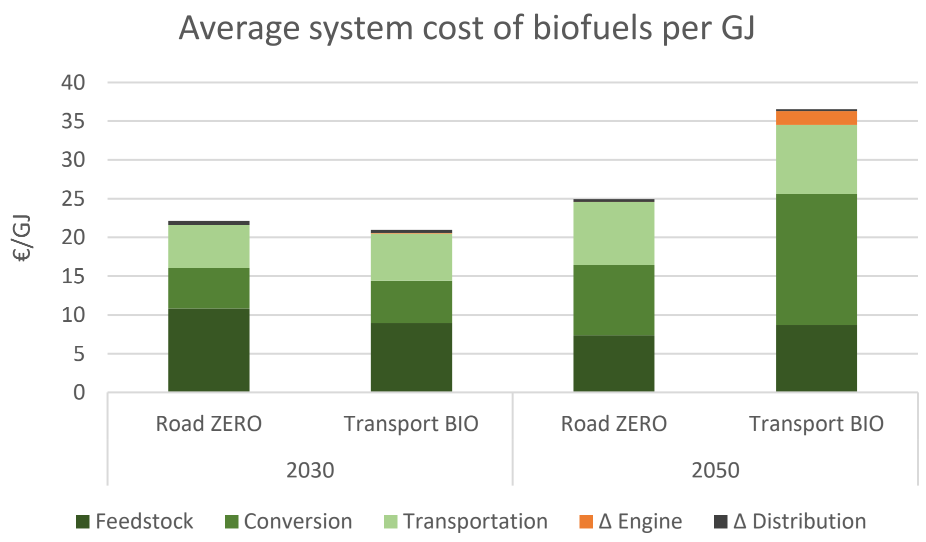


*Figure 14. Average biofuel cost [€/GJ] for both scenarios in 2030 and 2050.*

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*Table 2. Average total system cost of biofuels [€/GJ] for both scenarios in 2050*

| | Road ZERO | Transport BIO |
|---|---|---|
| Feedstock | 7 | 9 |
| Conversion | 9 | 17 |
| Transportation | 8 | 9 |
| Δ Engine | 0 | 2 |
| Δ Distribution | <1 | <1 |
| Total | 25 | 37 |

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# 4. Employment assessment

This chapter details the estimation of employment impacts of the two scenarios discussed in Chapter 2. The RESolve Biomass modelling results have been the main basis for this assessment. A modelling approach is used, the methodology of which is discussed in Section 4.1. The assessment results are presented in Section 4.2 and compared to other employment estimates for biofuel production technologies and scenarios in Section 4.3. Lastly, key inadequacies of the modelling approach are discussed in Section 4.4.

## 4.1. Methodology

The employment effects of ADVANCEFUEL scenarios are calculated based on the methodology developed by the Energy research Centre of the Netherlands (ECN)[8] for the EurObserv'ER project.[9] For the EurObserv'ER project gross employment effects of renewable energy deployment in Europe are estimated. While the EurObserv'ER project covers a broad range of topics, when referring to the project in this chapter we refer exclusively to the employment analysis.

The methodology uses a 'follow-the-money' approach, in which revenue streams generated from investment and exploitation of advanced fuel production capacity are attributed to different economic sectors. The employment effects are estimated through the share of revenues that are used to compensate employees in these sectors, based on economic statistics for these sectors. All calculations are performed at EU member state level and it is assumed that most activities use local workers. Only for equipment and biomass feedstocks it is assumed that member states can trade with one another and with non-EU countries. The employment conversion module, which estimates employment effects based on revenues, includes a correction factor based on differences in labour costs per member state (ECN, 2017). An overview of the methodology can be found in *Figure 15*.

For the ADVANCEFUEL project the methodology has been applied to a model that only includes biofuel technologies. Renewable electricity and PtX options are not included. The assessment considers direct employment in the construction and operation of biofuel production plants as well as indirect employment in feedstock supply, equipment manufacturing, transport and storage, etcetera. Induced employment effects, the broader impact on the economy due to reinvestment of worker's wages, are not considered. All employment estimates refer to *gross* employment. Displacements of employment in the fossil fuel sector, agricultural and forestry sectors, or any other sector are not considered.

[8] As of April 2018 ECN and TNO merged. TNO is currently member of the EurObserv'ER consortium.

[9] For the latest results see the 19th annual overview barometer on the EurObserv'ER project website: https://www.eurobserv-er.org/19th-annual-overview-barometer/. See ECN (2017) for an overview of the methodology used in the EurObserv'ER project.

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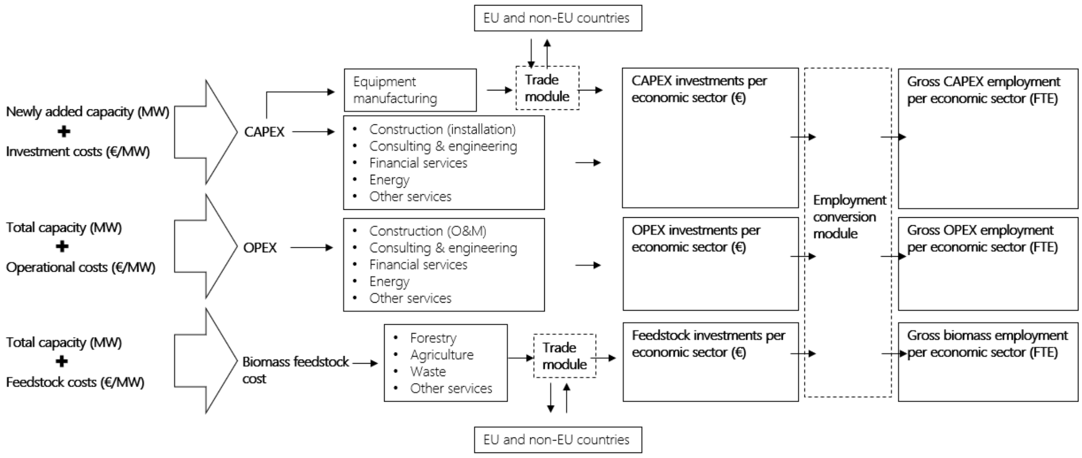


*Figure 15. Overview methodology employment analysis (adapted from ECN (2017))*

### 4.1.1. Main assumptions

For the employment analysis, the amount of biofuel production routes in the model was increased from six to 16 (see comparison in Table 3). Each production route makes use of either agricultural, forestry or organic waste feedstocks, which are processed separately in the model. Installed capacities, cost data, and technical data (load hours and efficiencies) were obtained from the deliverable “D6.2 Role of renewable fuels in transport up to 2050" of the ADVANCEFUEL project. 2018 is used as a reference year so results can be compared to the latest estimates available from the EurObserv’ER project (EurObserv’ER 2020). The methodology for the EurObserv’ER project was developed for year on year monitoring of employment effects, which is not ideal for assessment of employment effects over periods of time (see Section 4.4 for more detail on model inadequacies for the ADVANCEFUEL employment assessment). To best assess employment effects over a period of time, taking into account the model shortcomings, the choice was made to estimate cumulative effects of CAPEX-related activity (which reflect temporary jobs such as manufacturing and construction) and compare estimates of employment effects of O&M and feedstock supply activities in key years (which reflects changes in permanent employment related to operational plants). Since CAPEX related employment estimates are cumulative and O&M and feedstock supply related employment estimates are yearly, no combined total estimate is presented in the results.

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*Table 3. Comparison biofuel production routes included in EurObserv'ER and ADVANCEFUEL*

| EurObserv'ER | ADVANCEFUEL |
|---|---|
| Biodiesel (conventional*) | Alcohol-to-jet fuel (ATJ) |
| Biodiesel (from HVO) | Bio-DME |
| Bioethanol (conventional) | Bio-FT |
| Bioethanol (advanced**) | Biodiesel (conventional*) |
| Biomethane (conventional*) | Biodiesel (from HVO) |
| Biomethane (advanced**) | Bioethanol (conventional*) |
| | Bioethanol (advanced**) |
| | Biomethane (gasification) |
| | Biomethane (digestion) |
| | HVO (conventional*) |
| | HVO (UCO) |
| | HTL |
| | Pyrolysis + upgrading |
| | Pyrolysis co-processing |

* Conventional refers to biofuels produced from food and feed crop-based biomass feedstocks.

** Advanced refers to biofuels produced from lignocellulosic feedstocks.

Figure 16 shows the total installed capacity in 2018 according to the model projections. According to the modelling results the total installed production capacity is estimated at 12.7 GW, with conventional biofuels and biodiesel from hydrotreated vegetable oil (HVO) accounting for 84% of the total installed capacity. The capacity increases to over 16 GW in 2030 in the Road ZERO scenario, with a decrease in biodiesel from HVO capacity and a larger role for biomethane from anaerobic digestion (up to 35% of installed capacity). In 2050, the installed capacity in the Road ZERO scenario increases to almost 61 GW with large roles for biochemical production routes (advanced bioethanol and alcohol-to-jet fuel) (26%) and thermochemical production routes that include bio-dimethyl ether (DME), bio-Fischer-Tropsch, hydrothermal liquefaction (HTL), and pyrolysis routes, accounting for around 50% of installed capacity. In the Transport BIO scenario the installed capacity increases to 44 GW in 2030 and up to almost 191 GW in 2050, with large roles for bioethanol and alcohol-to-jet fuel (19% of installed capacity in 2030 and 33% in 2050), and thermochemical production routes (40% of installed capacity in 2030 and 58% in 2050).

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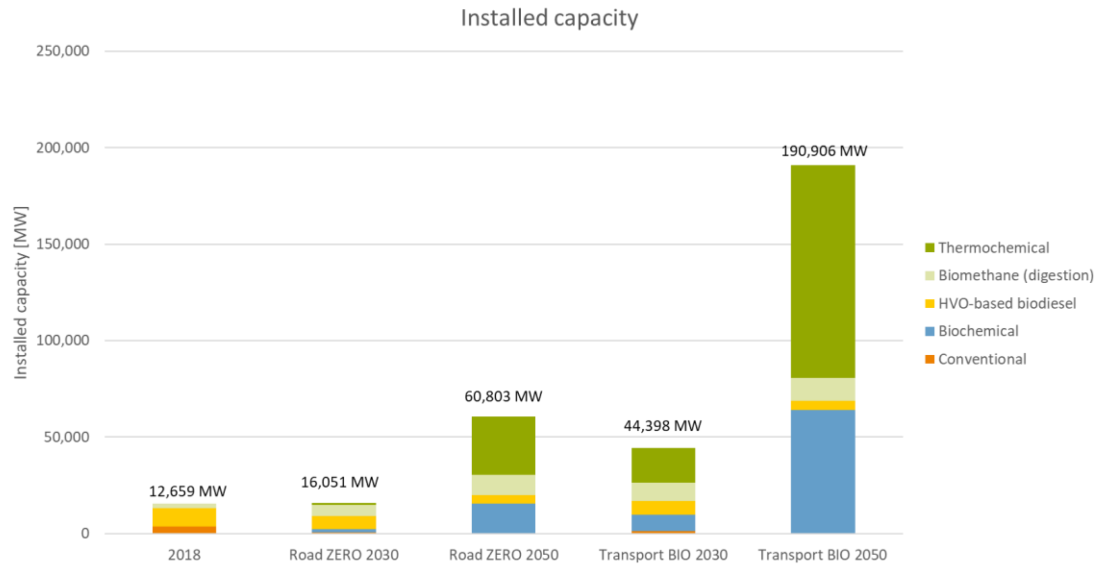


*Figure 16. Installed production capacity in 2018 and in 2030 and 2050 in the Road ZERO and Transport BIO scenarios (MW output)*

While the investment and O&M cost data are different in the Road ZERO and the Transport BIO scenarios, they are assumed identical in both scenarios for the employment analysis, in order not to mix up different modelling effects. There is a decrease in costs over time though for some technologies, due to e.g. learning effects. With the follow-the-money approach higher costs automatically result in higher employment estimates if economic statistics (i.e. % of investment spent on labour, average salaries, etc. that influence number of jobs per € spent) are not adjusted. While higher investment or O&M costs can be caused by an increase in the amount of labour required, this will not always be the case. As it is very challenging to forecast changes in economic statistics over longer time horizons, economic statistics are assumed to remain unchanged throughout the years in this analysis. To avoid that higher costs lead to higher employment estimates, costs are assumed similar for both scenarios. With this assumption, differences in investment-related employment and O&M-related employment between scenarios are only caused by differences in installed capacity (both type and quantity, per member state). The investment and O&M costs of the Transport BIO scenario are used, as these are the lower cost estimates of the two scenarios.

In Annex I, an overview of the investment and O&M cost data can be found in Table 10 and the assumptions regarding the load hours and efficiencies per production route can be found in Table 11.

The allocation of revenues to economic sectors is based on a variety of sources. Equipment manufacturing is split further, as equipment trade depends on equipment type. Table 14The equipment trade module is based on Eurostat production and trade data (ECN, 2017). Since the Eurostat production and trade statistics are reported for a limited amount of equipment types, categories do not always perfectly fit for the production routes. Similarly, O&M costs are assigned to economic sectors. An overview of the CAPEX, equipment manufacturing split used per production route and the OPEX split can be found in Table 13, Table 14 and Table 15 in Annex I .

A number of steps are required for the allocation of expenditure on biomass feedstocks to economic sectors. Six types of feedstocks are included in the model: solid wood, feedstocks

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suitable for anaerobic digestion, like manure, oily crops suitable for biodiesel production, starch and sugar crops for bioethanol, municipal solid waste (MSW) and used cooking oil (UCO) and animal fats for HVO. The feedstocks are linked to economic sectors: solid wood is considered a forestry product, wet biomass, oily crops, and starch and sugar crops are considered agricultural products and MSW and the feedstocks for HVO are considered as waste products. An overview of what feedstocks are used by each technology type can be found in Table 4. All production routes use one of these six feedstock categories, with the exception of alcohol-to-jet fuel, which uses ethanol as feedstock. It is, therefore, assumed that alcohol-to-jet fuel does not have a direct employment impact from feedstock supply.

Expenditures on feedstocks are determined based on the average feedstock costs, which differ per production route. Similar to increases in investment and O&M costs, increases in feedstock costs would be reflected in increased employment estimates. This is not necessarily realistic as price inflations can be caused by the different market mechanisms , including the variations in supply and demand. To avoid this, a single set of biomass feedstock cost assumptions is used for both scenarios and for all years (see Table 5).

*Table 4. Type of biomass feedstock used per production route*

| Production technology | Solid wood | Wet biomass feedstocks | Oily crops | Starch and sugar crops | MSW | UCO |
|---|---|---|---|---|---|---|
| ATJ[10] | | | | | | |
| Bio-DME | X | | | | | |
| Bio-FT | X | | | | | |
| Biodiesel (conventional) | | | X | | | |
| Biodiesel (HVO) | | | | | | X |
| Bioethanol (conventional) | | | | X | | |
| Bioethanol (advanced - wood) | X | | | | | |
| Bioethanol (advanced - straw) | | X | | | | |
| Biomethane (gasification-wood) | X | | | | | |
| Biomethane (digestion-wet biomass) | | X | | | | |
| HVO/HEFA (conventional) | | | X | | | |
| HVO/HEFA (UCO) | | | | | | X |
| HTL | X | | | | | |
| Pyrolysis + upgrading | X | | | | | |
| Pyrolysis co-processing | X | | | | | |

[10] ATJ uses ethanol as feedstock and therefore only has an indirect employment effect through biomass feedstock supply for ethanol production.

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*Table 5. Biomass feedstock cost per production route and scenario*

| Production route | Feedstock cost (€/MWh) |
|---|---|
| ATJ | - |
| Bio-DME | 22.8 |
| Bio-FT | 22.3 |
| Biodiesel (conventional) | 68.8 |
| Biodiesel (HVO) | 54.4 |
| Bioethanol (conventional) | 56.7 |
| Bioethanol (advanced - wood) | 20.9 |
| Bioethanol (advanced - straw) | 7.9 |
| Biomethane (gasification) | 20.9 |
| Biomethane (digestion)[11] | 0 |
| HVO (conventional) | 68.8 |
| HVO (UCO) | 54.4 |
| HTL | 20.9 |
| Pyrolysis + upgrading | 22.5 |
| Pyrolysis co-processing | 22.5 |

The feedstock trade data from the EurObserv'ER project has been updated with modelling projections of feedstock imports from outside of the EU (see Table 6). Domestic production levels per member states and trade between member states is assumed not to change compared to the 2018 data from the EurObserv'ER project (based on Eurostat production and trade data).

*Table 6. Share of imported feedstocks in total consumption.*

| Production route | 2018 | Road ZERO | | Transport BIO | |
|---|---|---|---|---|---|
| | | 2030 | 2050 | 2030 | 2050 |
| Wood (pellets and chips) | 2.0% | 0.2% | 1.4% | 3.0% | 8.0% |
| Straw | 0.0% | 0.0% | 1.3% | 0.6% | 11.3% |
| Oil-bearing crops | 31.2% | 0.5% | 0.0% | 3.7% | 0.0% |
| Ethanol crops (food and feed) | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| MSW | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| UCO | 62.2% | 87.4% | 83.6% | 73.3% | 61.8% |

Finally, the equipment trade and employment modules are used as in the EurObserv'ER project. These modules are based on Eurostat data (ECN, 2017). Without foresight on how trade and economic statistics will change in the future, they have not been altered.

## 4.2. Results

The results are split in i) employment effects from capital investments, ii) effects from operations and maintenance, and iii) effects from the feedstock supply chains.

[11] Feedstock for digestion is mostly manure, which is assumed to be a waste product that does not cost anything.

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Figure 17 presents the total employment impacts of investments in new production capacities over a period of time. The results are presented in *job years*[12], which are defined as 1 full-time-equivalent (FTE) job for the duration of 1 year. An FTE job that last two years is equal to two job years. Job years give an indication of total employment over a period of time. Actual yearly employment will depend on how investments are spread over the period.

Investment related employment estimates are relatively modest for the 2018-2030 period, 116 thousand job years for the Road ZERO scenario and 440 thousand job years for the Transport BIO scenario. Employment over the 2018-2050 scenarios are significantly higher, reaching 1.1 million job years for the Road ZERO scenario and 3.4 million job years for the Transport BIO scenario. Thermochemical routes account for the largest share of the capital investment related employment for the 2018-2050 period, corresponding to 67% of the total employment in the Road ZERO scenario and 70% in the Transport BIO scenario. Over the same period advanced ethanol and alcohol-to-jet fuel investment related jobs contribute around 19% of the total investment related employment in the Road ZERO scenario and 24% in the Transport BIO scenario.

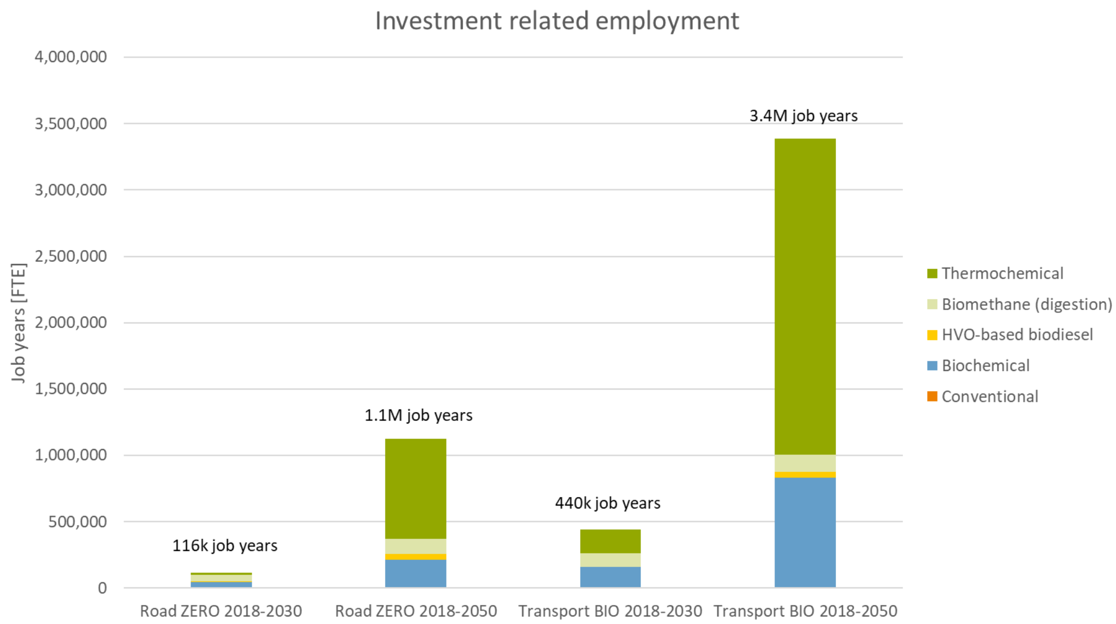


*Figure 17. Employment related to capital investment.*

For O&M and feedstock supply activities, employment in single years are considered and are therefore expressed in FTEs. Employment in 2030 and 2050 under both the Road ZERO and Transport BIO scenarios are compared to 2018 as reference year. Employment in 2018 is compared to the EurObserv'ER estimate for 2018 in Section 4.3.1.

O&M related employment is estimated at 17 thousand FTE in 2018 (see Figure 18). O&M related employment decreases slightly in 2030 in the Road ZERO scenario led by a decrease in O&M jobs related to conventional biofuels. Employment in the Road ZERO scenario in 2050 increases

[12] Job years can also be interpreted as total FTEs over a certain period.

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fourfold to 69 thousand FTE, with advanced bioethanol and alcohol-to-jet fuel and thermo-chemical routes contributing 80% of O&M jobs. In line with the increases in installed capacity, O&M related employment increases more in the Transport BIO scenario. Advanced bioethanol and alcohol-to-jet fuel and thermochemical routes also account for most jobs in the Transport BIO scenario: 60% in 2030 and 94% in 2050.

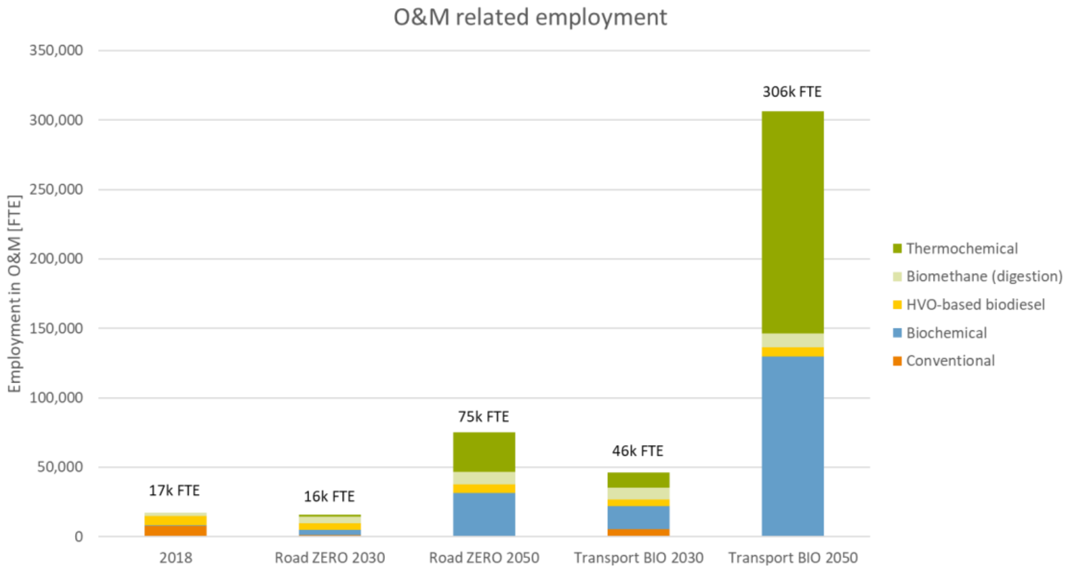


*Figure 18. Employment related to operations and maintenance*

Employment in feedstock supply is significantly higher than employment in operations and maintenance (see Figure 19). As with employment related to O&M, the employment effects related to feedstock supply are most significant in 2050 in both scenarios. Effects in 2030 in the Transport BIO scenario are also significantly higher than in 2018.

The conventional biofuel feedstocks supply accounts for 54% of feedstock related employment in 2018. Its role is smaller in 2030 where it accounts for 15% of feedstock related employment in the Road ZERO scenario and 10% in the Transport BIO scenario. In 2050 conventional feed-stocks supply account for <1% of jobs in both scenarios. Jobs in HVO supply decrease from 29 thousand in 2018, to 8 thousand FTE in the Road ZERO scenario in 2030, slightly increasing again to 9 thousand FTE in 2050. HVO supply jobs also decrease in the Transport BIO scenario, but less than in the Road ZERO scenario (15 thousand FTE in 2030 and 24 thousand FTE in 2050). The decrease is less prominent in the Transport BIO scenario because more HVO is sourced domestically compared to the Road ZERO scenario (see Table 6). The largest contribution to the total employment is from the advanced bioethanol and thermochemical routes (97% of jobs in Road ZERO 2050, 83% in Transport BIO 2030 and 96% in Transport BIO 2050).

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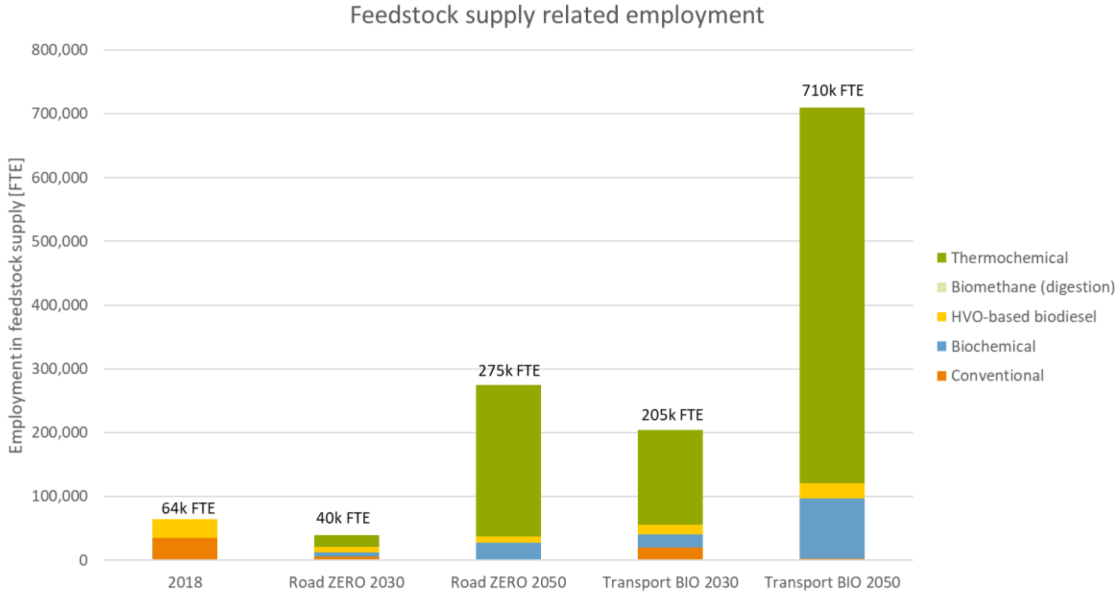


*Figure 19. Employment related to feedstock supply*

### 4.2.1. Results per unit output

In this section results per MW new installed capacity and per PJ output are presented. This will make it easier to compare results to other studies, as presented in Section 4.3. These results are sensitive to input assumptions and model setup. The results vary per scenario, not only because some input assumptions change in time (e.g. CAPEX and feedstock costs), but also because the model calculations are performed at member state level and installed capacities per member state vary per scenario. Costs and labour statistics vary per member state, for which corrections are performed in the employment conversion module. Average employment effects per MW or per PJ for a scenario depend on the types of capacity invested in, the amount of each type that is invested in, which member states production capacity is installed in, cost assumptions, and for feedstock supply employment effects the assumption on proportion of feedstock imports from outside the EU. Average results per scenario are presented in Table 7 and Table 8.

*Table 7: Average CAPEX-related employment effects per MW*

| Scenario and period | Average CAPEX-related employment effect (job years/MW) |
|---|---|
| Road ZERO 2018-2030 | 18 |
| Road ZERO 2030-2050 | 20 |
| Transport BIO 2018-2030 | 13 |
| Transport BIO 2030-2050 | 19 |

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*Table 8: Average O&M and feedstock supply related employment per PJ*

| Scenario and year | Average O&M-related employment effect (FTE/PJ) | Average feedstock supply-related employment effect (FTE/PJ) |
|---|---|---|
| 2018 | 39 | 144 |
| Road ZERO 2030 | 35 | 88 |
| Road ZERO 2050 | 43 | 160 |
| Transport BIO 2030 | 37 | 163 |
| Transport BIO 2050 | 56 | 130 |

Employment effects per unit differ per production route, which are presented in Figure 20 and in Figure 22. The results per production route also depend on the member state in which the capacity is installed, which differs per scenario. Therefore ranges of employment effects per MW installed and PJ output are presented.

Results from both scenarios and for both the 2018-2030 and 2018-2050 periods have been used to calculate investment related employment impacts per MW newly installed capacity. The calculations result in ranges of results for each production route, which are presented in Figure 20. The values range from 5.3 job years/MW for ATJ up to 31.4 job years/MW for bio-FT. The largest spread can be seen for Bio-DME and bio-FT, two production routes for which the investment costs drop significantly from 2030 to 2050 (see Figure 20).

O&M related employment effects per PJ produced have been calculated for 2018, 2030 and 2050 for both scenarios. The ranges of estimates for each production route are presented in Figure 21, which also shows a large spread of results between production routes. Particularly bioethanol routes that are based on food and feed crops (conventional) have relatively high O&M related employment per PJ output. The spread is largest for advanced bioethanol from straw due to sharp decreases in both investment costs and relative O&M costs (see Figure 21).

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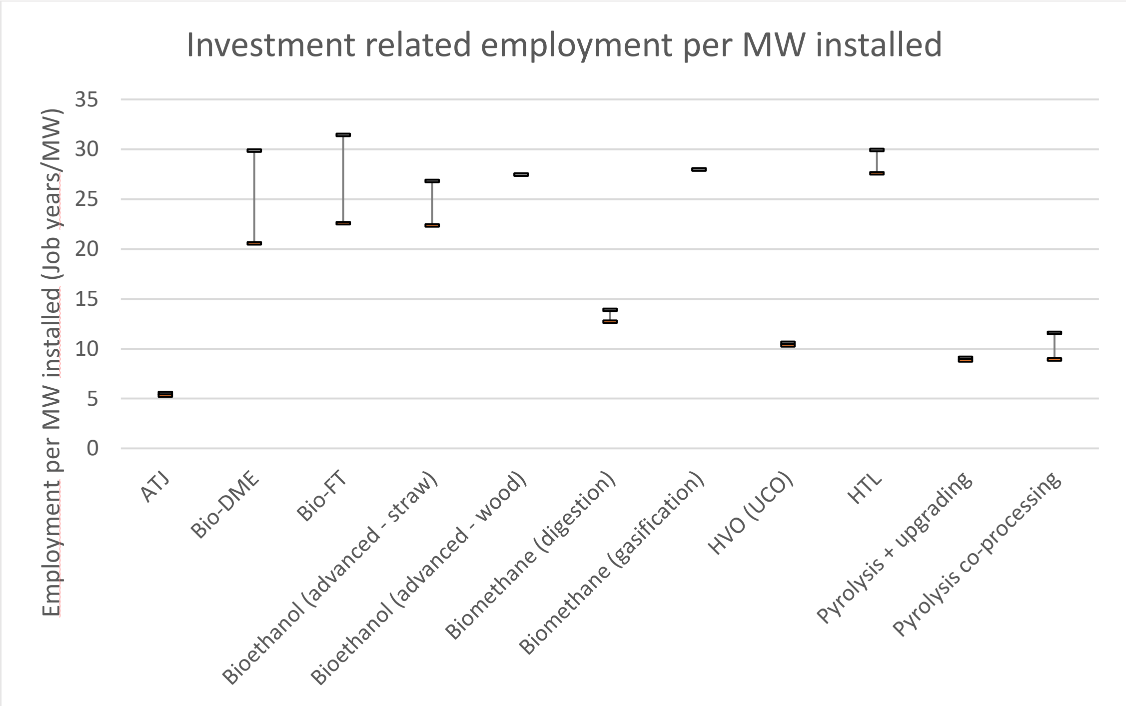


*Figure 20. Employment effect from investment in new capacity, per MW installed.*

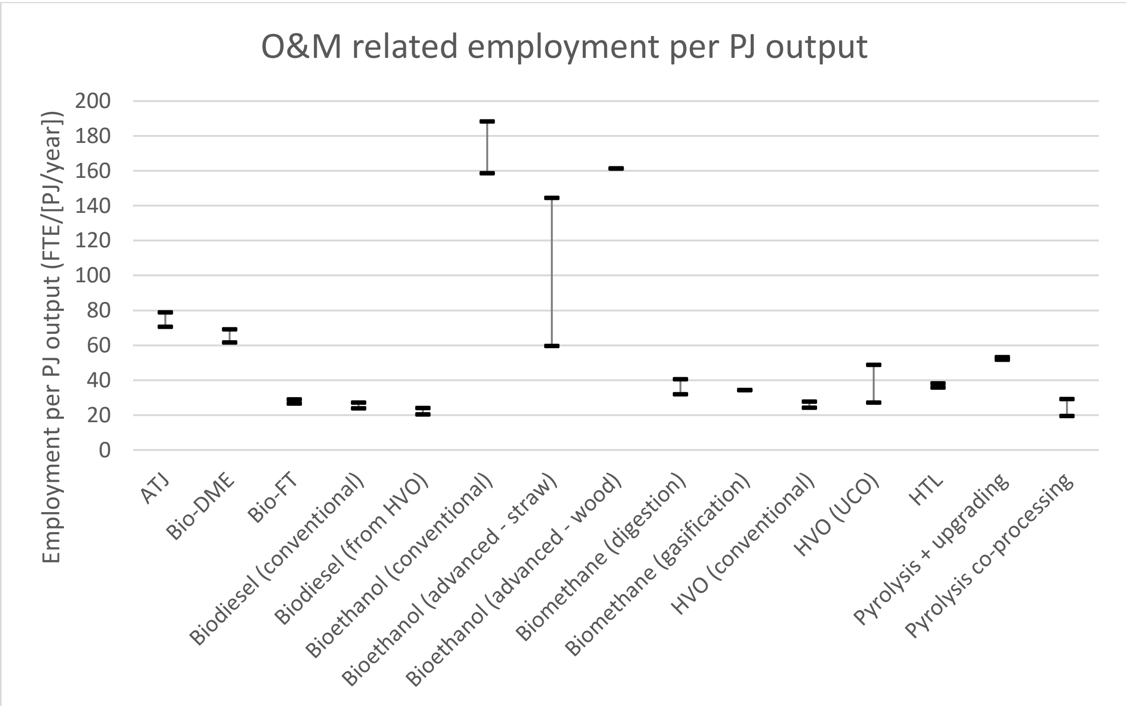


*Figure 21. Employment effect from O&M activities, per PJ output.*

Similarly, employment effects per PJ production have been calculated for feedstock supply in 2018, 2030 and 2050 for both scenarios. Ranges of the results are presented in Figure 22. As with total employment numbers, the numbers for employment from feedstock supply per PJ output are large relative to O&M related employment. For most production routes employment is in the range of 50 FTE/PJ up to 400 FTE/PJ. Employment related to conventional bioethanol crops is higher (450-700 FTE/PJ) due to the assumed high cost of the feedstocks (see Table 5).

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Low average salaries in the agricultural sector translate large investments in conventional bioethanol crops into high employment estimates. The spread in employment per PJ is largest for conventional bioethanol and pyrolysis co-processing. The spread is caused by differences between installed capacity assumptions per member state in each scenario. In scenarios where most of the feedstocks are sourced from states with relatively lower wages, the estimated employment per € spent on feedstocks increases. The opposite is true when larger amounts of feedstocks are sourced from member states with high wages. As feedstock costs are not varied between the scenarios and over years, any differences in estimates relate to where capacity is installed, where feedstocks are sourced from, and how much is imported (from other EU countries and from outside EU).

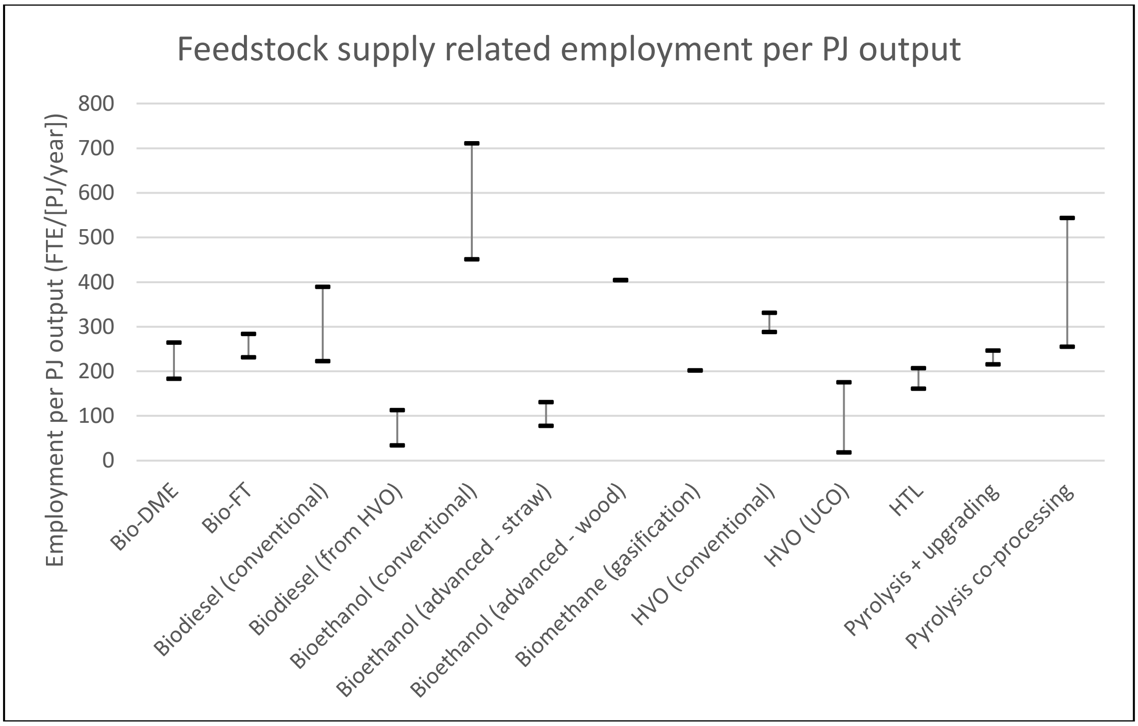


*Figure 22. Employment effect from feedstock supply, per PJ output.*

## 4.3. Comparison of the results with other studies

In this section, employment estimates presented in the previous section are compared to estimates from other studies. O&M and feedstock supply employment effects for 2018 are compared to the most recent EurObserv'ER employment estimates for biofuels (also for 2018, from EurObserv'ER (2020)). As the same methodology is applied in the EurObserv'ER project, the differences in O&M and feedstock supply employment estimates are purely due to differences in input assumptions. The results are also compared with other studies where both differences in methodology and main assumptions can cause significant differences in estimates.

### 4.3.1. Comparison to EurObserv'ER 2018 results

There are a number of differences between the assumptions made for the ADVANCEFUEL employment analysis and the assumptions for biofuels in the EurObserv'ER employment analysis.

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The first is a difference in installed production capacity in 2018, which is shown in Figure 23. EurObserv'ER assumes over 20 GW of installed capacity in 2018, 5 GW higher than is assumed in the ADVANCEFUEL case. Due to a lack of comprehensive data on the currently installed biofuel production capacity, it was assumed in EurObserv'ER that all capacity is conventional biodiesel and bioethanol production capacity. On the other hand a significant portion of installed capacity in the ADVANCEFUEL scenario is biodiesel from HVO and biomethane.

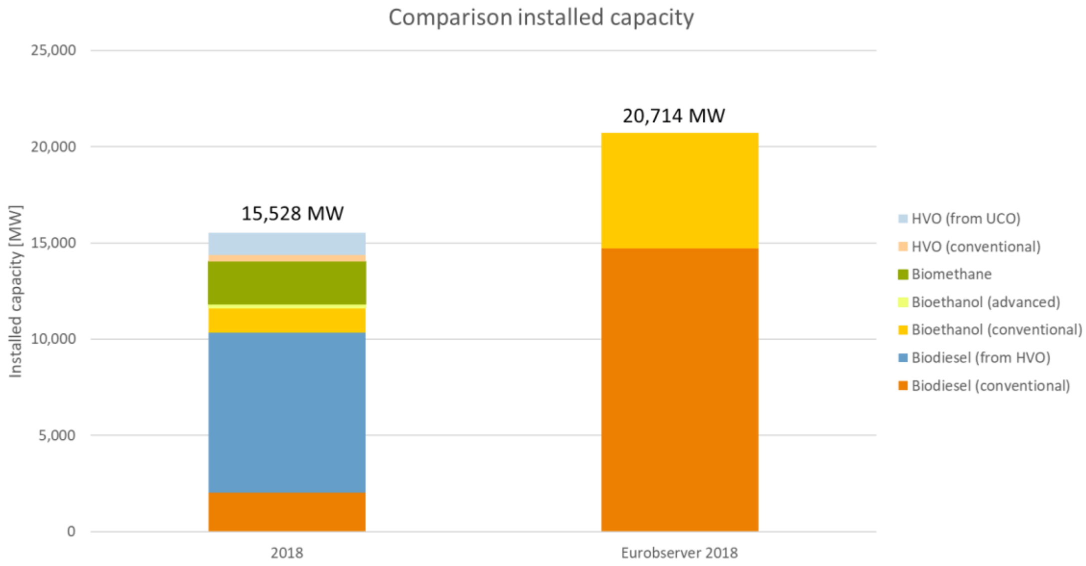


*Figure 23. Comparison installed capacity ADVANCEFUEL and EurObserv'ER 2018.*

Efficiencies for conventional routes are also assumed to be lower in the EurObserv'ER analysis (see Table 12 in the Annex), which means more feedstock is required per unit of output. On the other hand, fixed O&M assumptions are significantly lower in EurObserv'ER. Variable O&M is higher for all technologies considered in EurObserv'ER, especially for advanced technologies. However, with no advanced production capacity considered in EurObserv'ER, the high assumptions for variable O&M cost assumptions for advanced routes do not impact the EurObserv'ER results.

The differences in assumptions are reflected in the results for O&M and feedstock related employment in 2018 (see Figure 24). The results show significantly lower O&M employment in the EurObserv'ER case due to the assumption that fixed O&M costs are lower. On the other hand, due to higher installed capacities and lower efficiencies assumed in the EurObserv'ER analysis, the demand for feedstocks is significantly higher. In both studies it is estimated that practically all 1st generation bioethanol crops are sourced domestically and that approximately 30% of 1st generation biodiesel crops are imported. In the ADVANCEFUEL scenario, however, a significant amount of biodiesel is produced from HVO, 62% of which is estimated to be imported (see Table 6). The combination of lower feedstock demand and higher dependency on imported feedstocks leads to significantly lower employment estimates from feedstock supply compared to the EurObserv'ER estimates. In total the ADVANCEFUEL estimate for employment in O&M and feedstock supply in 2018 is about one-third of the EurObserv'ER estimate.

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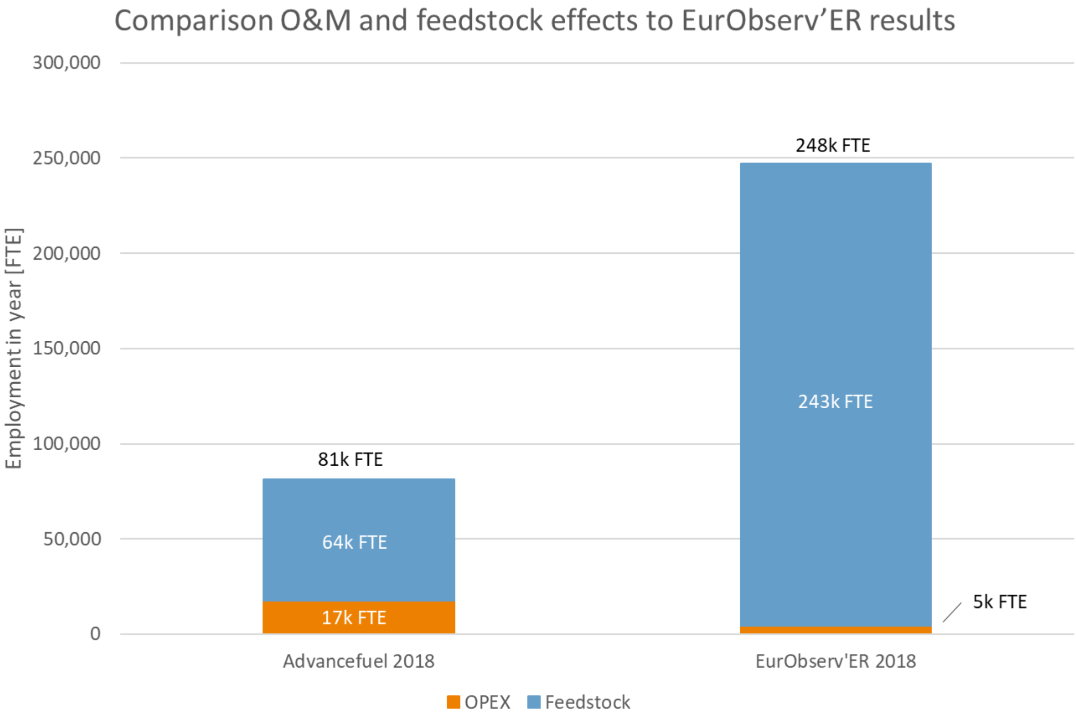


*Figure 24. Comparison O&M and feedstock supply employment estimates to EurObserv'ER 2018 results*

### 4.3.2. Comparison to other studies

Comparison to other studies is challenging as employment estimates depend on approach (e.g. survey or modelling exercise), model design (does it include indirect and induced employment) and input assumptions, and the way results are reported (total FTEs, job years, FTEs per plant, FTEs per PJ, FTEs per 1000 tonnes feedstock per day, etc.). Keeping this in mind, the results presented in Section 4.2 are compared to other studies in this section.

Zhang *et al.* (2016) compare economic impact estimations of three cellulosic biofuel production pathways: ethanol from biochemical conversion, renewable diesel blendstock via biological conversion and renewable diesel and gasoline blend stock via fast pyrolysis. The reference plants process 2000 dry metric tonnes (DMTs) of biomass per day, but employment from plants sized 1000 DMT/day and 500 DMT/day are also estimated. Zhang *et al.* (2016) estimate that employment does not decrease linearly with plant capacity, which means employment estimates per unit biofuel produced is higher in the 1000 DMT/day and 500 DMT/day plants. Zhang *et al.* (2016) distinguish between direct employment (at the plant) and indirect employment (supply chain effects, e.g. equipment manufacturing for construction related activities or feedstock supply for O&M activities).

An overview of the comparison to the estimates from Zhang *et al.* (2016) is presented in Table 9. Construction-related employment per MW installed is comparable for advanced ethanol, but for advanced renewable diesel and fast pyrolysis even the lower estimates are significantly higher than the ADVANCEFUEL estimates. For O&M and feedstock employment per PJ output the estimates for advanced ethanol are similar, the estimates for advanced renewable diesel are lower in the ADVANCEFUEL case and for fast pyrolysis the ADVANCUEL estimates are within the range from Zhang *et al.* (2016),

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*Table 9. Comparison Zhang et al. (2016) and ADVANCEFUEL employment estimates for three production pathways. Source: own calculations based on Zhang et al. (2016) and Section 4.2.1.*

| | Advanced ethanol | Advanced renewable diesel | Fast Pyrolysis |
|---|---|---|---|
| Zhang *et al.* (2016) | | | |
| Feedstock consumption | 500-2000 DMT/day | 500-2000 DMT/day | 500-2000 DMT/day |
| Biofuel output | 0.29-4.6 PJ per year | 0.25-4.0 PJ/year | 0.4-7.0 PJ per year |
| Construction-related employment | 730-1720 FTE direct<br>910-2140 FTE indirect<br>27-180 job years per MW | 950-2010 FTE direct<br>1250-2760 FTE indirect<br>37-275 job years per MW | 1130-2880 FTE direct<br>1080-2730 FTE indirect<br>25-160 job years per MW |
| O&M-related employment | 49-60 FTE direct<br>130-450 FTE indirect<br>111-623 FTE per PJ | 49-60 FTE direct<br>200-660 FTE indirect<br>179-988 FTE per PJ | 64-83 FTE direct<br>210-670 FTE indirect<br>108-629 FTE per PJ |
| ADVANCEFUEL | | | |
| Construction-related employment | 22-28 job years per MW | 10-11 job years per MW | 9-12 job years per MW |
| O&M-related employment | 138-566 FTE per PJ | 46-224 FTE per PJ | 268-300 FTE per PJ |

NNFCC (2013) estimate that an additional 147-307 thousand full time jobs in the biofuel sector can be added in the EU if the available sustainable EU feedstock resources are completely mobilized and utilised. Of these jobs, between 56-133 thousand would be in the agricultural and forestry sector, 4-13 thousand from the operation of biofuel plants and 87-162 thousand temporary jobs from construction. The estimates are based on employment factors[13] in terms that are not used in the ADVANCEFUEL employment assessment (FTE per 1000 t fresh straw, FTE per 1000t forest residue, FTE per plant), making comparisons challenging.

The employment estimates from NNFCC (2013) are lower than the estimates from the employment assessment conducted in this study, where it is estimated that there could be 1.1-3.4 million job years in construction over the period from 2018-2050, employment in operation and maintenance of biofuel plants could increase to 75-265 thousand FTE in 2050 and employment in feedstock supply could increase to 379 thousand to 1.69 million FTE in 2050 (see Section 4.2). The assessment by NNFCCC (2013), however, is limited to European feedstocks which are estimated to be able to produce a maximum of 8-11% of European road transport demand. With imported feedstocks more biofuel production capacity can be constructed and operated in Europe, increasing the potential for employment in construction and equipment manufacturing, as well as employment in operations and maintenance of European biofuel plants. Employment in feedstock supply could also increase slightly through the import of feedstocks (jobs in trade and transport), but we estimate this effect to be limited compared to employment in the European agricultural and forestry sectors.

[13] Used employment factors: 0.47-0.68 FTE/1000 t fresh straw, 0.34--.62 FTE/1000 t forest residue, 50-80 FTE per advanced biofuel plant (also depends on type of pathway).

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JRC estimate 26 thousand people to be directly employed in the biofuel sector in 2015 (Ronzon *et al.* 2017[14]). The estimate is about 50% higher than the estimated employment in O&M of biofuels plants in 2018 (see Figure 21). In addition the authors estimate 9.2 million jobs in the agricultural sector and 539 thousand jobs in the forestry sector. The study does not include an assessment of which portion of the employment in the agricultural and forestry sectors is related to the biofuels sector.

Fragkos & Paroussos (2018) estimate employment effects of renewables expansion in Europe using employment factors (job years/MW, jobs/MWh, or jobs/ktoe fuel). The assessment includes an employment estimate from biofuels production, estimated at 1.63 jobs/ktoe for biomass supply. The employment factor is compared to labour intensities reported in other studies, which report labour factors from 1.51-1.75 jobs/ktoe (36-42 jobs/PJ). These employment factors are much lower than the estimates from the ADVANCEFUEL estimate (see Figure 22).

Two scenarios are compared by Fragkos & Paroussos (2018): a reference scenario and a scenario designed to meet EU 2030 targets of 40% GHG emissions reduction, 27% renewables in gross energy consumption and a 30% energy efficiency target (the EUDEC scenario). Under the reference scenario direct employment in the biofuels sector is estimated to increase from 75 thousand in 2015 up to 83 thousand in 2030 and 84 thousand in 2050. In the EUDEC scenario direct employment in the biofuels sector is expected to increase to 94 thousand in 2030 and 476 thousand in 2050.

## 4.4. Model inadequacies

The model used for the employment analysis only considers employment related to (advanced) biofuel production capacity. To include estimates for employment from alternative paths to low-carbon transport such as electrification or green hydrogen for transport and to account for the displacement of employment in the fossil fuel sector, additional analysis is required. Macroeconomic models considering complete energy system transformations and the whole economy are suitable for such analyses, but are more complex and therefore require greater modelling efforts than the model used here.

The methodology developed for the EurObserv'ER project is a partial analyses that was developed for year on year monitoring of changes in employment based on changes in installed capacities and economic statistics. Using the methodology for forecasting has a number of shortcomings. Firstly, considering employment effects from investments over a period of time gives insights on total employment effects, but not how employment varies throughout the period. Similarly, comparing O&M and feedstock supply employment for 2030/2050 to a reference year (2018) gives insight on the potential growth in employment, but not the trajectory of growth.

Secondly, by considering employment effects over a period additionally introduces a risk of missing employment from capacity that is installed and decommissioned within the period. This risk was limited by reducing period lengths (from 2018-2050 to 2018-2030 and 2030-2050). Thirdly, the model does not consider employment from capacity that is decommissioned and replaced (only net increases in capacity are considered), which can also lead to an underestimation of construction and manufacturing related employment.

[14] Database can be accessed here: https://datam.jrc.ec.europa.eu/datam/mashup/BIOECONOMICS/index.html

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The model makes use of economic statistics that are based on the current situation. While it is a fact that these statistics will develop in the future, it is very difficult to forecast how these will change over the coming decades. Assuming these statistics do not change is a simplification which can have significant effect on the final results. Therefore, the figures presented in the current assessment can be used to make comparisons between the two scenarios, but one should be careful with comparing the presented figures with assessments that take into account the development of economic statistics over time. Macro-economic models can take into account developments in economic statistics over time, but how these statistics develop will still depend on the model and input assumptions. While these models can provide additional insights, they do therefore not necessarily lead to improved accuracy of results.

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# 5. Conclusions

A decomposition of the total system cost of the transport sector has been presented for two scenarios. The total system cost of the Road ZERO scenario is significantly lower than in the Transport BIO scenario. This comparison requires some further attention. Both scenarios describe worlds with different external factors, which result in a different energy mix for the transport sector. It can simply be concluded that electricity prices (and the cost for electrical vehicles) have a very large impact on the energy mix of the transport sector.

From the cost figures it has been illustrated why direct electrification is much more attractive in Road ZERO than in Transport BIO. Furthermore it has also been illustrated that the average biofuel cost can significantly increase after 2030 in a scenario like Transport BIO. Such a strong increase in average biofuel cost can be attributed to the fact that a large part the biomass potential is utilized, which means that the expensive part the of the biomass cost supply curve is utilized as well, while cheap first generation and used cooking oil based biofuels are capped and that mainly expensive advanced biofuels are utilized that serve the market segments best for which biofuels are the most cost effective mitigation option.

Results of the employment analysis show an estimated 116 and 440 thousand job years can be created in sectors related to the construction of new advanced biofuel production capacity (including jobs in project planning, construction, equipment manufacturing and related services) over the period 2018-2030 and 1,1-3,4 million job years over the period 2018-2050 according to Road ZERO and Transport BIO, respectively. Employment in operation and maintenance of advanced biofuel production plants is estimated to go from 17 thousand FTE in 2018 to 16 and 46 thousand FTE in 2030 and increase to 75 and 306 thousand FTE in 2050 for Road ZERO and Transport BIO. Feedstock supply is estimated to account for 64 thousand FTE in 2018, increasing to 40 thousand FTE in 2030 and 275 thousand FTE in 2050 in Road ZERO. In Transport BIO the increase is much higher thanks to higher biomass feedstock use. It increases to 205 thousand FTE in 2030 and 710 thousand FTE in 2050. Employment is highest from thermochemical routes such as Bio-DME, bio-FT, HTL and pyrolysis. The biochemical routes, advanced bioethanol and alcohol-to-fuel are the second largest contributor to employment in the ADVANCEFUEL scenarios. Employment estimates are related to the amount of biofuel production capacity installed and employment effects for the Transport BIO scenario are therefore consistently higher than for the Road ZERO scenario.

ADVANCEFUEL estimates for employment effects in O&M and feedstock supply in 2018 have been compared to estimates from the EurObserv’ER project, which uses a similar modelling approach to estimate yearly changes in employment in renewable energy in the EU based on the most recent renewable energy capacity data. Due to higher assumptions for O&M costs, the O&M employment estimates in ADVANCEFUEL are higher than the EurObserv’ER (17 thousand compared to 5 thousand FTE). Estimates for feedstock supply employment in ADVANCEFUEL are lower than the EurObserv’ER estimate, 64 thousand FTE compared to 243 thousand FTE. The significant difference in estimates feedstock supply employment is caused by differences in assumptions about installed capacities, lower efficiencies assumed in EurObserv’ER (higher feedstock requirement per PJ output), and higher feedstock import from outside the EU assumed in the ADVANCEFUEL case.

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Comparisons to other studies show there is a significant range in the estimates for employment effects, due to (amongst other things) scope, modelling approach and input assumptions. Differences in formats for reporting employment estimates also complicates comparison to other studies.

The model used for the employment analysis has some issues, such as it does not have the possibility to (easily) obtain yearly estimates of employment effects for longer periods. While more complex models can provide additional insights, they require significantly greater effort than the follow-the-money approach used here. The relatively simple modelling approach gives adequate first estimates of employment effects and useful insights on employment effects from different production routes and scenarios.

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# References

**Atsonios, K., Kougioumtzis, M. A., Panopoulos, K. D., & Kakaras, E. (2015).** Alternative thermochemical routes for aviation biofuels via alcohols synthesis: process modeling, techno-economic assessment and comparison. *Applied Energy*, **138**, 346-366. doi: https://doi.org/10.1016/j.apenergy.2014.10.056.

**Collett, J. R., Billing, J. M., Meyer, P. A., Schmidt, A. J., Remington, A. B., Hawley, E. R., Hofstad, B. A., Panisko, E. A., Dai, Z., Hart, T. R., Magnusson, J. K., Hallen, R. T., Jones, S. B. & Santosa, D. M. (2019).** *Renewable diesel via hydrothermal liquefaction of oleaginous yeast and residual lignin from bioconversion of corn stover*. Applied energy, 233, 840-853. doi: https://doi.org/10.1016/j.apenergy.2018.09.115

**De Jong, S.(2018)** *Green horizons – On the production costs, climate impacts and future supply of renewable jet fuels*. PhD thesis Utrecht University (2018). Internet: https://dspace.library.uu.nl/handle/1874/364514.

**ECN (2017).** *Renewable Energy Employment Effects in the EU and Member States: Methodology Report*, Petten. Internet: https://publicaties.ecn.nl/ECN-E--17-076.

**EurObserv'ER (2020).** *The State of Renewable Energies in Europe, 19th edition*, Paris. https://www.eurobserv-er.org/19th-annual-overview-barometer/.

**Haas, M. J., McAloon, A. J., Yee, W. C., & Foglia, T. A. (2006).** *A process model to estimate biodiesel production costs*. Bioresource technology, 97(4), 671-678. doi:10.1016/j.biortech.2005.03.039.

**Jones, S. B., Valkenburt, C., Walton, C. W., Elliott, D. C., Holladay, J. E., Stevens, D. J., Kinchin, C. & Czernik, S. (2009).** *Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case* (No. PNNL-18284 Rev. 1). Pacific Northwest National Lab (PNNL), Richland, WA (United States).

**Jones, S. B., Meyer, P. A., Snowden-Swan, L. J., Padmaperuma, A. B., Tan, E., Dutta, A., Jacobson, J. & Cafferty, K. (2013).** *Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels: fast pyrolysis and hydrotreating bio-oil pathway* (No. PNNL-23053; NREL/TP-5100-61178). Pacific Northwest National Lab (PNNL), Richland, WA (United States).

**Karka, P., Papadokonstantakis, S., Johnsson, P. (2019).** *First data on efficient, low-risk ramp-up of liquid biomass conversion technologies - from short time to long term.* Deliverable 3.5 of the ADVANCEFUEL project. Internet: http://www.advancefuel.eu/contents/reports/d35-liquid-biofuel-conversion-technology.pdf.

**Fragkos, P., & Paroussos, L. (2018).** *Employment creation in EU related to renewables expansion.* Applied Energy, 230, 935-945. doi: https://doi.org/10.1016/j.apenergy.2018.09.032.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799. 

**Kazi, F. K., Fortman, J., Anex, R., Kothandaraman, G., Hsu, D., Aden, A., & Dutta, A. (2010).** *Techno-economic analysis of biochemical scenarios for production of cellulosic ethanol* (No. NREL/TP-6A2-46588). National Renewable Energy Lab (NREL), Golden, CO (United States).

**National Energy Foundation, Academy of Champions for Energy, Local United (2014).** *Energy Farms – Anaerobic Digestion: How to develop a community-led agricultural anaerobic digester.*

**NNFCC (2013).** *Use of sustainably-sources residue and waste streams for advanced biofuel production in the European Union: rural economic impacts and potential for job creation.* York, United Kingdom.

**Ramirez, J. A., & Rainey, T. J. (2019).** *Comparative techno-economic analysis of biofuel production through gasification, thermal liquefaction and pyrolysis of sugarcane bagasse.* Journal of Cleaner Production, 229, 513-527. doi: https://doi.org/10.1016/j.jclepro.2019.05.017

**Ronzon, T., Piotrowski, S., M'Barek, R., & Carus, M. (2017).** *A systematic approach to understanding and quantifying the EU's bioeconomy.* Bio-based and Applied Economics Journal, 6(1050-2018-3682), 1-17. doi: 10.13128/BAE-20567

**Spöttle, *et al* (2013).** Low ILUC potentials of wastes and residues for biofuels – Straw, forestry residues, UCO, corn cobs. Ecofys Netherlands B.V.

**Uslu, A., van Stralen, J., Pupo Nogueira, L. (2020).** *Role of transportation fuels in transport up to 2050 – a scenario based analysis to contribute to Paris Agreement goals.* Deliverable 6.2 of the ADVANCEFUEL project. May 2020. Internet: http://www.advancefuel.eu/contents/reports/d-62-deliverable-final-15may.pdf

**Zhang, Yimin, Goldberg, Marshall, Tan, Eric, & Meyer, Pimphan Aye (2016).** *Estimation of economic impacts of cellulosic biofuel production: a comparative analysis of three biofuel pathways.* United States. doi:10.1002/bbb.1637.

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# Annex I

*Table 10. Investment and O&M cost assumptions per production route*

| Technology | CAPEX (€/kW) | | | Fixed OPEX (€/kW/year – given in % of CAPEX) | | | Variable OPEX (€/MWh) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2018 | 2030 | 2050 | 2018 | 2030 | 2050 | 2018 | 2030 | 2050 |
| ATJ | 477 | 454 | 418 | 38.6% | 40.6% | 44.1% | 2.75 | 4.31 | 4.44 |
| Bio-DME | - | 2,481 | 1,810 | 5.0% | 12.3% | 16.8% | 1.89 | 2.5 | 0.79 |
| Bio-FT | - | 2,562 | 1,838 | 5.0% | 4.9% | 6.8% | 0 | 0 | 0 |
| Biodiesel (1G) | 307 | 307 | 307 | 29.6% | 29.6% | 29.6% | 0 | 0 | 0 |
| Biodiesel (HVO) | 307 | 307 | 307 | 29.6% | 29.6% | 29.6% | 0 | 0 | 0 |
| Bioethanol (1G) | 1,190 | 1,190 | 1,190 | 40.9% | 40.9% | 40.9% | 0 | 0 | 0 |
| Bioethanol (advanced - wood) | 3,292 | 2,422 | 2,157 | 14.9% | 18.4% | 20.0% | 0 | 0 | 0 |
| Bioethanol (advanced - straw) | 2,744 | 1,951 | 1,631 | 17.9% | 10.0% | 10.0% | 0 | 0 | 0 |
| Biomethane (gasification) | - | 1,829 | 1,317 | 2.0% | 6.9% | 9.7% | 1.09 | 1.41 | 0.19 |
| Biomethane (digestion) | 1,543 | 1,149 | 1,149 | 7.8% | 7.8% | 7.8% | 0.43 | 0.77 | 0.76 |
| HVO (1G) | 607 | 607 | 607 | 14.8% | 14.8% | 14.8% | 2.92 | 4.28 | 4.18 |
| HVO (UCO) | 607 | 607 | 607 | 14.8% | 14.8% | 14.8% | 2.92 | 4.2 | 4.11 |
| HTL | 2,536 | 2,536 | 2,536 | 5.0% | 5.0% | 5.0% | 1.01 | 1.79 | 1.78 |
| Pyrolysis + upgrading | - | 720 | 720 | 5.0% | 5.0% | 5.0% | 15.74 | 22.68 | 21.26 |
| Pyrolysis co-processing | - | 693 | 693 | 9.6% | 9.6% | 9.6% | 0.52 | 0.92 | 0.91 |

Efficiency is defined as fuel output relative to feedstock input, which means efficiencies are high when large amounts of auxiliary energy inputs (e.g. electricity, natural gas or hydrogen) are used in a process.

*Table 11. Technical data assumptions per production route*

| Technology | Load hours | Efficiency |
|---|---|---|
| ATJ | 7896 | 95.4% |
| Bio-DME | 8000 | 47.0% (2015)<br>52.4% (2030)<br>58.1% (2050) |
| Bio-FT | 7884 | 51.6% |
| Biodiesel (1G) | 8000 | 76.2% |
| Biodiesel (UCO) | 8000 | 92.5% |
| Bioethanol (1G) | 8000 | 50.2% |
| Bioethanol (lignocellulosic)) | 8000 | 38.5% |
| Biomethane (gasification) | 7500 | 59.7% |
| Biomethane (digestion) | 7750 | 59.7% |
| HVO (1G) | 8000 | 108.9%[15] |
| HVO (UCO) | 8000 | 108.9%[13] |
| HTL | 8000 | 56.4% |
| Pyrolysis + upgrading | 7884 | 50.2% |
| Pyrolysis co-processing | 7920 | 42.5% |

15 The efficiency of HRD is high because of the large amount of auxiliary energy input (mainly hydrogen).

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*Table 12. Comparison technical data assumptions ADVANCEFUEL and EurObserv'ER*

| Technology | ADVANCEFUEL | | | EurObserv'ER | | |
|---|---|---|---|---|---|---|
| | Efficiency | Fixed O&M (% of Capex) | Variable O&M (€/MWh) | Efficiency | Fixed O&M (% of Capex) | Variable O&M (€/MWh) |
| Biodiesel (conventional) | 76.2% | 29.6% | 0.00 | 52% | 4.5% | 1.39 |
| Biodiesel (advanced) | 92.5% | 29.6% | 0.00 | 30% | 4.5% | 42.04 |
| Bioethanol (conventional) | 50.2% | 40.9% | 0.00 | 52% | 4.5% | 1.39 |
| Bioethanol (advanced - wood) | 38.5% | 14.9% | 0.00 | 22% | 4.5% | 27.38 |
| Bioethanol (advanced - straw) | 38.5% | 17.9% | 0.00 | - | - | - |
| Biomethane (gasification) | 59.7% | 2.0% | 1.09 | 58% | 4.5% | 22.39 |
| Biomethane (digestion) | 59.7% | 7.8% | 0.43 | 49% | 4.5% | 36.86 |
| HRD (conventional) | 108.9% | 14.8% | 2.92 | - | - | - |
| HRD (advanced) | 108.9% | 14.8% | 2.92 | - | - | - |

*Table 13. Capex split per economic sector per production route*

| Technology | Construction | Equipment manufacturing | Consulting and engineering services | Financial services | Energy | Source |
|---|---|---|---|---|---|---|
| ATJ | 34% | 50% | 10% | 7% | 0% | Atsonios *et al.* 2015 |
| Bio-DME | 21% | 67% | 7% | 5% | 0% | Karka *et al.* 2019 |
| Bio-FT | 34% | 50% | 10% | 7% | 0% | Assumed same as pyrolysis[16] |
| Biodiesel (conventional) | 33% | 42% | 13% | 5% | 2% | EurObserv'ER project |
| Biodiesel (HVO) | 33% | 42% | 13% | 5% | 2% | EurObserv'ER project |
| Bioethanol (conventional) | 27% | 60% | 8% | 5% | 0% | Kazi *et al.* 2010 and Jones *et al.* 2009 |
| Bioethanol (advanced) | 27% | 60% | 8% | 5% | 0% | Kazi *et al.* 2010 and Jones *et al.* 2009 |
| Biomethane (gasification) | 23% | 64% | 8% | 5% | 0% | Karka *et al.* 2019 and Jones *et al.* 2009 |
| Biomethane (digestion) | 27% | 60% | 8% | 5% | 0% | Assumed same as conventional bioethanol[17] |
| HVO (conventional) | 34% | 50% | 10% | 7% | 0% | Assumed same as pyrolysis[5] |
| HVO (UCO) | 34% | 50% | 10% | 7% | 0% | Assumed same as pyrolysis[5] |
| HTL | 34% | 50% | 10% | 7% | 0% | Assumed same as pyrolysis[5] |
| Pyrolysis + upgrading | 34% | 50% | 10% | 7% | 0% | Jones *et al.* 2009 and Jones *et al.* 2013 |
| Pyrolysis co-processing | 34% | 50% | 10% | 7% | 0% | Jones *et al.* 2009 and Jones *et al.* 2013 |

[16]Assumed the same as pyrolysis because hydrotreating is an important part of both processes.
[17]Assumed the same as conventional bioethanol as both are biochemical routes

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*Table 14. Equipment manufacturing split per economic subsector per production route*

| Technology | Turbines, engines and generators | Biomass boilers, processing and storage | Electrical equipment and cables | Metal equipment and pipes | Civil construction materials | Source |
|---|---|---|---|---|---|---|
| ATJ | 0% | 41% | 22% | 19% | 19% | Atsonios *et al.* 2015 and Karka *et al.* 2019 |
| Bio-DME | 9% | 39% | 14% | 37% | 0% | Karka *et al.* 2019 and Jones *et al.* 2009 |
| Bio-FT | 13% | 34% | 34% | 19% | 0% | Jones *et al.* 2009 |
| Biodiesel (conventional) | 0% | 63% | 7% | 30% | 0% | EurObserv'ER project |
| Biodiesel (HVO) | 28% | 43% | 4% | 26% | 0% | EurObserv'ER project |
| Bioethanol (conventional) | 0% | 49% | 14% | 12% | 24% | Kazi et al. 2010, Jones *et al.* 2009, Karka *et al.* 2019 |
| Bioethanol (advanced) | 0% | 49% | 14% | 12% | 24% | Kazi et al. 2010, Jones *et al.* 2009, Karka *et al.* 2019 |
| Biomethane (gasification) | 5% | 35% | 17% | 38% | 5% | Karka *et al.* 2019 |
| Biomethane (digestion) | 0% | 49% | 14% | 12% | 24% | Assumed same as conventional bioethanol[18] |
| HVO (conventional) | 0% | 51% | 31% | 31% | 0% | Assumed same as pyrolysis[19] |
| HVO (UCO) | 0% | 51% | 31% | 31% | 0% | Assumed same as pyrolysis[7] |
| HTL | 7% | 52% | 23% | 19% | 0% | Collett *et al.* 2019 |
| Pyrolysis + upgrading | 0% | 51% | 31% | 31% | 0% | Jones et al. 2009 and Jones *et al.* 2013 |
| Pyrolysis co-processing | 0% | 51% | 31% | 31% | 0% | Jones *et al.* 2009 and Jones *et al.* 2013 |

*Table 15.O&M split per economic sector per production route*

| Technology | Construction | Energy | Consulting & engineering services | Financial services | Source |
|---|---|---|---|---|---|
| ATJ | 21% | 20% | 31% | 29% | Assumed same as conventional bioethanol[20] |
| Bio-DME | 11% | 79% | 10% | 0% | Assumed same as gasification[21] |
| Bio-FT | 11% | 79% | 10% | 0% | Assumed same as gasification[9] |
| Biodiesel (conventional) | 36% | 58% | 0% | 6% | Haas *et al.* 2006 |
| Biodiesel (HVO) | 36% | 58% | 0% | 6% | Assumed same as biodiesel |
| Bioethanol (conventional) | 21% | 20% | 31% | 29% | Kazi *et al.* 2010 |
| Bioethanol (advanced) | 21% | 20% | 31% | 29% | Assumed same as conventional bioethanol[8] |
| Biomethane (gasification) | 11% | 79% | 10% | 0% | Ramirez and Rainey 2019 |
| Biomethane (digestion) | 30% | 19% | 12% | 40% | ACE, NEF, Local United (2014) |
| HVO (conventional) | 21% | 57% | 22% | 0% | Assumed same as pyrolysis[22] |
| HVO (UCO) | 21% | 57% | 22% | 0% | Assumed same as pyrolysis[10] |
| HTL | 10% | 50% | 40% | 0% | Ramirez and Rainey 2019 |
| Pyrolysis + upgrading | 21% | 57% | 22% | 0% | Ramirez and Rainey 2019 |
| Pyrolysis co-processing | 21% | 57% | 22% | 0% | Ramirez and Rainey 2019 |

[18] Assumed the same as conventional bioethanol as both are biochemical routes.
[19] Assumed the same as pyrolysis as hydrotreating is an important part of both processes.
[20] Assumed the same as conventional bioethanol as both are biochemical routes.
[21] Assumed the same as gasification as both processes include high temperature gasification.
[22] Assumed the same as pyrolysis as both processes include mild gasification.

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