From raw material to fossil-free mobility:

Europe's potential for a renewable fuel market

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Executive summary

The transformation of the entire transport sector and its transition towards petroleum-free energy presents a challenge that cannot be met through the electrification of powertrains alone. It is therefore essential to exploit the CO_2 savings potential of all energy sources. The focus here – alongside hydrogen, for example – is on liquid fuels that can be integrated into the existing supply infrastructure without requiring technical modifications. Renewable fuels – so-called Carbon Neutral Fuels (CNF) – is a collective term encompassing all fuels with a lower carbon footprint than fossil fuels. This study examines the substitution potential of advanced renewable fuels derived from biological feedstocks as replacements for fossil fuels across all sectors of the EU.

Based on current scientific literature and various scenarios, this study analyses the availability of advanced raw materials, their conversion to renewable fuels and the development of fuel demand for road transport in the European Union for the target years 2030, 2035 and 2040, adopting a free-market-oriented approach. The shipping and aviation sectors, as well as other sectors with vehicles and machinery that are difficult to electrify, will ensure long-term demand for CNF. However, the introduction of a new vCNF (Carbon Neutral Fuels Vehicle) class will be crucial for the market ramp-up and the long-term availability of these fuels.

The long-term objective is to establish CNF mobility as a complementary pathway to electrification for road transport, without fossil CO_2 emissions, and to evaluate its feasibility both quantitatively and qualitatively – not only to meet the needs of a vCNF fleet, but also to assess the potential to replace the entire fuel market, with renewable fuels, including volumes required by the existing fleet.

Key findings on raw material availability

The evaluation of several studies shows that, even without imports, sufficient advanced raw materials are available within the EU to produce CNF in relevant quantities. The requirements of other sectors, such as industry, energy, aviation and shipping, have already been factored into the analysis. This study focuses on advanced raw materials, as listed in Annex IX, Parts A and B of the current Renewable Energy Directive (RED), and considers both a mid and a high realisation scenario, which differ in the assumed mobilisation rate of the respective feedstocks. To fully assess the potential of advanced biofuels, additional feedstocks – such as agroforestry intermediate and cover crops, as well as renewable non-food crops from marginal land – are also included. For this purpose, certain restrictions in Annex IX Part B are partially relaxed, and further potential feedstocks are incorporated.

The diversity is considerably broader than is often reflected in public discourse, which tends to focus narrowly on HVO and the specific raw materials used for its production, such as used cooking oil (UCO). However, UCO accounts for only 1% of the total spectrum of available raw materials. Figure 1 shows the breakdown of bioenergy potential by different advanced raw materials for the year 2030 in the mid-scenario, i.e. the potential already accounts for only the quantities available for energy use, after deducting materials allocated for other purposes, such as straw for stables. This study calculates both the renewable diesel and gasoline that can be produced from these quantities.

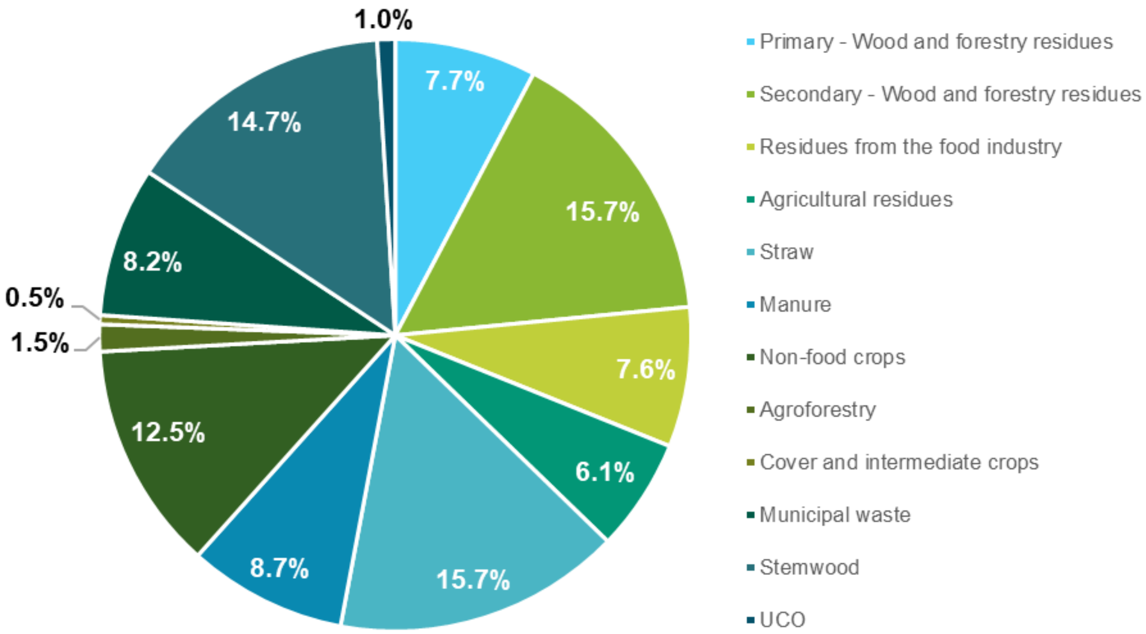


Figure 1: Share of the feedstock categories in the bioenergy potential in the Mid-scenario for 2030.

In 2030 and 2035, the raw material base in the EU will already be sufficient to cover more than 50% of total road transport fuel demand with renewable alternatives, after accounting for the requirements of the other sectors mentioned above and for material usage. For example, in 2030, 38 - 55% of the total EU road transport fuel demand can be met, increasing to 44 - 67% in 2035, as shown in Table 1 and Figure 2. If 100% substitution of the entire market, including shipping and aviation, is the political goal, the supply gap for 2030 - 2035 could be readily supplemented through raw material imports to support the CNF market start-up phase and advance the transition to petroleum-free energy sources. The global raw material potential is up to 43 times larger than the EU's maximum import requirements, thus guaranteeing that global supply has the potential to meet EU demand.

Table 1: Potential share of advanced biofuels in the total road transport market in the EU.

	2030	2035	2040
Raw materials bioenergy potential [Mtoe]	280 - 361	279 - 371	285 - 380
Available CNF* [Mtoe]	89 - 135	71 - 127	64 - 137
Fuel demand total road fleet [Mtoe]	238 - 247	162 - 188	95 - 128
CNF share on demand of total fleet	**38 - 55%**	**44 - 67%**	**67 - 107%**

*incl. 1st Gen acc. RED and RFNBO acc. German legislative proposal for national implementation of RED III [8]

In the High-scenario, CNF will be able to meet 107% of the projected total EU road transport fuel demand using raw materials available within Europe from 2040 onwards (Figure 2).

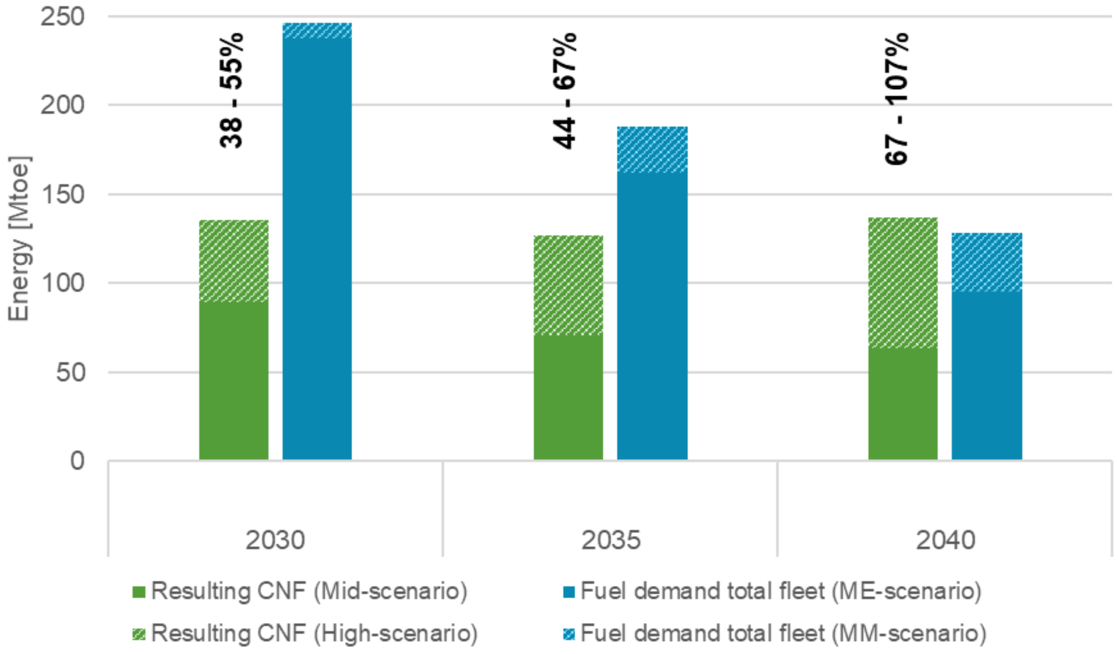


Figure 2: Coverage of the total fuel demand of the road sector with renewable fuels.

This assumes that sustainability potentials are systematically realised, that competition for use is managed and that technological economies of scale are achieved. The findings underline that CNF does not require structural dependency on imports in the long term but rather allows for a high degree of energy and climate policy resilience.

Conclusion

The study clearly finds that renewable fuels (CNF) represent a viable, scalable pillar for road transport without fossil CO_2 in the EU. In the short term, moderate imports of raw materials or products will still be necessary to achieve 100% substitution of all fossil fuels in the EU. In the medium term, however – no later than 2040 – it will be possible to fully meet fuel demands with renewable raw materials available within Europe. This will require reliable political framework conditions, investment security and a coordinated ramp-up of CNF value chains.

Contents

1 Introduction

Reducing greenhouse gas emissions in the transport sector is a fundamental prerequisite for achieving the EU's climate-protection goals. In addition to efficiency improvements in drive technologies and changes in transport demands, the transformation of the energy sources used will also play a vital role. While growing electrification is seen as a key lever for reducing final energy demand and lowering greenhouse gas emissions in the long term, it is becoming increasingly clear that this alone will not be sufficient to de-fossilise all transport segments in a timely and complete manner. In this context, advanced renewable fuels derived from biogenic feedstocks are gaining importance. The focus is on raw materials that can be classified in accordance with RED Annex IX, Part A (Advanced Biofuels) and Part B (Waste & Residues). [17, 18] To assess the expanded potential of advanced biofuels, additional feedstocks, such as agroforestry, must be considered and the cap on Annex IX, Part B feedstocks must be lifted.

Public debate often calls for the use of sustainable fuels exclusively in sectors where battery-electric solutions face technical, economic or infrastructural limits, such as aviation and shipping. However, a key success factor for the market ramp-up will be not only scaling renewable fuel production, but also mobilising potential feedstocks and generating strong, reliable demand. To achieve this, all sectors, but especially road transport, must be involved. Shared multi-modal demand enables the creation of markets where economies of scale can be realised and production costs reduced. This also makes sense from a technological perspective: The equipment used to manufacture synthetic fuels generally produces a range of different fuel fractions that can be used in different drive technologies. Dedicated facilities – for example, plants that produce only Sustainable Aviation Fuels (SAF) – do not exist in this form. Economies of scale lead to lower costs for all sectors, rather than creating competition for distribution.

In addition to climate protection, locally produced renewable fuels also contribute to energy independence. Developing biomass potentials in Europe can reduce dependency on imports and strengthen regional value chains. The creation of decentralised production capacities increases supply security and makes the energy and resource system more adaptable in the face of climate and geopolitical risks. In addition to fuels, increased mobilisation of renewable feedstocks provides essential raw materials and energy sources that can be used flexibly in the heating and industrial sectors.

The aim of this study is to provide a clear picture of how advanced raw materials from the EU can be used to produce different types of fuel and how they can help meet the needs of the existing fleet and of a new category of vehicles with CO_2-reduced internal combustion engines (vCNF). A reliable political and regulatory framework that offers long-term investment and planning security and specifically supports the market ramp-up of renewable fuel technologies is a prerequisite for realising the described potential.

2 Methodology

This study provides a comprehensive comparison between European road transport fuel demand (EU27 + Norway, Switzerland and the UK) and the potential production quantities of advanced fuels from European feedstocks (EU27 + UK). The methodology is shown in Figure 3.

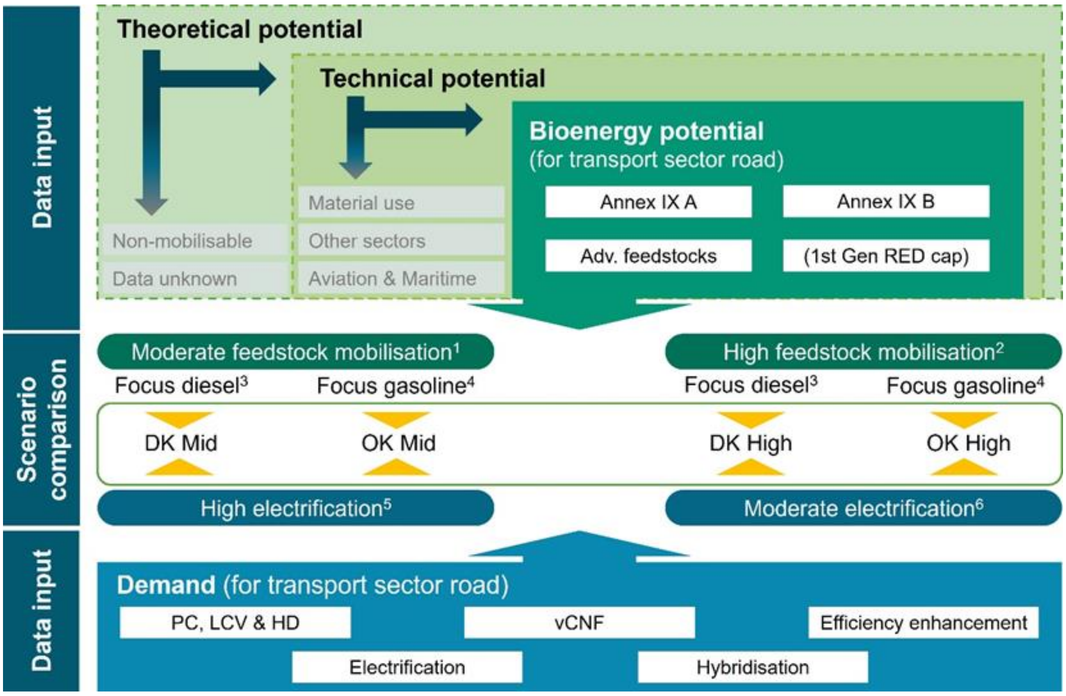


Figure 3: Methodology overview for the final comparative analysis between the available amount of advanced liquid fuels and the demand in the road sector. DK = Dieselkraftstoff / Diesel, OK = Ottokraftstoff / gasoline, 1 = Feedstock potential „Mid“, 2 = Feedstock potential „High“, 3 = Max Middle Distillate, 4 = More Naphtha, 5 = Max Electron, 6 = More Molecule

2.1 EU feedstock potential

Several studies are used to aggregate the bioenergy potential for production of advanced fuels derived from European feedstocks, including the potentials of marginal land, intermediate and cover crops, and agroforestry. This deviates from the regulatory framework of the RED, adjusting the constraints for Annex IX, Part A and Part B feedstocks and supplementing the previously mentioned feedstocks to demonstrate the expanded European feedstock potential. This results in a Mid- and High-scenario, which essentially differ in their feedstock mobilisation rates.

2.2 Conversion to liquid fuels

From the two bioenergy potentials mentioned above, the requirements of other sectors (industry, energy, households, agriculture, aviation and shipping) are deducted (Section 4.3.3) and the remaining biomass allocated to different conversion pathways. The selected conversion pathways are optimised with respect to the characteristics of the available feedstocks, e.g. UCO follows the HVO pathway. The efficiencies underlying these conversion pathways are consistent with current scientific findings. Two scenarios are developed here:

- *Max-Middle Distillate scenario (Max-MD)*: Conversion pathways are selected to ensure the maximum energy output is generated using middle distillates (diesel).
- *More Naphtha scenario*: Based on the Max-Middle Distillate scenario, the conversion is controlled to ensure that total demand for liquid fuels in both the diesel and gasoline sectors can be met optimally.

2.3 EU demand for liquid fuels

On the European fuel demand side, the More-Molecule- (MM) and Max-Electron-scenarios (ME) form the basis of the S&P Global Study [47], but only liquid fuel demand is considered here. These scenarios outline the needs of the entire road transport fleet, with the MM scenario assuming a moderate increase in electrification, while the ME-scenario assumes a highly ambitious increase. The current study also simulates a vCNF fleet for diesel and gasoline internal combustion engines, which is factored into calculations from the second half of 2027 (diesel) and the second half of 2030 (gasoline), respectively.

2.4 Comparative analysis

In the following, the demand and fuel quantities derived from the feedstock potentials are compared. The conversion scenarios from the Mid-scenario for feedstock potential are paired with the more highly electrified ME-scenario (DK-Mid or OK-Mid, respectively). The higher demand for liquid fuels in the MM-scenario is reflected in the higher feedstock mobilisation rate of the High-scenario and the resulting fuel quantities in the conversion scenarios (DK-High or OK-High, respectively). The methodology for creating the scenarios is shown schematically in Figure 4.

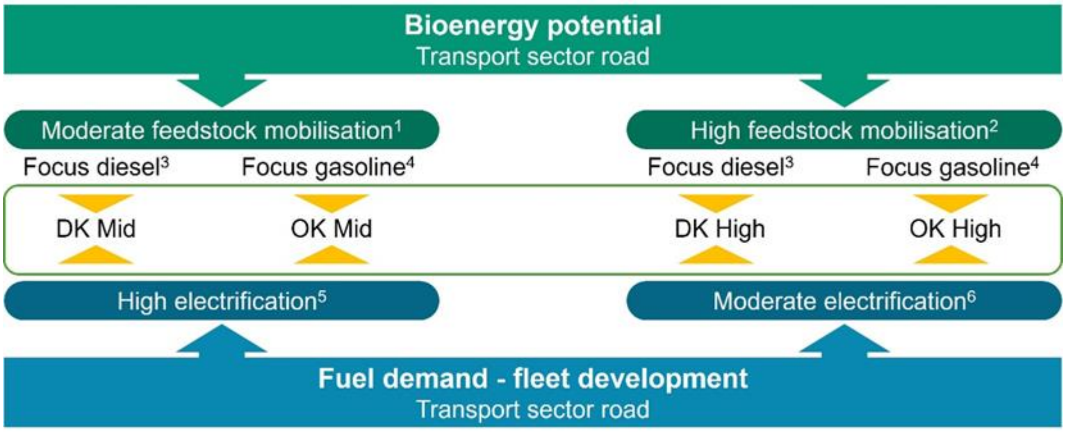


Figure 4: Scheme of the applied scenarios and how they were paired in the comparative analysis. DK = Dieselkraftstoff / diesel, OK = Ottokraftstoff / gasoline, 1 = Feedstock potential „Mid“, 2 = Feedstock potential „High“, 3 = Max Middle Distillate, 4 = More Naphtha, 5 = Max Electron, 6 = More Molecule

3 Feedstock potential

The following section provides an overview of biomass potentials in Europe, as well as a look at the global context. A regulatory classification of biogenic resources for the production of renewable fuels is provided in Annex 7.1.1. The focus is on biogenic residues and waste materials. The analysis is supplemented by a qualitative assessment and assumption-based potential scenarios for non-food crops from marginal or degraded land, intermediate and cover crops, as well as agroforestry, with a focus on the EU. Food and feed plants, on the other hand, are not part of the potential analysis.

3.1 Methodology & procedure

3.1.1 Potential of biogenic residues and waste materials in the EU

The EU potential studies included in the analysis are defined based on specific selection criteria, with particular emphasis on the potential of biogenic residues and waste materials, methodological transparency and the recency of the studies. The following potential studies were considered: ENSPRESO [46], Concawe [43] and Searle [48]. To ensure comparability, scenarios with similar characteristics are preferred, focusing on Mid- and High-scenarios. In addition, the biomasses used in the studies are aggregated into overarching biomass categories and potential levels to enable standardised representation. Figure 5 provides an overview of the biomass potential levels used in the individual studies.

- Technical potential is defined as the share of theoretical potential that can be utilised under technical constraints (e.g. recovery rate) and specific sustainability requirements (e.g. humus balance) [7]. This could also be described as extractable yield.
- The mobilisable technical biomass potential is the unused portion of the technical potential as calculated on a balance-sheet basis. This corresponds to the technical potential minus energy use, non-energy use and, where applicable, other uses [40].
- Bioenergy potential encompasses the technical biomass potential that is not currently used as material and is thus theoretically available for energy use. Existing energy uses, as well as the mobilisable technical potential, are elements of the bioenergy potential [40].

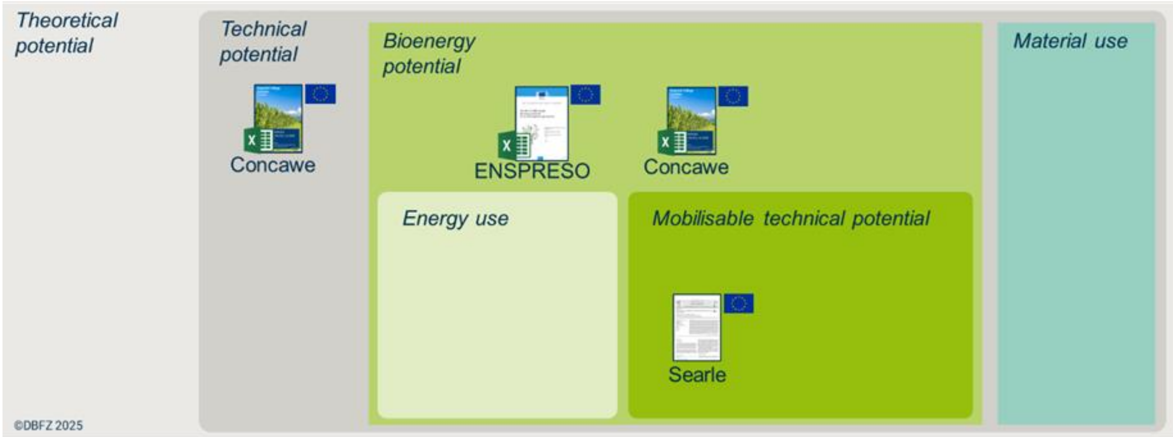


Figure 5: Hierarchy and overlap of different biomass potential levels and assignment of the studies examined for the EU; Figure based on Naumann et al. [40, 41].

The quantities and units specified in the studies, such as tonnes of dry matter or petajoules, are shown in million tonnes of oil equivalent (Mtoe), using appropriate calorific values and conversion factors (dry or fresh mass). For dates not explicitly identified in the underlying studies (e.g. 2027, 2035 and 2040), an estimation is made using linear interpolation of the respective biomass subcategories. To adequately reflect their specific relevance for certain conversion routes, oil-containing residues and waste materials are presented separately, provided they were previously explicitly included in overarching biomass categories.

3.1.2 Global potential of biogenic residues and waste materials

The selection of relevant potential studies for the global context is based on defined criteria, with the aim of ensuring the most comprehensive coverage possible of the potential of biogenic residues and waste materials. To achieve a broad data basis, the focus is on global meta-studies of biomass potentials. In particular, the IRENA meta-study [31], which evaluates global biomass potential studies from 2003 to 2014, is taken into account. Further studies on the global context can be found in Annex 7.1.3. The biomass potentials of the different studies included in IRENA [31] do not refer to a uniform potential level. In fact, the IRENA meta-study refers to a total of 35 studies with different potential levels (theoretical, technical, economic, sustainable or other). To estimate the maximum global biomass potential and highlight possible European import requirements in a global context, further analysis is limited to the Max scenario. All units in the global potential studies are indicated in Mtoe, using appropriate conversion factors. For the purposes of the study [31], potentials for certain periods (e.g. 2025-2035) are uniformly assigned to the target years (2025, 2027, 2030 and 2035). Separate reporting of oil-containing residues and waste materials for specific conversion routes is not possible in studies of global biomass potentials, since these are not individually identified in the underlying studies, due to the high degree of aggregation of biomass.

3.1.3 Potential scenarios for non-food crops from marginal or degraded land, intermediate and cover crops, and agroforestry in the EU

The data for intermediate[1] and cover crops[2] is based on a report compiled for the European Commission on the ramp-up of production infrastructure for advanced biofuels [52], which sets out scenarios for the cultivation of intermediate and cover crops in the EU, based on the Mid- and High-scenarios outlined below. These scenarios factor in various assumptions regarding land, yield and mobilisation rates. In addition, relevant vegetation zones for the possible cultivation of intermediate and cover crops are considered in the cited study, based on the publication by Metzger [39] (see Figure 6).

1 Crop sown after the growing period of the main crop. i.e. vegetation period must be long enough for both the main crop and short intermediate crop [52].

2 Crop sown after the main crop during the winter to prevent soil loss. i.e. vegetation period for the main crop only [52].

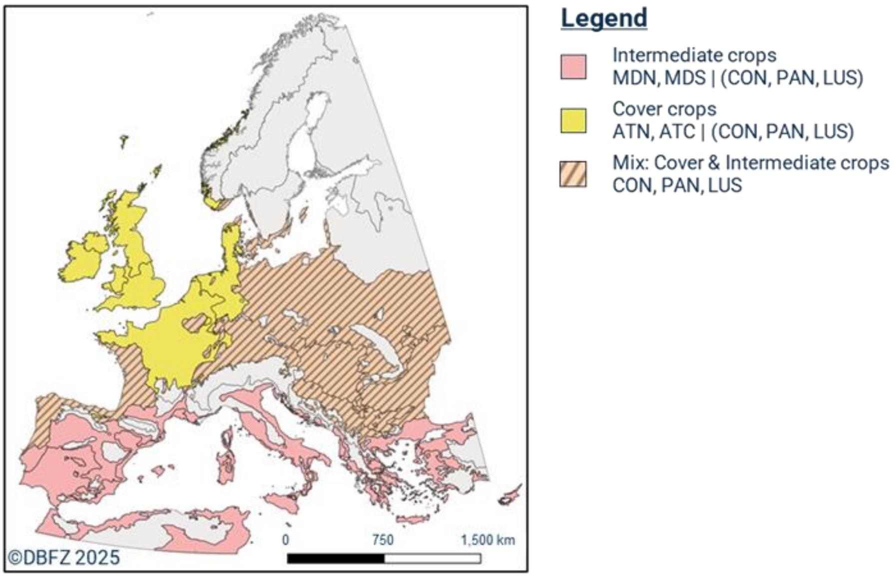


Figure 6: Assumptions for vegetation zones for intermediate and cover crops; Own illustration based on [39, 52].

The expanded list of raw materials for advanced and waste-based biofuels [23] includes non-food crops from severely degraded land, defined by RED II as land "that, for a significant period of time has either been significantly salinated or presented significantly low organic matter content and has been severely eroded" [17]. Precise limits for these requirements are not yet available, but are likely to be implemented going forward through Implementing Regulation (EU) 2022/996 [22]. However, to address this issue, the study uses data based on the Mid- and High-scenario of non-food crops from severely degraded land according to Wageningen [52], whose land estimates are based on the methodology of Conservation International [9]. The non-food crops suitable for cultivation and their corresponding yields are based on the EU projects MAGIC and BIKE included in the Wageningen study [45, 15, 52].

Although non-food crops from marginal land have not yet been included in the EU raw materials list [23], they could also qualify as low ILUC (Indirect Land-Use Change) feedstocks [13]. Therefore, further data for non-food crops from marginal land is presented as a scenario in line with Vera et al. [51]. The study by Vera et al. [51] considers land-use and land-cover data [24, 36], marginal land based on MAGIC [14] and land-exclusion criteria according to RED II Article 29 [17] for the possible cultivation of non-food crops. Furthermore, a distinction is made between a mid (75%) and high (100%) mobilisation scenario, based on Hoefnagels et al. [30] and relating to the mobilisation of identified potentials according to Vera et al. [51]. Since the potential does not include oil-containing non-food crops, a small share of 2.4-2.5% is also assumed for the period 2030 to 2040, based on the percentage of vegetable oil obtained from oil-containing non-food crops on degraded land according to Wageningen [52]. It should be noted that, in accordance with the new requirements of the revised RED II, heathland areas are also excluded [18] and parts of the land identified by Vera et al. [51] is already in use [53]. This is not accounted for in the data. In addition, data from the scenarios for severely degraded and marginal land is not simultaneously assumed for use or conversion in Section 4, as certain overlaps between areas are likely.

Finally, a scenario for the cultivation of agroforestry in the EU is presented. Driving force behind this is that, according to studies, agroforestry systems can have a positive influence on crop yields, especially in dry soils (e.g. by providing shade and shelter from wind). In contrast, according to Böhm et al. [6], the positive effect on crop yields is small or non-existent for soils with a plentiful water supply. The potential increase in productivity of agroforestry systems compared to monocultures is described using the Land Equivalent Ratio (LER). If the overall productivity of arable crop production increases such that yield gains partially or almost entirely compensate for land losses (due to hedgerows), wood from agroforestry could potentially be assessed as a low-ILUC feedstock, provided this positive impact on yield can be demonstrated. In quantitative terms, agroforestry is considered to be an assumption-based potential scenario aligned with Germany’s political objectives (200,000 ha by 2027) [37], targeting an arable land share of around 1.7% in Germany. With no precise targets for the EU as a whole, the agroforestry efforts of individual member states vary greatly. It is therefore assumed that Germany’s 1.7% target will count towards the EU's arable land from 2030, corresponding to a total area of around 1.7 million hectares. The assumptions for yields (~5-7 t_{TM}/ha/a) and the corresponding calorific values (18.65 MJ/kg_{TM}) are based on Wageningen and Kaltschmitt et al. [52, 32]. Potential overlaps between these areas and the previously mentioned marginal or severely degraded land cannot be ruled out, although, in general, dry arable land is the primary focus of this agroforestry scenario. Therefore, this data is subject to considerable uncertainty and is strongly assumption-based regarding ambitious implementation of agroforestry systems.

3.2 Findings

3.2.1 Potential of biogenic residues and waste materials in the EU

The EU's biomass potentials (mean values and min/max values, see Figure 7) show a wide range. This is mainly due to the respective potential levels considered, the individual biomass types, assumptions regarding competition for use and sustainability criteria, the underlying data basis, the time horizon and the scenario-specific assumptions [40, 41]. The bioenergy potential based on Concawe averages 314-321 Mtoe for the period from 2030 to

2040. The bioenergy potential of biogenic residues and waste materials (excluding roundwood/stemwood, energy crops and imports) averages 197 Mtoe for this period. The ENSPRESO database outlines a bioenergy potential of 259-270 Mtoe for the years 2020 to 2040. In this study, biogenic residues and waste materials (excluding roundwood/stemwood and energy crops) amount to 142-131 Mtoe (trending downward). Searle's data for the potential level of mobilisable technical biomass potential (exclusively biogenic residues and waste materials) ranges from 71 to 70 Mtoe between 2020 and 2030. The High-scenarios for bioenergy potentials are significantly higher than the scenarios and potential levels previously referred to. Concawe’s High-scenario for bioenergy potential amounts to 395-412 Mtoe (residual and waste materials: 236-244 Mtoe) for the period from 2030 to 2040. ENSPRESO’s High-scenario assumes a range of 414-461 Mtoe for 2020 to 2040.

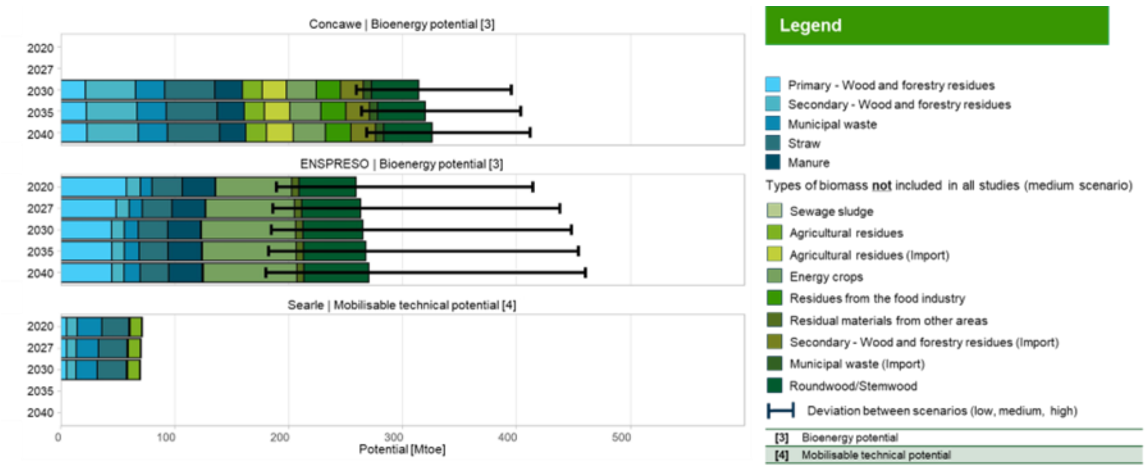


Figure 7: Biomass potentials (mean values and scenario ranges) of different studies for the EU.

As already outlined in Section 3.1.1, only Concawe and ENSPRESO employ the same potential level; for this reason, the results of the Searle study are not considered further in Section 4. The further calculations in that section concentrates on the Concawe data [43], since the study focuses on raw materials in the context of RED II [17] and on biogenic residues and waste materials, in particular. The study also includes greater detail on oil-containing residues and waste materials, which are particularly suitable for use in the HVO conversion pathway. Furthermore, Section 4 and/or potential usage for conversion to renewable fuels focus on the Mid- and High-scenarios, as the aim is to show a free-market-oriented approach. This is also intended to illustrate the extent of utilisation that could potentially result if there is corresponding hypothetical market demand.

3.2.2 Global potential of biogenic residues and waste materials

The biomass potentials highlighted by studies with a global focus show even greater differences and associated uncertainties than European studies. For this reason, no comparison is drawn at this point, and only the IRENA meta-study is [31] considered and visualised in Figure 8. The findings of further global biomass potential studies can be found in Annex 7.1.3. In the Max-scenario, the study [31] shows biomass potentials of up to around 9,000 Mtoe (arithmetic mean of 3,342 Mtoe) for 2025 to 2035 and up to almost 28,000 Mtoe (arithmetic mean of 5,780 Mtoe) for the period from 2040 to 2050. However, these potentials not only include residual and waste materials, but also renewable raw materials (energy crops) and algae. The share of energy crops in the Mid-scenario is 35% for 2025 to 2035 and 44% for 2040 to 2050. In the High-scenario, on the other hand, the share climbs from 25% (2025 to 2035) to 59% (2040 to 2050). It is also worth noting that, in addition to the global quantities of raw material shown, there is a further significant but unquantified potential that could not be taken into account due to limited data.

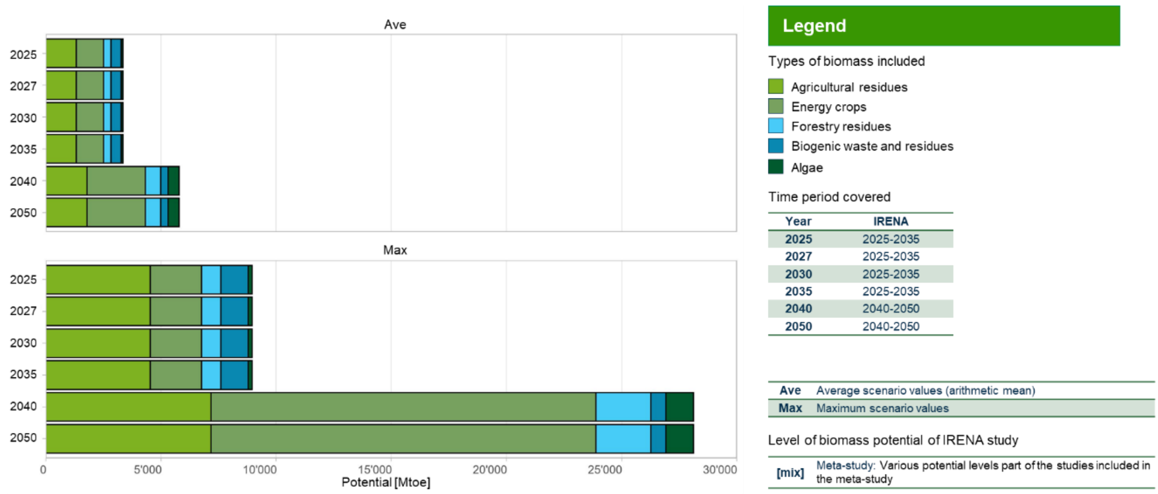


Figure 8: Global biomass potential (mean and max value) [31].

3.2.3 Potential of non-food crops from marginal or degraded land, intermediate and cover crops, and agroforestry in the EU

Figure 9 shows the potential for intermediate and cover crops, as well as non-food crops, from degraded land in the EU, in line with the Wageningen scenarios [52]. The cultivation scenarios make assumptions about mobilisation rates, i.e. the share of land used or mobilised as a percentage of the maximum area reported. For intermediate and cover crops, this rate ranges from 0.5-5% in 2030 to 1-10% in 2050. For degraded areas, the percentages range from 2-10% in 2030 to 5-20% in 2050. The mean value for the potential of the identified cultivation scenarios for intermediate and cover crops is 1.4 Mtoe in 2030, 1.8 Mtoe in 2035 and 2.2 Mtoe in 2040. The minimum and maximum ranges represent the scenarios and/or corresponding assumptions made regarding the cultivated area and mobilisation rates. In the High-scenario, intermediate and cover crops account for 3.7 Mtoe in 2030, 5.1 Mtoe in 2035 and 6.4 Mtoe in 2040. The potential of the cultivation scenarios for non-food crops from degraded land averages 0.9 Mtoe (High: 1.6 Mtoe) in 2030, 2.5 Mtoe (High: 5.6 Mtoe) in 2035 and 4.1 Mtoe (High: 9.6 Mtoe) in 2040.

The potentials of non-food crops from marginal land, based on Vera et al. [51], are much greater. This is primarily due to the assumptions made in the study. According to the study, around 21 Mha of land qualify as marginal areas under RED II. In the Mid-scenario, which assumes a mobilisation rate of 75%, the potentials are 35 Mtoe in 2030, 37 Mtoe in 2035 and 38 Mtoe in 2040. The High-scenario assumes a mobilisation rate of 100%, resulting in potentials of 47 Mtoe in 2030, 49 Mtoe in 2035 and 51 Mtoe in 2040.

The agroforestry cultivation scenarios are based on a consistent area assumption for the EU from 2030 onwards, with a mobilisation rate of 100% for this designated area. The increase in agroforestry potentials therefore largely stems from the range of yield assumptions, calculated using average values and interpolation based on calorific values [52][32] . Overall, this results in agroforestry potentials (mean and high) of 4.1-4.7 Mtoe in 2030, 4.2-4.8 Mtoe in 2035 and 4.3-5.0 Mtoe in 2040.

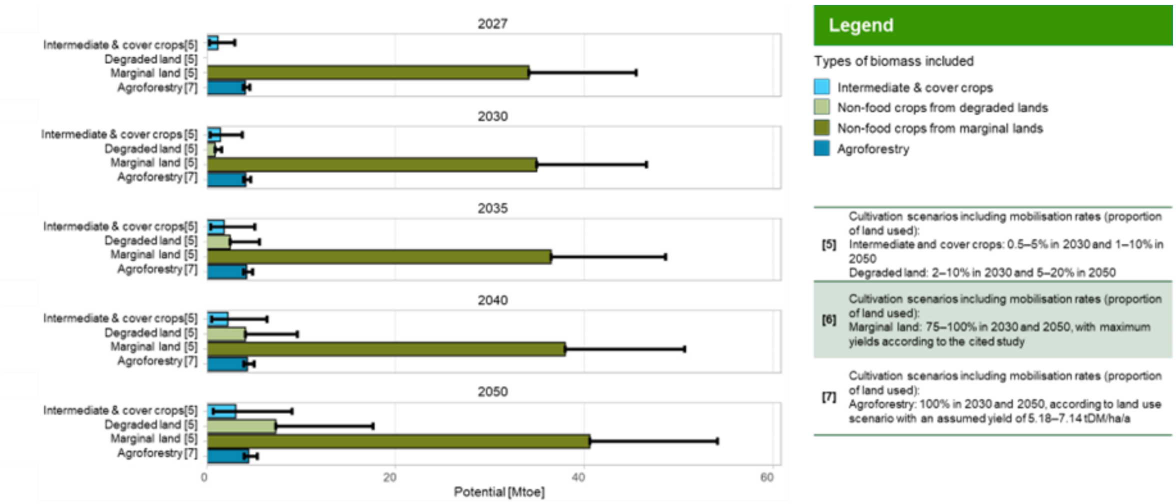


Figure 9: Biomass potentials (mean values and scenario ranges) of intermediate and cover crops, non-food crops from degraded and marginal lands as well as agroforestry; based on [52, 51].

3.2.4 Summary of findings

Finally, Table 2 summarises the EU biomass potential scenarios used in the further course of the study and for the conversion step in Section 4, according to biomass category and timeframe. The data for residual and waste materials, as well as for roundwood/stemwood are based on the Concawe Mid- and High-scenario [43] as shown in Figure 7. The potential data for non-food crops from marginal land [51], intermediate and cover crops [52] and agroforestry (own scenario) are based on the mean and high values of the respective biomass categories in accordance with Figure 9.

Table 2: EU biomass potential scenarios by biomass category over time.

		Bioenergy EU - Mid-scenario -			Bioenergy EU - High-scenario -		
Biomass	**Source**	**2030**	**2035**	**2040**	**2030**	**2035**	**2040**
Residue and waste	Concawe	198.1	194.4	198.1	236.0	239.8	243.7
Roundwood/stemwood	Concawe	41.2	41.7	42.2	70.4	72.2	73.9
Non-food crops from marginal land	Vera et al.	34.9	36.5	38.0	46.6	48.6	50.6
Intermediate and cover crops	Wageningen	1.4	1.8	2.2	3.7	5.1	6.4
Agroforestry	own scenario	4.1	4.2	4.3	4.7	4.8	5.0
Sum		279.7	278.6	284.8	361.4	370.5	379.6

Note: The biomass potential data relating to imports and renewable raw materials reported in the Concawe study [43] are not taken into account here.

Figure 10 visualises the total potentials selected in this chapter, based on the data in Table 2.

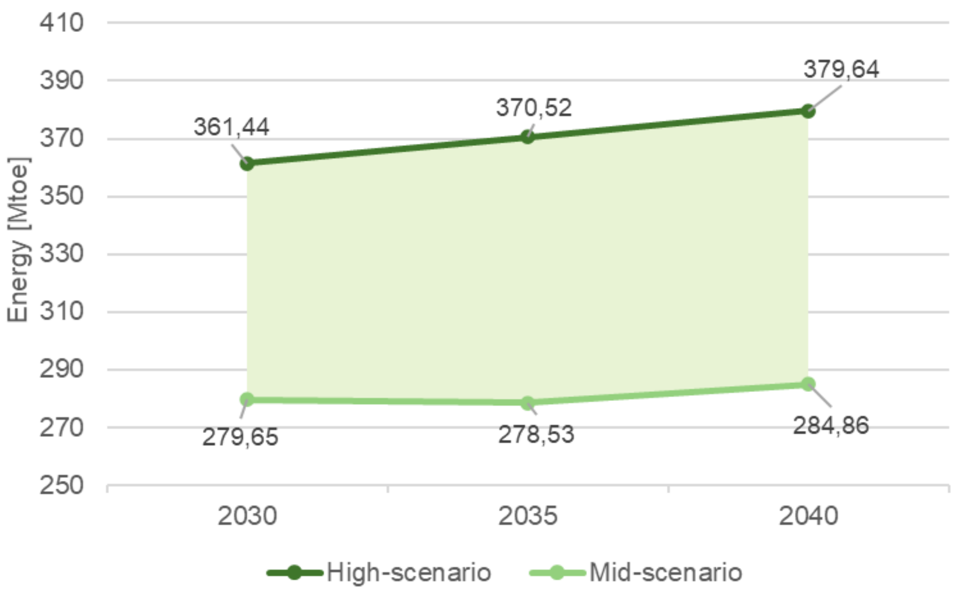


Figure 10: Bioenergy potential in the Mid- and High-scenario, which will be used for the further analyses of the present study.

Data from the Mid- and High-scenarios of the Concawe study is used, and the above potential scenarios for intermediate and cover crops, as well as agroforestry, are taken into account. The potential for energy crops from the Concawe study is replaced by the potential for non-food crops from marginal land according to Vera et al., [51], since the latter includes a much more detailed, far-reaching analysis. The potential for degraded land according to Wageningen [52] is not taken into account here. An illustration of the percentage of individual raw materials in the two scenarios between 2030 and 2040 can be found in Figure 11.

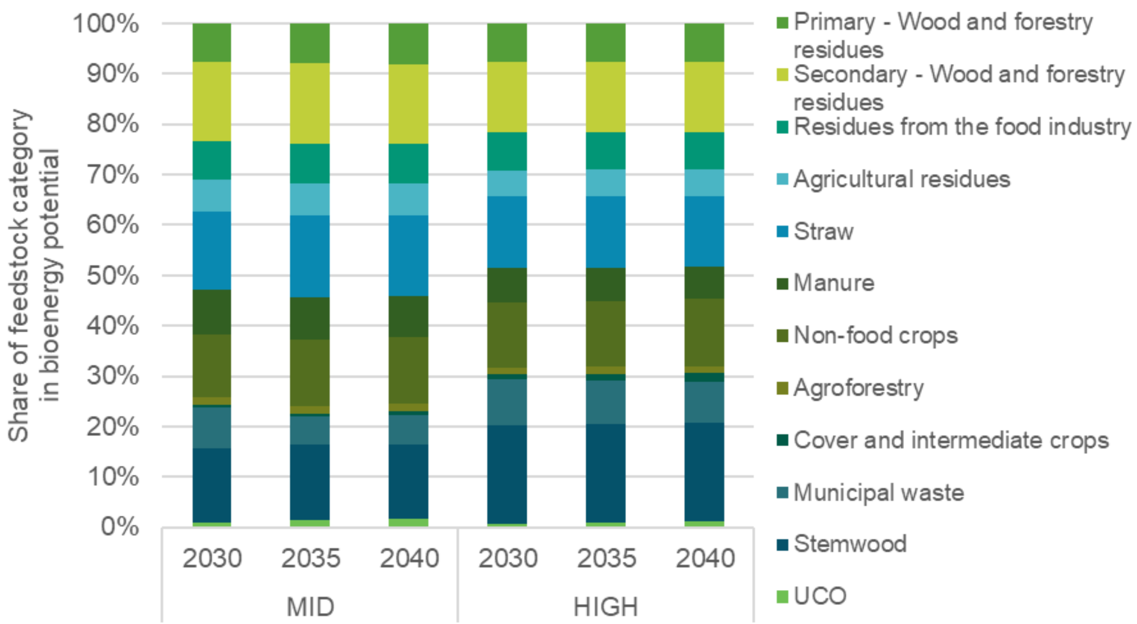


Figure 11: Share of feedstock categories in the bioenergy potential in the Mid- and High-scenario over the years 2030 - 2040.

3.2.5 Notes on interpreting results

The results shown represent an excerpt from the state of research into the biomass potential of biogenic residues and waste materials, both in Europe and globally, as well as potential scenarios for non-food crops from marginal or degraded land, intermediate and cover crops, as well as agroforestry, with a focus on the EU. The comparative analysis of the above biomass potential studies primarily indicates the range of future biomass potentials and highlights the associated uncertainties. For this reason, several publications were reviewed, but the focus subsequently shifted to the EU study [43], which places greater emphasis on advanced residues and waste materials and relies on RED II for context. It should also be noted that the studies analysed do not yet fully take into account RED II/RED III [17, 18] requirements or other sustainability requirements (EU Biodiversity Strategy, LULUCF Regulation). Although the studies make various assumptions about competing uses (within each scenario), future competition for use is not fully addressed, due to increasing demand across different sectors of the bioeconomy (for materials and energy). However, potential requirements for other energy sectors are taken into account in this study, using the EU Impact Assessments for Fit-for-55 and the RED II revision [19, 20], including projected requirements for the maritime and aviation sector. These are then subtracted from the potentials shown here. Finally, it should be noted that overlaps may occur between certain areas in potential scenarios for non-food crops from marginal or degraded land and agroforestry. Therefore, to avoid double-counting, this study examines only contributions from marginal land. Potential scenarios for non-food crops from degraded land are omitted.

4 Conversion to biofuels

4.1 Technical background

Different technologies can be used to convert biomass into various advanced renewable fuels in accordance with the RED. This study calculates the quantities of fuel that can be produced, based on projected biomass potentials. Most notably, the following technologies are considered:

1.) The hydrogenation of fats and fatty acids to hydrocarbons, referred to here as the HVO or HEFA process, or HVO for short.
2.) Partial oxidation of biomass to synthesis gas, with subsequent (multistage) synthesis of hydrocarbons, in particular through
    a.) Methanol synthesis and subsequent oligomerisation with dehydration to hydrocarbons, resulting in chain lengths in the range of typical gasoline (petrol) fractions, referred to here as the methanol-to-gasoline process or MtG for short.
    b.) Methanol synthesis with subsequent dehydration to short-chain olefins, followed by their oligomerisation and hydrogenation to hydrocarbons, predominantly with chain lengths in the range of typical middle distillates (diesel and kerosene fractions), referred to here as the methanol-to-X process, or MtX for short.

Other technologies are available, but not considered here, due to a lower expected conversion efficiency and yield; however, these are, in principle, also suitable for production of advanced biofuels.

4.2 Determination of conversion factors

To calculate the quantities of fuel that can be produced from the projected raw material potentials, energy conversion factors are determined for the process chains outlined above. After allocation to the appropriate processes, these can then be used to convert raw material potentials into corresponding fuel quantities.

4.2.1 Data basis

The main data basis for determining the conversion factors for synthesis-gas-based processes (MtG and MtX) is the evaluation of operating data from the bioliq® pilot plant [16, 33] at KIT Campus North and various design studies on methanol-based fuel syntheses [42], which have been compiled within the scope of research projects by plant engineering companies and technology providers (as contractors), as well as KIT-IKFT. This is empirical, unpublished data.

To determine the conversion factor for HVO production, available literature is used and supplemented by the study's own calculations [50].

4.2.2 Conversion factors

First, using the available data, mass and element balances are created for each process step. These are then used to calculate conversion factors (based on carbon and mass) for the respective block, comparing only the relevant carbon-containing material flows. A total conversion factor is calculated by multiplying the conversion factors of the blocks relevant to the overall process. The energy conversion factor can then be calculated from the mass-related conversion factor for the overall process, using calorific values known from the literature [49] or determined by the study's own measurements.

In the standard synthetic fuel process chain, the H_2/CO ratio in the synthesis gas is adjusted by a water-gas shift (WGS) reaction, producing CO_2, which is no longer available for synthesis. Alternatively, hydrogen can be added, if available, thereby significantly increasing the carbon yield and thus the fuel yield. This is referred to as the PBtL variant (Power-and-Biomass-to-Liquid vs. BTL – Biomass-to-Liquid) of the respective process. Conversion factors are also calculated for this case. These factors, like the standard factors, merely relate the quantity of fuel that can be produced to the amount of biomass used for this purpose; the additional hydrogen is therefore not taken into account energetically.

In each of the above mentioned processes, several hydrocarbon fractions are produced, with the design studies focusing on production of at least one standard-compliant fraction. However, these differ between the various publications, and by-products and fuel fractions not relevant to this study are also considered. Furthermore, this study focuses on liquid fuels for road transport, on the one hand, and, on the other, on the maximum quantities that can be produced without factoring in other framework conditions. The relevant material streams are therefore aggregated into the categories "naphtha" for gasoline-like fractions and "middle distillate" for diesel-like fractions.

The conversion factors listed in Table 3 result from the processes considered here. The factors are provided for both the naphtha and middle distillate fractions.

Table 3: Conversion factors used in the different conversion paths.

Process	Fraction	BtL conversion factor	PBtL conversion factor	PBtL-H_2-demand [Mtoe]
HVO	Naphtha	0.06	-	-
	Middle distillate	0.88	-	
MtX	Naphtha	0.09	0.16	0.56
	Middle distillate	0.43	0.77	
MtG	Naphtha	0.46	0.83	0.56
	Middle distillate	-	-	

4.3 Calculation of fuel potentials

To calculate fuel potentials, the biomass potentials previously determined under appropriate assumptions, as outlined in Section 3.1, are multiplied by the conversion factors. Biomass potentials are allocated proportionally to the processes considered here, with the percentages depending, in particular, on the suitability of the feedstocks for the respective process chains and the projected demand.

The available biomass potentials are divided into broad categories, in some cases including very different biomasses that exhibit diverse processing characteristics. Since these categories cannot be meaningfully further broken down, certain assumptions must be made regarding their composition and resulting suitability for the respective processes. In addition to allocation to the conversion methods considered here, competing uses with other industrial sectors and other modes of transport must also be taken into account.

4.3.1 HVO feedstocks

Feedstocks for production of HVO are very limited. However, HVO is a high-quality renewable fuel, produced at an acceptable cost, that is already established on the market. Therefore, from a free-market perspective, it is assumed that all suitable feedstocks will be used for this purpose and are not subject to competing uses.

4.3.2 MtG and MtX feedstocks

The two processes share the same upstream process chain up to methanol; therefore, in principle, the same feedstocks are suitable. The distribution of feedstocks between the MtG and MtX process chains is thus based on demand for petrol and diesel fuels. Two scenarios are developed: a balanced scenario in which approx. 15-20% of the feedstocks used are allocated to the MtG process (More-Naphtha-scenario), and a scenario with maximum middle distillate yield, in which available feedstocks are fully allocated to the MtX process (Max-Middle-Distillate-scenario).

Both process chains are based on the partial oxidation of biomass, following prior pyrolysis of the biomass for energy densification. Dry, lignocellulosic materials such as wood and straw are particularly suitable for this purpose. These are also the raw materials used at the bioliq® pilot plant, on which this calculation is based. In principle, (almost) all biogenic organic materials can be subjected to gasification after appropriate pretreatment, although this may require the use of other technologies. For simplicity, it is assumed that the same conversion factors can be applied, regardless of the biomass used.

4.3.3 Deductions for other sectors

Biomass is generally subject to competition for use, both for material and energy. Raw material potentials are therefore reduced by certain quantities, which are derived from the literature [19, 20]. Annex 7.2.1 outlines the methodology for deductions for each feedstock category.

Table 4: Deduction of the demand of other sectors from the bioenergy potentials.

	2030	**2035**	**2040**
Other industries [Mtoe]	143	174	206
Other transport modes [Mtoe]	6	14	22
Sum [Mtoe]	**149**	**188**	**228**

In the results, potentials are not presented separately but are assigned to categories in accordance with RED III, Annex IX.

4.3.4 Quota-based additions for RFNBOs and conventional biofuels

Based on the requirements of the RED [17, 18] and the bill to revise the (German) GHG reduction quota [8], the minimum quotas (excluding multipliers) for RFNBOs and the capped maximum quantities of conventional biofuels are added to the resulting quantities of advanced biofuels.

4.4 Findings

4.4.1 Effective biomass potentials

The original biomass potentials, as outlined in Section 3, increase slightly over the period under review, but remain at a comparable level. However, due to increasing deductions over time resulting from competing use, the biomass potentials effectively available for conversion are significantly lower.

Figure 12: Total and effective bioenergy potentials.

In the High-scenario, the total bioenergy potential lies between 349 and 365 Mtoe over time, with effective potentials between 212 and 114 Mtoe. Accordingly, the share of effectively available potential decreases from 61% to 31%. In this context, bioenergy potentials from non-food crops, intermediate and cover crops, and agroforestry are aggregated in Figure 10 in the category "Other". For the Mid-scenario, values are similarly between 265 and

269 Mtoe for original bioenergy potential and between 212 and 114 Mtoe for effective bioenergy potential. The share of effective potential is consistently lower than in the High-scenario, with values between 49% and 21%.

4.4.2 Fuel potentials

Converting the biomass potentials (Mid- and High-scenarios), using the previously determined energy conversion factors in the two conversion scenarios (Max-Middle-Distillate and More-Naphtha), results in a total of four scenarios (see Figure 3).
The two conversion scenarios show some parallels in their timelines. The increasing share of feedstocks allocated to PBtL routes with significantly higher conversion factors partially offsets the decline in effective bioenergy potentials over time. In the High-scenario, the total amount of fuel thus remains at the same level throughout the period under review, while in the Mid-scenario, only the decrease in fuel production is offset. This is also reflected in the effective overall conversion factors, which increase significantly during the period under review, although the factors in the High-scenario are consistently 1-2 percentage points lower than in the Mid-scenario. This is due to the higher proportion of HVO feedstocks, with the quantity remaining roughly constant across scenarios.
Only the results for the Max-Middle-Distillate-scenario are discussed in more detail below.

4.4.2.1 Max-Middle-Distillate-scenario

In the Max-Middle-Distillate-scenario, only the HVO and MtX process routes are used; naphtha is produced solely as a by-product, albeit in relevant quantities.

The fuel potentials range between 117 and 113 Mtoe over time in the High-scenario and between 73 and 43 Mtoe in the Mid-scenario (Figure 13). The effective overall conversion factors increase on average from 56% to 75%. Due to the share of feedstocks allocated to PBtL variants increasing from approximately 5% to approximately 50%, demand for PBtL hydrogen rises from 5.4 to 38.7 Mtoe in the High-scenario and from 3.3 to 14.3 Mtoe in the Mid-scenario.
The naphtha fraction accounts for around 17% of total fuel potential in both the Mid- and High-scenarios. The High-scenario also shows a slight decrease in the naphtha share, but only in the decimal range.

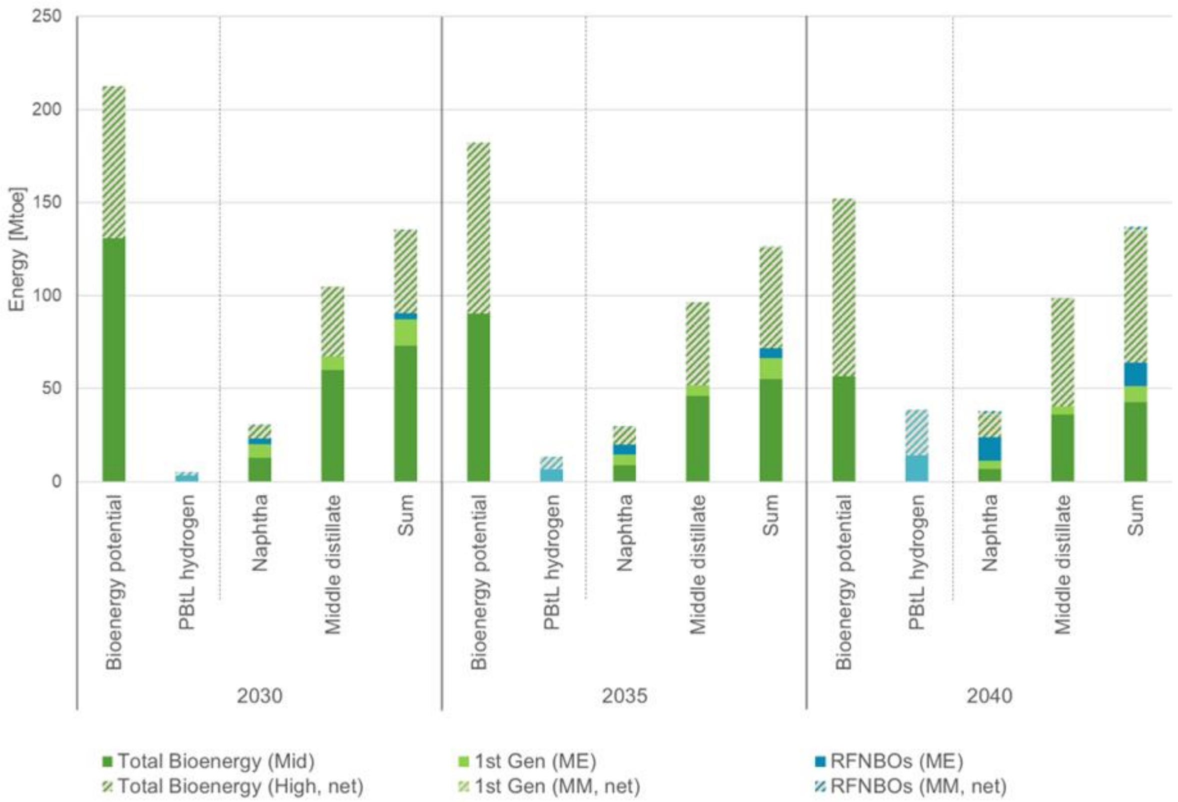


Figure 13: Fuel potentials EU including additions for 1st Gen and RFNBO, Max Middle Distillate scenario.

To calculate potential quantities of available renewable fuels, quota-based additions for conventional biofuels and RFNBOs are assumed, as outlined in Section 7.2.2 . This results in total fuel potentials that are 18 to 24 Mtoe higher in the High-scenario and 18 to 21 Mtoe higher in the Mid-scenario, ranging from 137 (2030 and 2040) to 127 Mtoe (2035) in the High-scenario and from 91 to 64 Mtoe in the Mid-scenario.

4.4.2.2 More-Naphtha-scenario

In the More-Naphtha-scenario, in addition to the HVO and MtX routes, the MtG route is also used, resulting in higher quantities of naphtha but lower volumes of middle distillates. The aim is to create a balanced scenario that achieves the most equal coverage of petrol and diesel demand possible. In this context, with respect to 100% replacement, the percentage substitution potential is not separately quantified, since it is assumed that the available quantities of naphtha could lead to insufficient production capacity utilisation no later than 2040. The total amount of fuel is slightly lower than in the Max-Middle-Distillate-scenario, because the MtG route has a slightly lower total conversion factor. There are no differences due to the specific feedstocks used in the HVO route.

The amount of fuel that can be produced ranges from 133 to 136 Mtoe in the High-scenario and from 89 to 64 Mtoe in the Mid-scenario. The effective overall conversion factors increase on average from 55% to 73%. Due to the share of feedstocks allocated to PBtL variants increasing from approximately 5% to approximately 50%, demand for PBtL hydrogen rises from 5.7 to 41.4 Mtoe in the High-scenario and from 3.5 to 14.3 Mtoe in the Mid-scenario.

The naphtha fraction's share of total fuel potential increases from 23% to 34% in the High-scenario and from 26% to 36% in the Mid-scenario. As desired, this is consistently higher than in the Max-Middle-Distillate-scenario but also ensures a more balanced result.

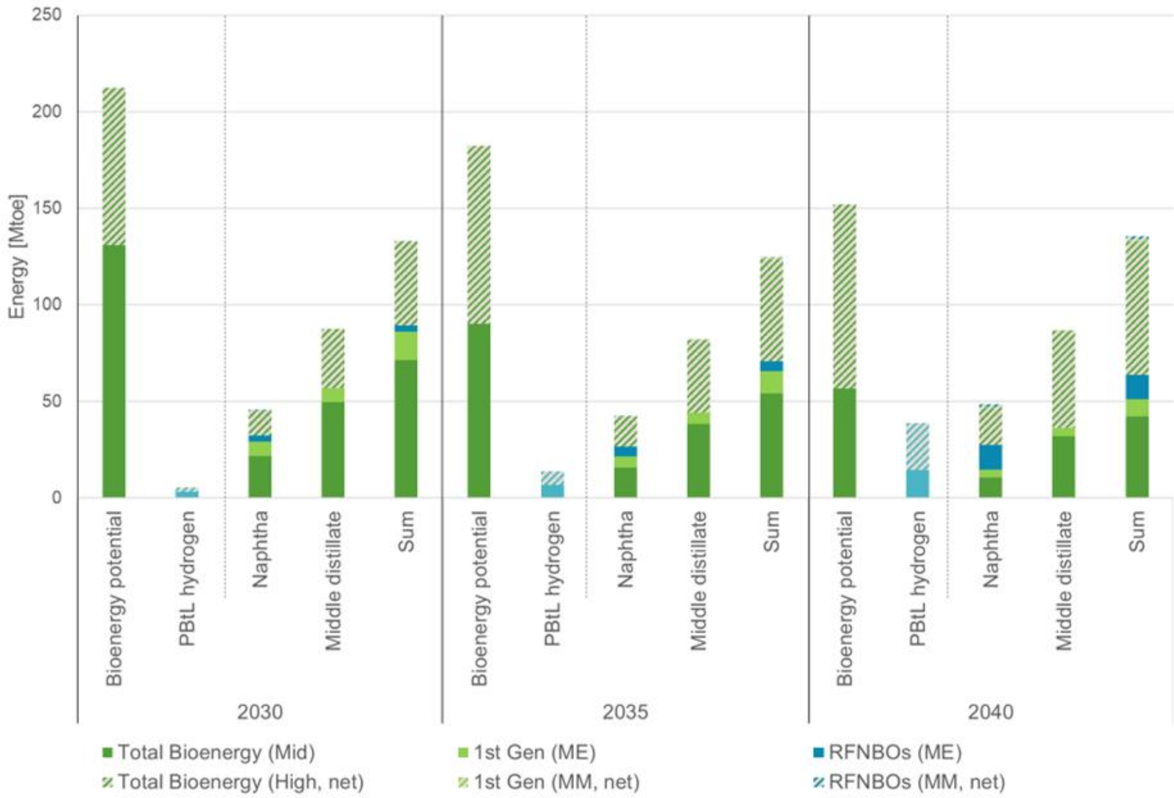


Figure 14: Fuel potentials EU including additions for 1st Gen and RFNBO, More Naphtha scenario.

Including the assumed quota-based supplements for conventional biofuels and RFNBOs, the total fuel potentials increase by 18-24 Mtoe in the High-scenario, and by 18-20 Mtoe in the Mid-scenario. The figures are thus 133 Mtoe (2030), 125 Mtoe (2035) and 136 Mtoe (2040) in the High-scenario and 89 Mtoe (2030), 71 Mtoe (2035) and 64 Mtoe (2040) in the Mid-scenario.

4.5 Conclusions

The findings show that relevant quantities of advanced biofuels can be produced. In addition to the underlying uncertainty inherent in estimating future biomass potentials, actual implementation is also subject to a number of conditions and associated limitations, which can only be considered in an illustrative manner in the scenarios used here.

On the one hand, this concerns the actual realisation of projected biomass potentials, which is associated with increasing effort and expenditure, especially if the potentials are to be fully exploited. On the other hand, an accelerated ramp-up of corresponding production capacity is necessary. This depends on numerous framework conditions and is subject to various technical and economic challenges. Overcoming these obstacles and achieving the targeted disruptive transformation of the energy system will require great effort and a coordinated approach from all parties involved.

How such a market ramp-up can succeed, which framework conditions are necessary and what concrete steps can be taken are currently being investigated in numerous research projects, including several involving KIT.

5 Demand of future vehicle fleet

To compare the identified fuel potentials with the quantities required in the mobility sector, the corresponding demand is determined and compared using fleet development models. For this study, the analysis is based on an existing fleet model [47]. The cited study provides two scenarios: a Max-Electron-scenario (ME) with a high degree of electrification and a More-Molecule-scenario (MM) with a stronger focus on renewable fuels. In the fleet scenario, the latter is reflected in a stronger emphasis on plug-in hybrid vehicles, with a reduced BEV fleet.

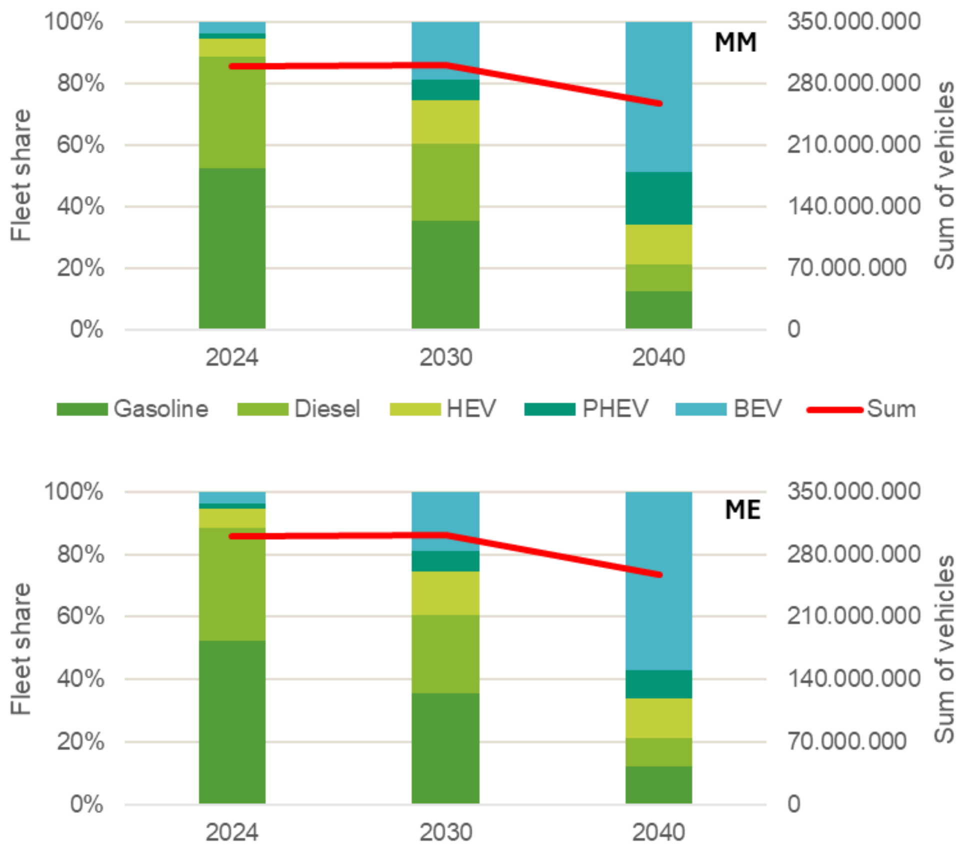


Figure 15: Development of the fleet according to MM- and ME-scenario.

5.1 Calculation of interim years

One aspect of the published fleet scenarios used in the underlying studies is the fleet size in anchor years, which also aligns with the time horizons considered in this study. For the study's own calculation of new vehicle numbers, this data basis is extended using linear interpolation to obtain the relevant data for all years between 2027 and 2040. The scenarios' underlying assumptions regarding the pace of fleet development remain unchanged.

5.2 Breakdown by petrol and diesel vehicles and consumption estimate

Neither scenario further differentiates between hybrid and plug-in hybrid passenger vehicles (HEVs and PHEVs) according to engine technology (gasoline and diesel engines). Since the analysis of fuel potentials is conducted separately for middle distillates and naphtha, further assumptions are made here for the demand assessment. Based on the 2023 distribution, for the purposes of this study, the fleet scenario will be expanded to assume a static distribution of 16% diesel for hybrids and 6% diesel for PHEVs[3].

To estimate trends in new vehicle registrations, a static share is calculated for new vehicles, based on the fleet size in the respective year, using 2023 registration data. The share of new cars in the total fleet in 2023 was 2.98% for gasoline vehicles and 1.58% for diesel vehicles. In the case of hybrid vehicles, the existing fleet is comparatively small, so current new car percentages are significantly higher (35% for HEVs and 15% for PHEVs). Here, the 4.29% average share of hybridised vehicles across all vehicle categories is applied[4]. The corresponding vCNF fleet is calculated as 100% vCNF for diesel vehicles from the second half of 2027 and 100% vCNF for gasoline vehicles from the second half of 2030, as derived from new vehicle distributions. The vCNF category encompasses all passenger cars (PC) powered, entirely or partially, by carbon-based fuels. LPG vehicles are not considered separately here. The classification is similar to dividing the entire fleet into diesel and gasoline vehicles. Calculation of the required fuel quantities assumes that vehicles will be refuelled exclusively with renewable fuels.

Fuel consumption figures for newly registered vehicles are factored into the demand calculation, based on data from the S&P study [47]. For each vehicle category, the vehicle fleet's total fuel consumption is estimated, based on annual mileage and average fuel consumption. The assumed fuel consumption of hybrid vehicles is lower than the figures observed in 2024 fleet monitoring[5]. In particular, the increased use of PHEVs leads, in this case, to a potential underestimation of fuel consumption if the anticipated reductions in average PHEV consumption do not materialise.

[3] Eurostat evaluation [29] based on [27, 26, 28].

[4] Own evaluation of 2023 registration data based on both new cars [27] and existing fleet [1].

[5] S&P estimates 3.97 L/100km for PHEVs; the figure measured in 2024 was 6.1 L/100km [25].

5.3 Total demand

To determine the vehicle fleet's total fuel demand, the fuel requirements of light and heavy utility vehicles are added to the requirements of the passenger car fleet. These are taken directly from the Max-Electron (ME) or More-Molecule-scenario (MM).

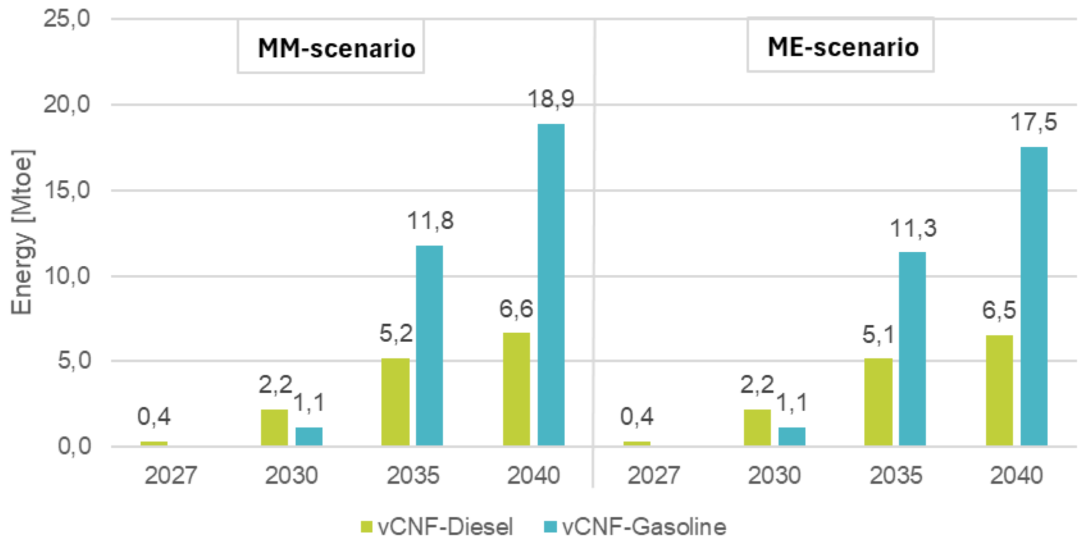


Figure 16: Fuel demand for the vCNF-fleet in the MM-scenario (left) and ME-scenario (right).

Findings

Figure 16 shows the trend in demand for vCNF vehicles with diesel and gasoline engines. In 2040, the difference in diesel fuel demand for these vehicles between the ME- and MM-scenarios is not significant. For vCNF gasoline vehicles, the calculated demand is between 17.5 and 18.9 Mtoe. This development is largely explained by the differing number of PHEV vehicles, which the S&P study [47] mainly assumes to be gasoline-powered. The stronger increase in gasoline demand is also due to the higher share of gasoline engines among newly registered hybrid vehicles, which themselves represent a larger proportion of new vehicle registrations.

Figure 17 also shows the total demand of vehicle fleets in the ME- and MM-scenarios, including an assessment of vehicle inventory. In 2040, vCNF vehicles will account for between 11% and 13% of diesel consumption. Total demand will primarily be driven by heavy duty vehicles (HD). Among gasoline vehicles, the share of the vCNF fleet is projected to rise to 43 - 48% by 2040.

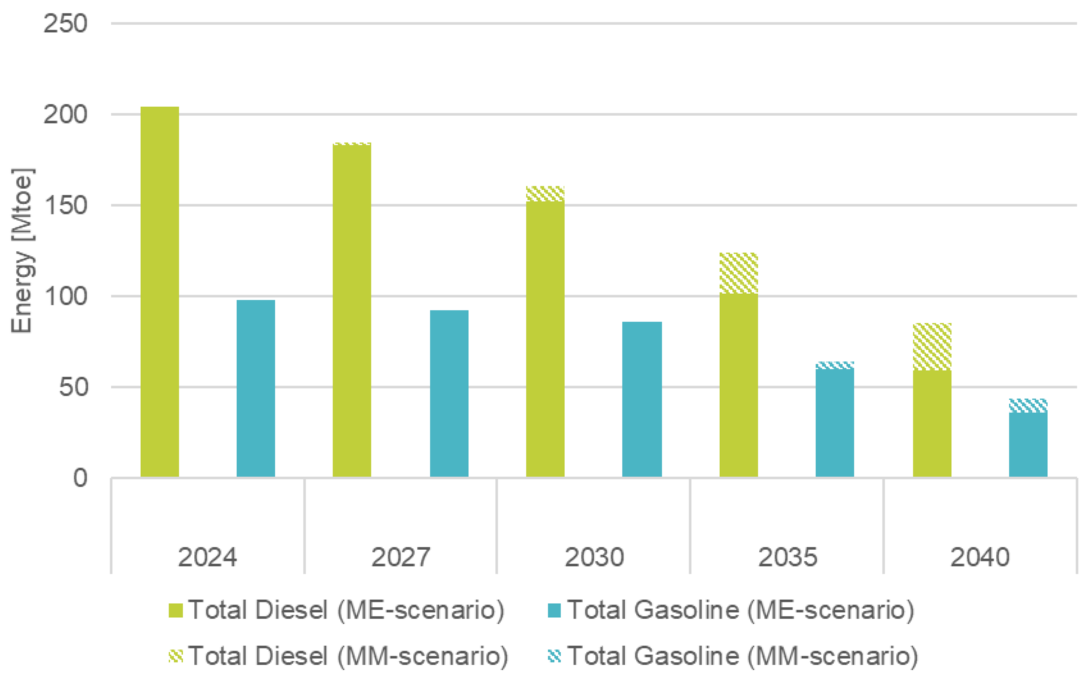


Figure 17: Demand of the total fleet in the ME- and MM-scenario over the years 2024 - 2040.

It should be noted that the values of the S&P study were evidently based on significant fleet replacement, which may not materialise to the same extent, depending on consumer behaviour.

6 Overall findings

The following section compiles the individual findings from Section 4 Conversion and Section 5 Demand and conducts a comparative analysis. For this purpose, as explained in Section 2 Methodology, the resulting CNF quantities from the Mid-scenario are compared to demand in the ME-scenario (OK-Mid and DK-Mid). The resulting CNF quantities from the High-scenario are compared to the MM-scenario (OK-High and DK-High). Information is also provided on the percentage of total demand that could potentially be substituted for each individual fuel, diesel and gasoline.

DK-Mid and OK-Mid-scenarios

The DK-Mid-scenario in Figure 18 shows that, by 2040, 68% of the fleet's total fuel demand can be met. The substitution of individual fuels can be estimated at 69% for diesel and 66% for gasoline.

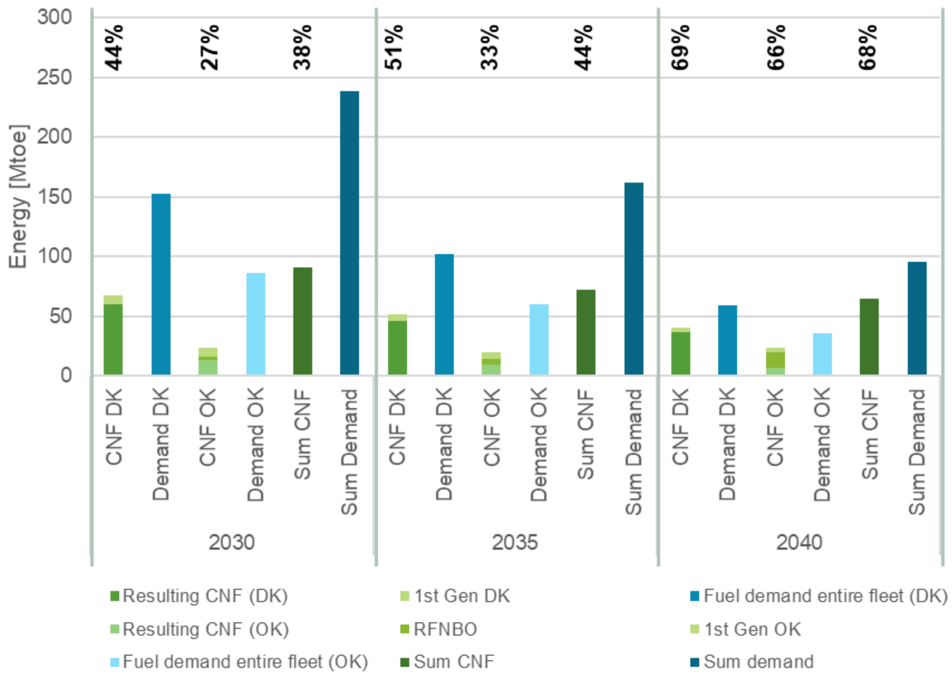


Figure 18: Comparison of the resulting quantities of CNF and the fuel demand of the total fleet for the years 2030 - 2040 in the DK-Mid-scenario.

In the OK-Mid-scenario in Figure 19, 67% of the fleet's liquid fuel demand can be met by 2040. 61% of diesel demand and 76% of gasoline demand can be replaced by renewable alternatives.

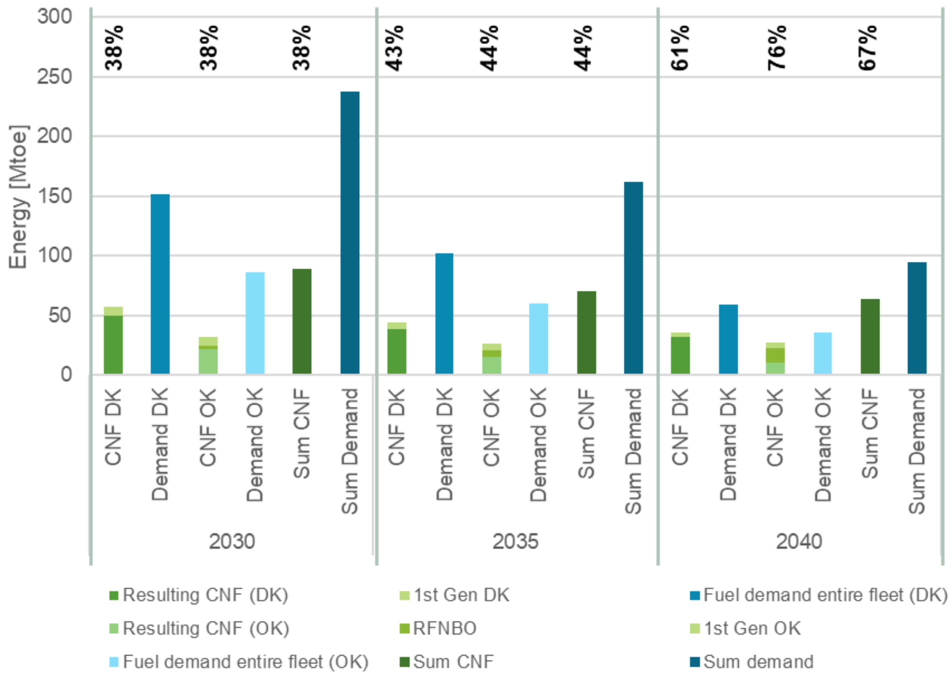


Figure 19: Comparison of the resulting quantities of CNF and the fuel demand of the total fleet for the years 2030 - 2040 in the OK-Mid-scenario.

DK-High and OK-High-scenarios

Analysis of the High-scenarios clearly shows that, by 2040, CNF could comfortably exceed the fleet's fuel requirements.

In the DK-High-scenario, the percentage of total demand that could potentially be substituted rises from 55% in 2030 to 67% in 2035 and 107% in 2040. The individual fuel analysis for 2040 shows that 116% of diesel demand and 88% of gasoline demand are met (Figure 20).

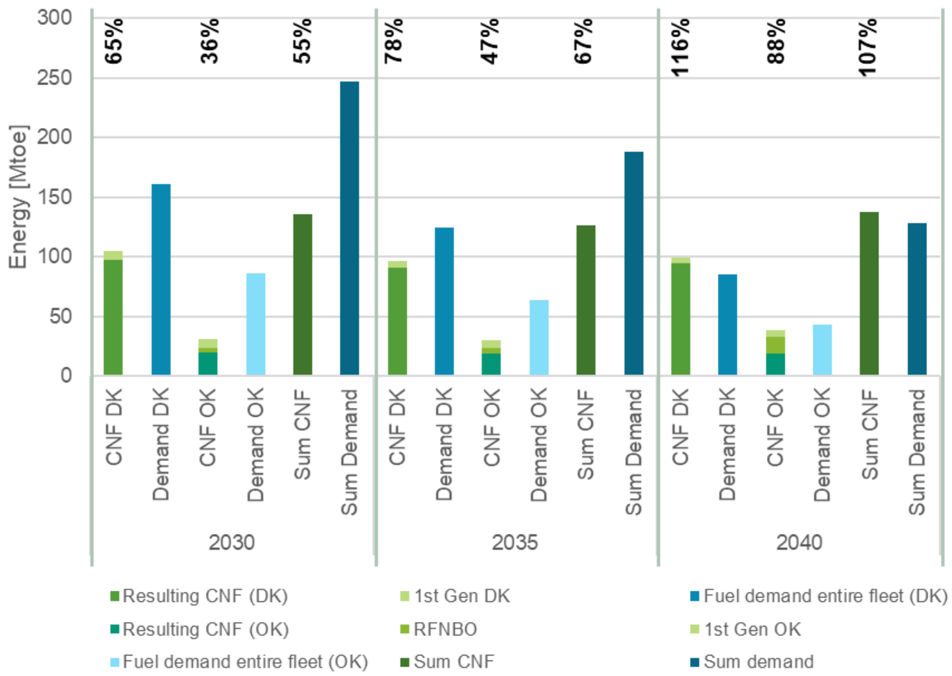


Figure 20: Comparison of the resulting quantities of CNF and the fuel demand of the total fleet for the years 2030 - 2040 in the DK-High-scenario.

A more balanced picture of the substitution potential of individual fuels emerges from the OK-High-scenario in Figure 21. Although the total substitution rate decreases slightly from 107% to 106%, gasoline and diesel demand can be met equally and fully, at 113% and 102% respectively.

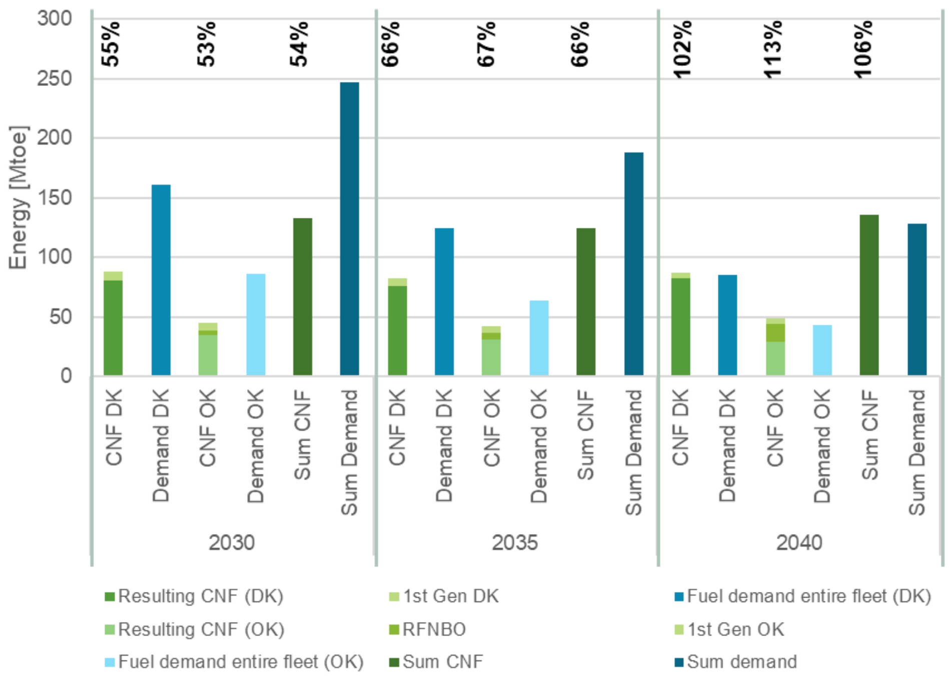


Figure 21: Comparison of the resulting quantities of CNF and the fuel demand of the total fleet for the years 2030 - 2040 in the OK-High-scenario.

Figure 22 provides an overview of the relationship between the resulting CNF quantities and the fleet's liquid fuel demand, when conversion of available feedstocks prioritises the production of diesel fuel.

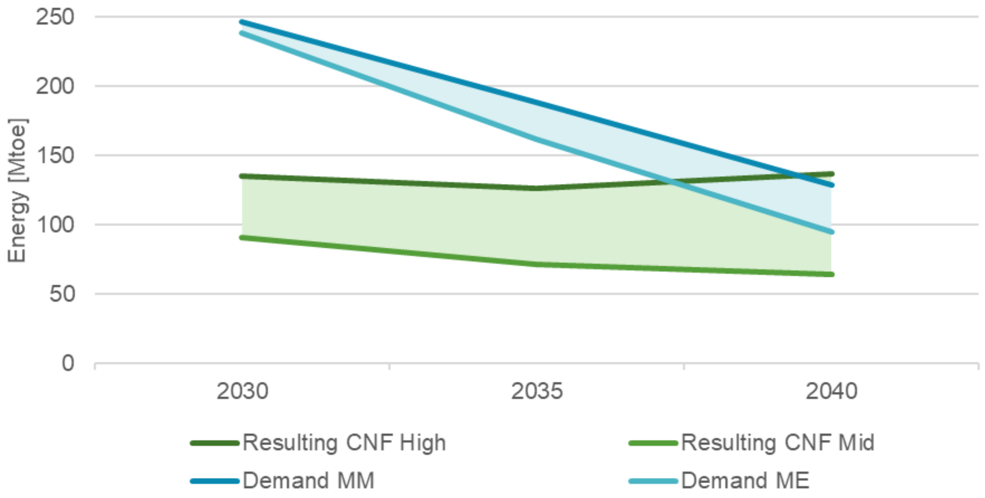


Figure 22: Overview of the relationship between the quantities of resulting CNF and the demand in the different scenarios with a focus on diesel in the conversion.

The analysis illustrates that the synergy between an ambitious electrification scenario (ME-scenario) and the High-feedstock-scenario allows for full coverage of fleet fuel requirements well before 2040. However, by 2040 at the latest, both scenarios result in an overfulfillment of the simulated demand for liquid fuels for road transport. Figure 23 shows a very similar picture, in which the focus of conversion is on achieving a balanced distribution between gasoline and diesel.

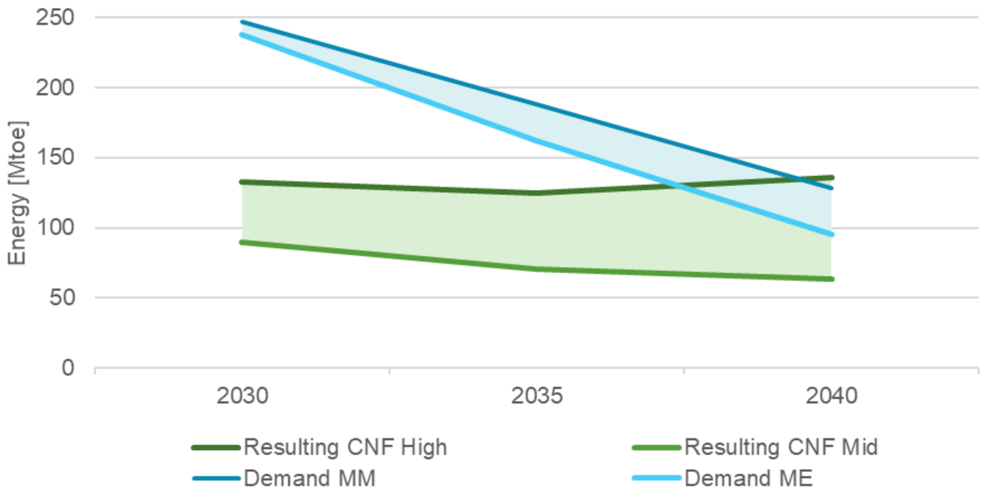


Figure 23: Overview of the relationship between the quantities of resulting CNF and the demand in the different scenarios with a focus on gasoline in the conversion.

The study clearly finds that renewable fuels (CNF) represent a viable, scalable pillar for road transport without fossil CO_2 in the EU and that CNF does not require long-term structural dependency on imports but rather enables a high degree of energy and climate policy resilience. In the short to medium term, imports of raw materials will still be necessary to achieve complete substitution of all fossil fuels. However, in the mid-term – no later than 2040 – it will be possible to meet the fleet's entire demand for liquid fuels from renewable raw materials available in Europe. This will require reliable political framework conditions, investment security and a coordinated ramp-up of CNF value chains.

7 Annex

7.1 Feedstock potential

7.1.1 General regulatory classification of biogenic resources for the production of renewable fuels

Biogenic resources suitable for fuel production can be systematised according to different criteria. Most notably, the regulatory framework and the origins of the resources result in a fundamental differentiation between primary biogenic products – mainly cultivated or agricultural crops, biogenic by-products and biogenic waste materials (see Figure 24). Beyond their origins, biogenic resources are also classified according to their physicochemical properties. In addition to this primarily technical classification, classification in the raw material categories for biofuels in accordance with the European Union's Renewable Energy Directive (RED II/RED III) and its extension by Delegated Directive (EU) 2024/1405 is of central importance [17, 23, 18]. Against this regulatory background, the relevant types of biomass can be classified in five biofuel categories:

- conventional biofuels (especially food and feed crops)
- advanced biofuels (Annex IX, Part A)
- waste-based biofuels (Annex IX, Part B)
- biofuels with a high risk of indirect land-use change (excluded, from certain food and feed crops)
- other biofuels

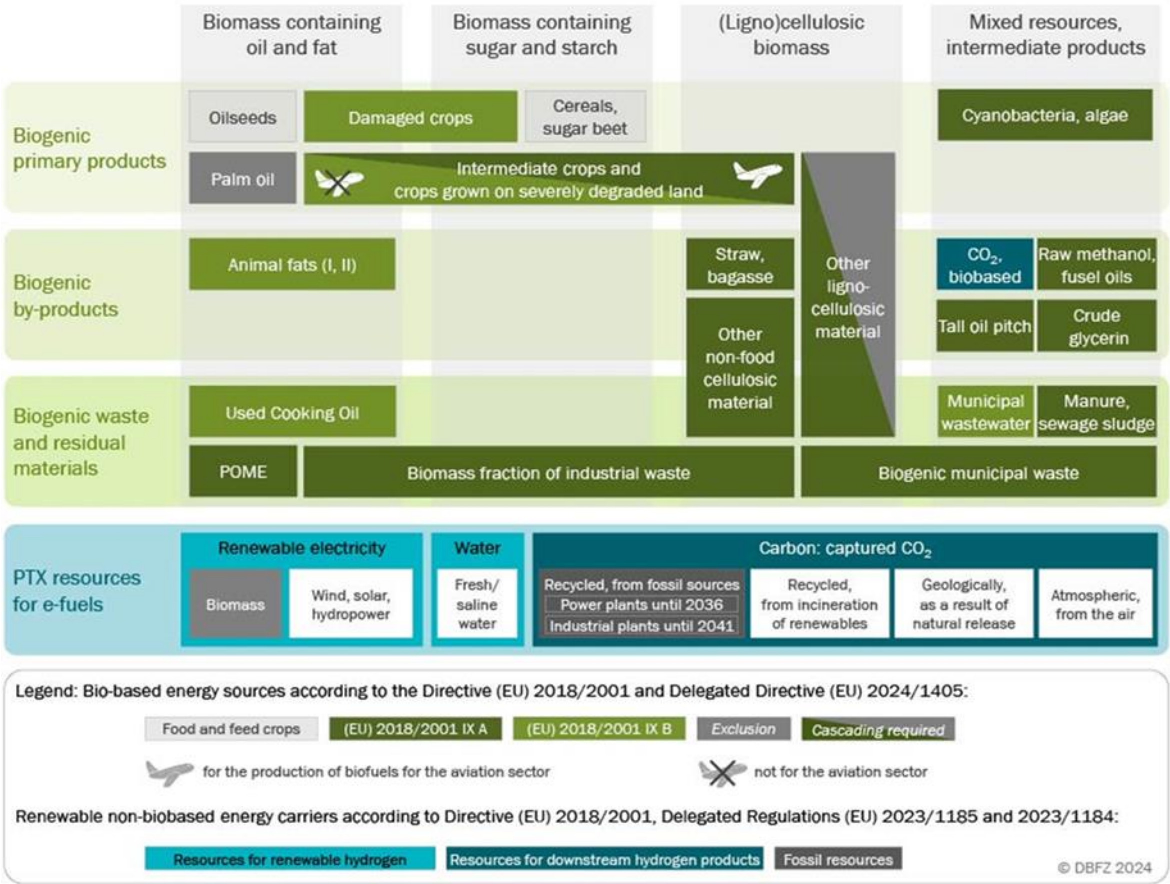


Figure 24: Resources for the production of renewable fuels, categorized according to legal requirements. Source: Naumann et al. [40, 41].

7.1.2 Prospective competition for use

Going forward, competition for use may result in various sectoral shifts in demand for biomass as a whole, as well as for specific types of biomass (e.g. certain residual and waste materials). This includes the following examples:

- Heating: Demand for biomethane could rise in the future, due to the requirements of the German Building Energy Act [11].
- Electricity: Due to the growing flexibility of biogas plants, as well as future policy objectives, the use of biomass for electricity is decreasing, while the share of biogenic residues and waste materials is increasing [2, 5].
- Transport: In line with the EU's ReFuel Aviation and FuelEU Maritime impact assessments, demand for biomass is increasing, above all for aviation and maritime shipping [40].
- Bioenergy: Depending on its national implementation, the cascade principle of RED III could restrict the usability of woody biomass for energy purposes [18]. Currently, woody biomass is used primarily in the heating sector [2].

- Industrial sector (high temperature, e.g. steel industry): The vast majority of climate-neutrality studies (e.g. Ariadne, BDI, Agora) expect demand for biomass in the industrial sector to increase [12]. For example, the Agora Climate-Neutral Germany study shows rising demand for the steel sector [44].
- Chemical industry: Various climate-neutrality studies for the chemical sector indicate growing biomass demand and/or shares [34]. EU political objectives also call for [21] increased use of renewable carbon (biogenic and direct air capture).
- Construction: In the construction sector, demand for wood could increase in the future, due to higher timber construction quotas [4].
- Agriculture/plant cultivation peat substitution: Demand for biofuels for agricultural and forestry machinery must be considered [35] in this segment. The need for certain residual materials for use as peat substitutes is also increasing, due to the reduction in peat extraction and peat use [3].

7.1.3 Other global potential studies

Methodology

In addition to the global meta-potential study [31], the data from the MIT global meta-potential study and [10], are also presented, with a focus on studies from 2011 to 2023. A limitation of both meta-studies is that no data is reported for the target years relevant to this analysis. For this reason, this data is supplemented by the individual study conducted by [38] focused on the global potential of biogenic residues and waste materials in five-year intervals up to 2050. To ensure comparability, moderate or business-as-usual scenarios (BAU) from the respective studies are preferred, also consider existing ranges in the form of minimum and maximum values. Additionally, the biomass reported in the studies is aggregated into overarching biomass categories. The two meta-studies on global biomass potentials do not show uniform potential levels, but rather a mix of different potential levels. In the meta-study from [10], the exact number of studies considered is not explicitly indicated; the potential level for the studies analysed is described as bioenergy potential, although this is probably also a mix of different potential levels. The study by [38] identifies bioenergy potentials, although it states that these refer to sustainable technical potentials. These are also presented in two scenarios; to ensure relevant comparability with the data of [31] and [10], the BAU scenario from the [38] study is used. For the target year 2027, which is not explicitly identified in the studies, an estimation is made for [38] based on linear interpolation of the respective biomass subcategories. By contrast, the data from the [10] study mainly relates to the year 2050.

Findings

In addition to the notes in Section 3.2.2, the meta-study [10] presents biomass potentials (arithmetic mean, focus on bioenergy potentials) of 3,509 Mtoe (excluding energy crops: 1,240 Mtoe) for 2050 (see Figure 25). The bioenergy potential for biogenic residues and waste materials in the study [38] from 2020 to 2050 indicates around 2,139-2,853 Mtoe in the BAU scenario. In this study, the potentials of manure and human excrements were not expressed as primary energy, but rather as biogas potential, including conversion.

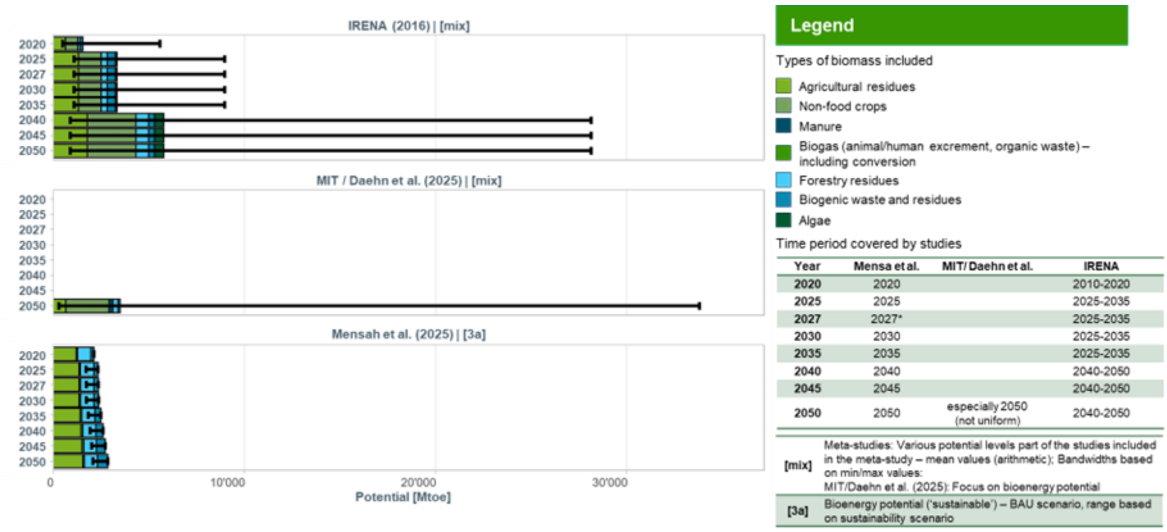


Figure 25: Global biomass potentials over time (mean values and min/max values) according to different studies.

Most notably, the meta-studies of [31] and [10] show extremely high ranges (minimum/maximum values). These ranges are particularly broad for energy crops, depending on the assumptions made regarding relevant cultivated areas. The ranges of the individual biomass categories in the cited studies are visualised in Figure 13.

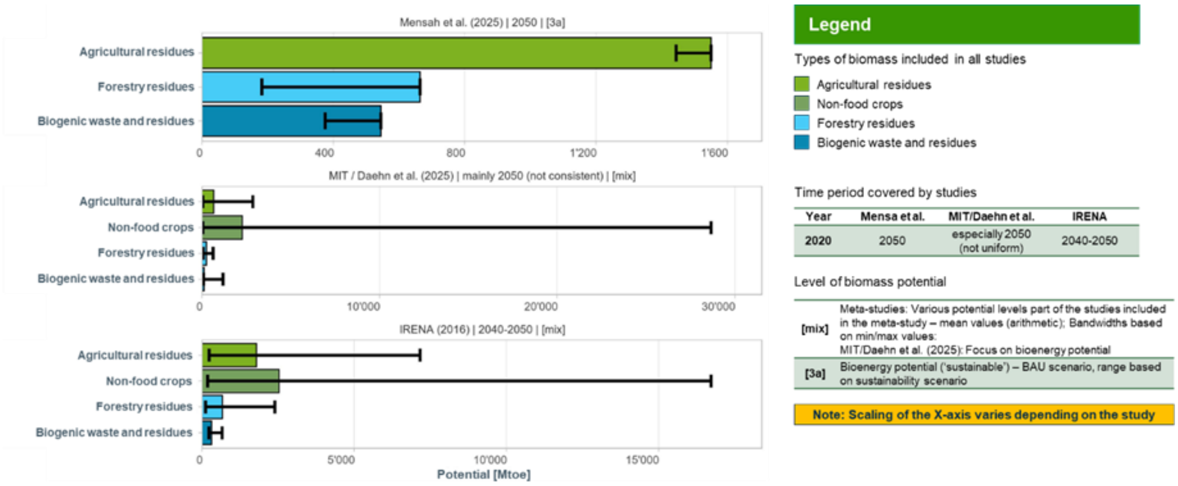


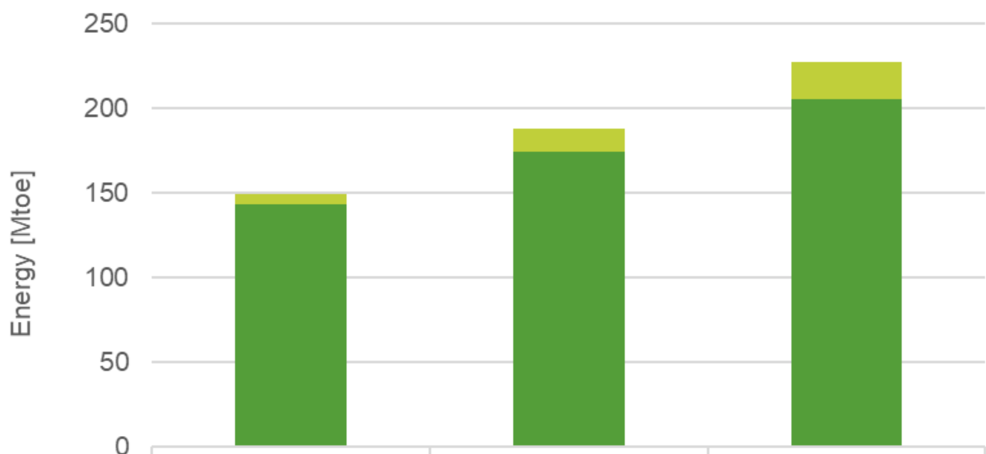
Figure 26: Global biomass potentials by biomass category (mean values and minimum/maximum values) according to different studies.

7.2 Conversion to biofuels

7.2.1 Deductions of bioenergy potential for other sectors

Amount of deductions & methodology

Road transport is not the only sector facing the challenge of transitioning towards petroleum-free energy sources. Other sectors (industry, energy, households, agriculture, aviation and shipping) also have a growing demand for bioenergy. This is taken into account in this study and thus reduces the bioenergy potential available for road transport. To determine raw material demand for the production of bioenergy – liquid, solid and gaseous – the Impact Assessments of the European Commission are used: Impact Assessment (2020) [19] regarding the RED I revision (leading to RED II) and Impact Assessment (2021) [20] on the RED II revision (leading to RED III). In Figure 27 , this demand is shown as mean values for the years 2030, 2035 and 2040, with values of 149 Mtoe (2030), 188 Mtoe (2035) and 228 Mtoe (2040). These amounts are then subtracted from the available bioenergy potential identified for conversion to advanced biofuels for road transport.



	2030	2035	2040
Aviation & Maritime	6	14	22
Other sectors	143	174	206

Figure 27: Demand for raw materials for the production of advanced bioenergy - solid, liquid, gaseous - from the other sectors (industry, energy, households, agriculture) as well as aviation and maritime.

To determine these values, as stated, two Impact Assessments from different dates had to be used. The graphs from these assessments are reproduced for ease of readability and to allow estimation of the underlying numerical values. The 2021 Impact Assessment in Figure 28 breaks down the data to show final bioenergy demand for the entire transport sector (road, air, water), as well as for the other sectors. This figure is used to determine demand for the entire transport sector, as currently projected by the European Commission. This is done using the mean value of the different scenarios, excluding the REF2020 scenario, since this only reflects the requirements of EU law in force at the time of publication of the assessment, and does not consider the more ambitious objectives incorporated in the other scenarios. This is particularly evident in the demand shown for 2050 in the REF2020 scenario in Figure 28.

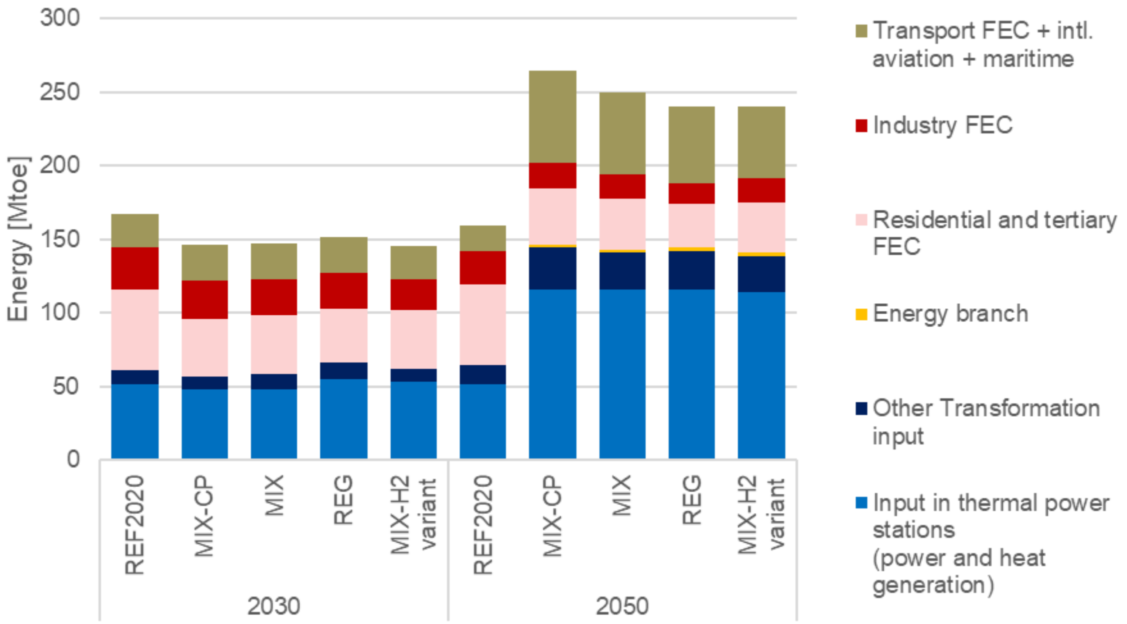


Figure 28: Demand for final bioenergy of the different sectors from the Impact Assessment (2021).

To break down the transport sector into road, air, and water, the 2020 Impact Assessment is used. Figure 29 shows this division, and its ratios are applied: demand from aviation and shipping accounts for 22% of transport sector demand in 2030 and 49% in 2050.

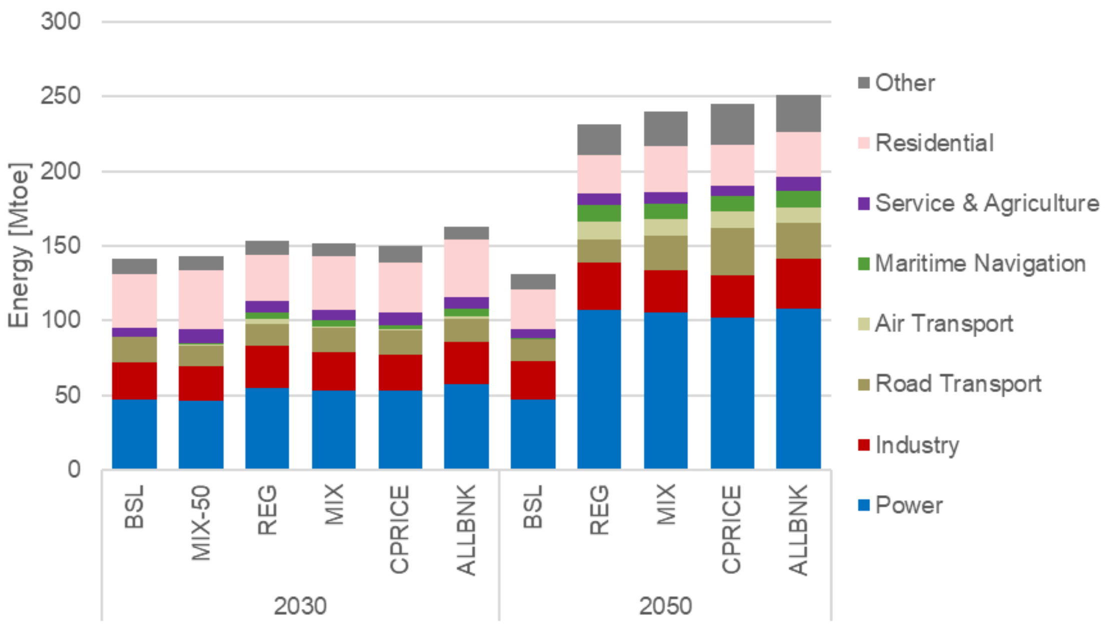


Figure 29: Demand for final bioenergy of the different sectors from the Impact Assessment (2020) with additional splitting of the transport sector into road / air / maritime.

It was thus possible to calculate that aviation and shipping will require an average of 5 Mtoe of final bioenergy in 2030 and 27 Mtoe in 2050. Here, the mean value from the various scenarios is used, and the reference scenario, in this case "BSL" (baseline), is excluded. The values for 2035 and 2040 were determined by linear interpolation.

To derive raw material requirements for all sectors from final bioenergy demand, the conversion efficiency used in the 2020 Impact Assessment – 86% in 2030 and 72% in 2050 – is applied (ratio between Figure 30 and Figure 29).

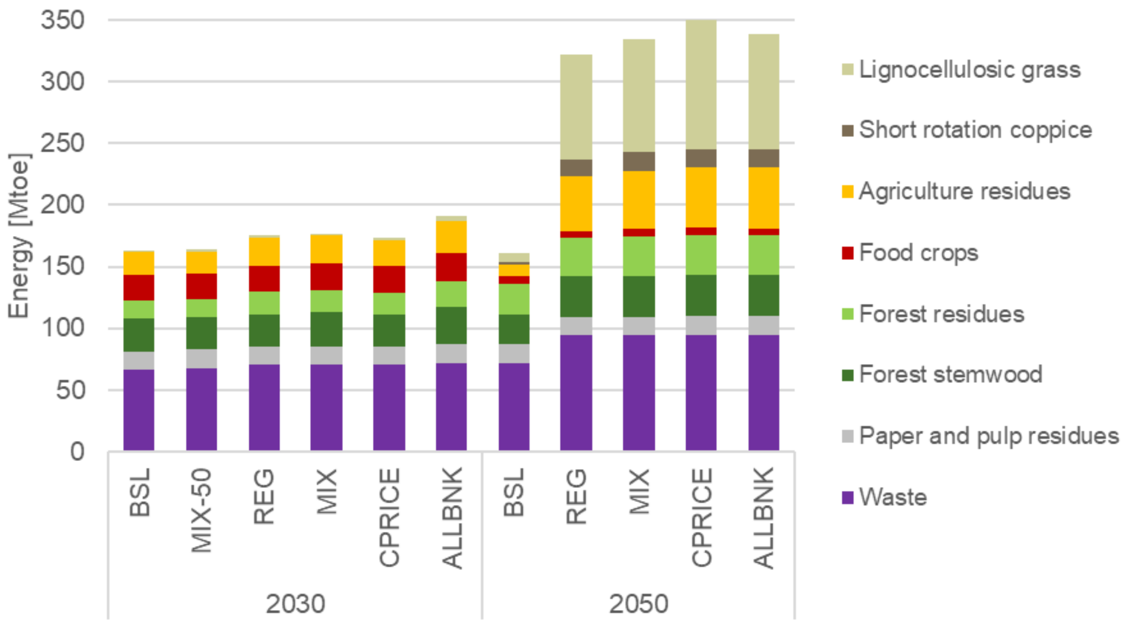


Figure 30: Demand for raw materials to produce the bioenergy shown in Figure 29 from the Impact Assessment (2020).

The generally high efficiency stems from the partial direct use of raw materials for energy generation without conversion losses, e.g. burning wood pellets. The decline in efficiency over time results from the increased use of raw materials that are not entirely suitable for energy generation without losses, such as lignocellulosic plants. Thus, demand for raw materials was recalculated from final bioenergy demand and used for further calculations (Figure 27).

Distribution of deductions across feedstock categories

Deductions for other industries are applied sequentially to the potentials in different ways, depending on the raw material category. This approach is based on a rough assessment of suitability for the processes considered here, possible localisation and existing use. Deductions for other modes of transport are then subtracted proportionally from each potential on a flat-rate basis, since it is assumed that they are basically part of the same process chains, but that the fuels produced are not available for the road transport considered here. The sequential, individual deductions for other industries are justified as follows for the respective raw material categories:

Primary – wood and forestry by-products

This material consists of trimmings from plant care. It tends to be moist and occurs directly at the site where the plant is grown. This material is less suitable for the processes under consideration and is more decentralised; however, no notable competing uses have been identified. A mean deduction of 20% per sequence is therefore assigned to the potential.

Secondary – wood and forestry by-products

These are residual materials from the wood processing industry, e.g. sawdust, offcuts, waste wood, etc. The material is well suited for conversion processes and tends to be centralised, but is also subject to strong competition for use, especially for heat generation (e.g. wood pellets). A mean deduction of 20% per sequence is therefore assigned to the potential.

Residual materials from the food industry

This is a highly diverse category that can include very different materials. It can be assumed that these materials typically have a high water content, making them less suitable for the conversion processes considered here. However, at least some of the material is available in centralised locations. Competition for use cannot be estimated. Overall, a mean deduction of 20% per sequence is therefore assigned to the potential.

Agricultural by-products

The same applies here as to residual materials from the food industry. In contrast, it is assumed that the water content is lower and that the material is available less centrally. It is also assumed that there is less competition for use. A lower deduction of 15% per sequence is therefore assigned to the potential.

Straw

Straw is well suited for the processes discussed here, but availability tends to be decentralised (across agricultural lands). Straw is also subject to strong competition for use. However, based on the premise of a free market, it can be assumed that the quantities available will depend on willingness to pay. Second use is also conceivable – for example, re-purposing straw previously used as bedding. A low deduction of 10% per sequence is therefore assigned to the potential.

Manure

Manure tends to be unsuitable for the processes used, due to its high water content. In addition, it is already used in biogas plants, for which it is an ideal feedstock. It is therefore assumed that this potential is not available for this use, unless there is an oversupply. A maximum deduction of 100% is therefore assigned to the potential in the initial sequence.

Energy crops

More specifically, this relates to non-food crops from marginal land, as well as intermediate and cover crops, as required by RED Annex IX, Parts A (aviation sector) and B (non-aviation sector). It can be assumed that, apart from a small percentage of oilseed crops (as discussed above), these are primarily "energy crops". After drying, these are highly suitable and, since their potential is not yet realised, they are also not subject to any competitive use. By contrast, it can be assumed that these potentials will only be exploited on the basis of demand for raw materials for renewable fuels. A low deduction of 10% per sequence is therefore assigned to the potential.

Municipal waste

Municipal waste, or rather its biogenic content, is, in principle, suitable for gasification, but remains technically challenging. Availability is centralised. Competition for use is difficult to estimate. Where the biogenic content is collected separately (as in Germany), it can be assumed that it is used in biogas or composting plants. If the biogenic content is not collected separately, the technical challenge is even greater. A higher deduction of 25% per sequence is therefore assigned to the potential.

Roundwood/stemwood

This category is, in principle, suitable for the processing envisaged here. Although it tends to be decentralised, established supply routes do exist. However, in addition to high competition for use for heat production, it remains unclear to what extent the potential meets the RED criteria. A higher deduction of 25% per sequence is therefore assigned to the potential.

UCO

UCO is ideally suited (after processing) for the production of HVO/HEFA. The potential is primarily realised due to demand. It is therefore assumed that the potential is fully available for production of renewable fuels and, therefore, no deductions are made for other industries.

7.2.2 Quota-based additions on potential fuel quantities

Since the quotas refer to the total energy demand (liquid, gaseous and electric) of the transport sector, Table 5 and Table 6 show the quota-based additions for the More Molecule and Max Electron demand scenarios [47].

Table 5: Additions for conventional biofuels and RFNBOs (Max-Electron).

Max-Electron	Type	Quota [%]	Demand [Mtoe]	Total quantity [Mtoe]	Fraction	Quantity [Mtoe]
2030	RFNBO	1.2	265.74	3.19	Naphtha	3.19
					Middle distillate	-
	1st Gen	5.5		14.62	Naphtha	7.31
					Middle distillate	7.31
2035	RFNBO	2.5	207.34	5.18	Naphtha	5.18
					Middle distillate	-
	1st Gen	5.5		11.4	Naphtha	5.70
					Middle distillate	5.70
2040	RFNBO	8.0	157.81	12.62	Naphtha	12.62
					Middle distillate	-
	1st Gen	5.5		8.68	Naphtha	4.34
					Middle distillate	4.34

Table 6: Additions for conventional biofuels and RFNBOs (More-Molecule).

More-Molecule	Type	Quota [%]	Demand [Mtoe]	Total quantity [Mtoe]	Fraction	Quantity [Mtoe]
2030	RFNBO	1.2	269.59	3.24	Naphtha	3.24
					Middle distillate	-
	1st Gen	5.5		14.82	Naphtha	7.41
					Middle distillate	7.41
2035	RFNBO	2.5	222.52	5.56	Naphtha	5.56
					Middle distillate	-
	1st Gen	5.5		12.24	Naphtha	6.12
					Middle distillate	6.12
2040	RFNBO	8.0	177.94	14.24	Naphtha	14.24
					Middle distillate	-
	1st Gen	5.5		9.78	Naphtha	4.89
					Middle distillate	4.89

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