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Renewable jet fuel supply scenarios in the European Union in 2021–2030 in the context of proposed biofuel policy and competing biomass demand

Sierk de Jong¹ | Joost van Stralen² | Marc Londo^{1,2,3} | Ric Hoefnagels¹ | André Faaij⁴ | Martin Junginger¹

¹Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands

²Energy Research Centre of the Netherlands (ECN), Amsterdam, The Netherlands

³The Netherlands Association for Renewable Energy (NVDE), Utrecht, The Netherlands

⁴Energy Academy Europe, University of Groningen, Groningen, The Netherlands

Correspondence

Sierk de Jong, Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands.
Email: s.a.dejong@uu.nl

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Abstract

This study presents supply scenarios of nonfood renewable jet fuel (RJF) in the European Union (EU) toward 2030, based on the anticipated regulatory context, availability of biomass and conversion technologies, and competing biomass demand from other sectors (i.e., transport, heat, power, and chemicals). A cost optimization model was used to identify preconditions for increased RJF production and the associated emission reductions, costs, and impact on competing sectors. Model scenarios show nonfood RJF supply could increase from 1 PJ in 2021 to 165–261 PJ/year (3.8–6.1 million tonne (Mt)/year) by 2030, provided advanced biofuel technologies are developed and adequate (policy) incentives are present. This supply corresponds to 6%–9% of jet fuel consumption and 28%–41% of total nonfood biofuel consumption in the EU. These results are driven by proposed policy incentives and a relatively high fossil jet fuel price compared to other fossil fuels. RJF reduces aviation-related combustion emission by 12–19 Mt/year CO₂-eq by 2030, offsetting 53%–84% of projected emission growth of the sector in the EU relative to 2020. Increased RJF supply mainly affects nonfood biofuel use in road transport, which remained relatively constant during 2021–2030. The cost differential of RJF relative to fossil jet fuel declines from 40 €/GJ (1,740 €/t) in 2021 to 7–13 €/GJ (280–540 €/t) in 2030, because of the introduction of advanced biofuel technologies, technological learning, increased fossil jet fuel prices, and reduced feedstock costs. The cumulative additional costs of RJF equal €7.7–11 billion over 2021–2030 or €1.0–1.4 per departing passenger (intra-EU) when allocated to the aviation sector. By 2030, 109–213 PJ/year (2.5–4.9 Mt/year) RJF is produced from lignocellulosic biomass using technologies which are currently not yet commercialized. Hence, (policy) mechanisms that expedite technology development are cardinal to the feasibility and affordability of increasing RJF production.

KEYWORDS

aviation, bio-economy, bioenergy, biofuel, energy policy, renewable jet fuel

1 | INTRODUCTION

Currently, approximately 2% of global anthropogenic greenhouse gas (GHG) emissions can be attributed to fuel combustion in aviation (Cames et al., 2015). While global air traffic is expected to rise by 4.9%/year up to 2040, international aviation was not covered by the Paris Agreement (Buxton, 2016; International Civil Aviation Organisation, 2013a). The aviation industry aims to cap net emissions by 2020 and halve emissions by 2050 relative to 2005 (International Civil Aviation Organisation, 2016a). Efficiency gains and operational improvements alone are likely insufficient to close the emission gap between projected and targeted CO₂ emissions from 2020 onwards (Cames et al., 2015; International Civil Aviation Organisation, 2013a). The introduction of renewable jet fuel (RJF), a liquid substitute for fossil jet fuel produced from renewable resources, should contribute to further emission reductions and close the gap on the long term (European Commission, 2013a; IATA, 2014; International Civil Aviation Organisation, 2016b, 2016c; International Energy Agency, 2017). These measures are supplemented by the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the European Union Emission Trading Scheme (EU ETS), which create an obligation for airlines to reduce emissions (through aforementioned measures) or surrender (purchased) emission offsets or allowances.

Renewable jet fuel produced from biomass (hereafter referred to as “RJF”) is currently considered the most technically feasible alternative to reduce the GHG intensity of jet fuel, as it can be produced commercially and is compatible with existing infrastructure (IRENA, 2017). The production, distribution, and use of RJF in commercial aircraft have been demonstrated over the past decade (IATA, 2014). However, the large-scale uptake of RJF has been impeded by the high cost differential between RJF and fossil jet fuel, limited number of commercialized conversion technologies, highly competitive and international character of the aviation industry, and current lack of adequate (policy) incentives (de Jong et al., 2015; Hamelinck et al., 2012; Kousoulidou & Lonza, 2016; Mawhood, Gazis, de Jong, Hoefnagels, & Slade, 2016). The future role of RJF depends on contextual factors, of which the most important ones comprise the regulatory context, the availability of (low-cost) sustainable feedstocks, the commercialization of conversion technologies, and future oil price development (de Jong, Hoefnagels, van Stralen, et al., 2017; Gegg, Ison, & Budd, 2015; IRENA, 2017; Mawhood et al., 2016; Wang et al., 2016).

Previous work has estimated the bottom-up supply potential of RJF based on biomass availability (El Takriti et al., 2017), production cost developments (Bauen et al.,

2009), and planned production capacity (E4tech, 2014; Kousoulidou & Lonza, 2016). Wise et al. (2017) were among the first to analyze the emergence of RJF in a more holistic manner, using an integrated assessment model to quantify RJF volumes under two global emission mitigation trajectories. However, few studies explicitly consider the role of RJF in relation to the wider bioenergy system, even though aviation may become an important end-use application of biomass as the sector lacks clear alternatives to reduce its GHG emissions (Tsiropoulos, Hoefnagels, van den Broek, Patel, & Faaij, 2017).

To our knowledge, this analysis is the first to quantify the role of RJF in the EU until 2030, based on the anticipated regulatory context, availability of biomass and conversion technologies, and competing biomass demand from other sectors (i.e., transport, heat, power, and chemicals). The scope of RJFs considered is confined to RJFs produced from nonfood biomass (i.e., advanced biofuels or biofuels produced from used cooking oils and animal fats (UCOAF)), based on the general aversion of airlines to use food-based biofuels. This is illustrated by the sustainability commitment of members of Sustainable Aviation Fuel Users Group “not to displace or compete with food crops” (SAFUG, 2017). Moreover, the policy trend in the EU toward phasing out food-based biofuels and stimulating the use of advanced biofuels suggests that future growth of biofuel consumption will mainly originate from increased advanced biofuel production (European Commission, 2016; European Parliament and the Council, 2015). Advanced biofuels are defined here as biofuels produced from feedstocks listed in Annex IX (part A) of the RED-II proposal (European Commission, 2016), which includes feedstocks such as algae, sludges, perennial crops, and agricultural and forestry residues.

In this study, we incorporated RJF production technologies in the RESolve-Biomass model. This model is able to explicitly analyze the interaction between different end-use sectors, as it covers bio-based power, heat, transport fuels (road, marine, and aviation), and chemicals. The RESolve-Biomass model was used to study the emergence of RJF supply scenarios and the associated technology portfolio, GHG emission reductions, and costs. This paper further discusses the requirements in terms of technology development and feedstock mobilization, as well as the impact of increased RJF supply on biofuel use in other sectors, such as road and maritime transport.

2 | BACKGROUND

2.1 | Aviation-related emission projections in the EU

Due to the projected growth of the aviation sector, GHG emissions from jet fuel combustion have been estimated to

increase by 150% in the EU in 2050 relative to 2005 (Figure 1) (International Civil Aviation Organisation, 2013b; Kousoulidou & Lonza, 2016). Despite anticipated efficiency gains and operational improvements, the gap between projected and targeted combustion emissions grows to 22 million tonne (Mt) CO₂-eq in 2030 and 166 Mt CO₂-eq in 2050 (Supporting Information Data S1 shows alternative growth scenarios). The emission gap is to be covered by carbon offsets and RJF (International Civil Aviation Organisation, 2016a). However, current consumption of RJF in the EU is negligible, despite an aspirational target of achieving 2 Mt of RJF to be used in EU aviation in 2020 as outlined in the EU Flightpath Initiative (European Commission, 2013a; Eurostat, 2016a).

2.2 | Regulatory context

The regulatory context relevant for RJF in the EU includes the Renewable Energy Directive I (RED-I) and its successor RED-II, the EU ETS and the global CORSIA. As these schemes were awaiting definitive implementation at the time of writing, the information below may deviate from the actual content of the schemes when implemented.

2.2.1 | The EU renewable energy directive

The RED-I promotes the use of renewable energy sources in the EU. It establishes a target of 20% renewable energy in the EU in 2020, with a 10% subtarget for renewable energy in the transport sector, most of which will probably need to be met by biofuels (European Parliament and the Council, 2009a). While the aviation sector is not an obligated party, the RED-I allows RJF to be counted toward the renewable energy targets (European Parliament and the Council, 2015). However, only few member states have explicitly adopted this in their national transposition (Hamelinck et al., 2012).

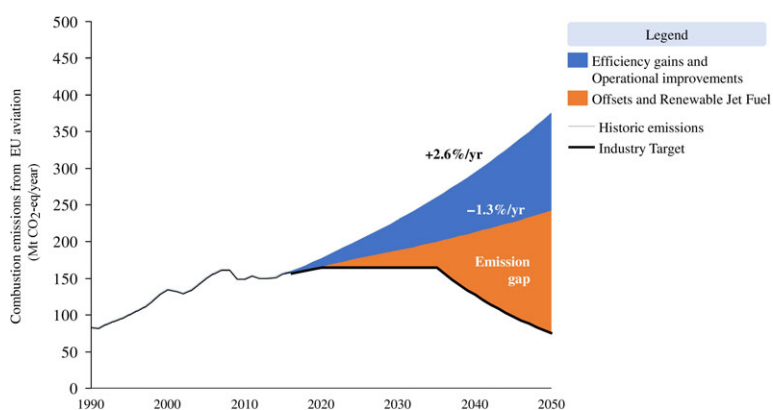
Recently, the European Commission proposed a recast of the RED-I for the period 2021–2030 (hereafter referred

to as “RED-II proposal”) (European Commission, 2016). The proposal is currently under review by the European Parliament and the European Council; final approval is expected in 2018, after which it will be transposed into national legislation. As it is the only comprehensive proposal at the time of writing, we base our analysis on the Commission’s proposal, while evaluating alternative policy options in the sensitivity analyses.

The RED-II proposal aims to increase the share of renewable energy sources to 27% by 2030, without specifying a subtarget for neither the entire transport sector nor specifically for the aviation sector. Instead, the proposal contains separate caps and binding targets for different renewable fuel categories to avoid adverse environmental impacts (e.g., land use change emissions) and promote the use of more advanced technologies (Supporting Information Data S2). Renewable fuels for transport produced from biomass (i.e., biofuels) are affected by two targets: the overall target for renewable transport fuels (1.5% in 2021 increasing to 6.8% by 2030) and a subtarget for advanced biofuels (0.5% in 2021 increasing to 3.6% by 2030). The overall target for renewable fuels may be fulfilled by advanced biofuels, biofuels produced from UCOAF, renewable electricity, waste-based fossil fuels, and renewable fuels of nonbiological origin (e.g., solar fuels and CO₂-based fuels). The share of UCOAF-based biofuels is capped at 1.7%. Food/feed-based biofuels are excluded from the renewable transport fuels target, but they may still contribute to the overarching 27% renewable energy target to a maximum of 3.8% of total transport fuel use by 2030.

The targets define the share of renewable transport fuels relative to the final energy consumption in the road and rail sectors. Renewable fuels supplied to the EU aviation and marine sectors may count 1.2 times their energy content toward the target. This multiplier mechanism aims to stimulate biofuel uptake in sectors which lack clear renewable options and cover higher production costs that may exist in these sectors.

FIGURE 1 Combustion greenhouse gas emissions from flights departing from EU airports (intra- and extra-EU) with improvements in fuel efficiency and operations vs. an industry target (Supporting Information Data S1)



2.2.2 | EU ETS and CORSIA

The EU ETS and CORSIA address emissions from intra- and extra-EU flights, respectively. The EU ETS sets an EU-wide emission cap covering multiple, mainly industrial sectors (civil aviation was added in 2012). Under international pressure, it was decided to apply EU ETS to intra-EU flights only, pending the development of a global measure by the International Civil Aviation Organization (ICAO) (Noh et al., 2016). In 2016, ICAO's general assembly decided to implement CORSIA, which is a measure prescribing aircraft operators to offset any annual increase in CO₂ emissions beyond 2020 from international aviation between participating states (International Civil Aviation Organisation, 2016b). Seventy-two states, including the EU member states, representing 87.7% of international aviation activity, intend to participate voluntarily from 2020 onwards (International Civil Aviation Organisation, 2017). The European Commission recently proposed to restrict the EU ETS scope to intra-EU flights while awaiting the development of CORSIA (European Commission, 2017).

The inclusion of aviation in EU ETS and CORSIA sets a price on combustion emissions from aviation. In EU ETS, fuels produced from biomass are allocated an emission factor of zero as long as they meet the RED-I sustainability criteria, thus, providing a financial incentive for the use of RJF equal to the price of an emission allowance (European Commission, 2012; European Parliament and the Council, 2009b). The role of RJF in CORSIA as well as the environmental integrity and credibility level of the offsets used (influencing their price) are still under discussion at the point of writing.

3 | MATERIALS AND METHODS

3.1 | RESolve-Biomass model

The role of RJF in the EU in 2021–2030 was assessed using the RESolve-Biomass model, developed by Energy research Centre of the Netherlands. RESolve-Biomass is a 1-year myopic cost optimization model that optimizes the feedstock-technology portfolio to fulfill a certain demand for bio-based products. The model minimizes the total additional well-to-tank system cost relative to a fossil reference. These costs comprise feedstock cultivation and transport, pretreatment, conversion, and distribution (e.g., blending). RESolve-Biomass includes a variety of feedstocks, technologies, and demand segments. It has a longstanding reputation and has been used in multiple European projects to address policy-related questions (e.g., REFUEL, Biomass Policies, Biomass Futures, and S2Biom) (Londo et al., 2017). The

exogenous model inputs shown in Figure 2 are discussed below.

3.2 | Biomass demand and supply scenarios

The supply of RJF is analyzed using four scenarios varying in biomass supply and biomass demand (Figure 3).

3.2.1 | Biomass supply

Current gross consumption of biomass for energy purposes in the EU is about 5.4 EJ, of which 4.4% is imported (AEBIOM, 2016). Various studies have quantified the future domestic biomass supply potential; however, its mobilization depends on a magnitude of social, technical, and economic factors (Creutzig et al., 2015). Extra-EU import potentials are possibly large, but depend on mobilization efforts and domestic consumption in the exporting countries (Mai-Moulin et al., 2017). This study attempts to capture this variation in a Low Biomass Supply (LS) and High Biomass Supply (HS) scenario. The supply potentials are used as a constraint on feedstock use. The mobilization of novel feedstocks was modeled as an S-curve as described in van Stralen et al. (2016).

The supply potential of biomass and biofuel in/to the EU increases from 11.4–11.8 EJ in 2021 to 13.4–16.9 EJ in 2030 in the LS and HS scenario (Figure 4a,b). The potential of domestic biomass was obtained from the Biomass Policies project, which quantifies the cost-supply potential of a wide range of agricultural, forestry, and waste biomass types on a member state level (Elbersen et al., 2016). The supply assessment employs exclusion criteria based on sustainability considerations (e.g., soil conservation, biodiversity, erosion control) and conventional competing uses (e.g., food, feed, bedding, material). The LS scenario follows the baseline scenario used in Biomass Policies; the HS scenario follows the B2 scenario which shows higher biomass supply, particularly of manure and agricultural and forestry residues due to higher mobilization and extraction rates (Elbersen et al., 2015, 2016). The cost for domestic biomass was based on market prices for biomass types which are already traded and road-side costs for feedstock for which the market is not yet developed. The cost declined by 10% between 2020 and 2030 because of technological learning and efficiency improvements (Elbersen et al., 2016).

The import potentials include liquid biofuels (food-based biodiesel, food-based and lignocellulosic bioethanol) and solid biomass (wood pellets) from countries that are or could become major export regions (e.g., Brazil, the US, and Canada). The import share available for EU consumption (after deduction of local demand) was based on the population size of the EU relative to countries with similar

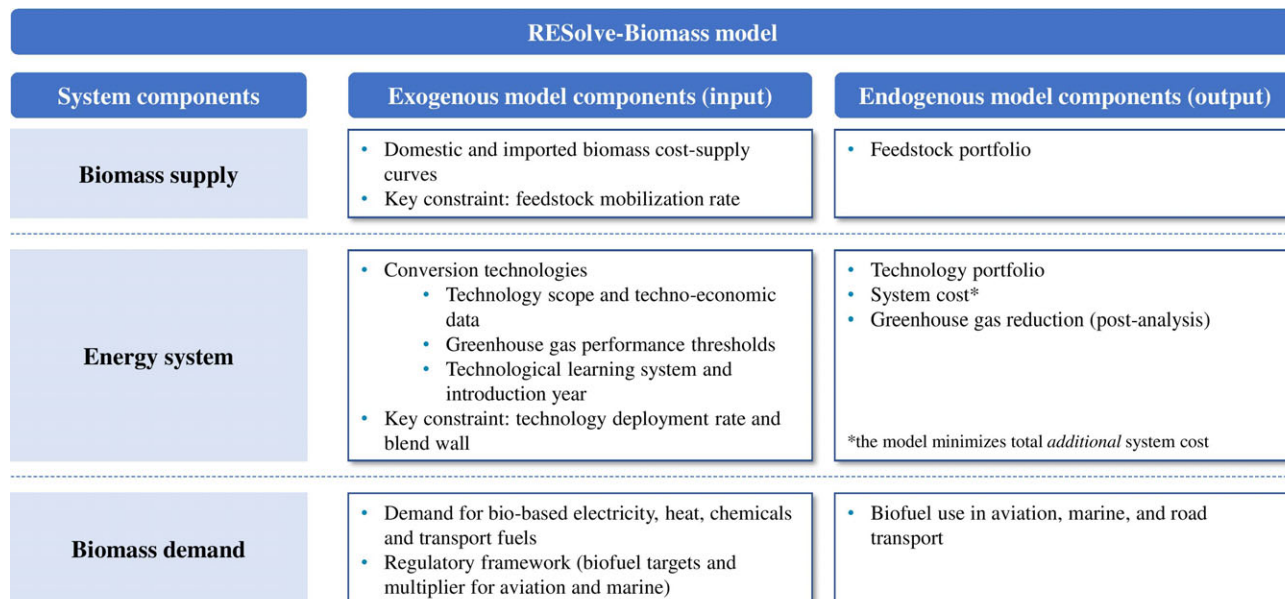


FIGURE 2 Exogenous and endogenous model components of RESolve-Biomass

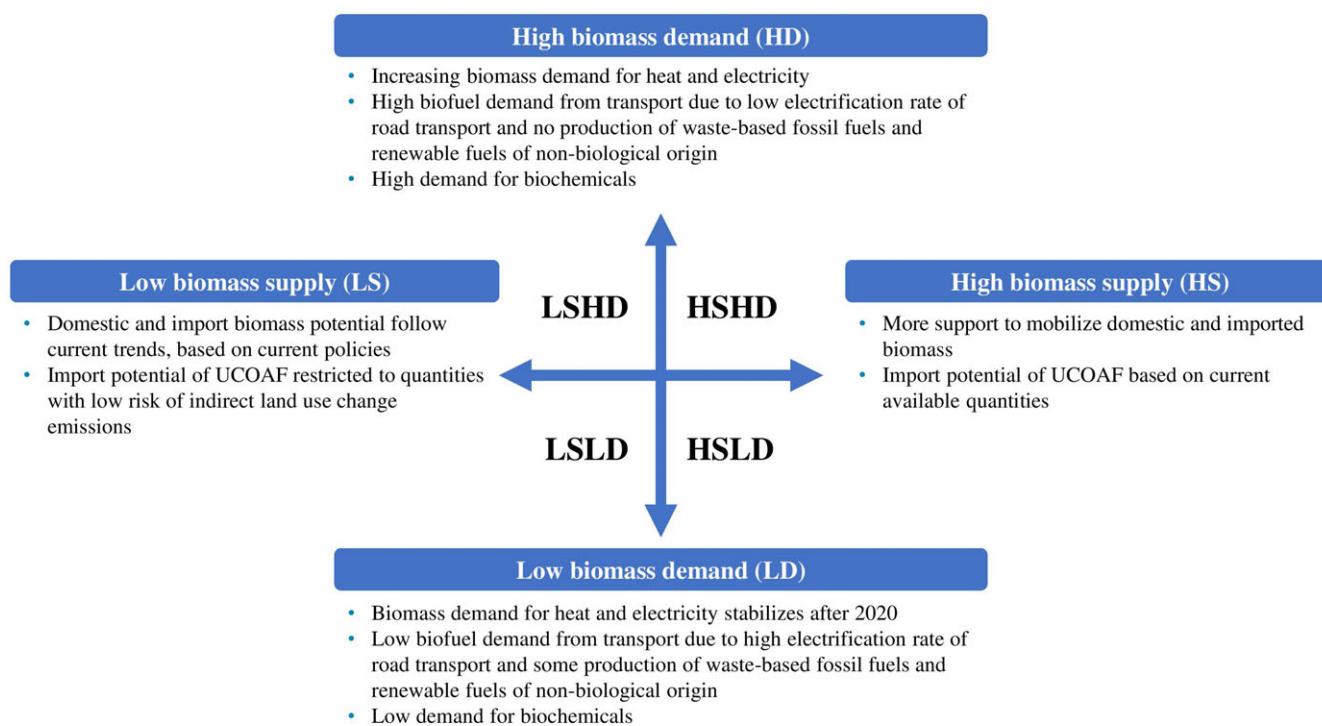


FIGURE 3 Four scenarios varying in biomass supply and demand

paying capacity (Fritsche & Iriarte, 2016). The costs comprise production, processing, transport, and certification. These potentials were supplemented with imports of palm oil (European Parliament, 2017; United States Department of Agriculture, 2017) and used cooking oil (Spöttle et al., 2013). The palm oil import potential in both supply scenarios was based on current palm oil imports into the EU for bioenergy use. The HS scenario uses the collectable

potential (165 PJ/year by 2030) of used cooking oil, while the LS scenario uses the “low indirect land use change (iLUC) potential” of used cooking oil (44 PJ/year by 2030) from which all competing uses except bioenergy and dumping were deducted. A large share (97 PJ) of the difference between the collectable and low iLUC potential arises from used cooking oil that is allegedly used for human consumption in China. Diversion of this feedstock

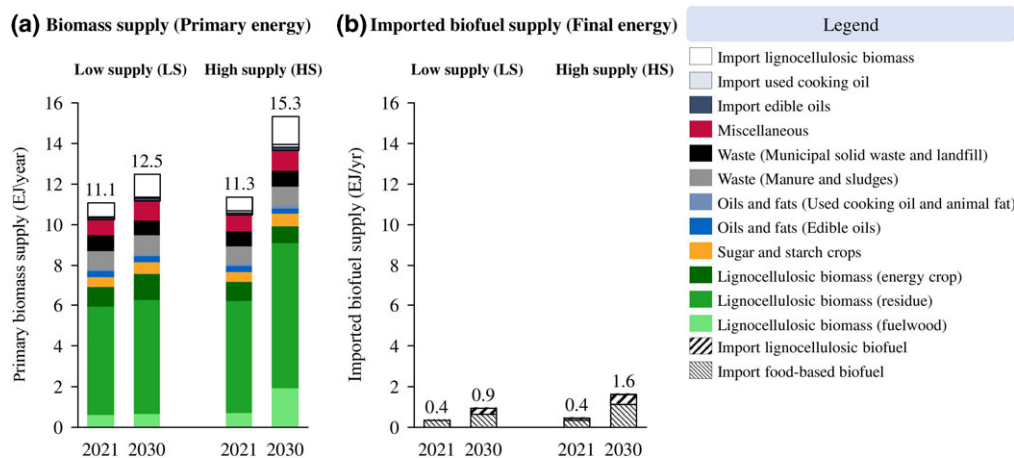


FIGURE 4 (a) Sustainable biomass potential in the EU and (b) imported biofuel potential in the EU

stream to bioenergy would likely instigate a growing demand of vegetable oils (potentially causing emissions), but would also reduce the health threat associated with used cooking oil consumption (Spöttle et al., 2013). The remaining competing uses include animal feed and the oleochemical industry. The used cooking oil potential increases by 270% in the HS compared to the LS scenario, but this is likely an overestimation of the sustainable potential. Supporting Information Data S3 provides supplementary data on the categorization of biomass types, cost-supply curves, and import regions.

3.2.2 | Biomass demand

Biomass supply for nonfood RJF production is primarily affected by nonfood biomass demand for heat, electricity, biochemicals, and biofuels. Demand for bio-based products in the low biomass demand (LD) and high biomass demand (HD) scenario is visualized in Figure 5. Biomass demand for bio-based heat and power comprises the largest share of overall biomass demand. Biomass demand for the HD scenario was obtained from the S2Biom project (van Stralen et al., 2016). For the LD scenario, a faster introduction of energy efficiency measures and other sources of renewable energy was assumed. Furthermore, it was assumed that demand for bio-based heat and power would stabilize after 2020 and decrease for applications where the HD scenario already showed a reduction. The demand for bio-based chemicals (ethylene, hydrogen, methanol, benzene, toluene, xylene, surfactants, solvents, and polymers) in the HD and LD scenarios, obtained from the S2Biom project, show only a marginal contribution to the total biomass demand (Figure 5) (Mozaffarian et al., 2015).

Biomass demand from the transport sector in 2021–2030 follows the renewable energy targets for nonfood biofuels as specified in the RED-II proposal where applicable. The

model was forced to fulfill the targets; hence, the option of noncompliance (at certain cost) was not analyzed. The demand for advanced biofuels was based on the subtarget for advanced biofuels (0.5% in 2021, increasing to 3.6% by 2030). In this study, the definition of advanced biofuels follows the RED-II proposal and includes lignocellulosics-based biofuels and gaseous biofuels from sludges and landfill gas. The overall target for renewable transport fuels (1.5% in 2021 increasing to 6.8% by 2030) was disaggregated to a combined biofuel demand for advanced biofuels and biofuels based on UCOAF by subtracting the projected share of renewable electricity, waste-based fossil fuels, and renewable fuels of nonbiological origin. The maximum share of UCOAF-based fuels (1.7%) specified in the RED-II proposal was incorporated as a model constraint.

The LD and HD scenarios assume a 0.5% and 0% share of waste-based fossil fuels and renewable fuels of nonbiological origin by 2030, respectively. The share of renewable electricity in the road transport sector in the HD scenarios was calculated from projections of electricity use in road transport (0.87% in the EU by 2030) and renewable electricity production in the PRIMES 2016 reference scenario (Capros et al., 2016). In the LD scenario, the share of renewable electricity in road transport was assumed to be twice as high, anticipating on a faster electrification of the car fleet across the EU and a higher share of renewables in the electricity mix. The projected share of renewable electricity in rail transport was added to the total renewable electricity usage in transport (Eurostat, 2016b). This leads to a renewable electricity share in road and rail transport increasing from 0.5% (2021) to 0.9% (2030) in the HD scenarios and 0.6% (2021) to 1.2% (2030) in the LD scenarios.

In the absence of dedicated policy targets for food-based biofuels in the RED-II proposal (it may only contribute to the overarching 27% renewable energy target), the share of

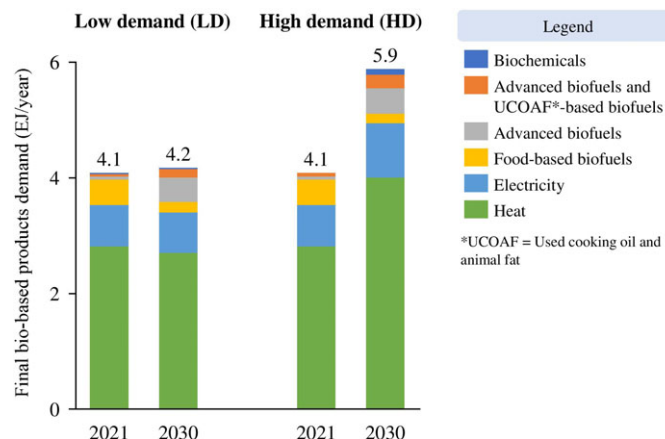


FIGURE 5 Final bio-based products demand in the EU

food-based biofuels was assumed to decline from 3.6% in 2021 to 1.6% by 2030, based on restrictions on the import of food-based biodiesel and the construction of new edible oil-based and starch-based biofuel facilities (Supporting Information Data S2). Although this is much lower than the proposed cap in the RED-II proposal (7.0% in 2021 and 3.8% by 2030), this assumption has limited impact on the production of advanced biofuels and UCOAF-based biofuels, because the demand for these biofuels is established by separate targets and these biofuels are produced from other types of biomass.

3.3 | Biofuel production technologies

The RESolve-Biomass model contains a wide range of bioenergy production technologies. This section focuses on nonfood biofuel production technologies. Supporting Information Data S4 provides the full technology scope of RESolve-Biomass and supplementary techno-economic and GHG emissions data.

3.3.1 | Technology scope and techno-economic data

Table 1 displays the scope and techno-economic data of nonfood biofuel technologies. Besides technologies able to produce RJF, the table also includes production technologies for other nonfood biofuels, as these are in direct competition with RJF to fulfill the renewable energy targets in transport. RESolve-Biomass includes existing technologies producing ethanol, biogas, Fatty Acid Methyl Ester (FAME) biodiesel, Hydrotreated Esters, and Fatty Acids (HEFA) diesel. Technologies expected to commercialize during 2021–2030 to be included in the model were selected based on their promising techno-economic performance (de Jong et al., 2015) and fuel readiness level (Mawhood et al., 2016). The data in the table represent the costs in 2021 or at technology introduction (Table 2 lists

the introduction years). The techno-economic data were obtained from prior studies, which generally model *n*th plant economics (as if the technology was deployed at large scale). Therefore, the CAPEX for new technologies was scaled to the initial plant capacity as outlined in Table 2 (using a scaling factor of 0.8) to reflect higher investment cost for the first-of-a-kind plant.

The model may use biofuels to replace conventional fuels in aviation, marine, car, bus, and truck segments. The eligible biofuels and blend walls were defined per transport segment (Supporting Information Data S5). The model includes versions of Hydroprocessed Esters and Fatty Acids (HEFA), Fischer–Tropsch (FT), pyrolysis and Hydrothermal Liquefaction (HTL) production capacity with and without RJF coproduction to incorporate the producer's flexibility to optimize their process for different end-use applications. The production of HEFA-RJF incurs additional cost relative to producing diesel only, due to lower middle-distillate yield and more stringent upgrading requirements (Pearlson et al., 2013). Due to lack of information for FT, pyrolysis and HTL, it was assumed that 25% of the energy content of the produced diesel could be used as RJF without additional production costs, as all process designs already include a distillation column (de Jong et al., 2015). The model could adjust the yield of gasoline, diesel, and jet fuel for FT, Pyrolysis, ATJ and HTL by $\pm 0.1 \text{ GJ}_{\text{product}}/\text{GJ}_{\text{biomass feed}}$ (without altering the overall yield) to resemble the variance and flexibility within the technology types.

3.3.2 | Greenhouse gas performance

The reduction in life-cycle and combustion emissions was quantified based on the feedstock-technology portfolio emerging from RESolve-Biomass. The life-cycle emission reduction represents the overall GHG emission reductions from the use of nonfood biofuels in EU transport. The GHG emission savings listed in Table 1 were obtained from Edwards et al. (2014) and De Jong, Antonissen,

TABLE 1 Nonfood biofuel production technologies (i.e., advanced and UCOAF-based biofuel) in the scope of RESolve-Biomass

Technology	Feedstock	Main products	Yield ^a GJ _{products} /GJ _{biomass feed}	Annualized CAPEX ^{a,b} € ₂₀₁₀ /GJ _{product}	OPEX ^{a,b} € ₂₀₁₀ /GJ _{product}	Typical GHG reduction ^c % savings relative to fossil reference	Reference
Renewable jet fuel (RJF) production technologies							
Hydrotreated Esters and Fatty Acids (HEFA)	UCOAF	D, HEFA-RJF, P, N	1.11	1.7	2.7	77	de Jong et al. (2015), Edwards et al. (2014) and Pearlson et al. (2013)
Fischer-Tropsch (FT)	Lignocellulosics	D, E, N, FT-RJF	0.45	9.6	9.1	93	de Jong et al. (2015) and Edwards et al. (2014)
Alcohol-to-Jet (ATJ)	Lignocellulosic ethanol	G, ATJ-RJF	0.89	1.4	1.7	73	de Jong et al. (2015), De Jong, Antonissen, Hoefnagels, et al. (2017) and Han, Tao, & Wang (2017)
Hydrothermal liquefaction (HTL) and full hydrodeoxygenation							
Hydrothermal liquefaction (HTL) and full hydrodeoxygenation	Woody biomass	D, G, HFO, HTL-RJF	0.56	3.4	3.0	81	De Jong, Antonissen, Hoefnagels, et al. (2017) and Tews et al. (2014)
Pyrolysis and full hydrodeoxygenation	Woody biomass	D, G, HFO, Pyrolysis-RJF	0.50	5.6	5.7	77	De Jong, Antonissen, Hoefnagels, et al. (2017) and Tews et al. (2014)
Other nonfood biofuel production technologies							
Fatty Acid Methyl Ester (FAME)	UCOAF	FAME, GI	1.07	0.6–0.9	2.5–2.8	79	Deurwaarder et al. (2007) and Edwards et al. (2014)
Hydrotreated Esters and Fatty Acids (HEFA)	UCOAF	D, P, N	1.09	1.8	2.8	77	de Jong et al. (2015), Edwards et al. (2014) and Pearlson et al. (2013)
Fermentation	Lignocellulosics	EtOH, H, E	0.61	10	9	78–90	Deurwaarder et al. (2007) and Edwards et al. (2014)
Digestion and biogas upgrading	Manure and sludges, landfill gas, and organic waste	B	0.57–0.6	2.7–12.9	1.2–4.9	50–179 ^c	Edwards et al. (2014), Lensink & van Zuijlen (2016) and Lensink et al. (2010)
Biogas liquefaction	Biogas from manure, sludges and landfill	LNG	0.92	1.7	0 ^d	60–163 ^c	Edwards et al. (2014), International Gas Union (2016) and Songhurst (2014)
Fischer-Tropsch (FT)	Lignocellulosics	D, E, N	0.45	9.6	9.1	93	de Jong et al. (2015) and Edwards et al. (2014)
		DME, H, E	0.55	7.4	4.1	93	Deurwaarder et al. (2007) and Edwards et al. (2014)

(Continues)

TABLE 1 (Continued)

Technology	Feedstock	Main products	Yield ^a GJ _{products} / GJ _{biomass feed}	Annualized CAPEX ^{a,b}		OPEX ^{a,b} € ₂₀₁₀ /GJ _{product}	Typical GHG reduction ^c % savings relative to fossil reference	Reference
				€ ₂₀₁₀ /GJ _{product}	€ ₂₀₁₀ /GJ _{product}			
Hydrothermal liquefaction (HTL) and full hydrodeoxygenation	Woody biomass	D, G, HFO	0.56	3.4	3.0	81	De Jong, Antonissen, Hoefnagels, et al. (2017) and Tews et al. (2014)	
Pyrolysis and full hydrodeoxygenation	Woody biomass	D, G, HFO	0.50	5.6	5.7	77	De Jong, Antonissen, Hoefnagels, et al. (2017) and Tews et al. (2014)	

Notes. B, Biogas; D, Renewable diesel; DME, Renewable Dimethyl Ether; E, Renewable electricity; EtOH, bioethanol; FAME, FAME biodiesel; G, Renewable gasoline; GI, Glycerine; GHG, greenhouse gas; H, Heat; HFO, Renewable heavy fuel oil; LNG, Renewable Liquefied natural gas; N, Renewable Naphtha; P, Renewable propane; and RJF, Renewable jet fuel.

^aRanges in cost and yield are due to feedstock-specific differences. Product yields may exceed unity due to the input of utilities. Supporting Information Data S4 shows product-specific yields. ^bThe annualized CAPEX was calculated using a discount rate of 7% and a lifetime of 20 and 12 years for biofuel and biogas installations, respectively. The OPEX listed here does not include the cost of feedstocks, utilities (i.e., hydrogen, electricity and natural gas) nor netbacks of co-products (i.e., LPG, naphtha), as these may change with model solution or modeling year. For all technologies, 8,000 full load hours were assumed. ^cRanges are due to variation in feedstock and technology design (a disaggregation can be found in Supporting Information Data S4). The RED-II fossil comparator for transport fuels (94 g CO₂-eq/MJ fuel) was used to calculate the GHG savings for diesel, gasoline, and jet fuel substitutes. Please note that for biogas and bio-LNG, the fossil comparators of natural gas (56.2 g CO₂-eq/MJ fuel) and LNG (76.4 CO₂-eq/MJ fuel) were used. When the RED-II fossil comparator was used, all biogas and bio-LNG pathways would achieve the 70% GHG emission savings threshold imposed by the RED-II proposal for installations commissioned from 2021 onwards. ^dThe utility requirement is covered by natural gas (incorporated in the yield); other OPEX was included in the CAPEX.

Hoefnagels, et al. (2017). All pathways listed in Table 1 achieve the 70% GHG savings threshold, which is imposed on installations commissioned from 2021 onwards by the RED-II proposal (European Commission, 2016). The combustion emission reduction quantifies the emission reduction allocated to the aviation, marine, and road transport sector. CO₂ emissions from the combustion of biofuels were assumed to be zero, in line with the IPCC Guidelines for National Greenhouse Gas Inventories emissions from biofuels (Maurice et al., 2006). The combustion emission reduction from nonfood biofuels was estimated by awarding an emission credit equal to the CO₂ emission factor for fossil jet fuel (71.5 gCO₂/MJ), gasoline (69.3 gCO₂/MJ), diesel (74.1 gCO₂/MJ), residual fuel oil (77.4 gCO₂/MJ), and natural gas (56.1 gCO₂/MJ) (Maurice et al., 2006).

3.3.3 | Capacity deployment

RESolve-Biomass was initialized in 2005 and aligned with actual production and consumption data during 2005–2016 (especially the spatial distribution of production and consumption) (EurObserv'ER, 2016; Eurostat, 2017a,b; United States Department of Agriculture, 2016). Model projections were used to establish the biofuel mix for 2020. These projections show a lower renewable energy share in transport in 2020 (8.7% on an EU average, including double counting biofuels) compared to the proposed RED-I target of 10%. This is largely due to limited announced advanced biofuel capacity and the imposed restrictions on the share of food-based biofuels (Supporting Information Data S2).

The maximum rate at which production capacity could be deployed was constrained at +150% in the first 3 years and +90% thereafter to better reflect historic biofuel deployment rates in the EU (Eurostat, 2016a). Premature closure (<20 years) was allowed up to 10% of total capacity per year. The growth potential of technologies was further constrained by their theoretical market size, which may be confined by fuel type (e.g., ethanol can only replace gasoline) or blend wall (7% for FAME biodiesel and 10% for ethanol on volumetric basis) (Supporting Information Data S5).

Table 2 lists the introduction year of the conversion technologies in scope. FT and Alcohol-to-Jet (ATJ) technology are assumed to be commercially available by 2020 (at 100 MW_{in}), as (components of) the technology have been validated for other products and feedstocks (Mawhood et al., 2016). It was assumed that pyrolysis and HTL are commercialized in 2023 and 2025 (at 50 MW_{in}), respectively, as several precommercial pyrolysis facilities are currently in operation, while HTL is yet to be demonstrated (Janssen et al., 2013; Mawhood et al., 2016). Moreover, full hydrodeoxygenation of the biocrude still poses technical challenges and the jet fuel fraction is yet to be

TABLE 2 Assumptions regarding capacity deployment and technological learning

Technology	Sub process	Introduction year	Market-driven learning Progress ratio %	Scale-driven learning			References
				Initial plant capacity MW _{input}	Maximum plant capacity MW _{input}	Doubling time ^a Years	
Fatty Acid Methyl Ester (FAME)		2005	90	—	—	—	de Wit et al. (2010)
Fermentation (Lignocellulosics)		2015	99	100	2,000	5	de Wit et al. (2010)
Hydrotreated Esters and Fatty Acids (HEFA)	Diesel	2007	90	—	—	—	^b
	RJF	2016	90	—	—	—	
Digestion and biogas upgrading		2005	100	—	—	—	Junginger et al. (2006)
Biogas liquefaction		2005	100	—	—	—	^c
Fischer–Tropsch (FT) ^d		2020	98	100	2,000	5	de Wit et al. (2010)
Alcohol-to-Jet (ATJ) ^d		2020	100	100	2,000	5	^c
Hydrothermal liquefaction (HTL) ^d		2025	98	50	400	5	van Stralen et al. (2016)
Pyrolysis ^d		2023	98	50	400	5	^b

Note. ^aOnly years in which new capacity was built were considered in the doubling time. ^bPyrolysis was assumed similar as HTL. HEFA was assumed similar as biodiesel. ^cNo market-driven learning was included as the components of the ATJ systems are widely used in the petrochemical industry, albeit separately. ^dThe data listed in this table were assumed equal for both versions of technologies with and without renewable jet fuel (RJF) coproduction.

certified for use in commercial aviation (Koks et al., 2016). The introduction year was varied in a sensitivity analysis, as these assumptions are uncertain and largely depend on future Research, Development and Demonstration (RD&D) efforts.

3.3.4 | Technological learning

RESolve-Biomass incorporates cost reductions over time through technological learning based on scale-dependent and market-driven learning effects (de Wit, Junginger, Lensink, Londo, & Faaij, 2010). Scale-dependent learning includes cost reductions caused by economies of scale as plant size may increase over time. Scale-dependent learning effects were initialized once the technology was introduced in the model. These effects were modeled exogenously and were defined by the time it takes to double the plant size (“doubling time”). Market-driven learning effects include process improvements, upscaling of individual process components, and increasing operation experience. It is modeled using experience curves, in which a progress ratio describes the CAPEX and OPEX reduction for every doubling in cumulative capacity. No endogenous learning was applied to feedstock cost or GHG emission reduction performance.

Table 2 summarizes the assumptions regarding technological learning, which were largely based on de Wit et al. (2010) and van Stralen et al. (2016). It was assumed that

upscaling is the most important driver during early commercialization of novel technologies, for which a doubling time of 5 years was utilized (de Wit et al., 2010). A conservative scaling factor of 0.8 was assumed to account for process components which have high scaling factors (e.g., feedstock handling or steam methane reformer) or require parallel production after a certain maximum capacity (de Jong, Hoefnagels, Wetterlund, et al., 2017; Towler & Sinnott, 2012). Furthermore, a 5% maximum market share was assumed for single plants to avoid unrealistic dependencies on one plant. The initial and maximum plant capacities were set to 100 MW_{in} and 2,000 MW_{in} for large-scale technologies and 50 MW_{in} to 400 MW_{in} for small-scale technologies. For existing technologies, only market-driven learning was incorporated. The cumulative capacity was determined endogenously by the deployed capacity in the model, thereby assuming the EU is a closed learning system (or the EU share of global deployed capacity remains constant).

3.4 | Fossil reference

The costs for the fossil reference products were based on price projections of crude oil, natural gas, and coal, taken from the PRIMES reference 2016 scenario (Supporting Information Data S6) (Capros et al., 2016). Fossil fuel price projections are highly uncertain and depend on the stringency of climate policy and the production costs of different supply options. The current projections show a

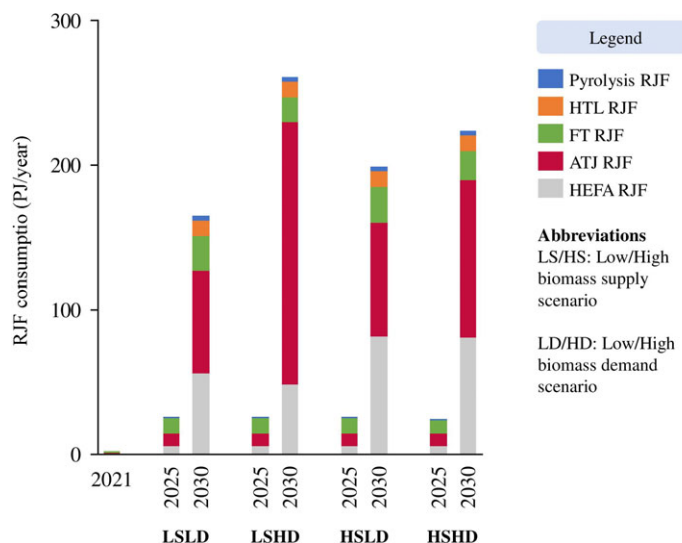


FIGURE 6 The mix of renewable jet fuel (RJF) by technology type for the four biomass supply-demand scenarios

constantly increasing oil prices (2.3%/year) during 2021–2030, driven by growing demand in developing countries, while production stabilizes in countries outside the Organisation of the Petroleum Exporting Countries. The average oil/product price ratio over 2007–2017 (energy basis) was used to determine the price ratio for jet fuel (1.30), diesel (1.18), gasoline (1.24), heavy fuel oil (0.78), marine gasoil (1.24), and other fossil products, relative to crude oil (Supporting Information Data S6).

The electricity price was projected using the electricity market model COMPETES (van Hout et al., 2014; van Stralen et al., 2016). A CO₂ price was added to fossil product use in sectors included in the EU ETS (i.e., electricity, large-scale heat applications, and intra-EU aviation). It was assumed that extra-EU aviation will be covered under CORSIA from 2021 onwards. The CO₂ price was assumed equal for EU ETS and CORSIA and grows progressively from 9 €/t in 2021 to 27 €/t by 2030 (Capros et al., 2016). It was assumed that RJF may be counted toward proposed RED-II biofuel targets as well as CORSIA or EU ETS.

4 | RESULTS

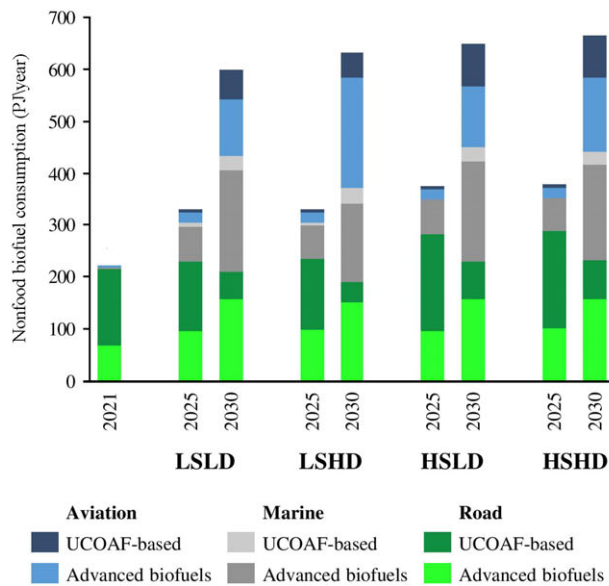
4.1 | Technology portfolio

Figures 6 and 7a,b show the biofuel mix by conversion technology and end-use sector for the four supply-demand scenarios. The results show two trends: (a) an increase in advanced biofuel production driven by the subtarget for advanced biofuels and (b) a growing share of nonfood biofuel consumption in the aviation and marine sectors driven by the multiplier for aviation and marine biofuels and the relatively high price for fossil jet fuel and marine gasoil relative to diesel and gasoline (making aviation and marine biofuels a cheaper substitute for fossil fuel).

As a result of these trends, the consumption of nonfood biofuels in the aviation sector grows from 1 PJ in 2021 to 165–261 PJ/year (3.8–6.1 Mt/year) of RJF by 2030, representing 24%–33% of total EU nonfood biofuel consumption. The RJF volume is positively affected by high supply of UCOAF (HS scenarios) and high demand for advanced biofuels production, of which RJF is often a coproduct (HD scenarios). Although the quantity of UCOAF-based biofuels remains roughly constant over time due to limits on feedstock supply (rather than the 1.7% cap imposed by the RED-II proposal), it is increasingly diverted to the aviation sector due to the multiplier mechanism; 41%–45% of UCOAF-based biofuels are consumed in the aviation sector by 2030. By 2030, 109–213 PJ/year (2.5–4.9 Mt/year) RJF is produced from lignocellulosic biomass using technologies which are currently not yet commercialized. RJF based on lignocellulosic biomass is initially produced using FT and ATJ. Pyrolysis and HTL are added to the technology portfolio upon commercialization, but their contribution is marginal due to low RJF yields.

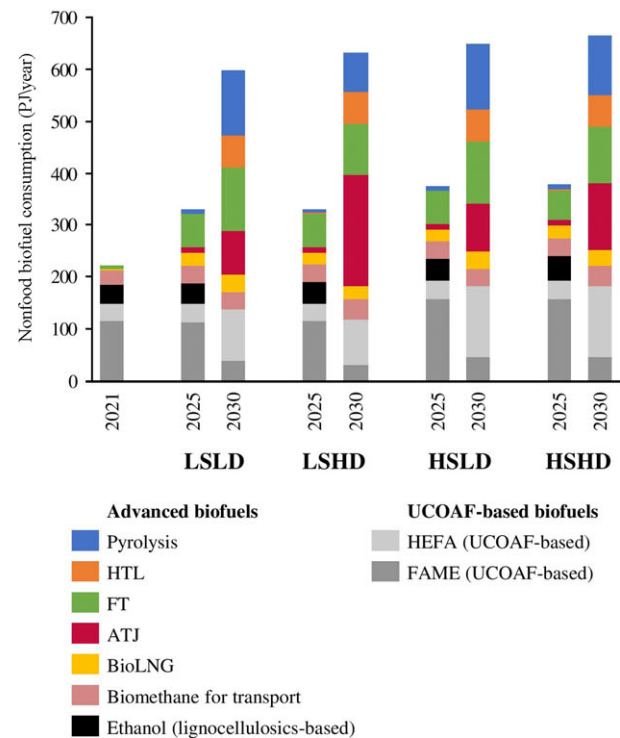
Figure 7a shows that nonfood biofuel consumption in road transport remains relatively constant, while it increases sharply in the aviation and marine sectors (instigated by the multiplier). The subtarget for advanced biofuels increases overall consumption in the EU from 71 PJ/year in 2021 to 460–515 PJ/year by 2030. Initial volumes are supplied through biogas from digestion and lignocellulosics-based ethanol; after 2025, a more diverse technology mix with ATJ, FT, pyrolysis and HTL emerges as these technologies commercialize. 393–450 PJ/year nonfood biofuel is produced from lignocellulosic biomass by 2030. The lack of variation among scenarios (especially before 2027) indicates that new technologies not necessarily emerge because of superior economic performance, but rather because the model has few technology options to

(a) Non-food biofuel mix by end-use sector

**Abbreviations**

LS/HS: Low/High biomass supply scenario
LD/HD: Low/High biomass demand scenario
UCOAF: Used cooking oil and animal fats

(b) Non-food biofuel mix by conversion technology

**FIGURE 7** The mix of nonfood biofuels by end-use sector (a) and conversion technology (b)

meet the biofuel targets. In the first years, nonfood biofuel options are mainly limited to lignocellulosic ethanol, because other advanced biofuel technologies have not commercialized and UCOAF-based biofuels are restricted by limited feedstock supply. As a result, the E10 blend wall is reached in 2023, instigating the need for ATJ and FT technologies to produce drop-in fuels (hence boosting RJF production), despite poorer economic performance compared to alternative technologies. New technologies generally follow the maximum deployment rates before 2027, after which the model has more room to maneuver.

4.2 | Biomass use

Figure 8a,b shows that total biomass use increases from 5.4 EJ in 2021 to 5.6 EJ in LD scenarios and 6.9–7.3 EJ in HD scenarios by 2030. HD scenarios show increased use of agricultural residues, primary forestry residues and imported wood pellets, sugarcane-based ethanol, and lignocellulosics-based ethanol. In the LD scenarios, the share of biomass use remains constant or declines slightly, while imports are particularly prominent in the first half of the decade.

Renewable jet fuel is mainly produced from UCOAF, agricultural residues (e.g., straw from cereals and corn stover), and forestry residues (i.e., sawmill by-products,

primary forest residues, industrial wood residues, landscape care wood, and black liquor). Intra- and extra-EU UCOAF potentials are fully exploited across all scenarios, which illustrates its key role in reaching biofuel targets cost-effectively, particularly in the short term. HD scenarios show a higher share of imported biomass (mainly wood pellets) and biofuels (mainly ethanol). Projected utilization rates of intra-EU biomass by 2030 (41%–62%) leave some room for further growth of advanced biofuels in the EU beyond 2030, especially since vast potentials of agricultural residues (0.8–1.8 EJ), forestry residues (0.7–2.6 EJ), and perennial crops (0.7–1.2 EJ) remain underutilized.

4.3 | Cost

Figure 9a,b shows the marginal cost differential (a) and the total additional cost (b) for RJF. Both graphs were based on the differential between fossil jet fuel price and the marginal production cost of RJF, which is an average over RJF types weighted by production volume (advanced RJFs typically show a higher marginal cost differential than UCOAF-based RJF, as the former have a separate biofuel target). The total additional cost is the product of the marginal cost differential and production volume. The marginal cost differential can be interpreted as the maximum cost of RJF production at which it is economically preferred to

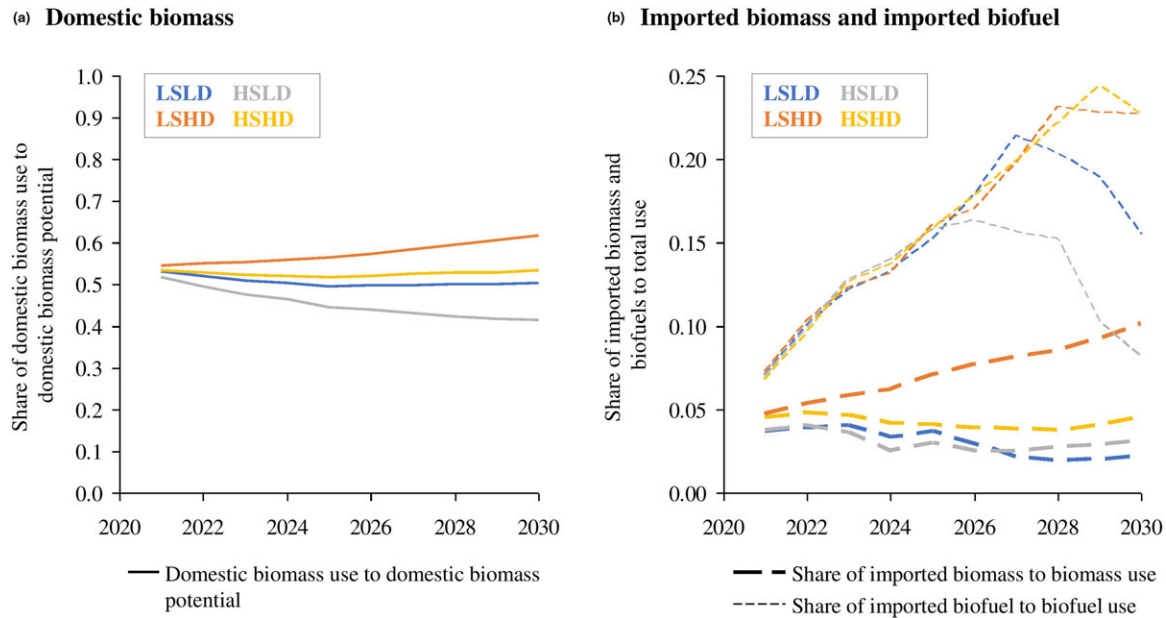


FIGURE 8 Domestic biomass (a) and Imported biomass and imported biofuel (b) in the EU

supply RJF than alternative biofuel options serving the same target. This preference is governed by the additional production costs of RJF relative to other nonfood biofuel options and the multiplier for RJF.

In all scenarios a cost differential between RJF and fossil jet fuel remains toward 2030, irrespective of conversion pathway. The cumulative additional costs in these scenarios vary between €7.7 and 11 billion over 2021–2030, which translates to an average cost differential of 11–16 €/GJ RJF (491–682 €/t). In all scenarios except LSHD, the cost differential decreases from roughly 40 €/GJ RJF (1,740 €/t) in 2021 to 7–13 €/GJ RJF (280–540 €/t) by 2030. This drop is partly caused by fossil jet fuel prices increasing by 9 €/GJ over this period; the remainder is due to the availability of cheaper feedstocks and a reduction in production cost because of technological learning.

Learning effects are mainly driven by scale-dependent learning and reduce conversion costs for lignocellulosics-based technologies between 15% for cellulosic ethanol to 21%–28% for HTL, FT, ATJ and pyrolysis over the period 2021–2030. For the LD scenarios, this reduction allows the RJF volume to double while additional costs stabilize during 2027–2030. Despite slightly larger cost reductions induced by market-driven learning (due to higher deployment) in the HD scenarios, total additional costs increase because of higher competition for biomass, high reliance on (more expensive) imports, and high RJF production volumes, which implies that the model moves higher up the cost-supply curve. The same dynamics also drive up the marginal costs of other products; relative to the LSLD scenario, marginal costs of bio-based electricity and heat increase by roughly 15% and 60% (HSHD scenario) and

100% and 225% (LSHD scenario) during 2025–2030. The results for LSHD in 2030 were excluded from Figure 9a,b, as they were an order of magnitude higher than the other scenarios, indicating the model requires very expensive solutions to fulfill the bioenergy demand.

4.4 | Greenhouse gas emissions

Figure 10a,b shows a threefold increase in reductions in combustion (a) and life-cycle (b) GHG emissions from nonfood biofuels between 2021 and 2030. This increase is mainly attributed to the aviation and marine sectors, while emission reductions in road transport remain constant over time. The introduction of RJF reduces combustion emissions in the aviation by 12–19 Mt CO₂-eq by 2030, which roughly equals the combustion emissions of domestic aviation (15 Mt CO₂-eq) (Eurostat, 2017c). The average life-cycle GHG emission reduction of RJF equals 77%–79% over 2021–2030. Total combustion emission reductions from nonfood biofuels in the marine sector (14–18 Mt CO₂-eq/year in 2030) are comparable to the current emissions of domestic navigation (16 Mt CO₂-eq/year) (Eurostat, 2017c). In comparison, renewable electricity use in road transport reduces combustion emissions by 7–11 Mt CO₂-eq in 2030 (cf. 5 Mt CO₂-eq in 2021).

4.5 | Sensitivity analysis and alternative policy scenarios

This section tests the impact of key assumptions on the model outcomes and explores alternative policy scenarios. The analyses were applied to the LSLD scenario.

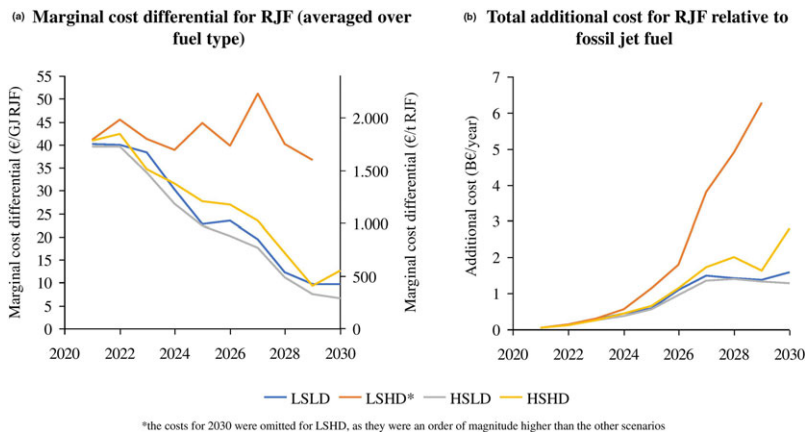


FIGURE 9 Additional cost of renewable jet fuel (RJF) introduction

4.5.1 | Technology development

As technology development is uncertain and highly depends on future RD&D efforts, this sensitivity analysis evaluates the impact of the pace of technology development and associated cost reductions by varying the introduction year, doubling time, scaling factor, and maximum deployment rate in a high technology development (HT) and low technology development (LT) case (Table 3).

Figure 11 shows the resulting mix of nonfood biofuels by end-use sector for the HT and LT case. The HT case provides more technology options, leading to lower cost of compliance (the cost differential for RJF almost dissolves toward 2030), reduced imports, and a more diverse feedstock-technology portfolio. Learning effects reduce production costs by almost 50% for HTL, ATJ, and pyrolysis (cf. 21%–28% in the base case). Moreover, the earlier introduction of HTL and pyrolysis increases the role of these technologies at the expense of FT, which generally has higher production cost. These effects halve the cumulative additional costs of RJF production (€ 3.9 billion) over 2021–2030 compared to the base case.

The LT case could not be solved, as the advanced biofuel target could only be fulfilled by biogas and lignocellulosics-based ethanol until 2023, both of which require adaptation to infrastructure and fleet at high deployment rates. Hence, policies to support and expedite technology development are cardinal to the feasibility and affordability of the proposed advanced biofuel targets.

4.5.2 | The multiplier for RJF

The RED-II proposal uses a multiplier to incentivize RJF production. However, the effectiveness of the multiplier depends on its size and the relative cost differential of RJF with respect to other biofuels. The following cases explore

the impact of key policy levers (case 1 and case 2) and volatility in fossil fuel prices (case 3 and case 4) (Figure 12):

1. *Size of the multiplier.* Case 1A and case 1B evaluate the impact of different multipliers for RJF (1.0 and 2.0). The multiplier for marine biofuels is kept at 1.2.
2. *Excise duties or CO₂ price on transport fuels.* Some Member States partly or fully exempt road biofuels from excise duties, which decreases the cost differential for road biofuels and thus affects the relative attractiveness of RJF. No such exemptions can be given to the aviation biofuels, as generally no excise duty is levied on fossil jet fuel. In case 2A, such exemption were applied to road biofuels equal to the minimum EU excise duty rates on petrol (10.4 €/GJ), diesel (9.2 €/GJ), and natural gas (2.6 €/GJ) used in transport (The council of the European Union, 2003). In case 2B, the CO₂ price on fossil jet fuel was removed.
3. *Change in jet to diesel/gasoline price spread.* Changes in the spread between fossil diesel/gasoline and jet fuel affect the relative cost differential. Case 3 investigates the effect of higher diesel/gasoline prices, by taking 2-year ratios instead of 10-year ratios for fossil fuels relative to crude oil. This particularly increases the ratios for diesel (1.31 cf. 1.18 in base) and gasoline (1.37 cf. 1.24 in base), while the ratio for jet fuel (1.29 cf. 1.30 in base) remains roughly constant.
4. *Elevated fossil fuel prices.* Case 4 evaluates the impact of a higher crude oil price scenario, which increases the oil price by 10%–30% during 2021–2030 (Supporting Information Data S6).

Figure 13 shows that the attractiveness of RJF is predominantly affected by the RJF multiplier and tax incentives for road transport biofuels. A multiplier of 2 (case 1B) leads to 273 PJ/year RJF (6.3 Mt/year) by 2030, but also results in a sharp decline in nonfood biofuel

FIGURE 10 Combustion (a) and life-cycle (b) greenhouse gas emission reduction from nonfood biofuels by end-use sector. Emission reductions from renewable electricity in road transport are not shown

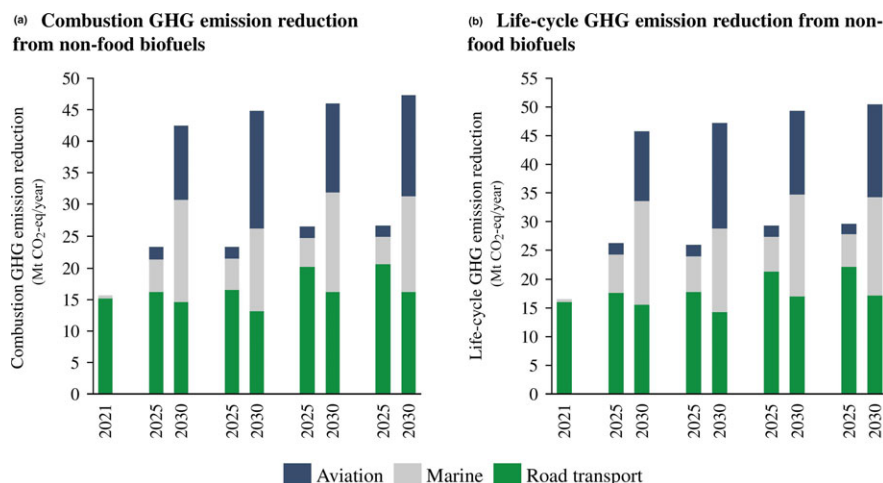


TABLE 3 An overview of the high technology development (HT) and low technology development (LT) case

	Introduction year			Doubling time			Scaling factor			Maximum deployment rate ^a		
	Base	LT	HT	Base	LT	HT	Base	LT	HT	Base	LT	HT
Fermentation (Lignocellulosics)	2015	2015	2015	5	7	3	0.8	0.8	0.7	150% (90%)	150% (90%)	200% (150%)
Fischer–Tropsch (FT)	2020	2023	2020	5	7	3	0.8	0.8	0.7			
Alcohol-to-Jet (ATJ)	2020	2023	2020	5	7	3	0.8	0.8	0.7			
Hydrothermal liquefaction (HTL)	2025	2027	2023	5	7	3	0.8	0.8	0.7			
Pyrolysis	2023	2025	2020	5	7	3	0.8	0.8	0.7			

Note. ^aThe values in between brackets indicate the maximum growth rate after 3 years.

consumption (514 PJ/year) and lower combustion emissions reductions (36 Mt/year CO₂-eq cf. 49 Mt/year CO₂-eq in base). A multiplier of 1 (case 1A) leads to 62 PJ/year RJF (1.4 Mt/year) by 2030, largely because the conversion to HEFA-RJF is no longer attractive. RJF is only produced as a coproduct of advanced biofuel production, as the price of fossil jet fuel is higher than diesel and gasoline. In case 1A, nonfood biofuel use in road and marine transport rises by 25% and 19% in 2030 relative to the base case. A tax exemption for road transport biofuels (case 2A) yields 96 PJ/year RJF (2.2 Mt/year), but in this case, RJF is produced as a coproduct of advanced biofuel production because of the 1.2 multiplier on RJF. Tax exemptions in road transport reduce nonfood biofuel consumption in the aviation and marine sectors by 42% and 6%, while increasing the use of nonfood biofuels in road transport by 32%. Although both cases still contain some RJF consumption, simultaneous removal of the multiplier and application of tax incentives for road transport biofuels will likely lead to negligible volumes of RJF.

The other cases were found to have insignificant impact when applied individually. It is shown that the current CO₂ prices potentially applied through EU ETS and CORSIA do not alter the amount of RJF produced. Similarly, the assumed volatility in fossil fuel prices is

not sufficient to change the mix of nonfood biofuels, suggesting the system dynamics are inert up to a certain tipping point.

4.5.3 | A biofuel target across all transport sectors

In this analysis, the overall target for renewable transport fuels was extended to cover intra-EU aviation and marine, while the multiplier for aviation and marine biofuels was removed. The use of nonbio-based fuels and renewable electricity in these sectors was assumed negligible. As this leads to 16% higher demand for nonfood biofuels over the period 2021–2030, this analysis could only be run using the high technology development case (Table 3). Fuel demand for aviation was aligned with own projections (Supporting Information Data S1). Fuel demand for marine transport was obtained from industry projections (International Maritime Organisation, 2015). The intra-EU share of total fuel use for aviation (39%) and marine (35%) was estimated from emission records (EEA, 2016; European Commission, 2013b).

Figure 14 shows a significant increase nonfood biofuels consumption in road transport compared to the base case (379 PJ/year in 2030 cf. 209 PJ/year in base), while

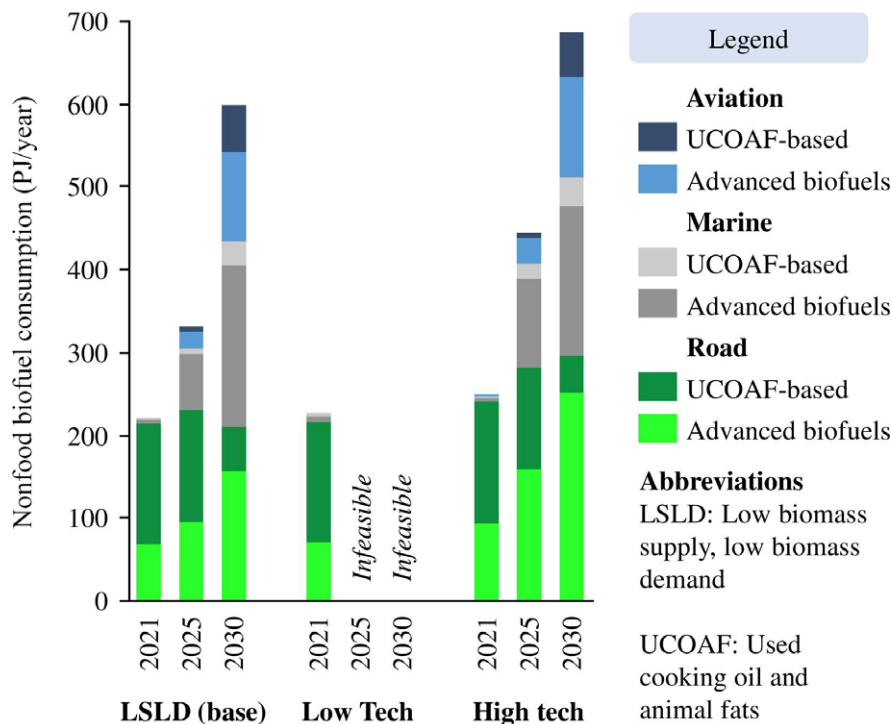


FIGURE 11 The mix of nonfood biofuels by end-use sector for the low and high technology development case

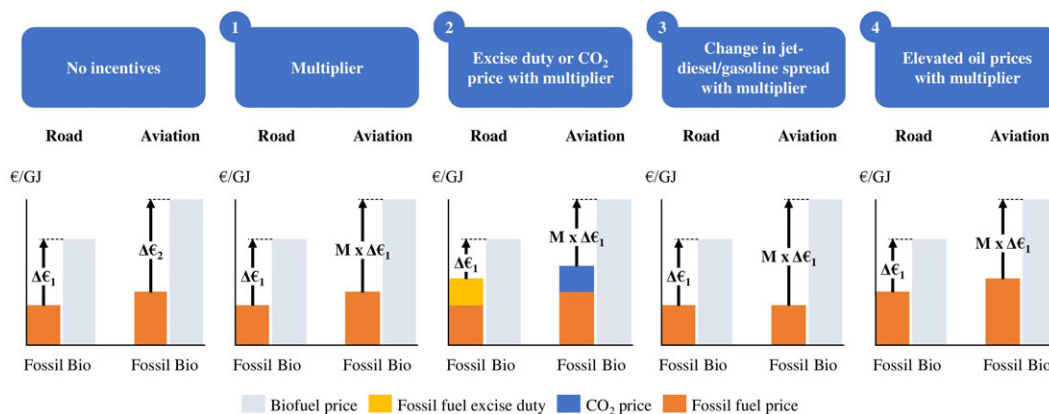


FIGURE 12 General dynamics of the multiplier for aviation biofuels. M indicates the multiplier for aviation biofuels. The relative size of the bars in the chart is illustrative only. Although only road and aviation are shown here, the pricing of marine (bio)fuels also affect system dynamics

RJF consumption increases slightly to 176 PJ/year (4.1 Mt/year) in 2030. The higher price for fossil jet fuel compared to diesel and gasoline is sufficient to instigate RJF production, but insufficient to cover the additional cost for HEFA-RJF relative to HEFA-diesel. RJF is mainly produced as a coproduct in cases where it does not increase production costs (i.e., FT, ATJ, HTL, and pyrolysis). ATJ is a particularly important technology in this analysis, as the E10 blend wall is already reached in 2021. The relative shares of UCOAF-based and advanced biofuels do not change significantly compared to the base case. However, this case shows increased imports, system

costs, and marginal costs due to increased pressure on the system. This case also involves a more ambitious growth of advanced biofuel production capacity than the base case.

The introduction of RJF could also be incentivized by a separate biofuel target for aviation and marine. However, this sensitivity analysis shows that a transport-wide target leads to a higher nonfood biofuel share in intra-EU aviation (15%) and marine (21%) than in road transport (3.1%). A separate target for aviation or marine of the size of the renewable transport fuels target (6.8% by 2030) will thus likely lead to higher cost of compliance.

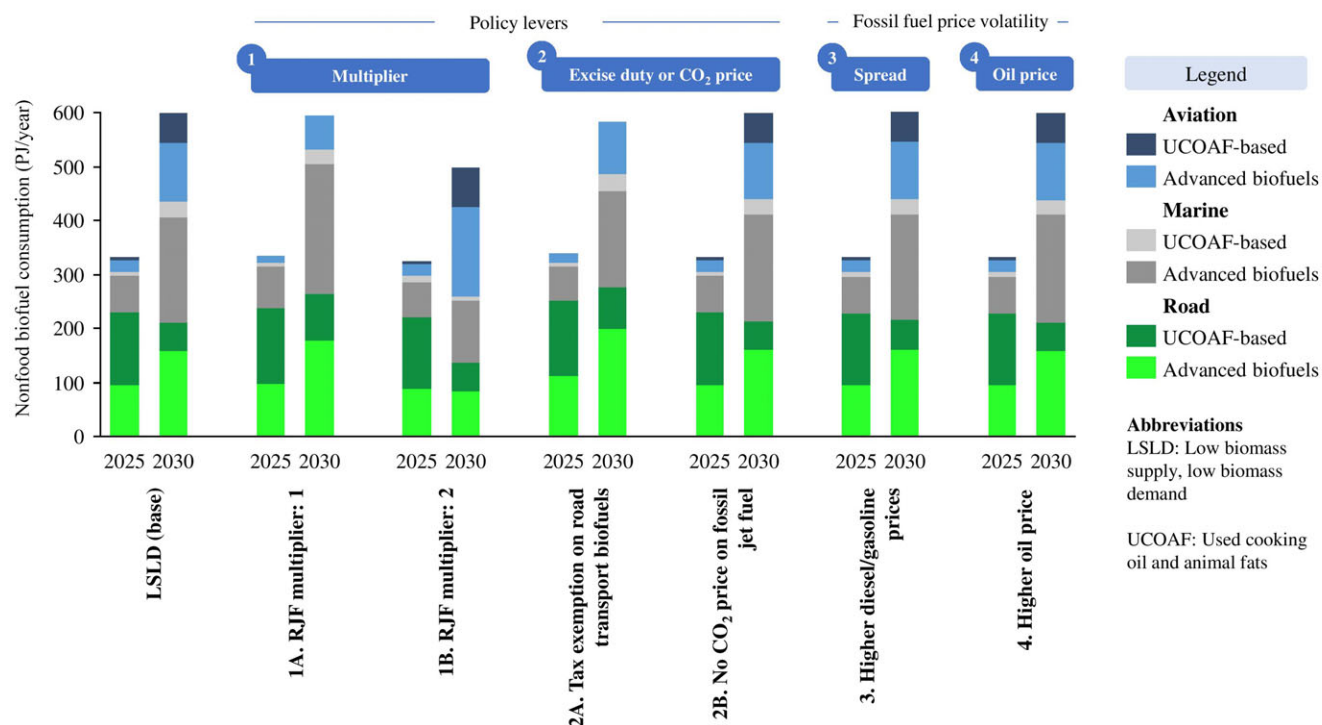


FIGURE 13 The mix of nonfood biofuels by end-use sector for the sensitivity cases affecting the attractiveness of renewable jet fuel (RJF)

5 | DISCUSSION

5.1 | Implications for RJF adoption in aviation

Depending on biomass supply and demand, the base case results show 165–261 PJ/year (3.8–6.1 Mt/year) RJF production by 2030, representing roughly 6%–9% of total EU jet fuel consumption. The RJF supply scenarios highly depend on the development of advanced biofuel technologies and the presence of adequate (policy) incentives. The introduction of RJF reduces aviation-related combustion emission by 12–19 Mt/year CO₂-eq by 2030, offsetting 53%–84% of projected emission growth of the sector in the EU by 2030. However, vast growth of RJF beyond 2030 is required if the emission gap continues to grow.

The introduction of RJF is largely driven by the 1.2 multiplier for RJF, (advanced) biofuel targets, and the high price of fossil jet fuel relative to other fossil fuels. Additional incentives for RJF will increase RJF volumes and increasingly shield RJF development from market volatility, but a higher multiplier may also dilute the biofuel targets and lead to lower overall GHG emission reductions. Increasing the use of RJF depends on biomass mobilization (especially UCOAF) and development of (advanced) biofuel technologies, including technical certification for use in commercial aviation.

The cost differential of RJF over fossil jet fuel drops significantly from 40 €/GJ in 2021 to 7–13 €/GJ in 2030, due to increasing oil prices and decreasing production

costs. The CO₂ abatement cost of RJF is high (91–176 €/t CO₂ in 2030) compared to projected CO₂ prices and other bioenergy options (Gerssen-Gondelach, Saygin, Wicke, Patel, & Faaij, 2014). EU ETS and CORSIA will thus likely provide a marginal incentive for RJF. The RED-II proposal allocates the cost of biofuel use to suppliers of road transport fuel, as road transport is the only obligated transport segment (jet fuel suppliers are not obliged to supply biofuels). The cost burden of RJF on the road transport sector is of the order of 0.24–0.31 €-cents per liter, averaged over 2021–2030. If the cost would be allocated to the aviation sector instead, the average costs would amount to 1.0–1.4 € per departing passenger on intra-EU flights.

5.2 | Implications for the EU biofuel portfolio

This study shows that the RED-II proposal increases consumption of nonfood biofuels, particularly in the aviation and marine sectors, which corresponds to 28%–41% and 29–34% of total nonfood biofuel consumption in the EU in 2030. This shift is caused by the imposed multiplier for aviation and marine biofuels and the high price for fossil jet fuel and marine gasoil relative to road transport fuels. Increased consumption of nonfood biofuels in the aviation and marine sectors, which have few options to reduce their GHG intensity, can lead to greater emission reductions in transport, provided renewable electricity use in road transport increases.

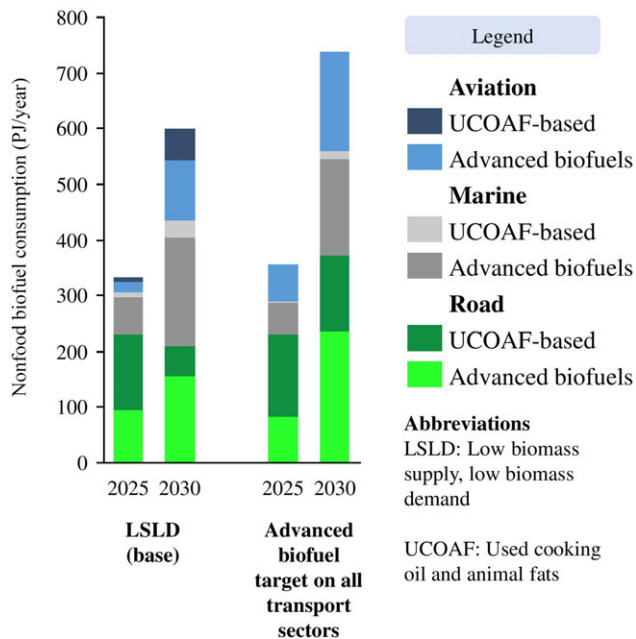


FIGURE 14 Mix of nonfood biofuels by end-use sector for a target across all transport sectors

The use of advanced biofuels grows rapidly because of the imposed subtarget. The conversion cost of advanced biofuels reduces by 15%–28% over the period 2021–2030 through technological learning, while the availability of cheaper feedstocks and higher oil prices further instigate cost reductions. Successful commercialization of advanced biofuel technologies is vital to the feasibility of biofuel targets, as 52%–58% of biofuel volumes (393–450 PJ/year) by 2030 are produced by technologies which are currently not yet mature (i.e., ATJ, FT, HTL, and pyrolysis) or widely commercialized (e.g., lignocellulosics-based ethanol). The deployment of these technologies requires persistently high deployment rates (30–42%/year) during 2021–2030, which implies a rapid acceleration compared to the average growth rate in biofuel production in the EU (10%/year) and the United States (13%/year) during 2006–2016 (BP, 2017). Categorized biofuel targets alone will not necessarily stimulate commercialization of new technologies, as was observed in the United States (Bitnere & Searle, 2017). A solid investment climate and incentives to mobilize domestic biomass and commercialize advanced biofuel technologies are therefore encouraged.

5.3 | Discussion on key assumptions and model characteristics

Several assumptions deserve additional attention as they are important drivers of model results:

- *The pace of technology development.* The introduction year, technological learning potential, and the

deployment rate of biofuel technologies largely drive model results (rather than cost minimization), but highly depend on RD&D efforts. Low technology development impedes target compliance, while faster technology development reduces imports and system costs and leads to a more diverse feedstock-technology portfolio.

- *Techno-economic and life-cycle emissions data.* The performance data of advanced biofuel technologies are largely based on process modeling studies. The variance in cost and GHG emission estimates can be significant due to lack of empirical validation, especially for immature technologies such as pyrolysis and HTL (de Jong et al., 2015; De Jong, Antonissen, Hoefnagels, et al., 2017). These assumptions particularly affect system cost and life-cycle GHG emission reduction, but marginally affect the technology portfolio, which is mainly driven by biofuel targets and the pace of technology development.
- *Additional cost of RJF production.* It was assumed that RJF production using FT, pyrolysis, or HTL does not incur additional costs compared to diesel-only production. Although additional costs affect the relative attractiveness of RJF production, the production of HEFA RJF illustrates that additional cost can be absorbed to a certain extent, under the assumption of a 1.2 multiplier and relatively high fossil jet fuel price compared to other fossil fuels.
- *Policy context.* Amendments to the RED-II proposal at EU or national level may impact the results, particularly when affecting nonfood biofuel targets, sustainability criteria, and incentives for nonfood biofuel use in the aviation and marine sectors and renewable electricity use in road transport (some of which were tested in the sensitivity analysis).
- *Biomass demand and supply.* Biomass demand and supply were modeled exogenously. For some biomass demand segments, exogenous modeling of biomass demand is justified because demand is defined by policy targets (i.e., advanced biofuels). Biomass demand from other segments (e.g., bio-based electricity and heat) depends on the competitiveness of bioenergy relative to other renewable energy technologies which was not explicitly modeled here. Furthermore, the development of extra-EU biomass markets may limit imports to the EU and/or instigate exports from the EU and thus affect the cost and feasibility of target compliance.

5.4 | Recommendations for further research

This study shows that RJF consumption could grow significantly in the coming decade, depending on policy incentives, technology development, and biomass supply. It is therefore encouraged to include RJF in other (bio)energy models to explore the potential of RJF on a national, regional, and global level. It is further recommended to include a more

detailed representation of RJF in sectoral models of the aviation industry to study the impact of RJF introduction and regulatory measures (e.g., a per-passenger surcharge) in terms of fuel cost, market growth, and climate impact.

The RESolve-Biomass model may be improved by a broader and more detailed technology scope. For example, the use of lower-quality biofuels (e.g., partially upgraded pyrolysis/HTL biocrude) for marine applications may contribute to higher biofuel use in the marine sector and faster development of these technologies.

The temporal scope of this study covers 2021–2030. It is encouraged to further explore the role of bioenergy in the EU beyond 2030, based on future policy options, trends in domestic biomass supply and demand, and development of bioenergy markets outside the EU. Moreover, as deep GHG emission reductions are required to reach climate mitigation targets, it becomes increasingly important to explore the optimal allocation of biomass among end-use sectors, while considering the interaction between bioenergy and other renewable energy sources.

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ORCID

Sierk de Jong  <http://orcid.org/0000-0002-8110-4527>

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SUPPORTING INFORMATION

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