

# The implications of geopolitical, socioeconomic, and regulatory constraints on European bioenergy imports and associated greenhouse gas emissions to 2050

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**Abstract:** Modern sustainable bioenergy can contribute toward mid-century European energy decarbonization targets by replacing fossil fuels. Fulfilling this role would require access to increased volumes of bioenergy, with extra-EU imports projected to play an important part. Access to this resource on the international marketplace is not governed by Europe's economic competitiveness alone. This study investigates geopolitical, socioeconomic, and regulatory considerations that can influence Europe's bioenergy imports but that are so far underexplored. The effect of these constraints on European import volumes, sourcing regions, mitigation potential, and their implications for European and global emissions is projected to the year 2050 using a global integrated assessment model. The projections show that Europe can significantly increase imports from 1.5 EJ year<sup>-1</sup> in 2020 to 8.1 EJ year<sup>-1</sup> by 2050 whilst remaining compliant with Renewables Energy Directive recast II (RED II) greenhouse gas (GHG) criteria. Under these conditions, bioenergy could provide annual GHG mitigation of 0.44 GtCO<sub>2</sub>eq. in 2050. However, achieving this would require a structural diversification of trading partners from the present. Furthermore, socioeconomic and logistical concerns may limit the feasibility of some of the projected major sourcing regions, including Africa and South America. Failure

to overcome these challenges within supplying regions could limit European imports by 60%, reducing annual mitigation to 0.16 GtCO<sub>2</sub>eq. in 2050. From a global perspective, regions with a comparatively carbon-intensive energy system offer an alternative destination for globally traded biomass that could increase the mitigative potential of bioenergy. © 2022 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Supporting information may be found in the online version of this article.

Key words: bioenergy; 2050; Europe; trade; imports; RED II; trade barriers

## Introduction

Climate-change mitigation pathways aimed toward meeting the Paris Agreement project an increased role for bioenergy.<sup>1,2</sup> The use of bioenergy is motivated by the potential to mitigate anthropogenic greenhouse gas (GHG) emissions by substituting fossil fuels. Besides emissions associated with land-use and land-use change, carbon in bioenergy is classified as biogenic. Hence accounting guidelines qualify combustion emissions as zero and, when paired with carbon capture and storage (BECCS), bioenergy can, in principle, deliver net-negative emissions. Furthermore, biomass can be converted into multiple energy carriers (liquid fuels, heat, electricity, and hydrogen), which can supply all end-use sectors, making it a flexible and attractive option for decarbonization strategies.

Currently primary bioenergy consumption in Europe stands at 6.7 EJ year<sup>-1</sup> and contributes 60% of total renewable as part of Europe's effort to mitigate climate change.<sup>3</sup> The majority (96%) of this biomass is EU sourced, with 89% consumed in the member state (MS) that produces the biomass. Much of this domestic supply is low-grade solid biomass (e.g. wood chips and fuelwood) for residential heating.<sup>4</sup> For large-scale heating and power, wood pellets form the dominant supply. The EU wood pellet market currently consumes 0.45 EJ year<sup>-1</sup>; extra-EU imports meet 40% of this. For the transport sector, liquid biofuel consumption stands at 0.65 EJ year<sup>-1</sup> (14% imported).

Over the past decade, the EU has been the largest global importer of modern bioenergy carriers.<sup>5</sup> Total imports are expected to increase in the decades ahead as bioenergy becomes increasingly important within decarbonization strategies. This is especially true when focusing on higher quality modern bioenergy carriers, deemed necessary for future decarbonization strategies.<sup>6</sup> Existing bioenergy trade projections show that, by 2030, the EU will be primarily sourcing this import from the same regions as at present; by 2050, projections point to a possible broadening of sourcing regions to meet increased demand.<sup>7,8,9</sup>

Long-term projections of bioenergy demand and trade in the context of mitigation targets rely upon global integrated assessment models (IAMs) that can capture trade between world regions. Integrated assessment models are often used to explore the large-scale global effects of climate policy on the energy system and its relationships with natural and human systems. To determine production and trade patterns, IAMs consider climate targets, relative production costs and trade costs.<sup>2,7,10</sup> These existing assessments make assumptions on different markets and their connections but typically search for cost-optimal use of the biomass resource base under a global emission constraint. These assessments capture the effects of climate-target induced global competition for bioenergy. However, they preclude the consideration of other factors that may influence this trade, such as regulatory, geopolitical, and socio-political constraints.

Regarding regulatory constraints, the EU-wide enforcement of the Renewables Energy Directive recast (RED II)<sup>11</sup> stipulates mandatory GHG reduction criteria for particular end-use applications compared to a fossil fuel comparator. This regulatory measure may constrain the potential of the resource base eligible to be used in Europe, which in turn may influence both European consumption and global bioenergy trade regimes. It is also important to consider geopolitical and logistical aspects. The production and export capacity in regions that currently do not supply the international market requires large-scale investment and logistical challenges to mobilize meaningful trade.<sup>8</sup> The challenges associated with expanding production within exporting regions are only being tackled at demonstration scale with large associated capital costs.<sup>12</sup> Furthermore, the formulation of bilateral trade agreements with emerging exporting regions face increased competition from other world regions. Finally, governance and socioeconomic feasibility must also be considered when sourcing bioenergy imports. Concerns have been raised regarding the negative impacts of increased bioenergy demand in regions with poor governance and regulatory accountability, where issues such as deforestation, land tenure insecurity, and inequitable supply chains are present.<sup>13,14,15</sup>

These barriers cast uncertainty over which regions can provide future bioenergy exports and the GHG emissions associated with imported bioenergy. Existing studies do not determine how trade barriers may influence sourcing strategies and the emissions attached to bioenergy. However, these barriers may have large implications for the European energy system, its ability to meet climate target commitments, and the logistical challenges of obtaining these imports. This study therefore investigates the potential effects of alternative bioenergy trade developments based on regulatory, geopolitical, and socioeconomic barriers for imports to Europe. The effects that are studied are (i) possible future sourcing regions, (ii) import volumes, and (iii) the emissions attached to bioenergy imports to Europe.

## Materials and methods

This study conducts a trade scenario analysis at the European level to the year 2050 to explore possible future extra-EU bioenergy trade developments and their effects on the GHG mitigation potential of the European bioenergy sector. A series of trade scenarios are investigated.

### Model description IMAGE 3.2

#### Bioenergy in IMAGE 3.2

This study uses the global integrated assessment model framework IMAGE 3.2,<sup>16</sup> which simulates the environmental consequences of energy and land-use systems worldwide. Integrated assessment models are an appropriate tool for exploring mid-term climate change mitigation pathways that meet exogenously defined climate targets while considering systemic and global effects. IMAGE represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change. The human system is represented through energy and agricultural demand, and its impacts in the form of greenhouse gas emissions and land-use change are communicated to earth system models for land, atmosphere, and ocean.

The IMAGE3.2 framework covers all stages of the bioenergy value chain, accounting for feedstock production, associated land-use change, conversion to secondary energy carriers, international trade, and final consumption in end-use sectors.<sup>17</sup> Biomass supply is represented by six aggregated primary feedstock categories: woody crops, grassy crops, maize, sugarcane, oil crops, and residues supplied from agricultural and managed timber operations. The potential bioenergy supply is determined at the grid level by the dynamic global vegetation model LPJml.<sup>18</sup> To ensure that bioenergy supply does not interfere with major

environmental and social criteria, specific land types are excluded from bioenergy production. These include urban areas, nature reserves, forests and areas projected to be used for food production by assuming a 'food first' principle.<sup>19</sup>

Primary biomass can be converted into liquid and solid bioenergy carriers. Liquids include first-generation and lignocellulosic biofuels. Solid bioenergy carriers (i.e. chips and pellets) can be further converted to hydrogen, electricity or heat. End-use final energy demand sectors include industry, transport, services, and residential. Additionally, biomass can also be used for non-energy purposes, acting as a feedstock for the production of ammonia, methanol, and higher value chemicals.<sup>17</sup> Sectoral bioenergy demand is based on its economic competitiveness for meeting specific energy services of the demand sectors relative to other energy carriers. Bioenergy costs include feedstock, conversion technology, labor, capital, and operation and maintenance costs. Bioenergy cost is also influenced by carbon prices implemented within mitigation scenarios, which promote low-carbon fuels by adding a price on the potential emission of different bioenergy production routes. For further details on the IMAGE model, see SM.1 in Appendix S1, in the supplementary material.

#### Emissions accounting for bioenergy

For bioenergy emissions accounting, pre-combustion upstream process emissions are determined dynamically at a regional level. They include land-use change, primary biomass production (including fertilizer production/application and energy inputs for cultivation), transport (including intra-regional primary biomass to processing/conversion site and inter-regional trade), and process energy for conversion into bioenergy/secondary carriers.<sup>20</sup> Smokestack emissions during final energy conversion from biogenic carbon are considered carbon-neutral as the carbon uptake during the growth phase is accounted for in the land-use component of IMAGE. The production of liquid bioenergy carriers, as well as bio-based electricity, hydrogen, and industrial heat, can be combined with carbon capture and storage at technology-specific capture rates to produce negative emissions during the conversion process.<sup>21</sup> Part of the carbon content of biomass used for non-energy purposes in chemical manufacture is also assumed to be indefinitely sequestered.<sup>22</sup> See SM.1 in Appendix S1, in the supplementary material, for a schematic of modeled bioenergy GHG sinks and releases.

#### Trade representation

The IMAGE model projects bilateral bioenergy trade across 26 macro-regions (see Figures SM.2.1–3 in Appendix S1, in

the supplementary material, for world region representation in IMAGE 3.2). The secondary bioenergy carrier trade is facilitated based on the regional production cost of bioenergy and associated transport costs. Regional cost supply curves of primary biomass are projected by determining and ordering spatially explicit biomass costs based on yields and land prices. These regional bioenergy supply curves and regional demand are used to determine the optimal bilateral trade. A region imports bioenergy when imported bioenergy cost (export region production plus international transport cost) is lower than domestic production or alternative fuel sources to match the equivalent secondary energy demand.

## Scenarios

Our scenario analysis builds upon the default SSP2-RCP2.6 scenario of the IMAGE 3.2 model.<sup>23</sup> That is, we present variations of a middle-of-the-road socioeconomic scenario meeting a 2 °C climate target. We explore three variations of trade narratives described in Table 1, which differ concerning restrictions on regions with which Europe can trade bioenergy. In the default ‘free trade’ scenario, trade is allowed with all regions based purely on trade optimization (see Fig. 1). In the first variation, ‘current partners’, trade is only allowed with current trading partners. The second variation, ‘feasibility’, excludes trade with regions that do not meet a pre-defined socio-political feasibility score. In the final variation, ‘RED II’, trade is only allowed for bioenergy that meets EU regulations on GHG emission savings.

Within this study, trade is calibrated up to 2020, after which the scenario-specific trade restrictions are applied to Europe. Besides their ability to trade bioenergy with Europe, other world regions are not constrained by the scenario variations.<sup>24</sup> In the ‘free trade’ default scenario, a global carbon budget is enforced by introducing a dynamic carbon price mechanism from 2020 onwards. It is applied to all energy carriers based on their carbon content, effectively promoting lower carbon fuel sources. The projected carbon price is identical across all scenarios, implying that cumulative global and regional emissions may differ across scenarios in order to isolate the effect of trade restrictions.

For European-level projections, to isolate the effect of bioenergy on total GHG emissions, a ‘no bio’ scenario is used for comparison. This scenario follows the same global carbon price trajectory as the default scenario. However, due to bioenergy import constraints, it does not meet an equivalent regional emissions trajectory, creating a ‘mitigation gap’. Thus, this scenario acts as a fixed counterfactual against all explored scenarios, highlighting the mitigation available from bioenergy imports and, on a global level, the effects of

bioenergy which may be re-routed to other regions due to European trade constraints.

## Indicators

In line with the aims of this study, projections include (i) net trade volumes of bioenergy imports to Europe, (ii) emission factors (EF) relating to these imports, and (iii) the mitigation potential derived from imported bioenergy. These results are calculated as follows:

### (i) Net trade volumes

The net trade of secondary bioenergy carriers between any two world regions is determined by the bilateral flow of secondary bioenergy carriers imported minus the export flows. A surplus indicates net export, and a deficit means net import:

$$\begin{aligned} \text{net bioenergy trade}_{r1 \text{ to } r2} \\ = \text{bioenergy trade}_{r2 \text{ to } r1} - \text{Bioenergy trade}_{r1 \text{ to } r2} \end{aligned} \quad (1)$$

where:

$r_1$  = importing region

$r_2$  = exporting region

### (ii) Emissions factors (EF) of European bioenergy imports

The emission factors of bioenergy imports to Europe are determined dynamically per unit of final energy provided and focus on the end-use streams regulated by the RED II GHG savings criteria outlined in SM.4.1 in Appendix S1. We determine the emission factor for solid bioenergy carriers (converted into electricity or heat in the importing region) and liquid carriers used as transportation fuels. The emissions accounting methodology for bioenergy used in this study is similar to the methodology laid out in RED II Annex V and VI. For a side-by-side comparison, see SM.4.2–3 in Appendix S1:

$$\begin{aligned} \text{EF of bioenergy imports}_{r1,t} \\ = \frac{E_{\text{prod}}_{r2 \text{ to } r1, bc} + E_{\text{luc}}_{r2 \text{ to } r1, bc} + E_{\text{conv}}_{r2 \text{ to } r1, bc} \\ + E_{\text{trans}}_{r2 \text{ to } r1, bc} - E_{\text{CCS}}_{r2 \text{ to } r1, bc, tech}}{FE_{r1, bc, tech}} \end{aligned} \quad (2)$$

where:

$E_{\text{prod}}$  = emission during cultivation, fertilizer production/application and extraction

$E_{\text{luc}}$  = emissions arising from land-use change

$E_{\text{conv}}$  = emissions during conversion of primary biomass to secondary bioenergy carriers (including negative emissions captured via CCS during liquid carrier production)

$E_{\text{trans}}$  = emissions from transportation steps (field to Europe’s border)

**Table 1. Overview of key trade constraints applied in the scenario protocol.**

Scenario	Trade constraints
Free trade	The 'free trade' scenario applies default model settings, where all regions freely trade bioenergy based on the relative cost of delivered bioenergy. Projected trade represents cost-optimal use of the global biomass resource base under a global emission constraint whereby regions with high techno-economic production potentials with low attached costs become global exporters. For this scenario, only techno-economic and biophysical constraints are considered. The scenario settings have been used in previous assessments of international bioenergy developments. <sup>7,9,25</sup> This scenario assumes a middle-of-the-road socioeconomic development as described by the Shared Socioeconomic Pathway (SSP2), <sup>26</sup> meeting a 2 °C climate target (RCP2.6). The SSP2 follows a path whereby social, economic and technological patterns, including the management of global commons, follow historical patterns. Whilst resource and energy intensities collectively decline, this occurs unevenly between world regions. A 2 °C climate target was selected in this study to represent an ambitious global mitigative effort, and the minimal bounds of the Paris agreement considering the observed delay in long-term strategies within recently communicated national determined contributions. <sup>44</sup> As this study reports mid-century developments, a 2 °C target provides a pathway more representative of current actions. For carbon price developments under this mitigative pathway, please see SM.7 in Appendix S1, in the supplementary material.
Current partners	Global trade patterns do not necessarily develop in line with a least-cost modeling assumption in the 'current partners' scenario. Competition for the global biomass resource base is set to intensify, <sup>7</sup> and significant geopolitical uncertainties exist for future trade developments within an immature international market. These developments may be steered by other major importing regions contesting available trade partnerships. Furthermore, regions with large bioenergy resource potentials, such as sub-Saharan Africa and developing Asia, still suffer from relative energy poverty and the 'natural resource curse'. <sup>27,28</sup> The energy strategies of these regions may dictate the market size for extra-EU imports. This scenario assumes that future European extra-EU bioenergy trade is limited to world regions that currently exhibit a meaningful export of modern bioenergy carriers to Europe. An assessment carried out by Proskurina <i>et al.</i> <sup>29</sup> quantifies recent EU trade flows for modern bioenergy carriers and is consistent with other studies. <sup>4,30,31,32</sup> For pellets, regions include Canada, the USA, and Russia. For the liquid carriers, bioethanol imports from the USA, Central America (Guatemala), Brazil, the Rest of South Asia (Pakistan). Biodiesel and palm oil imports from Southeast Asia (Malaysia), Indonesia and South Korea.
Feasibility	The 'feasibility' scenario incorporates techno-economic and socio-political challenges attached to biomass production. This scenario is based on a country-level feasibility assessment for land-based mitigation measures presented in Roe <i>et al.</i> <sup>33</sup> Their study refines and updates the economic mitigation potential for 20 land-based measures in >200 countries via comparing bottom-up sectoral-level estimates with those from IAMs. The feasibility of implementing the actions required to realize mitigation is highly contextual, considering each country's unique circumstances. Their study aims to quantify a qualitative feasibility framework, conducting a detailed literature review followed by an expert review and only including indicators that provide data from the last 5 years and hold a demonstratable relationship to the feasibility of implementation. This process resulted in 19 indicators (including bioenergy-specific indicators, for instance, the technical feasibility of BECCS), spanning six dimensions: economic, institutional, geophysical, technological, socio-cultural, and environmental-ecological. The indicators used are listed in SM 2.3 in Appendix S1. From this, a quantitative index is developed as a proxy for country-level feasibility to implement these measures and realize mitigation potential through assessing barriers and enabling conditions <sup>33</sup> The country-level feasibility index from Roe <i>et al.</i> <sup>33</sup> is translated into scores for IMAGE3.2 regions via weighting the scores of constituent countries by total agriculture and forested land cover using FAO statistics. Bioenergy trade to Europe is prohibited for regions that score substandard to itself. This limit was selected as a proxy to represent regions with a governance system that can uphold European bioenergy sustainability criteria. The regional restrictions and feasibility scores are shown in SM 2.3 in Appendix S1. Feasible future trading partners include Canada, the USA, Japan, and Oceania.
RED II	The introduction of RED II sets binding GHG emission reduction criteria for bioenergy entering the transport, electricity heating and cooling sectors after 2026. These reductions equate to (at least) 65% in transport, 80% in heating and cooling and 80% in electricity generation. <sup>11</sup> Domestically produced and imported bioenergy must comply with these emission reduction requirements within this scenario. Within this scenario, the GHG emission reduction criteria is assumed to be fixed from 2020 to 2050.

$E_{\text{ccs}}$  = emissions captured via CCS during conversion to final energy carrier (electricity or heat).

$FE_{\eta}$  = conversion efficiency of secondary bioenergy carrier into final energy

$b_{\text{c}}$  = type of bioenergy carrier,  $\in$  {solid bioenergy carriers, liquid bioenergy carriers per feedstock(s)}

$tech$  = final end use conversion technology

(iii) Marginal mitigation from European bioenergy imports

To determine the effects of trade constraints on the marginal mitigation provided by bioenergy imports (i.e. the avoided regional emissions from fuel substitution via imported bioenergy). The trade scenarios are compared to a 'no bio' counterfactual scenario, which blocks all bioenergy technologies globally.

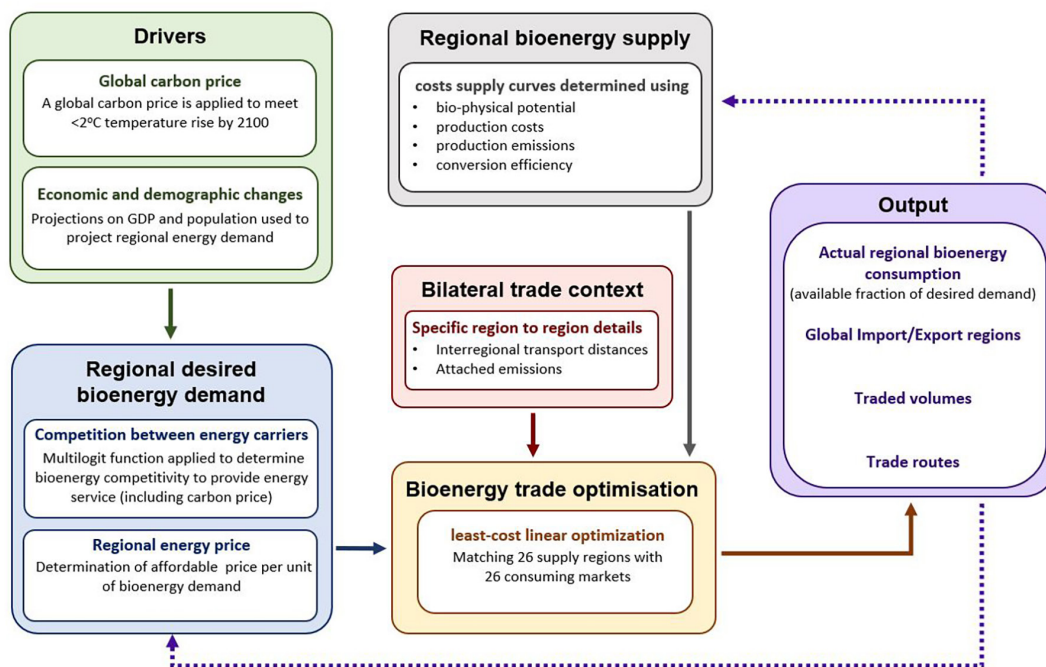


Figure 1. Schematic of the drivers, constraints, and formulation of bioenergy trade within IMAGE 3.2. Dashed lines indicate feedbacks from modeled trade and final consumption.

$$\text{mitigation from bioenergy} = \text{emissions}_{\text{trade scenario}} - \text{emissions}_{\text{nobio}} \quad (3)$$

## Results

### European bioenergy imported volumes and sourcing regions

By 2030 European bioenergy demand is projected to remain static at the 2020 level (3.8 EJ year<sup>-1</sup>). The trade constraints applied in the scenarios do not interfere with Europe's bioenergy consumption over the next decade, with similar levels of sourcing largely achieved through a re-routing of supplying regions or increased domestic production. By 2050, however, Europe's bioenergy demand and thus import volumes are projected to increase substantially across all scenarios, driven by a globally enforced <2 °C carbon budget, making low carbon energy carriers increasingly attractive. Figure 2 shows that the trade constraints lead to significantly different import volumes and sourcing regions. Results for 2030, cumulative (2020–2050) import volumes, and delivered cost projections are provided in Figures SM.5.1–3 in Appendix S1.

In the 'free trade' scenario in 2050, 60% of European bioenergy demand is met through imports, with the vast majority (74%) arriving from West Africa. According to the

default assumptions, the prominent role of this region is due to a large potential for land availability and projected yield improvements, supported by relatively cheap production costs. This global exporting role for the sub-Saharan Africa region is aligned with other major IAMs.<sup>7</sup>

Within the 'current partners' scenario, blocking trade with the African continent leads to: (i) slightly increased trade with North American regions, (ii) an increase of imports from Brazil for liquid carriers, and (iii) re-routing of substantial amounts of forestry residue imports to Russia. Imports of solid carriers are limited (–33% in 2050 compared to 'free trade') due to sourcing from more expensive production regions. The stricter 'feasibility' scenario further limits imports, with the only remaining sources of solid bioenergy imports being Canada and the USA. Due to their high domestic demand, these regions hold relatively little export potential for favored low emission residues. In 2050 projected solid bioenergy import is just 35% of what is projected in the 'free trade' scenario. Besides Canada and the USA, the only other available trade partner is the Oceania region, where liquids are projected to be imported. However, due to higher delivered costs and limited export potential, European access to liquid imports is projected to decrease further (50% of the 'free trade' scenario in 2050). The 'current partners' and 'feasibility' constraints lead to respective import deficits of 2.7 and 4.9 EJ year<sup>-1</sup> in 2050.

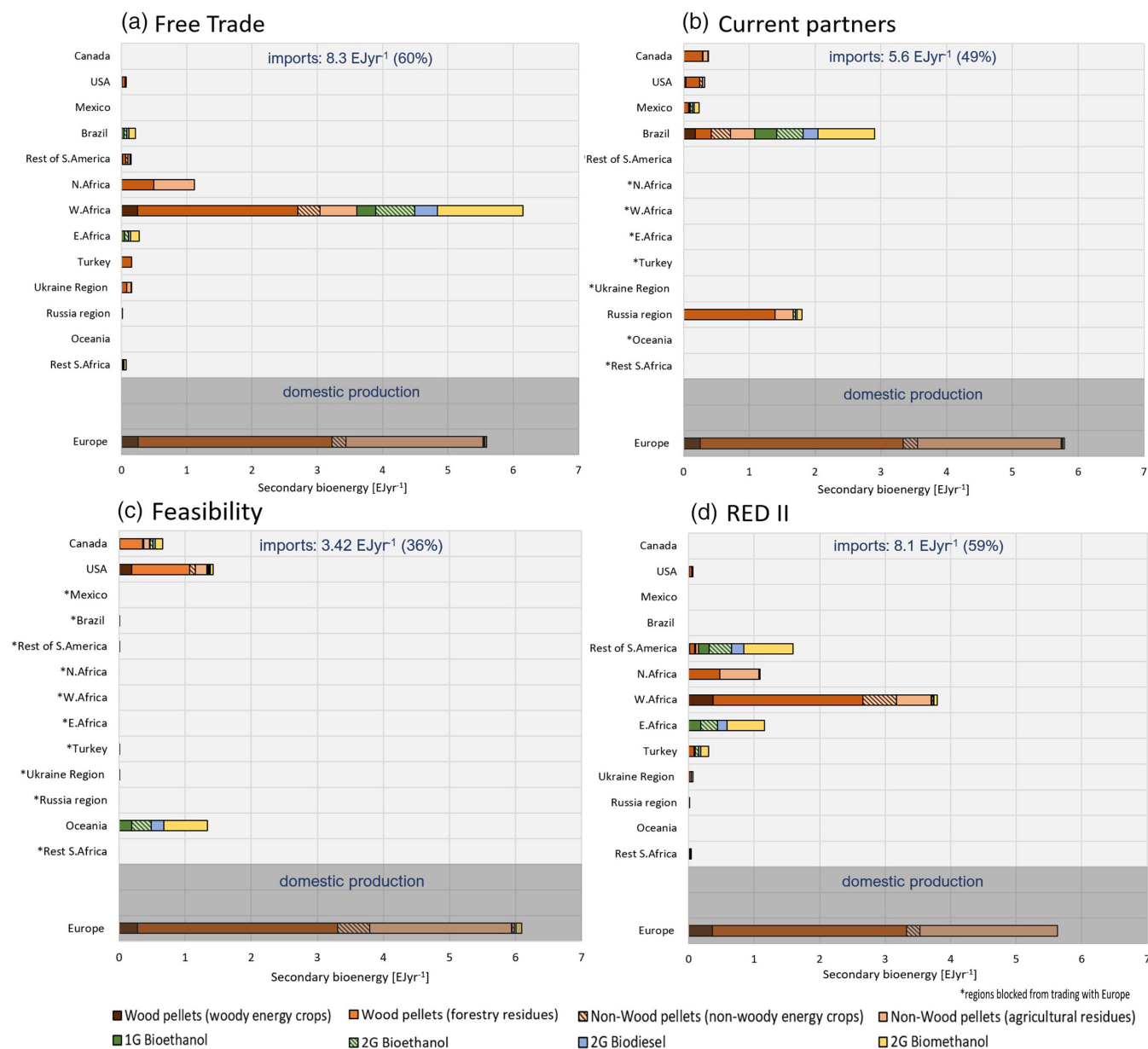


Figure 2. European bioenergy import volumes by energy carrier and sourcing regions in 2050 – only regions that provided bioenergy to Europe in one (or more) of the trade scenarios are presented, with imports expressed as percentages of annual European consumption.

The ‘RED II’ scenario can closely match the projected demand seen for ‘free trade’ to 2050. However, to meet this demand whilst remaining RED II compliant requires significant changes to Europe’s trading strategy. When comparing trading patterns in 2050 with the ‘free trade’ scenario, a diversification of supplying regions is observed. This occurs because, as regions such as West Africa become dominant global exporters, the emissions during the production stage increase due to expansion into lands with higher carbon content and exhaustion of residue supply

(see SM.3 in Appendix S1 in the supplementary material for a detailed explanation). Europe must diversify supply to regions where production emissions remain within the RED II GHG criteria thresholds but hold higher production costs. This results in a need to spread the import of liquids over several regions (the Rest of South America, East Africa, and Turkey). Interestingly, the ‘RED II’ scenario has immediate implications, as European liquid bioenergy production is determined to be non-compliant, leading to an overall increase in imports to 2035.

The projections show that Europe has limited domestic capacity to cover the import deficit created by trade constraints, as domestic production is similar across all scenarios. This is due to the limited techno-economical potential for bioenergy production at assumed carbon prices. Comparing annual domestic production in the ‘free trade’ scenario with the most constrained ‘feasibility’ scenario suggests a possible increase in domestic production of 0.5 EJ year<sup>-1</sup> (or +9%) in 2050, mainly from the expansion of pellet production from non-woody crops.

### Greenhouse gas emissions attached to imported European bioenergy

Across scenarios, the emission factors for solid bioenergy carriers consumed in Europe decrease heavily between 2030 and 2050, becoming negative in the long term (Fig. 3). This dynamic is driven by the increased deployment of BECCS for electricity generation after 2040 (see Figure SM.5.4 in Appendix S1), which offers much deeper emission reduction than other end-use streams. For the ‘free trade’ scenario, the emission factor for imported bioenergy ranges from –100 to –200 gCO<sub>2</sub>eq./MJ. Solid carrier supply from the dominant export region, West Africa, has one of the highest emission factors observed while still being negative. However, the total volume available affords Europe substantial mitigation (see Figures SM.6.2–6.3 in Appendix S1 for total European annual mitigation potential from bioenergy 2030 and 2050).

In comparison, the ‘current partners’ scenario in 2050 effectively replaces residue supply from North Africa with Russian supply that carries slightly larger transportation emissions. The import deficit left by West African supply in the ‘free trade’ scenario is partly compensated by lower emission-factor Brazilian supply and higher emission-factor Canadian supply. Restricting imports increases the emission factor of domestic European supply from –140 to –130 gCO<sub>2</sub>eq./MJ due to increased production in less favorable areas.

In the ‘feasibility’ scenario, the emission factor of domestic supply further increases to –123 gCO<sub>2</sub>eq./MJ due to the expansion of European sourced non-woody energy crops. A noteworthy observation is the decreased emission factor from Canadian supply compared to the ‘current partners’ scenario, even though import volumes are comparable. This is a direct influence of supply switching in other regions from Canada to the now accessible and cheaper Brazilian and Russian sources from which Europe is prohibited in this scenario. The knock-on effect for Europe is access to the same amount of Canadian supply but with a lower emission factor. While this finding has limited implications for Europe, it highlights the complex interactions between regional bioenergy trading strategies and global mitigation (see the section headed ‘cumulative GHG emissions of Europe and the effect on global bioenergy developments’, below).

Although sourcing regions for solid bioenergy imports in the ‘RED II’ scenario in 2050 are similar to the ‘free trade’ scenario, a significant difference is observed in the emission

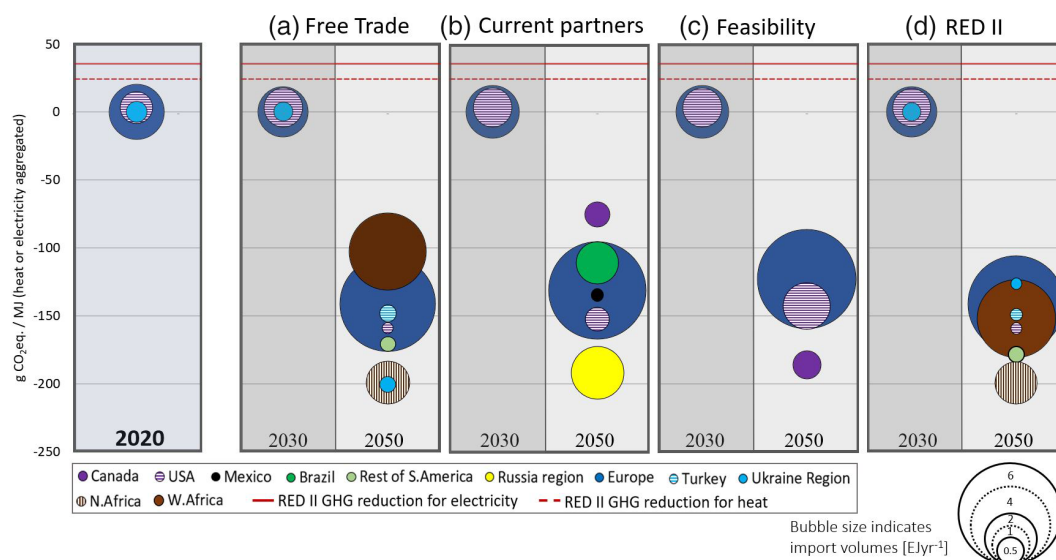


Figure 3. Average emission factors attached to European solid bioenergy sourcing in 2030 and 2050. The center point of the bubble represents the emission factor associated with sourcing from that region. The presented emission factors are aggregated on two levels: (i) solid bioenergy supply categories (i.e. residues, energy crops), (ii) end-use application(s) in Europe (seen in Figure SM.5.4 in Appendix S1), and weighted based on their actual energetic demand.



factors. Imports from the dominant supplier, West Africa, improve, providing an additional 50 gCO<sub>2</sub>eq./MJ emission reduction. This enhanced mitigation is brought about by prohibiting the production of second-generation (2G) liquid carriers from West Africa in the ‘RED II scenario’. In the ‘free trade’ scenario, these energy carriers compete for the same lignocellulosic resource base. This effectively increases production emissions for pellets due to reaching maximum residue supply earlier and expansion of short-rotation woody energy crop production into areas with less favorable land-use change emissions, higher fertilizer/energy inputs and transportation distances to conversion sites.

The aggregated emission factors presented for solids bioenergy carriers in Fig. 3 show complete compliance with RED II GHG regulations across all scenarios due to a sufficient supply of low-emission residues. However, unaggregated assessment of feedstock categories and regulated end-use streams in SM.4.2 in Appendix S1 rule certain combinations uncompliant. These occur after 2045 for non-residue feedstocks for electricity production without BECCS or heat production within the cement and steel industry, owing to the low energy conversion factors associated with these applications.

Unlike solid bioenergy carriers, which benefit primarily from a sufficient supply of residues and the ability for large-scale pairing with CCS technologies at the point of combustion, the emission factors of liquid carriers are projected to be significantly higher (Fig. 4). Across scenarios, there is a general trend towards decreased emission factors

related to liquid carrier supplies from 2030 to 2050, caused by shifting towards less emission-intensive lignocellulosic feedstocks and increased rates of CCS implementation during production. Projections indicate a failure to meet RED II requirements for most sourcing regions, with few sourcing options that satisfy the RED II criteria.

For the ‘free trade’ scenario, West Africa is extremely important, providing the majority of liquid bioenergy supply in 2050. However, competition for the lignocellulosic resource base for both 2G fuel and solid carrier production plus West Africa’s position as a major global exporter cause the emission factor of imports to Europe to come in just above the RED II GHG savings threshold.

Although the ‘current partners’ scenario maintains 70% of imports observed in the ‘free trade’ scenario in 2050, the majority of the supply comes from Brazil, which has a higher emission factor than most of the excluded regions. By 2050 this scenario offers the least mitigation potential from liquid bioenergy. Other regions switch to West African supply prohibited to Europe in this scenario, effectively lowering the emission factor of Brazilian supply (in comparison with the ‘free trade’ scenario).

The ‘feasibility’ scenario provides contrasting results. The 2030 projections show a substantial increase in the emission domestic supply factor caused by increased first-generation bioethanol production due to the restrictive trade constraints. By 2050 a large proportion of supply (83%) is RED II compliant, benefiting from low emission factor imports from Oceania. Due to a reliance on North American regions for solid carrier imports, which exhaust the remaining residue

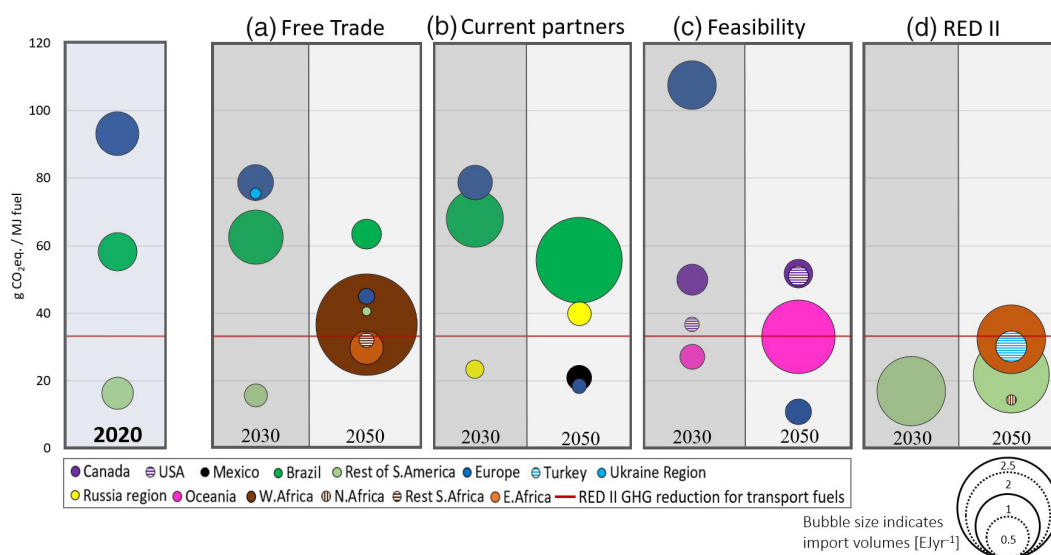


Figure 4. Average emission factors attached to European liquid bioenergy sourcing in 2030 and 2050. The center point of the bubble represents the emission factor associated with sourcing from that region. The emission factors shown are aggregated by supply liquid carrier categories (i.e. biomethanol, bioethanol, biodiesel).

supply and move European imports to dedicated woody crops, 2G lignocellulosic fuels from these regions hold emission factors that exceed the RED II threshold.

The projections show large volumes of liquid fuel import with significantly improved emission factors for the ‘RED II’ scenario. Imports are sourced from more expensive sourcing regions of the Rest of South America, East Africa, North Africa and Turkey (16–32 gCO<sub>2</sub>eq./MJ<sub>fuel</sub> in 2050). As a result, mitigation stemming from biofuels in the transport sector is significantly increased in the ‘RED II’ scenario in comparison with all other scenarios (see Figure 5) because significant imports are maintained via diversification of sourcing reg.

### Cumulative GHG emissions of Europe and the effect on global bioenergy developments

#### Cumulative net mitigation for Europe

All upstream emissions for bioenergy production are allocated to the consuming region in this study. For the ‘free trade’ scenario, in concurrence with previous studies deploying these model settings,<sup>7,25</sup> Europe follows an emission trajectory tightly aligned with its Paris agreement commitments. This amounts to a cumulative net mitigation contribution from bioenergy of 6.2 GtCO<sub>2</sub>eq. (Fig. 5(a)).

Limiting bioenergy imports to ‘current partners’ does not significantly hamper European mitigation to 2050. This is because Europe largely retains the ability to source solid bioenergy imports, with the solid carrier deficit fully covered via increasing domestic production of pellets from agricultural residues. This allows Europe to capitalize on the deep reduction occurring in the power sector with BECCS (see Figure SM.5.4 in Appendix S1).

However, the 6 EJ shortfall in liquid bioenergy carriers and higher upstream emissions attached to liquid imports cannot be entirely mitigated by other low-carbon fuels in Europe’s energy mix at the carbon price explored. This culminates in 0.35 GtCO<sub>2</sub>eq. of additional emissions (2020–2050) in comparison with the ‘free trade’ scenario. The ‘feasibility’ scenario provides the lowest GHG mitigation for Europe. Under this trade constraint, liquid and solid bioenergy imports generally have favorable emission factors. However, import volumes are significantly lower (1.5 EJ year<sup>-1</sup> for liquids and 3.5 EJ year<sup>-1</sup> for solids in 2050) in comparison with the ‘free trade’ scenario. Domestic supply cannot cover these deficits, which lead to a cumulative net emissions increase of 1.6 GtCO<sub>2</sub>eq. in comparison with the unrestricted ‘free trade’ scenario. Limiting Europe to REDII-compliant bioenergy consumption means 9% less liquid bioenergy carrier imports than the ‘free trade’ scenario, whereas solid imports remain unaffected. This lower supply for Europe is

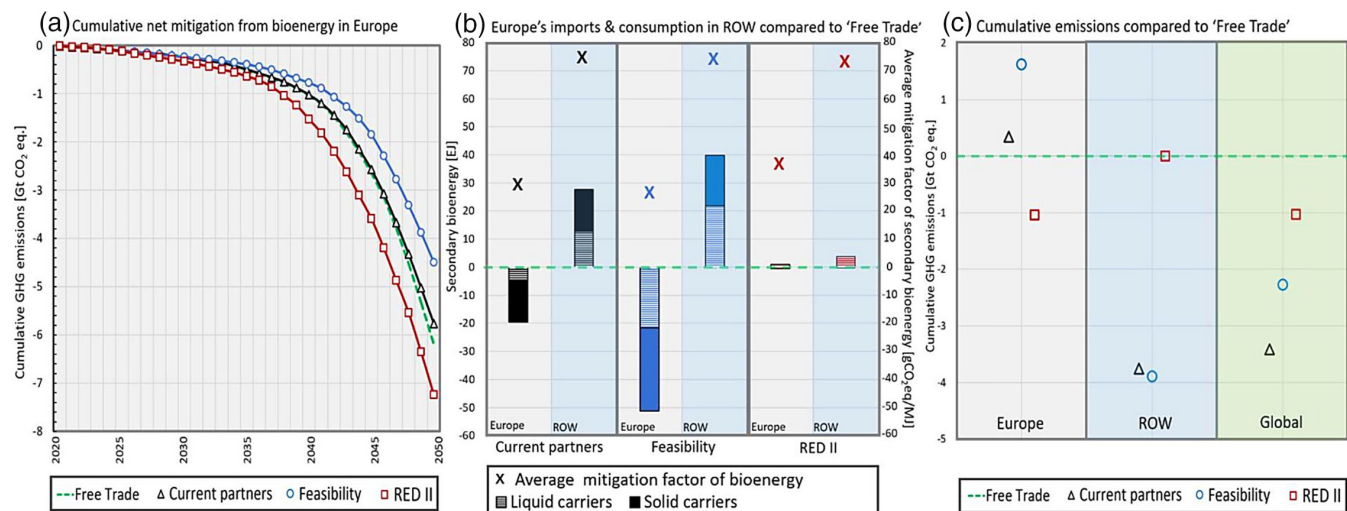


Figure 5. The effects of trade constraints on Europe’s cumulative GHG mitigation, global bioenergy consumption and global emissions, where: (a) Cumulative net mitigation from bioenergy in Europe across trade scenarios compared to a ‘no bio’ counterfactual. (b) Difference in cumulative bioenergy imports for Europe and bioenergy consumption in the rest of the world (ROW) compared with the ‘free trade’ scenario. Including the attached average mitigation per unit bioenergy consumed [averaged over liquid and solid carriers and over time (2020–2050)] compared with the ‘free trade’ scenario. (c) Greenhouse gas emissions for Europe, the ROW and globally for trade-constrained scenarios compared with a ‘free trade’ scenario. Numerical data, specifically including the data from the ‘free trade’ scenario used as a benchmark in panels (b) and (c), are provided in SM.6.4 in Appendix S1.

due to higher prices of imports and an inability to produce compliant supply before 2035 domestically. However, the benefits of obtaining biofuels with lower emission factors are evident and more than compensate for total volume deficits. Europe increases cumulative mitigation to 7.3 GtCO<sub>2</sub>eq.

### Effects of European bioenergy trade constraints on global bioenergy consumption

In comparison with the unrestricted 'free trade' scenario, cumulative European imports of secondary bioenergy fall in the trade constrained the 'current partners' and 'feasibility' scenarios by 20 and 51 EJ, respectively. A fall in European imports of bioenergy creates a situation where the ROW can increase consumption (Fig. 5(b)). For the 'current partners' scenario, the ROW increases bioenergy consumption by 28 EJ compared to 'free trade'. There is a disproportionate increase in the ROW's liquid bioenergy consumption. Whilst Europe cumulatively imports 5 EJ of liquid biofuels less over the period, the ROW increases consumption by 13 EJ. This dynamic is due to Europe moving to more expensive supplying regions, thus, allowing other world regions, which are otherwise priced out of the international market, to capitalize on cheaper supply from West and East Africa. In the 'feasibility' scenario, the ROW benefits from a large volume of cheaper bioenergy entering the international market. However, the surplus left on the international market does not see complete uptake which is limited to 11 EJ or 20% less than what Europe does not import. This surplus remains because the carbon price is insufficient to promote further fuel switching within the ROW as a cost-minimal <2 °C mitigation trajectory has already been reached. The 'RED II' scenario witnesses small increases in liquid imports for Europe because all domestic production is determined uncompliant. However, as Europe diversifies its supplying regions, the ROW observes small increases in consumption of liquids as some cheaper sources, which are also not compliant with REDII constraints, are opened to other regions.

### Effects of European bioenergy trade constraints on global emissions

Bioenergy can be utilized in other world regions with a much stronger mitigative effect. The difference in average mitigation factor from bioenergy between Europe and the ROW ranges between 36–46 gCO<sub>2</sub>eq./MJ, with the minimum occurring for the 'RED II' scenario because a larger proportion of low emission factor bioenergy is consumed in Europe (Fig. 5(b)). All trade constrained scenarios lead to lower cumulative global emissions than the 'free trade' scenario (Fig. 5(c)). In

the case of the 'current partners' and 'feasibility' scenarios, this is due to an increased supply of bioenergy to the ROW, where bioenergy holds a significantly higher mitigation factor. This increased mitigation in the ROW more than compensates for the subsequent emissions increase experienced in Europe, providing net global cumulative mitigation of 3.4 and 2.3 GtCO<sub>2</sub>eq., respectively. Deeper global emission reductions occur for the 'current partners' scenario because Europe can maintain a lower emission trajectory due to sustaining solid carrier supply through domestic production. The 'RED II' scenario takes a trading approach that diversifies European supply across low emission factor regions. Europe effectively moves away from the lowest cost export regions for marginal supply as their total production for RED II-compliant supply is saturated. This allows Europe to retain comparable import volumes to the 'free trade' scenario; hence, there is no effect on the GHG mitigation for the ROW.

## Discussion

### Implications of European trade barriers on bioenergy development

The results suggest that a European energy system transition in line with a <2 °C global climate target may require substantially increased bioenergy imports and diversification of trade partners by 2050. The projections for biomass supply and associated costs point to diverse sourcing options that can match RED II-compliant European demand. However, whilst technically able to meet EU decarbonization goals, sourcing of bioenergy may be socioeconomically infeasible from these regions. This is highlighted by a stark contrast in supplying regions between the 'RED II' and 'feasibility' scenarios (Fig. 2). European operators must be flexible over time to keep imported bioenergy emission factors compliant as major exporters maximize residue supply and expand dedicated energy feedstock production into lands with higher carbon stocks, lower yield, and increased transportation requirements. Furthermore, Europe's demand for low emission factor bioenergy holds global implications by raising the risk that other regions are restricted to cheaper bioenergy with higher emissions. Thus, Europe may become partially responsible for emissions from additional marginal production in these regions, raising concerns about indirect impacts and questions on where bioenergy on the international market is best deployed.

### Priority areas for European bioenergy sourcing policy

Substantial bioenergy contributions of secondary energy to Europe's mitigation targets are technically obtainable under

the regulatory confinements of RED II at 3.7 EJ year<sup>-1</sup> by 2030 and 13.8 EJ year<sup>-1</sup> in 2050. However, this increased role depends on importing large volumes of bioenergy that should be fostered and steered by timely policy interventions.

### Facilitating a transition to the diversification of extra-EU supplying regions

Meeting the projected European bioenergy demand in 2050 will likely require a substantial diversification of current sourcing regions into areas that hold increased socioeconomic challenges. In order to facilitate the accessibility of sustainable bioenergy from these regions, Europe could pro-actively participate in developing bioenergy policy frameworks and strategic action in key exporting regions within the South Americas and Africa. Bilateral development must be at the core of this process to stimulate and accelerate biomass production and processing and conversion plants to unlock mitigation potential on both sides of the trade agreement. This would ensure increased value retention in producing countries and contribute to economic development. Trade relations could be further strengthened through knowledge sharing and secured investment schemes which include a thorough risk assessment to minimize project failure. Additionally, infrastructure development within exporter regions is an essential component of a successful trade relationship, with poor infrastructure deterring needed foreign investment.<sup>34</sup> Such efforts are needed to safeguard the benefits of trade relations between the EU and the global south. The wider socioeconomic implications of trade activities must be considered and monitored closely to ensure that issues such as conflicts, human rights, poverty, land grabbing, and biodiversity loss are actively addressed, thereby fostering the bioenergy industry's contribution to alleviating these concerns. Whilst diversification of supply is a challenge for Europe. It provides the opportunity to improve energy security due to a larger array of sourcing options than fossil incumbents that suffer from political and economic shocks.

### Improving the transparency of GHG accounting

Projections show that the extra-EU import emission factors can vary dramatically across supplying regions and time scales, leading to possible RED II GHG criteria breaches. Importantly, non-compliance may occur even when production expansion is limited to abandoned and marginal lands, as explicitly specified in the IMAGE 3.2 model. Clearly, a rigorous accounting for the whole supply chain from production to combustion is vital to ensure RED II compliance. This study allocates all bioenergy-

related emissions to the consuming region to illustrate the consequences onto European mitigation efforts. The current accounting framework for GHG emissions derived from imported bioenergy is currently not fit for this purpose due to the complexity of different emissions across the bioenergy supply chain being attributed to different sectors (i.e. Land Use, Land-Use Change and Forestry (LULUCF) and energy) and the GHG inventories of different countries (i.e. importer, exporter). Furthermore, international transport emissions are accounted for in neither import nor exporter inventories but instead as 'international bunker fuel emissions'. Whilst the location of emissions is irrelevant from a global climate perspective, it is crucial for determining regional compliance. The latest recast of RED is a minimum safeguard, stipulating that imported biomass is only permitted from exporting nations that *report* their LULUCF-sector emissions within the United Nations Framework Convention on Climate Change (UNFCCC).<sup>35</sup> It stops short of insisting that the exporter must *account* for these emissions. Mandatory emission accounting introduced in the Kyoto Protocol<sup>36</sup> for Annex I countries is now absent in the Paris agreement.<sup>37</sup> In fact, none of the major exporting regions projected in this study *account* for their LULUCF emissions, meaning upstream production emissions are missing at global-level bookkeeping.

To alleviate these issues, Europe should seek to establish into its international supply chains standardized guidance to demonstrate RED II compliance that transcends European borders. Simultaneously, national-level reporting of bioenergy emissions in Nationally Determined Contributions (NDCs) could benefit from simplifying accounting frameworks rather than splitting the allocation of point source emissions in a cumbersome manner during the supply chain between the energy and LULUCF sectors. This is especially important given the projected increase of lignocellulosic feedstocks and may ease the burden on reporting procedures and increase confidence that complete accounting is occurring. Beyond Europe, appropriate LULUCF emissions accounting principles must be introduced into the Paris agreement framework NDC reporting as soon as possible as projections show bioenergy trade volumes at a global scale will increase significantly already by 2030.

### Bolstering logistical network and operations

Bioenergy logistics present a unique challenge due to seasonality, spatial distribution, and quality variances of feedstocks. The associated costs can therefore be considerable and act as a significant barrier to the widespread use of bioenergy.<sup>38</sup> The projections show that bioenergy from domestic production and extra-EU imports may rise to

5.6 and 8.3 EJ year<sup>-1</sup> by 2050, inferring increased freight transport and distribution networks at both intra- and inter-regional levels. In addition, projections for a 'RED II' scenario observe immediate growth in extra-EU imports (+50% or 0.75 EJ year<sup>-1</sup>) already by 2030, triggered by increased liquid carrier imports. The volumes and time relevance indicate a need for a flexible inter-modal freight network that maximizes integration with the current fossil fuel distribution network and minimizes associated transportation costs. Furthermore, this increased import dependency will likely require major European shipping ports to bolster capacity with linked storage and rail distribution facilities to the rest of the continent.

### Effects of European bioenergy trade on the global emissions trajectory

The results indicate that the European energy sector may not be the most effective destination for available low-emission-factor bioenergy on the global marketplace (Fig. 5(b) and (c)). European imports may be better used in other world regions where more emission-intensive energy systems afford greater mitigation per unit of bioenergy. Furthermore, there is a saturation point at which redirected European imports offer no additional global mitigation above 4 GtCO<sub>2</sub>eq. over the period 2020–2050. However, it is too simplistic to conclude that European-bound bioenergy imports should be redirected towards regions with the highest mitigation potential because several aspects are not considered in this analysis. These include (i) the ability of regions to afford these imports; (ii) the rate of technological development, specifically BECCS within these regions; and (iii) whilst Europe may have a relatively 'cleaner' energy system, it is also tasked with a relatively higher regional mitigation target, aiming for GHG neutrality by mid-century.<sup>39</sup>

The 'RED II' scenario observes no effect on the emissions trajectory for the ROW in comparison with the 'free trade' baseline. This is because re-routing liquid supply to more expensive sourcing regions does not interfere with demand from the ROW. There is an argument that real-world transactions would observe Europe paying a premium for the West African supply's lower emission factor compliant proportion to avoid regional supply switching. Whilst a valid point, a counter-argument is that Europe would then be partially responsible for indirect land-use change emissions derived from additional marginal production in West Africa to feed the global market. Ultimately unilateral regionally imposed sustainability criteria such as RED II likely lead to leakage of higher emission factor feedstocks to other world regions that are absent of similar regulations on the global trade market.

### Study limitations and future research avenues

The use of the global-level IAM IMAGE 3.2 carries notable limitations regarding regional techno-economic representation. These include (i) a lack of internal European trade requirements; (ii) no explicit representation of logistical and infrastructure costs for increased transport network capacity; (iii) limited and aggregated representation of bioenergy feedstocks and conversion routes; and (iv) the assumption that bioenergy on the international market is a fungible commodity that does not account for discrepancies in technical specifications often required in end-use application.

The scenario protocol investigated allows for projections of future bioenergy trade implications under long-run RCP 2.6 climate pathways applied to the 'free trade' scenario whilst considering a diverse set of constraints for future extra-EU bioenergy trade. However, the scenario analysis can be further extended to include unexplored geopolitical considerations which may act as key determinants for investment decisions and energy market dynamics. These include territorial conflicts, tariff wars, and financial crises that could further affect Europe's access to imports.<sup>40,41</sup> This study deploys an SSP2 baseline as the basis for important macro socioeconomic parameters, including population growth, technological change and economic growth. These assumptions hold important implications for bioenergy development by influencing crucial factors such as resources, energy, agricultural demand, and land availability.<sup>17</sup> Future assessment could explore how other SSP pathways may influence bioenergy shares between world regions through varying assumptions on evenly distributed progress between world regions where SSP2 assumes historical trends continue that route bioenergy deployment into wealthier and more developed economies, as shown in SM.8 in Appendix S1. Furthermore, at the climate change conference of the Parties (COP 26), a strengthened commitment to a 1.5 °C temperature limit was reaffirmed,<sup>42</sup> recognizing the need for accelerated efforts that need to be initiated this decade. The increased mitigation efforts of 1.5 °C scenarios (compared to 2 °C) require a more rapid bioenergy deployment, making the feasibility concerns highlighted in this assessment more pressing.<sup>2</sup>

Future research should seek to improve understanding of required bioenergy logistics and constraints by linking global modeling to dedicated regional energy and land-use models. This would allow for a detailed representation of intraregional transport requirements, national-level demand distribution, bioenergy technology developments, feedstocks and BECCS storage capacities. The proposed combined modeling framework holds the advantages of a more technologically

detailed assessment, better equipped to represent importer and exporter market dynamics. Quantitative projections stemming from this framework could allow for a more holistic strategic guidance regarding where bioenergy related policy prioritization should be focused towards 2050 to stimulate the projected deployment volumes. Regional EU-level energy models can also be better equipped to place IAM projections into the context of recent EU energy system policies that can hold significant implications for bioenergy developments. For instance, in the recent EU response to energy-security concerns exacerbated by geopolitical conflicts in the Ukraine region, the European Commission called for a 'rapid clean energy transition' within its REPowerEU plan.<sup>43</sup> This address proposes 20 Mt of renewable hydrogen deployment to 2030 and increasing targets for renewable electricity from non-biological sources. Such regional developments can shape the EU's future energy mix.

Moving beyond the expansion of modeling frameworks into real-world feasibility, projections should be fed into the process of stakeholder engagement at the local, national, and supranational levels. This is essential to design effective policy instruments and principles that address techno-economic, socioeconomic and political concerns. Stakeholder engagement is valuable on both the import and export axis to validate the feasibility and desirability of projected bioenergy volumes to cover aspects such as technological readiness, investment time-frames and public perception. In turn, engagement activities could enhance the current understanding of the logistical costs of large-scale EU bioenergy imports by providing a broader representation of data and valuable input for future modeling studies.

## Conclusion

This study presents projections of extra-EU bioenergy trade and the associated GHG consequences for Europe's mitigation obligations for a series of trade scenarios that explore the effects of geopolitical, socioeconomic, and regulatory GHG criteria as trade constraints.

### Europe's bioenergy imports are expected to increase and diversify significantly to 2050

The results indicate that Europe can increase domestic bioenergy production from 2.3 to 5.7 EJ year<sup>-1</sup> by 2050. Nevertheless, European bioenergy imports are projected to increase significantly across all trade scenarios explored, with imports increasing to 8.3 EJ year<sup>-1</sup> according to the default scenario settings. The highly restrictive 'feasibility' scenario

entails pessimistic assumptions on the availability of extra-EU supply but projects annual European imports to double from 1.5 EJ year<sup>-1</sup> in 2020 to 3.4 EJ year<sup>-1</sup> by 2050. Trade volumes would extend much more in a 'RED II' scenario, i.e. 8.1 EJ year<sup>-1</sup>. To meet these high import volumes, projections show a major reliance on large low-cost exporters with currently immature bioenergy markets, namely, West Africa, East Africa, North Africa and the Rest of South America.

### The biggest risk to the future expansion of European bioenergy imports concerns socio-political, technical, and logistical challenges

The projections presented in this study identified that the largest barrier to EU bioenergy development to 2050 is overcoming potential socioeconomic and technical feasibility issues within major exporting regions. The EU must recognize the impact of this uncertainty on the availability of imports for its mitigation obligations. For example, the 'feasibility' scenario suggests that annual European emissions would increase by 0.26 GtCO<sub>2</sub>eq. by 2050 in comparison with a 'free trade' baseline. To avoid this, whilst maintaining a cost-minimal energy transition, the EU can aim at capacity-building within these highlighted regions to improve the viability of realizing the projected export potentials. The significance of these findings suggest default bioenergy trade dynamics in global IAM modeling activities would benefit from expanding the representation of feasibility considerations.

### Renewables Energy Directive recast II sustainability and GHG criteria are not necessarily a long-term barrier to EU bioenergy development

Despite increasing costs of bioenergy imports due to GHG criteria constraints, sufficient extra-EU supply options remain to fulfil the demand for the projected energy transition to 2050. Renewables Energy Directive recast II holds minor consequences for pellets due to most of the supply projected coming from low emission factor residue feedstocks. The projections indicate a 10% drop in European supply for biofuels compared to a 'free trade' situation over the period assessed.

### The role of BECCS technologies for mitigation is central to climate effective bioenergy deployment in Europe

Bioenergy with carbon capture and storage is pivotal for realizing the projected demand volumes while remaining RED II compliant due to the beneficially lower emission

factor afforded via the technology. Most bioenergy-related mitigation is projected to arrive from pairing solid bioenergy carriers with CCS for electricity and heat generation. This effectively keeps the emission factor of these applications very low and allows dedicated woody energy crop imports with higher production emissions to be utilized post-2040 when residue supply saturates. Solid bioenergy supply remains stable across the trade scenarios explored (>90% of supply in 'Free Trade'). These results indicate that pellet supply for BECCS in power generation in 2050 ranges from 5.3 to 7.5 EJ year<sup>-1</sup>, with extra-EU imports contributing between 23–50% of pellet supply across the scenarios. In order to unlock the potential of BECCS, installations for the generation of electricity and district heat by power plants and CHP must scale up at unprecedented levels. This would require immediate investments, which are not at present adequately incentivized, owing to a lack of remuneration or support for negative emissions.

## Europe may not be the most effective end-user market for interregional traded bioenergy from a global climate perspective

Our projections show that bioenergy deployment in world regions outside of Europe provides greater mitigation (35–45 g CO<sub>2</sub>eq. MJ<sup>-1</sup> in 2050) due to these regions' more carbon-intensive energy systems. Under the carbon budget explored, global emissions are lowest when Europe limits extra-EU imports to less than 6 EJ year<sup>-1</sup> in 2050. Further import restrictions result in no additional global GHG mitigation due to the remaining biomass being too expensive for other regions. However, prioritization of end-use regions for bioenergy should also consider regional legislative trajectories of climate mitigation targets to 2050 and the ability to ameliorate international technology diffusion of immature technologies such as BECCS.

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