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Integrated assessment of the role of bioenergy within the EU energy transition targets to 2050

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Abstract

Bioenergy is considered an important component within the European Union (EU) energy transition to meet mid-century climate targets. Model assessments that have highlighted the role of bioenergy in decarbonising EU energy systems fail to account for the fact that mitigation strategies and bioenergy supply take place within a global decarbonisation effort. Thus, they do not account for inter-regional competition for the resource base that Europe may face. This study shows how bioenergy can contribute to EU climate targets, highlighting its possible role within the energy system and developments required to facilitate its scale-up. We use the global integrated assessment model IMAGE 3.2 to project bioenergy demand, sectoral deployment, feedstock, and inter-regional import for Europe to 2050. Employing a global model allows for projections of EU decarbonisation strategies consistent with global climate targets and captures the effects of biomass production and consumption in other world regions. Bioenergy is projected to account for up to 27% of total primary energy demand, increasing from the current 5EJ to 18EJ/yr. To match this demand, the model projects imports of biomass to increase from 4% of its current supply to 60%. Bioenergy could provide up to 1GtCO2 or 40% of the overall mitigation needed by the EU in 2050. This is based on large-scale use for power production, with the transport, industry and buildings sectors getting smaller shares. By 2050 it is projected that 55% of total EU bioenergy use is coupled with Bioenergy with carbon capture and storage (BECCS). Bioenergy supply comes primarily for agricultural and forestry residues, as these sources have low upstream greenhouse gas emissions. However, as demand increases, energy crops are increasingly used, especially in the provision of advanced liquid fuels. The results show that one route for achieving an EU energy transition is based on rapid deployment of BECCS and the mobilisation of sustainable imports of second-generation feedstocks.

KEYWORDS

BECCS, bioenergy, energy system, EU bioenergy policy, GHG emissions, integrated assessment modelling, scenario analysis

1 | INTRODUCTION

The goal of the 2015 Paris Agreement is to limit the global mean temperature increase to 'well below' 2°C and preferably 1.5°C (United Nations, 2016). Currently, energy production and use are responsible for more than 70% of global anthropocentric greenhouse gas (GHG) emissions (IPCC, 2021). Hence, complying with the Paris Agreement requires the deep decarbonization of the energy sector. The European Union (EU) has pledged to implement strategies that align with these global objectives, aiming for 55% reductions in EU GHG emissions by 2030 and net-zero by 2050 with respect to the 1990 levels (European Commission, 2019b).

The use of renewable energy resources is a crucial decarbonization strategy, alongside other measures such as optimizing energy efficiency and reducing demand. Bioenergy is considered a possible future option for attaining climate targets (IPCC, 2018a), with current EU consumption standing at 5.7 EJ year^{-1} and accounting for 64% of renewable energy consumption (Eurostat, 2021b). This position is primarily due to biogenic carbon being considered climate neutral at the point of consumption. Furthermore, it can act as a flexible producer to balance the power system when paired with other renewables. It also offers versatility in end-use applications for heat, power and transport fuels (Eurostat, 2021b).

From a sourcing perspective, EU bioenergy demand is currently comprised of 60% forestry (woody) sources (split evenly between direct (fellings and residues) and indirect (industry by-products) sources), 27% agricultural residues and energy crops and 13% waste streams (European Commission, 2019a). A recent review of EU-wide biomass supply-side projections shows that future domestic EU biomass supply (2030–2050) is expected to consist of forestry biomass (29%–50%), and agriculture residues and energy crops (30%–70%; Mandley et al., 2020). This indicates a projected mismatch between current demand and future supply for feedstock categories and agrees with other studies that suggest the greater the dependence on forestry biomass, the more the EU needs to import (Jones et al., 2015; PWC, 2017). Future European feedstock demand composition has implications for interregional biomass trade and access to sustainable biomass. While currently 96% of biomass used for energy is EU-sourced, import is expected to increase to 2050 under scenarios meeting strict climate change mitigation targets (Daioglou, Muratori, et al., 2020; Junginger et al., 2019).

Bioenergy with carbon capture and storage (BECCS) provides an opportunity to attain net-negative GHG emissions, which may compensate for emissions from more difficult-to-decarbonize sectors (Hanssen, Daioglou, Steinmann, Doelman, et al., 2020; IIASA, 2020; IPCC, 2018b). At EU level, BECCS is targeted in 11 member states national energy and climate plans (NECPs) as an essential carbon removal technology. However, significant uncertainties remain regarding the techno-economic capabilities including storage capacity, investment costs and social feasibility (Fajardy et al., 2019; Fridahl & Lehtveer, 2018). This uncertainty propagates to future feedstock requirements, total biomass demand and bioenergy's GHG emission mitigation potential.

Bioenergy, as a mitigation option, faces opposition in the global climate debate. Critique is built around several core arguments, including access to sustainable feedstocks, uncertainty surrounding bioenergy with carbon capture and storage (BECCS) deployment, dependency on subsidies and competition between different biomass end uses (Reid et al., 2020). The Renewables Energy Directive recast to 2030 (RED II; EU, 2018) partly addresses these concerns. RED II introduces stricter minimal GHG savings thresholds on biogenic energy sources, withdraws subsidies to electricity-only installations and promotes the cascading principle of biomass. Still, understanding the role of bioenergy in decarbonizing Europe's energy system towards 2050 requires a better understanding of these critiques and uncertainties.

The multifaceted nature of bioenergy, from the supply, conversion, trade and multiple final consumption possibilities, calls for an integrated approach when assessing its mitigation potential. Key aspects that need to be investigated include the access to appropriate feedstocks, sectors where bioenergy use should be prioritized and the potential contribution of BECCS. Integrated assessment models (IAMs) are often used to study climate change mitigation strategies, including bioenergy deployment. These models describe the dynamics of energy and land-use system and their relationships with natural and human systems. Therefore, IAMs can be used to investigate the potential transition of the energy and land systems under varying degrees of policy intervention and can, for instance, explore mitigation pathways that meet exogenously defined climate targets (Weyant, 2017).

Previous assessments with IAMs focus on a global level and thus fall short of a detailed analysis of how these dynamics shape the supply and use of bioenergy, and its role in the energy system transformation, at a European level. Other regional bottom-up approaches fail to capture the global context of bioenergy supply through interregional trade and competition for the resource base when considering global climate change mitigation efforts.

This research aims to investigate the projections of bioenergy demand, its contribution to climate change mitigation and import dependency of the European region between 2020 and 2050. The analysis further aims to provide insights into bioenergy dynamics that are considered

vital for climate mitigation and raised within EU policy debate, including BECCS deployment, sectoral demand and feedstock category demand. This study uses existing baseline and RCP 2.6 projections from the IAM IMAGE 3.2 that illustrates the effects of a global <2°C mitigation pathway that seeks to bring about a least-cost energy transition. Counterfactual scenarios are formulated that explore the future European energy system when BECCS is prohibited and when bioenergy is absent. Using global modelling to produce regional results is a novel approach that allows the research to capitalize on the systemic effects of other world regions' production and consumption behaviour for bioenergy and subsequently the access to imports for Europe.

2 | MATERIALS AND METHODS

2.1 | Model overview

This study uses the global integrated assessment model framework IMAGE 3.2 (Stehfest et al., 2014), which simulates the environmental consequences of energy and land-use systems worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change and human well-being for 26 world regions. IAMs such as IMAGE 3.2 hold the benefit of modelling planetary boundaries including resources, stocks and flows of the agricultural, forestry, water and energy systems, and represent their interactions and the effect of climate change, policy and socio-economic developments. Human system impacts in the form of emissions and land-use change are communicated to dedicated earth system modules for land, atmosphere and ocean. Accordingly, IAMs are an appropriate tool for exploring mid-term climate change mitigation pathways that meet exogenously defined climate targets while considering systemic and global effects.

In the IMAGE 3.2 framework, the energy system is represented by the recursive dynamic global energy system model TIMER (de Boer & van Vuuren, 2017). TIMER includes a representation of primary energy supply, including fossil and renewable resources, which can be converted to secondary and final energy carriers. TIMER is calibrated to IEA energy data in the period 1971–2018 to replicate observed fuel and electricity consumption trends (Vuuren et al., 2021). From 2018 onwards, scenario settings are applied.

Demand for energy services is projected by linking socio-economic drivers (e.g. population and economic activity) to five key economic sectors: industry (including cement, steel, paper and chemicals), transport, residential, services and 'others'. It includes fossil and renewable

primary energy carriers, where primary energy carriers can be converted to secondary and final energy carriers (solids, liquids, electricity, hydrogen, heat) in order to provide energy services for different end-use sectors. Technological learning within TIMER is endogenously based on learning by doing, where investment and associated conversion costs are projected to decrease as a function of cumulative installed capacity. Competition between final energy carriers is based on their relative cost of providing energy services, formulated at regional and sectoral levels. Constraints on GHG emissions increase the competitiveness of low-carbon sources by applying an endogenously calculated price on fuels' carbon content. The implementation of this pricing dynamic means that bioenergy's competitiveness in the power system is based primarily on its mitigation potential. However, other VRE sources suffer from integration curtailments (storage requirements, back-up and system load) that increase their relative cost as their shares increase. As a non-variable source, bioenergy's competitiveness increases under these circumstances (Pietzcker et al., 2017). See supplementary material SM.1.1 for further details on the model, including a schematic overview of how bioenergy is treated.

Techno-economic assumptions of IMAGE3.2 (capital costs, conversion efficiencies, feedstock costs, operation and maintenance costs, CCS capture rates, technology readiness, technology lifetimes and emission factors) are similar to those provided in the supplementary material of Daioglou, Rose, et al. (2020). The development of the applied carbon price, energy carrier price and levilized cost of electricity production for the mitigation scenarios presented in this study are available in supplementary material 1.3.

2.2 | Bioenergy dynamics within the model framework

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 (Daioglou et al., 2019). Potential bioenergy supply within the IMAGE 3.2 framework is determined at the grid level by the dynamic vegetation model LPJml, which describes crop growth based on local biophysical conditions (Müller et al., 2016). In order to ensure that bioenergy supply does not interfere with major environmental and social criteria, specific areas are excluded from bioenergy production, including urban areas, nature reserves, forests and areas used for food production (Hoogwijk et al., 2009). The model additionally assumes a 'food

first' principle, that is, food demand is allocated first before biomass for energy. Consequently, primary biomass is grown on either abandoned agricultural areas or natural lands deemed available. Biomass supply is represented by six aggregated primary feedstock categories: woody crops, grassy crops, maize, sugarcane and oil crops. Residues (agricultural or forestry residues) can be harvested from agricultural and managed timber operations. A disaggregation of feedstock flows is provided in SM.1.1.

Primary biomass can be converted into liquid and solid bioenergy carriers. Liquids include first generation and advanced biofuels. Bioenergy carriers may also be used for non-energy purposes, such as the production of ammonia, methanol and higher value chemicals (Daioglou et al., 2014). Solid bioenergy carriers (i.e. chips and pellets) can be further converted to hydrogen or electricity. The delivery cost of bioenergy includes feedstock, conversion technology, labour, capital and O&M costs, represented through dynamic cost supply curves (Daioglou et al., 2019).

Interregional trade of bioenergy carriers is facilitated based on the regional production cost of bioenergy and associated transport costs. These costs are used to determine the optimal regional price of delivered bioenergy, including bilateral trade between 26 world regions. Allocation of bioenergy production regions and trade of bioenergy carriers entering the global market are determined via global-level cost optimization.

BECCS is incorporated into the model during the conversion to secondary energy carriers (liquid fuels, hydrogen, electricity) and during heat generation within industry. For bioenergy emissions accounting, smoke-stack emissions during conversion that result from biogenic carbon are considered carbon-neutral. When paired with CCS, sequestered biogenic emissions are considered net-negative. Precombustion upstream process emissions include land-use change, primary biomass production (including fertilizer production and application), transport of primary biomass to processing/conversion site, process energy for conversion into bioenergy/secondary carriers (Daioglou et al., 2017).

See SM.1.1 for a schematic of modelled bioenergy GHG sinks and releases.

2.3 | Scope, scenarios and indicators

2.3.1 | Scope

This study represents the European region by combining IMAGE regions West Europe and Central & Eastern Europe (Stehfest et al., 2014). The list of nations included within the modelled 'Europe region' is presented in SM1.2. Although the geographical boundaries of this European region are not an exact match with the EU 27, the results are relevant for comparison of relative emission mitigation targets at EU level. The results from this study focus on the modern applications of biomass only, that is, excluding traditional uses (e.g. fuelwood for heating and cooking). Bioenergy developments included in the analysis are total bioenergy demand, sectoral level demand, feedstock demand, regional mitigation potential and interregional trade. Limitations of the approach are discussed in Section 4.3

2.3.2 | Scenarios

Scenario analysis is performed to 2050 to explore the effects of introducing global-scale climate targets in line with the Paris agreement and the role of bioenergy and BECCS deployment within the European energy system. The scenario protocol is presented in Table 1 and outlined below.

A 'baseline scenario' is included that follows the Shared Socio-economic Pathway SSP2. The IMAGE projections of the SSP scenarios are described (Vuuren et al., 2021). SSP2 is commonly referred to as a 'middle of the road' narrative and holds key assumptions concerning population growth, GDP and technological trends that are in line with historical patterns (Fricko et al., 2017; O'Neill et al., 2017).

A 'Global <2°C target' scenario projects achieving the Paris Agreement target via introducing a global carbon

TABLE 1 Scenario protocol

Scenario	Technology constraint	Emission price trajectory
Baseline	None	None
Global <2°C	None	Consistent with RCP2.6 radiative forcing target
No BECCS	BECCS technologies not allowed	Same as Global <2°C
No Bio	No new bioenergy investments after 2020	Same as Global <2°C

price from 2020 onwards. This is applied to all energy carriers based on their carbon contents. The carbon price mechanism is dynamic and promotes lower carbon fuel sources to ensure total emissions are in line with a cumulative global carbon budget ≈1000 GtCO$_2$eq. The carbon price trajectory applied to scenarios aiming for a <2°C global target in this study is presented in SM.1.2.

The 'No BECCS' scenario prohibits the future investment and expansion of bioenergy fuelled technologies paired with carbon capture and storage (CCS). The combination of CCS with fossil fuels remains permitted, as does bioenergy without CCS. The 'No Bio' scenario is incorporated to identify the mitigation levels that can be achieved in Europe in the absence of bioenergy for the same system cost as the mitigation scenarios. Therefore, projections for this scenario are only relevant for GHG emission analysis. The 'No Bio' scenario assumes that the consumption of modern bioenergy is prohibited within the global energy system; after 2020, bioenergy-related assets are phased out by their technical life span.

The 'No BECCS' and 'No Bio' scenarios follow the same emission price trajectory of the 'Global <2°C', but due to a constrained technology portfolio, they do not meet the carbon budget, creating a 'mitigation gap'. Thus, they act as counterfactuals indicating the mitigation these technologies provide in the 'Global <2°C' scenario.

The study's modelling structure, that is, utilizing a global model in which a global <2°C target is applied, allows for a simulation of bioenergy import to Europe under conditions in which other world regions also act to meet strict mitigation targets. Hence, the scenario includes the use of bioenergy in parallel with other climate change mitigation options (other renewables, efficiency improvement), regional carbon budgets (based on economic optimization) and their subsequent mitigation efforts and economic competition between regions for limited biomass resources.

2.3.3 | Indicators

Table 2 describes the indicators used for assessing bioenergy developments in terms of total bioenergy demand, sectoral level demand, feedstock demand, regional mitigation potential and interregional trade.

3 | RESULTS

3.1 | The Influence of a <2°C target and BECCS on Europe's bioenergy demand

Europe's primary bioenergy demand is projected to increase across the three scenarios explored (see Figure 1a). Until 2030 bioenergy demand remains relitavely constant

at approximately 5 EJ year^{-1} across scenarios. This stagnation is because Europe's total primary energy demand (TPED) is reduced from 72 to 64 EJ year^{-1} (−12%) through the rapid adoption of measures with low marginal abatement costs. These include increased efficiency and price-induced energy demand reduction.

Post-2030, Europe's TPED stays constant at ~64 EJ year^{-1}, meaning demand reduction measures are limited. Further mitigation efforts focus on decarbonizing the energy system through fuel switching to renewables; hence, bioenergy demand increases. SM.2.1 presents the demand development of all modelled energy carriers. In the '<2°C' scenario, bioenergy demand is considerably higher than the 'Baseline' scenario by 2050, with Europe's bioenergy demand standing at 18 EJ year^{-1}. In the 'No BECCS' scenario, the prohibition of BECCS limits biomass's competitiveness within the system due to the lack of economic benefits from net-negative emissions. Hence, demand decreases, resulting in a 3 EJ year^{-1} difference in 2050 with the '<2°C' scenario with BECCS.

In Figure 1b, the 'Baseline' scenario displays an increase (>5% points) for bioenergy contribution to TPED over the period. Projected system-wide energy efficiency improvements and activity reductions under the '<2°C' scenario lead to a substantial increase in bioenergy's contribution to Europe's TPED. Bioenergy demand rises to 27% of Europe's TPED. Underpinning this development is the direct replacement of coal with bioenergy for electricity production and indirect oil displacement in the transport sector via bioelectricity and electric vehicles. To put this scale of bioenergy demand into context, at the projected contribution to Europe's TPED, bioenergy would match the current oil and petroleum products contribution (IEA, 2020). At the same time, Europe's TPED reliance on fossil fuels falls from 82% to 58% over the period assessed. Comparison with the 'No BECCS' scenario indicates that BECCS can contribute 4.5% of Europe's TPED by 2050, roughly equivalent to the shares provided by all other renewables combined at present (IEA, 2020).

Although bioenergy demand is projected to increase in Europe, as seen in Figure 1a,b, Europe's share of global bioenergy demand decreases (Figure 1c). This is due to a relatively greater increase in bioenergy uptake in other world regions, even in the absence of global decarbonization targets. This dynamic is vital to consider because it has implications for interregional bioenergy supply as Europe faces stiffer competition in the global market. This increased global demand is driven by a growing global primary energy demand which increases 11% over the period assessed, increasing fossil fuel prices due to depletion (in the Baseline), decreasing costs of bioenergy due to learning and increased efforts to decarbonize energy systems in

TABLE 2 Indicators used to report Europe's bioenergy development, grouped by the bioenergy developments analysed in this study

Indicator	Description	Equation
Total demand		
Bioenergy demand **EU_bioD**[a]	Summation of primary bioenergy demand (*bioD*) across end-use sectors (*s*) in Europe only	$\text{EU\_bioD} = \sum_s bioD_{s,r=\text{EU}}$
Bioenergy share of total primary energy demand **EU_bio%**[a]	The share of the EU's total primary energy demand (EU_*energyD*)) that is derived from bioenergy	$\text{EU\_bio\%} = \frac{\text{EU\_bioD}}{\sum_s \sum_{ec} \text{EU\\\_}energyD_{s,ec,r=\text{EU}}}$
Share of global bioenergy **Global_bio%**	The share of global primary bioenergy demand attributed to the EU	$\text{Global\_bio\%} = \frac{\text{EU\_bioD}}{\sum_s \sum_r bioD_{s,r}}$
Sectoral demand		
Sectoral bioenergy demand **EU_SECT_bioD**[b]	Secondary bioenergy demand of feedstock (*FeedBiod*) within each end-use sector in Europe only	$\text{EU\_SECT\_bioD} = \sum_f \text{FeedBioD}_{f,s,r=\text{EU}}$
Feedstock demand		
Feedstock demand **EU_FEED_D**[b]	Demand per feedstock type consumed in all sectors combined in Europe only	$\text{EU\_FEED\_D} = \sum_s \text{FeedBioD}_{f,s,r=\text{EU}}$
Mitigation		
Total GHG emissions **EU_Emis**	Energy system emissions of Europe under any given scenario run. An activity level (*energyD*) is determined per end-use, sector, technology and energy carrier. This is multiplied by the specific emissions factor (EF) for the corresponding activity.	$\text{EU\_Emis} = \sum_e \sum_{ec} \sum_t energyD_{t,s,ec,r=\text{EU}} {}^*EF_{t,ec}$
Mitigation from bioenergy **EU_BioMitig**	GHG mitigation contribution brought about by bioenergy deployment in Europe compared to a counterfactual (No bio) scenario	$\text{EU\_BioMitig} = \text{EU\_Emis}_{scen=2°C} - \text{EU\_Emis}_{scen=\text{Nobio}}$
Mitigation from BECCS **EU_BECCSMitig**	GHG mitigation contribution brought about by the deployment of BECCS in Europe compared to a counterfactual (No BECCS) scenario	$\text{EU\_BECCSMitig} = \text{EU\_Emis}_{scen=2°C} - \text{EU\_Emis}_{scen=\text{NoBECCS}}$
Trade		
Net trade of bioenergy **EU_Trade**[b]	Net trade of bioenergy carriers between Europe and rest of the world. *r* refers for this indicator to all regions except Europe	$\text{EU\_Trade} = \sum_r \text{EUBioImport}_r - \sum_r \text{EUBioExport}_r$

Abbreviations: ec, energy carrier; EF, emissions factor; f, feedstock; r, regions; s, sectors; scen, scenario; t, technology.

[a]Reported in primary energy (i.e. the energy content of biomass before conversion into secondary energy carriers).

[b]Reported in secondary energy (i.e. the energy content of ready-to-combust modern bioenergy carriers).

the '<2°C' scenario. See SM.2.2 for projected global TPED developments.

3.2 | Sectoral level demand developments

Figure 2 shows the demand for bioenergy for key sectors across the scenarios. In the 'Baseline' scenario, the small levels of bioenergy use in the power sector are phased out, becoming a less economically attractive option due to the absence of a carbon price. For power generation, in the 'Baseline', fossil fuels hold the majority share of production, with coal and natural gas consumption increasing towards 2050. Fossil fuels are increasingly used in the power system due primarily to their affordability in the absence of a carbon price. See SM.3 for a detailed breakdown of power sector consumption. Post-2035, there is a significant increase of bioenergy in the non-energy sector which has a higher demand in the baseline than in the mitigation scenarios, where biomass feedstocks provide a cost-competitive option to produce chemicals. This greater demand in non-energy
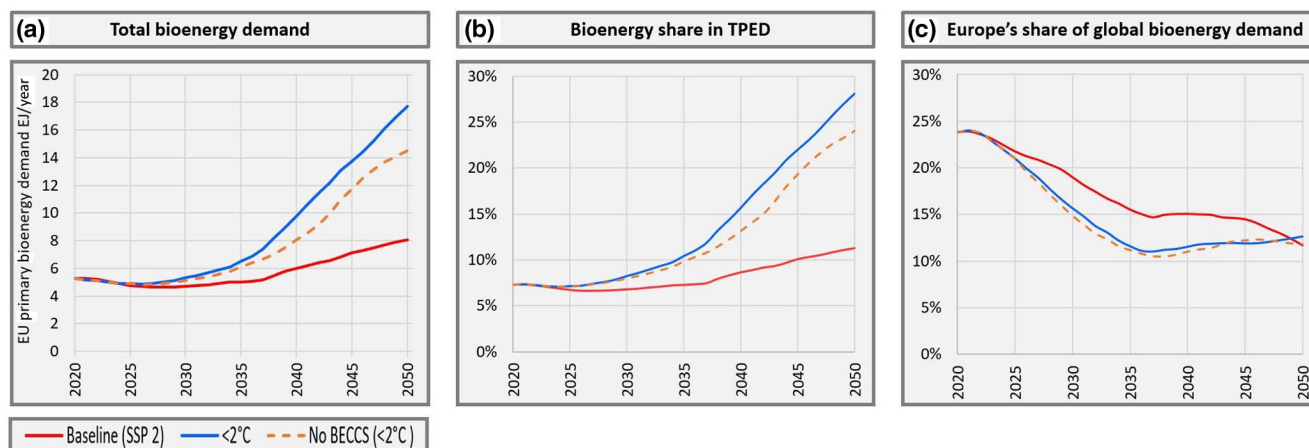
FIGURE 1 Climate mitigation and BECCS effects on the development of Europe's primary bioenergy demand (a), bioenergy's share in total primary energy demand (b) and Europe's share in global bioenergy demand (c)
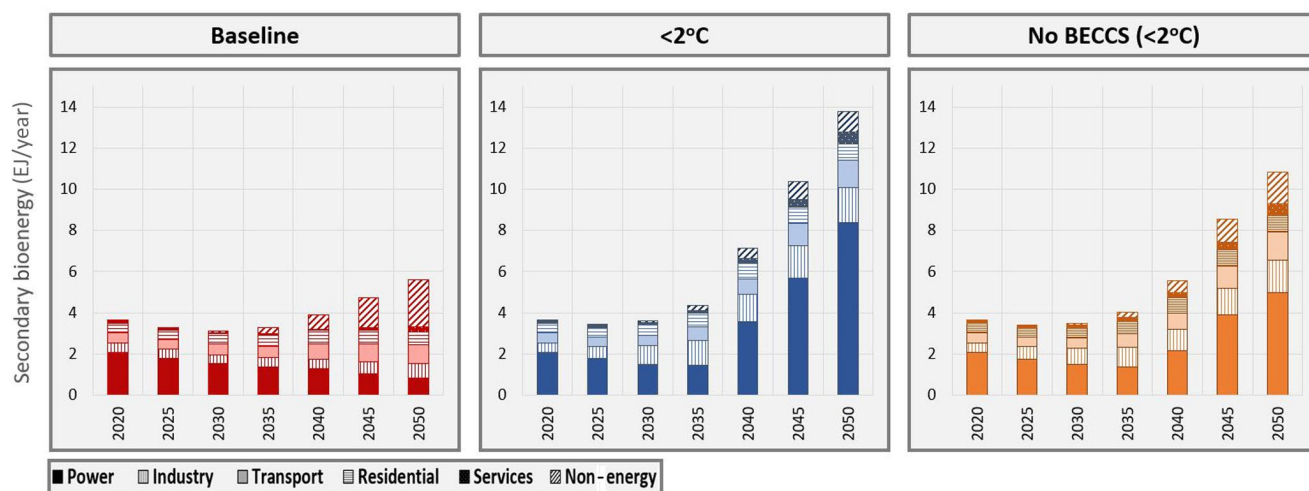

FIGURE 2 Sectoral secondary bioenergy demand in Europe under different scenarios

applications within the 'Baseline' is due to three dynamics: (i) a greater absolute demand (compared to mitigation scenarios) for non-energy sector products due to the absence of price-induced demand reduction, (ii) bio-based energy carriers become economically competitive at replacing oil in chemical manufacture when as oil prices rise due to depletion and (iii) access to cheaper biomass feedstock and conversion technologies due to yield increases and learning by doing (Daioglou et al., 2019). See SM.4.1 for detailed non-energy sector fuel demand.

The '<2°C' scenario projects a 2.5-time increase in total secondary bioenergy demand by 2050 compared to the 'Baseline'. There is an initial depression in power sector demand to 2035 because Europe's TPED decreases in line with the carbon price-induced efficiency gains. Post-2035, bioenergy deployment increases in the power sector mainly in the form of BECCS (where 90% of bioenergy is paired with CCS by 2050). The ability to attain net-negative emissions and an increasing carbon price tilts

BECCS technology into favour. This results in annual bioenergy consumption in the sector quadrupling from 2 to 8 EJ year^{-1}. The mitigation scenarios show an increase in bioenergy used for heat within the industry sector where other low-carbon technologies are costly, and bioenergy displaces coal (see SM.4.4 for subsector breakdown of industry). A similar trend occurs for the transport sector with a tripling in demand over the assessed period. Liquid biofuels displace conventional oil in freight, notably for land-based freight, and fulfil almost half of the fuel demand for marine freight. Passenger travel energy demand in Europe is met 50% by electricity in 2050, of which a third is generated via bioenergy. See SM4.5 for a breakdown of energy carrier demand in the transport sector. Within the non-energy sector, consumption falls compared to the 'Baseline' scenario due to a rerouting of biomass and bioenergy into sectors (services, residential, transport or electricity production) where it can provide more significant mitigation for the same system cost.

A decreased overall bioenergy demand is observed within the 'No BECCS' scenario. This is primarily caused by the prohibition of BECCS within the power sector, where the use of biomass to produce electricity without BECCS is less economically attractive, as the benefits from net-negative emissions are unavailable. However, in the absence of BECCS, bioenergy still retains 60% of the power sector deployment projected for the '<2°C' scenario in 2050. Furthermore, in 2050, the 'No BECCS' scenario shows an increase of 0.5 EJ year^{-1} use within the non-energy sector compared to when BECCS is allowed. This occurs from a rerouting of freed-up biomass at a competitive price to replace oil.

3.3 | Feedstock demand developments

Figure 3 shows the projected demand for secondary bioenergy carriers when disaggregated across biomass feedstock categories represented in IMAGE 3.2. See SM1.1 for details on feedstock categories composition and conversion routes. Liquid biofuels demand increases to 2050, doubling in the 'Baseline' and tripling in the mitigation scenarios. Over the period assessed, there is a transition away from first-generation ethanol produced from sugar crops to higher yielding sources. Particularly towards temperate region sourced advanced lignocellulosic fuels (woody and non-woody feedstocks). An increased liquid bioenergy demand is observed for the mitigation scenarios. This increase is caused by greater demand for biofuels in the transport sector (particularly for marine freight) produced from dedicated energy crops. See SM.5 for the sectoral deployment of liquids and solid bioenergy carriers.

In all scenarios, demand for solid bioenergy carriers (chips/pellets) increases, driven by their increasing consumption in the power and industry sectors. Solid bioenergy carriers are almost exclusively sourced from residues as they are the cheapest feedstock. There is moderate growth of solid bioenergy carrier demand in the 'Baseline' scenario at 0.6 EJ year^{-1} (+23%) by 2050. For the '<2°C' scenario, residue uptake increases 7 EJ year^{-1} (+260%). When BECCS is prohibited, residue consumption falls by 2 EJ year^{-1} (−20%) in 2050. Pellets from residues are primarily used for power generation and industry but also provide process energy for the non-energy sector. The large-scale deployment of electricity generation with BECCS in the '<2°C' scenario reaches the limit of affordable residues supply for Europe by 2050, approximately 10 EJ year^{-1}. At these levels, other solid bioenergy sources, that is, 'woody' and 'non-woody', become economically viable for power generation. This dynamic and the near-term importance of residues as a cheap resource aligns with other IAM results (Hanssen, Daioglou, Steinmann, Frank, et al., 2020).

3.4 | Mitigation potential of European bioenergy

Figure 4a projects the cumulative European-wide GHG emissions attached to each scenario. The SSP2 'Baseline' scenario projects that Europe will emit 110 Gt CO_2eq cumulatively over 2020–2050. Under the '<2°C' scenario, projections show that Europe's energy system needs to limit cumulative emissions to 78 Gt CO_2eq over the same period to meet climate targets.

In the absence of BECCS, cumulative emissions reach 85 Gt CO_2eq by 2040. Thus, BECCS availability contributes
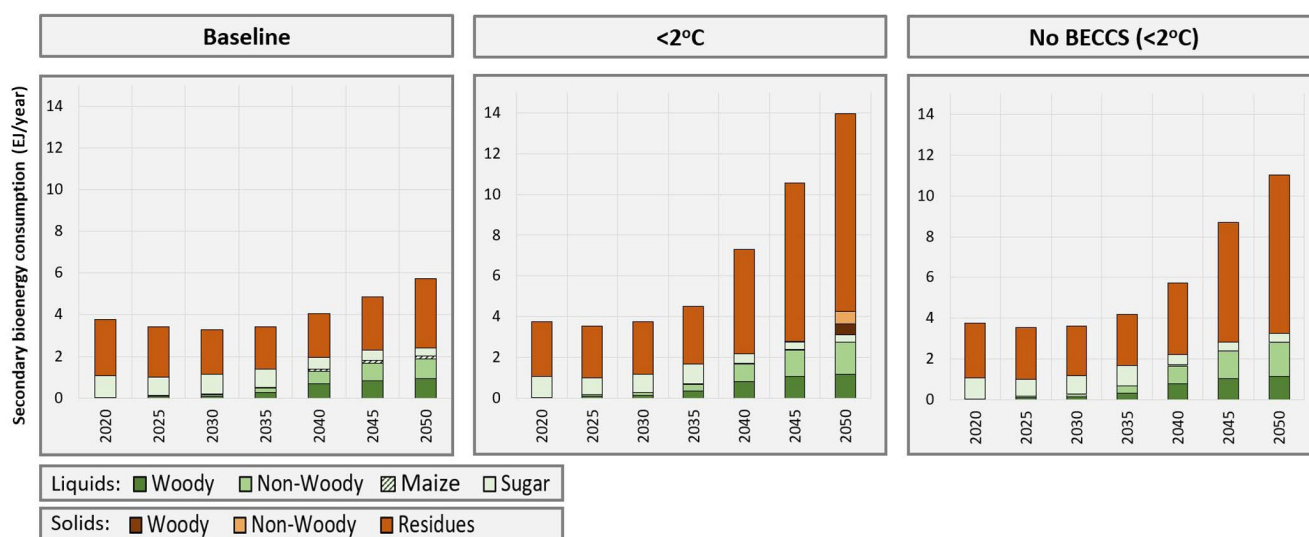

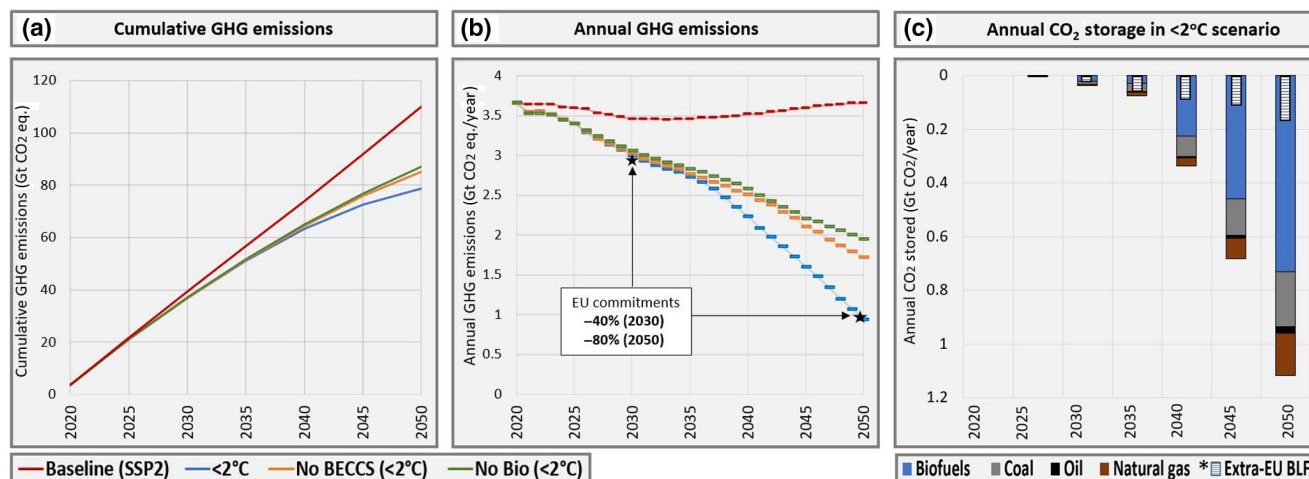**FIGURE 3**   Demand for biomass feedstocks used to produce secondary bioenergy carriers for Europe

FIGURE 4 Mitigation from bioenergy in Europe for 2020–2050 presented for total cumulative emissions (Gt CO_2eq) for all scenarios (a), annual GHG emissions (Gt CO_2eq year^{-1}) for all scenarios (b) and annual mitigation from CCS in the <2°C scenario (Gt CO_2eq year^{-1}) (c). *'Extra-EU BLF' refers to CO_2 storage from BECCS for biofuel production outside of Europe

6.5 Gt CO_2eq (20%) of the total projected mitigation required in the '<2°C' scenario. The complete absence of bioenergy in the 'No Bio' scenario results in cumulative emissions of 87 Gt CO_2eq. Thus, bioenergy as a whole is responsible for 27% (8.5 Gt CO_2eq) of total mitigation required in Europe to 2050. Non-bioenergy-based mitigation is largely achieved through the increased uptake of natural gas combined with CCS. Key developments of the European energy system in the absence of bioenergy are shown in SM.6.

Concerning the '<2°C ' scenario, as seen in Figure 4b, there is a very tight fit to the current legislative EU regional emissions trajectory targets of 40% by 2030 and 80% by 2050 compared to 1990 baseline values (United Nations, 2020). Therefore, the regional emission reduction trajectory projected within this study is in line with EU policy.

Figure 4b highlights the critical role of BECCS in achieving the '<2°C' scenario, showing accelerated reductions post-2035 whereby BECCS utilizing residues for electricity generation allows for mitigation via net-negative emissions. In the year 2050, bioenergy without CCS provides an annual reduction of 0.23 Gt CO_2eq year^{-1} in 2050, which is approximately the current annual emissions of Spain (Eurostat, 2021a). BECCS provides an additional 0.78 Gt CO_2eq year^{-1}, approximately the current annual emissions of Germany (Eurostat, 2021a). BECCS is projected to account for 78% of annual bioenergy mitigation by 2050.

In Figure 4c, negative emissions resulting from CCS are displayed only for the '<2°C' scenario. By 2030, CCS technology is deemed too expensive for significant uptake. Only a small amount of BECCS occurs during the production of liquid biofuels from lignocellulosic sources and for process heat in industry. See SM.7 for projections of sectoral

BECCS deployment in Europe. Post-2030, a combination of an increasing carbon price, emission credit for atmospheric CO_2 removal and technological learning creates a situation where rapid deployment of CCS technologies is possible. Total European CCS deployment increases from 0.03 to 1.12 Gt CO_2eq year^{-1} between 2030 and 2050. In 2050, Europe is projected to capture 1.12 Gt CO_2eq year^{-1} (54%) of emissions occurring within the energy system. Of this, 0.73 Gt CO_2eq year^{-1} (65%) is captured via BECCS due to its ability to deliver net-negative emissions and thus favourable carbon price, especially when delivered via residues. This combination steers BECCS deployment into the power sector. As annual residue supply for Europe reaches maximum capacity, applying CCS to power generation with coal and natural gas becomes increasingly important to reduce Europe's emissions further. The projected role of CCS technologies in the power sector is available in SM.3. In Figure 4c, 'Extra-EU BLF' refers specifically to BECCS during the production of imported liquid biofuels to Europe. Biogenic CO_2 emissions captured during biofuel production are allocated to the exporting country in IMAGE 3.2. Note that they are significant as almost all European liquid bioenergy is imported. They represent 3 EJ year^{-1} in 2050, with 46% refined with CCS. This equates to additional cumulative BECCS mitigation of 1.7 Gt CO_2eq over the period 2020–2050.

3.5 | Interregional bioenergy trade requirements for Europe

Figure 5a displays the net interregional bioenergy trade between Europe and the rest of the world. The import requirement is projected to rise in tandem with total demand
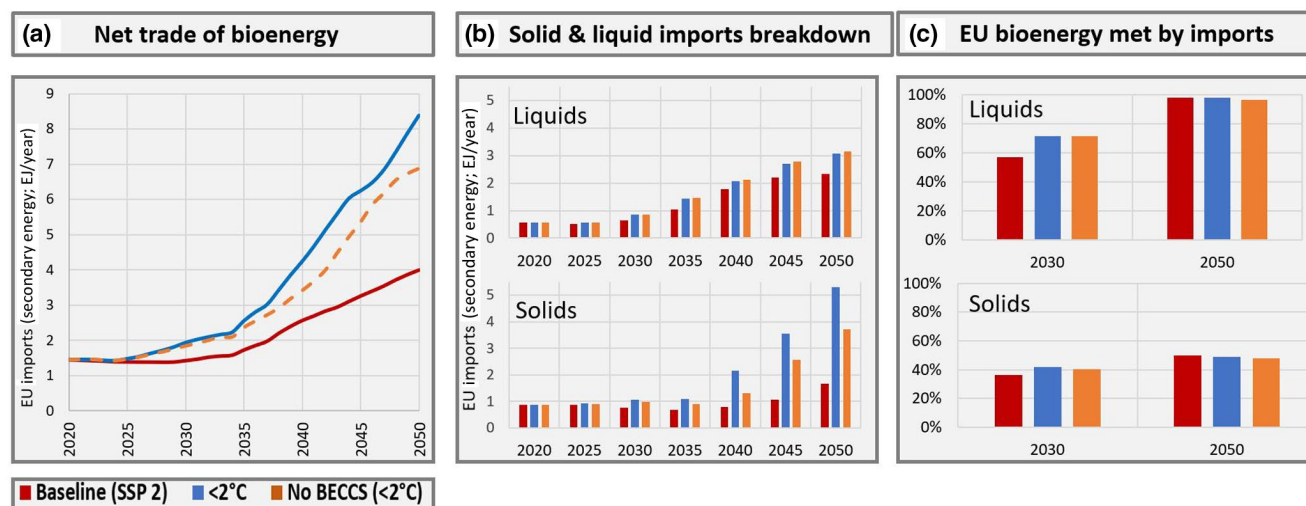
FIGURE 5 Europe's bioenergy trade with other world regions, shown for total net trade (a), solid and liquid imports breakdown (b) and share of Europe's bioenergy met by imports (c)

across all scenarios. To meet the '<2°C' target, the model projects an increase in annual import from 1.4 EJ year^{-1} in 2020 to 8.4 EJ year^{-1} by 2050. In the 'No BECCS' scenario, the demand for imports is 1.5 EJ year^{-1} lower in 2050 due to a decrease in solid bioenergy carrier demand of BECCS. The breakdown of import and domestic supply for feedstock categories is provided in SM.8.

Figure 5b,c project European import requirements when disaggregated into liquid and solid bioenergy carriers. For liquid fuels, we see a steady rise in import demand across all scenarios. Cheap imported advanced lignocellulosic fuels outcompete European-produced first-generation biofuels. They compete with fossil incumbents primarily in the transport, buildings (residential and services) and non-energy sectors. See SM.8 for a breakdown of domestic and imported bioenergy carriers. Post-2030, lignocellulosic biofuels become Europe's dominant supply and boost import dependency of liquid biofuels to >95% by 2050.

For solid bioenergy carriers, there is a pronounced difference in trends between the baseline and mitigation scenarios. When Europe's energy mix begins to decarbonize post-2030, solid fuel imports increase over the period, driven by the increase in bio-electricity production. Over the period assessed for the '<2°C' scenario, annual imports of solid bioenergy increase by 4.4 EJ year^{-1} and in the 'No BECCS' scenario, they increase by 2.84 EJ year^{-1}. Interestingly, the economic benefits of BECCS from negative emission crediting mobilizes 1.4 EJ year^{-1} of more expensive solid bioenergy carriers that are domestically produced in Europe, effectively keeping solid bioenergy import levels below 50% for the '2°C' scenario.

The major sourcing regions for Europe are projected to change over the period assessed. For solid bioenergy carriers, the United States provides >80% of European imports

in 2030, and by 2050, West Africa is projected to be the dominant supplying region providing 70%. For liquid bioenergy carriers, 80% of European imports is supplied by Brazil in 2030, and by 2050, West Africa provides >80%. These projected sourcing regions hold favourable land availability and production costs making them important future bioenergy exporters according to the cost-optimization formulation for inter-regional trade in TIMER. The drivers and implications of these trade projections are discussed in the context of an IAM intercomparison project for bioenergy trade (Daioglou, Muratori, et al., 2020).

4 | DISCUSSION

4.1 | Observations and implications for European bioenergy dynamics

4.1.1 | Bioenergy demand and sectoral deployment

For the '<2°C' scenario, secondary bioenergy can provide 4 EJ year^{-1} in 2030 and 14 EJ year^{-1} in 2050; this represents 50% and 70% of the required energy from renewables in Europe. The projected results show a complete restructuring from the current secondary bioenergy deployment within Europe's energy system. Currently, heating and cooling account for 2.9 EJ year^{-1} (75%), electricity for 0.5 EJ year^{-1} (13%) and transport for 0.5 EJ year^{-1} (12%; Scarlat et al., 2019). In projections for 2050, we find heating and cooling use 4.2 EJ year^{-1} (30%), electricity 8.3 EJ year^{-1} (60%) and transport 1.4 EJ year^{-1} (10%). For a <2°C target, the projections show increased bioenergy deployment across all sectors represented in the model. Bioenergy

deployment is prioritized into the power sector, notably for bioelectricity production and the substitution of coal.

The projections suggest a fuel switching from coal to biomass in the power sector. Under such a development, the power sector should aim to capitalize on the projected phase out of coal via implementing strategies to prolong asset life and minimize associated conversion costs for biomass plants. System-wide identification of plants to convert and retrofit should be in place by 2030 when bioenergy uptake accelerates. However, uncertainty surrounding long-term projections on Europe's access to sustainable biomass may result in lower supply volumes than projected. Acknowledging this, European bioenergy policy should seek to follow a 'merit order of end uses' (Ueckerdt et al., 2021), prioritizing bioenergy to sectors where direct electrification and decarbonization are harder to attain.

4.1.2 | Feedstocks

The biomass feedstock composition in Europe alters significantly from the present, which is predominantly sourced from direct woody supply. Projections for the '<2°C' scenario show residues (forestry and agriculture) as the main source of bioenergy (70%) by 2030. By 2050, European access to affordable residues will have reached maximum capacity, shown by uptake of more expensive woody feedstock from forest plantations and energy crops entering the system post-2045. This dynamic is observed elsewhere in a recent study by Hanssen, Daioglou, Steinmann, Frank, et al. (2020), who compared residue demand at a global-level across a suit of eight IAMs. The share of residues within bioenergy supply decreases around mid-century as supply cannot match increasing bioenergy demand. Thus, the importance of lignocellulosic bioenergy crops and short rotation forestry sources emerge around this time. The projections of the '<2°C' scenario suggest that domestic mobilization of residues and short rotation forestry in Europe needs to be maximized. This requires effective forest management within these time frames to meet the levels of projected solid bioenergy carrier demand and is in agreement with findings of others (Londo et al., 2018).

The model projections show post-2030 a rapid transformation for liquid bioenergy demand from first-generation to second-generation advanced lignocellulosic feedstocks due to a favourable emissions profile and production costs. In reality, for Europe, first-generation feedstocks currently dominate the liquid fuel market. For example, lignocellulosic feedstocks make up only 1% of current bioethanol consumption (Hoefnagels & Germer, 2018). A recent survey of European bio-based companies highlights the importance of local access to feedstocks

(Nattrass et al., 2016). However, only a small share of Europe's crop/marginal lands are for dedicated lignocellulosic energy crops. Although feedstocks will likely be available on the global market as projected in this study, there remains uncertainty regarding the wide variety of lignocellulosic conversion technologies required. These technologies hold varying levels of readiness ranging from lab to commercial scale (Hoefnagels & Germer, 2018).

4.1.3 | BECCS

The projections from this study indicate that BECCS can contribute significantly to European climate targets. The '<2°C' scenario projects carbon capture and storage from bioenergy of 0.73 $GtCO_2eq$ $year^{-1}$ by 2050. Recent studies that utilize partial equilibrium energy system models (Bollen, 2017; Solano Rodriguez et al., 2017) project 1 Gt CO_2eq $year^{-1}$ captured through BECCS in the European power sector in 2050, which is similar to the results presented in this study.

At present, there are only two operational commercial-scale CCS facilities in Europe (Sleipner & Snøhvit), capturing 1.5 Mt CO_2eq $year^{-1}$. Many EU member states have placed limitations or complete restrictions on CO_2 storage and have documented unfavourable public opinion (IOGP, 2019). Scaling up to the projected levels of CCS from this study by 2050 requires timely policies with national and EU-level strategies that support the business case of BECCS (incl. infrastructure development) and address implementation barriers and uncertainties.

4.1.4 | Compliance with European mitigation targets

Our projections show that Europe can meet the EU's Paris agreement GHG emissions trajectory commitment of a 40% reduction by 2030 and 80% by 2050. However, the revised European Green Deal and proposed European climate law seek to attain GHG neutrality by 2050 in-line with a global 1.5°C target. Achieving these proposed deeper reductions would likely require the increased use of bioenergy or integration of other renewables at a higher system cost.

For sectoral-level targets, the European Green Deal seeks a 90% reduction in GHG emissions from transport by 2050 (European Commission, 2019b). Current EU transport emissions are 1.1 Gt CO_2eq $year^{-1}$ (Eurostat, 2021b). Projected transport sector emissions in the '<2°C' scenario are 0.21 Gt CO_2eq $year^{-1}$ in 2050. Thus, an 80% reduction for the modelled European region is realized. This is achieved through a combination of electric vehicles and biofuel uptake. In addition, RED II aims for a 14%

penetration of renewables in the transport sector by 2030 (EU, 2018). However, in our projections, this target is only met in 2043. Power sector GHG emissions in the '<2°C' scenario fall from 1.2 Gt CO_2eq in 2020 to 0.8 in 2030 and −0.3 by 2050. The power sector is projected to attain net neutrality by 2046. This neutrality in the power sector aligns with the European commission's 2050 roadmap targets (European Commission, 2011).

4.1.5 | Trade

For Europe to achieve a <2°C target, the projections indicate a substantial increase in interregional imports. Currently, 4% of Europe's bioenergy arrives via import. Projections show that this increases to 60% (8.4 EJ year^{-1}) by 2050, with large differences between liquid and solid bioenergy. Approximately half (5.3 EJ year^{-1}) of all solid bioenergy carrier demand is imported by 2050, while this is over 95% (3 EJ year^{-1}) for liquid bioenergy carriers. At 2050 levels (8.4 EJ year^{-1}), bioenergy trade reaches approximately 40% of current European crude oil imports. This scale presents a logistical challenge, especially when considering supply regions are likely to become more widespread and diverse. The challenge to achieve such levels of interregional trade projections holds three main concerns. First, strengthening internal EU bioenergy trade infrastructure, including interregional hubs, is needed to cope with a significant surge in demand arriving post-2030. Second, incentives for exporting regions are needed to support increased feedstock production and build the required infrastructure to develop the international market. Third, interregional trade regulations are needed to safeguard Europe's GHG saving targets, including emissions from direct/indirect land-use change.

4.2 | Comparison of bioenergy deployment in other studies

The projections presented in this study are subject to uncertainty surrounding employed techno-economic assumptions. These include technological efficiencies, biomass supply potentials and sensitivity to technological costs, especially for BECCS. Although comparisons of our results with other studies are complicated by inherent differences in these assumptions, key trends projected in this study are compared to other recent assessments and approaches below.

4.2.1 | Other IAMs

As part of the 33rd study of the Stanford Energy Modelling Forum (EMF-33; Bauer et al., 2018), a multi-model comparison of 11 IAMs was conducted. The comparison was under similar climate mitigation restrictions and BECCS availability constraints as deployed in this study. Their results at a global scale show that most models conclude that when BECCS is prohibited, bioenergy consumption decreases. A detailed assessment was not performed at the European level; however, a subsequent assessment of the projects' database was performed by Mandley et al. (2020). At a European level, IMAGE 3.2 projections fall within the ranges of the other participating IAMs for both total bioenergy demand and trade. SM.9 provides further detail on this European intermodel comparison. IAMs have acknowledged limitations (Gambhir et al., 2019), especially in regard to cost sensitivities; thus, comparison to other approaches is beneficial, as is done in the following.

4.2.2 | Recent projections from EU-centred approaches

The REFLEX project (Möst et al., 2021) combines several detailed EU regional bottom-up energy system models with LCA tools and explores a similar below <2°C emissions trajectory. Their results show that by 2050, 6 EJ year^{-1} of primary bioenergy will enter the EU power system compared to 18 EJ year^{-1} projected in our study. This significant disparity is caused by the REFLEX projections indicating almost no biomass application for electricity generation. Instead, a combination of solar and wind capacity leads to 60% of installed capacity by 2050 compared to 10% in our study. This is not only a result of more favourable assumptions on grid integration and technology costs for solar but also due to an absence of BECCS as a technology option in the study's power system module ELTRAMOD (ESA[2], 2013).

Another recent study by Zappa et al. (2021) utilized the power system modelling framework *plexos*. The study projects future cost-optimal energy mixes within the electricity sector for the central-western Europe region in line with a <2°C target. Their results project that BECCS deployment initiates post-2037 when economic incentives from net-negative emissions allow the technology to become profitable, in agreement with our results.

4.3 | Study limitations

Global IAMs such as IMAGE 3.2 aim to capture the complex relationships between human systems such as the energy system explored in this study with natural systems. Due to their global scale and long-run projection horizons, computational power as well as

inherent uncertainties on how these systems may develop limit the resolution at which these systems can be represented. Notable uncertainties in global IAMs include interpretation of historical trends, technological change and estimates on resource and land availability. However, a recent comparative study on IAMs that were used to produce IPCC projections determined that SSP2 scenarios as used in our study tended to closely follow observed CO_2 emission and socio-economic drivers over a 30-year period 1990–2020 (Strandsbjerg Tristan Pedersen et al., 2021). Some of the key uncertainties which may affect the interpretation of our results are discussed below.

4.3.1 | Intra-regional specificity

This study used the global IAM IMAGE 3.2 to analyse regional bioenergy development, focusing on Europe. This approach provided for an assessment at the regional level whilst incorporating the activities of other world regions under an imposed global climate budget. Global IAMs are well suited to determine supply and demand dynamics in relation to socio-economic drivers and climate constraints. However, a trade-off is that they are highly aggregated and lack detailed regional geographical representation meaning technological (including feedstock conversion routes) and resource representation of the European energy system is homogeneous. This approach fails to represent supranational and national level decarbonization strategies and policy priorities that could significantly steer bioenergy development.

4.3.2 | Technological representation

The use of annual time steps implies that IAMs cannot directly represent important aspects which may determine technology selection, such as grid-balancing or regional systems demand flexibility. This weakness extends to the types of conversion technologies and also feedstocks they are able to represent. For instance, some currently significant biomass supply streams, including forest management, pulp wood and black liquor, are not present in IMAGE. See SM.1 for IMAGE 3.2 feedstock representation.

4.4 | Future research avenues

4.4.1 | Deeper mitigation targets

The projections in this study explore bioenergy development in Europe under an emissions trajectory in line with current EU climate legislation. However, given the proposal of the European Green Deal (European Commission, 2019b) to strengthen commitments to a 1.5°C temperature increase limit, future work should seek to expand the scenario protocol to explore a deeper mitigation pathway and its effects on bioenergy deployment.

4.4.2 | Bilateral trade analysis

This study presents the net bioenergy trade requirements required for Europe to meet overarching mitigation targets. However, it is not clear from this modelling set-up if these trade flows comply fully with EU sustainability criteria. An in-depth analysis of where future imports could be sourced from and the GHG emissions attached to these supply chains would bolster the understanding of the logistical and implementation challenges faced. As trade within IAMs such as IMAGE 3.2 is formulated on a least-cost approach, future analysis should seek to incorporate other influential factors. These include geopolitical and regulatory constraints and the ability of sourcing regions to uphold European minimum requirements for GHG reduction values or other sustainability requirements.

4.4.3 | Coupling to regional models

A drawback of global IAMs is that they suffer from interregional specificity and detailed representation, as mentioned in Section 4.3. An extension of this study could seek to feed globally consistent outputs for demand and import requirements into a more technologically and regionally detailed model that is better suited to evaluate these drawbacks. Coupling with a regional model with intra-regional specificity would also allow for the accounting of detailed system variables at the national level. Examples are desired demand flexibility, energy storage, penetration of other renewables, bioenergy policy, CCS policy and intra-regional trade throughout Europe.

5 | CONCLUSIONS

This study provides projections of bioenergy demand, mitigation potential and interregional trade in the European region between 2020 and 2050. Scenario analysis explored the effects of (i) introducing a global <2°C mitigation pathway that seeks to bring about a least-cost energy transition, (ii) prohibiting BECCS and (iii) the absence of bioenergy. The effects on bioenergy demand, including sectoral and feedstock category demand, are also

analysed. Under these conditions, the following conclusions can be drawn.

5.1 | European bioenergy demand is projected to increase significantly and play a substantial role within a low-cost European energy system transition aiming to meet mid-century climate targets

The IMAGE 3.2 projections suggest that a <2°C emission trajectory that closely follows the current legislated climate targets of the EU is possible for Europe to 2050. Achieving this at the least system cost requires a tripling in bioenergy deployment that equates to a 27% (18 EJ year^{-1}) contribution to Europe's TPED by 2050. As a result, there is a substantial restructuring of bioenergy deployment, with power generation becoming the dominant end-use sector, representing 60% of bioenergy consumption in 2050. Bioenergy could contribute up to 27% (8.5 Gt CO_2eq) of the cumulative GHG mitigation required, with BECCS providing 0.7 Gt CO_2eq year^{-1} net-negative emissions by mid-century.

5.2 | Residues and lignocellulosic crops are projected to become the dominant sources of bioenergy for Europe to 2050, in line with EU policy aims

The projections of bioenergy are within the boundaries set by the EU, avoiding primary forestry. Under the <2°C scenario, the model projects a substantial shift away from first-generation feedstocks for liquid bioenergy carriers to advanced and lignocellulosic sources, whose shares increase from 20% (0.3 EJ year^{-1}) in 2030 to 90% (3 EJ year^{-1}) by 2050. For solid bioenergy carriers, residues are the exclusive feedstock utilized except in the '<2°C' scenario post-2045, where Europe reaches maximum access of residue supply. For mid-century climate targets, the projections from this study indicate that residues can provide 9.7 EJ year^{-1} of secondary energy demand predominantly within the power generation and heavy industry sectors.

5.3 | Biomass affords Europe versatility in its decarbonization strategy

The projections demonstrate a significant role for biomass under the scenarios explored. Bioenergy enters all modelled end-use sectors, including difficult to decarbonize sectors such as transport. In the baseline, liquid bioenergy carriers are directed into the non-energy sector for use as platform chemicals as a substitute for more expensive fossil counterparts. For the mitigation scenarios, bioenergy deployment at minimum doubles in each sector to 2050. For the '<2°C' scenario, biomass and bioenergy deployment across the sectors is distributed as follows: 62% Power, 12% Industry, 10% Non-Energy, 8% Transport and 8% Buildings.

5.4 | Bioenergy with CCS can contribute to meeting Europe's mitigation targets

In the '<2°C' scenario, bioenergy contributes 27% of the required GHG mitigation. By 2050, 55% of bioenergy consumed in Europe is paired with CCS, with annual storage of 0.7 Gt CO_2eq. In the absence of BECCS, Europe would fall short of EU-aligned climate commitments by 20% (7 Gt CO_2eq), at the same system cost. The importance of emission reduction technologies is projected to increase further with the introduction of more stringent European climate targets that align with 1.5°C global warming ambitions and could further strengthen the business case of BECCS to facilitate a low-cost energy transition. Obviously, the effectiveness of BECCS requires that biomass is sourced only for locations that lead to an overall negative contribution.

5.5 | For Europe, interregional bioenergy imports could increase substantially to 2050

This pattern is observed across all scenarios explored. In a world that meets a <2°C target, import of bioenergy carriers stands at 60% of the total supply by 2050. The projections show that competition for solid bioenergy carriers on the international market tightens towards 2050. This is reflected in a diversification towards the demand of solid feedstocks from dedicated energy crops post-2045 when Europe reaches maximum residue supply. For Europe to capitalize on this global resource at the scale projected in this study, measures to stimulate sustainable supply in sourcing regions and increased logistical infrastructure would have to be in place before 2030.

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