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LETTER

Strategic uses for ancillary bioenergy in a carbon-neutral and fossil-free 2050 European energy system

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Abstract

Biomass is a growing renewable energy source in Europe and is envisioned to play a role for realising carbon neutrality, predominantly using dedicated energy crops. However, dedicated biomass is controversial for reasons including its competition with food production or its land-use and emissions impacts. Here we examine the potential role of a land-free alternative: ancillary bioenergy (AB) from biomass sources not primarily grown for energy and without land/food/feed competition. We provide the first dataset of 2050 ancillary biomass potential using the agricultural system model SOLm, which encompasses untapped by-/co-products and detailed agricultural residues. Results show that there is a limited future potential for AB in Europe (2394–10 342 PJ, which is 3–6 times lower than other estimates including dedicated biomass). We design and investigate alternative scenarios where this bioenergy resource can be fully utilised, not utilised at all, or utilised optimally by the sector-coupled energy system model Euro-Calliope. We find that fully utilising ancillary biomass can help phase out controversial nuclear or land-intensive dedicated biomass, so might achieve higher societal acceptability. Using all ancillary biomass as a negative-emissions source at stationary bioenergy carbon capture and storage plants in a nuclear-free system provides additional climate benefits. It is also possible to leave the AB potential completely unused, which barely increases total system cost, but would preserve agricultural nutrients. We conclude that there are synergies and trade-offs among possible strategic uses of AB, which can provide guidelines for a more coherent European bioenergy strategy. Although the 2050 potential of AB is limited, our findings suggest that it could fill critical strategic niches for realising carbon-neutrality.

1. Introduction

The European Union envisions to achieve climate-neutrality by 2050 through implementing the European Green Deal (European Commission. Directorate General for Communication 2021). The energy sector is one of the largest greenhouse gas emitters requiring full decarbonisation to meet the 2 °C or 1.5 °C target (IPCC 2022). Bioenergy appears to be an attractive option especially for its unique negative emissions potential using carbon capture and storage (CCS) (Fajardy and Dowell 2017, Muri 2018) and for supplying hard-to-decarbonise sectors such as aviation or shipping (O'Connell *et al* 2019). Bioenergy is also attractive for a fully renewable European power system because it is dispatchable and flexible for balancing solar/wind intermittency (Cornelissen *et al* 2012, Masson-Delmotte *et al* 2018, Bogdanov *et al* 2019). Bioenergy is seemingly envisioned to play strategic roles among competing energy usages, albeit its contentious availability and sustainability.

Europe has been imposing stricter bioenergy sustainability criteria (European Parliament 2018), in particular with regards to indirect land-use change emissions. The European Commission amended the first Renewable Energy Directive (RED-I) by highlighting guidelines to estimate indirect land-use change emissions from biofuels (ANNEX V) (European Commission 1998, p 70)—capping conventional biofuels and promoting advanced biofuels (Cansino *et al* 2012, Panichelli and Gnansounou 2017). By 2030, dedicated energy crops with high indirect land-use risks (e.g. palm oil) will be phased out even if they fulfil previous sustainability requirements (Dusser 2019), according to the new EU bioenergy sustainability certification scheme in RED-II (Moustakidis 2018). Despite substantial efforts on sustainable bioenergy supply, an overarching long-term strategy of bioenergy deployment is missing in the European policy context, especially towards a highly renewable and carbon-neutral European energy system in 2050 (International Renewable Energy Agency (IRENA) 2018, Mandley *et al* 2020).

Meanwhile, most energy system models used to produce European decarbonisation pathways include predominantly dedicated biomass from energy crops or forests in 2050 scenarios (Ruiz *et al* 2015, European Commission. Directorate General for Energy *et al* 2016, Huppmann *et al* 2019) (e.g. about 70% of the bioenergy potential is from dedicated biomass in JRC-EU-TIMES). There is potential land/food/feed competition when sourcing dedicated biomass from arable land (Searchinger and Heimlich 2015, Muscat *et al* 2020) and forests (Popp *et al* 2012). The 'sustainability' of biomass, difficult to define in any case, appears to be treated highly inconsistently when comparing policy goals and modelling studies. Here, we wish to examine the potential strategic use of non-dedicated and sustainable bioenergy without land-use competition for deep energy system decarbonisation, for which we define sustainability in a more explicit manner based on the underlying agricultural system. By strategic uses, we refer to critical roles not easily filled by another technology, which bioenergy may play to realise carbon-neutrality, to enhance energy safety, or to increase societal acceptability.

Existing literature shows that Europe has a substantial potential of untapped 'ancillary bioenergy' (AB) without land-use/food/feed competition—that is, various non-dedicated bioenergy feedstocks recovered from residue and co-/by-products from agriculture, forests, and human settlements (Wu and Pfenninger 2022). AB encompasses the additional co-/by-products of high energy density that waste-to-energy lacks (e.g. additional by-products such as nutshells and animal fats). We define this as 'sustainable' bioenergy based on the absence of land/food/feed competition.

There is a number of estimates on the future residue potential (Daioglou *et al* 2016, Elbersen and Voogt 2020, Mandley *et al* 2020, Panoutsou 2021), but these studies either report aggregated agricultural feedstocks with mixed energy properties (i.e. not suitable for the same conversion technology and thus not suitable for a detailed assessment of the different types and quantities of bioenergy that can be derived from it) or do not completely rule out feed/food conflicts, especially for the agricultural biomass. Therefore, it is necessary to re-estimate the detailed ancillary biomass potential with stringent assumptions and additional by-/co-products not provided in the current literature. The aim of this paper is to explore whether a limited biomass potential accounting for strict sustainability criteria (i.e. land/food/feed-free ancillary biomass) can play a strategic role in a sector-coupled and fossil-free European energy system. Furthermore, we intend to explore how and where to utilise which ancillary biomass feedstocks in an optimised way.

Here, we answer this research question by using a sector-coupled energy system optimisation model to analyse the potential strategic role for non-dedicated, i.e. AB. To do so, we first systematically quantify the future potential of AB resources without land-use or food/feed competition. We review literature on potentials and use the agricultural and food system model SOLm to estimate the detailed residue and by-/co-products potential sustainably available for bioenergy purposes (section 3.1). We then design and investigate alternative scenarios where this bioenergy resource can be fully utilised, not utilised at all, or utilised optimally by the sector-coupled energy system model Euro-Calliope and identify strategic bioenergy use cases (sections 3.2–3.5). Finally, we conduct a range of sensitivity analyses to examine the robustness of our model (section 3.6).

2. Methods and data

This study applies two models to first estimate AB potential in 2050 (SOLm) and then optimises its strategic role in a 2050 carbon-neutral European energy system (Sector-coupled Euro-Calliope). Here we provide a brief overview of the two models.

2.1. Agricultural and food system model—SOLm

SOLm (Sustainability and Organic Livestock model) is a bottom-up mass-flow model of the agricultural production and food sector originally having a focus on livestock and organic production but now, in its sixth version, covering the whole food system and also conventional production in similar detail (Muller *et al* 2017). It is by default calibrated with Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) data and categories of crops and livestock at the national level. Thanks to its detailed categorisation and flexible model assumptions, we can estimate the ancillary biomass potential per crop/livestock and per activity (e.g. 114 types of primary crops residues and 16 types of nuts shells, as documented in appendix A). Therefore, we can extract the annual flow of residues and by-products not used for food or

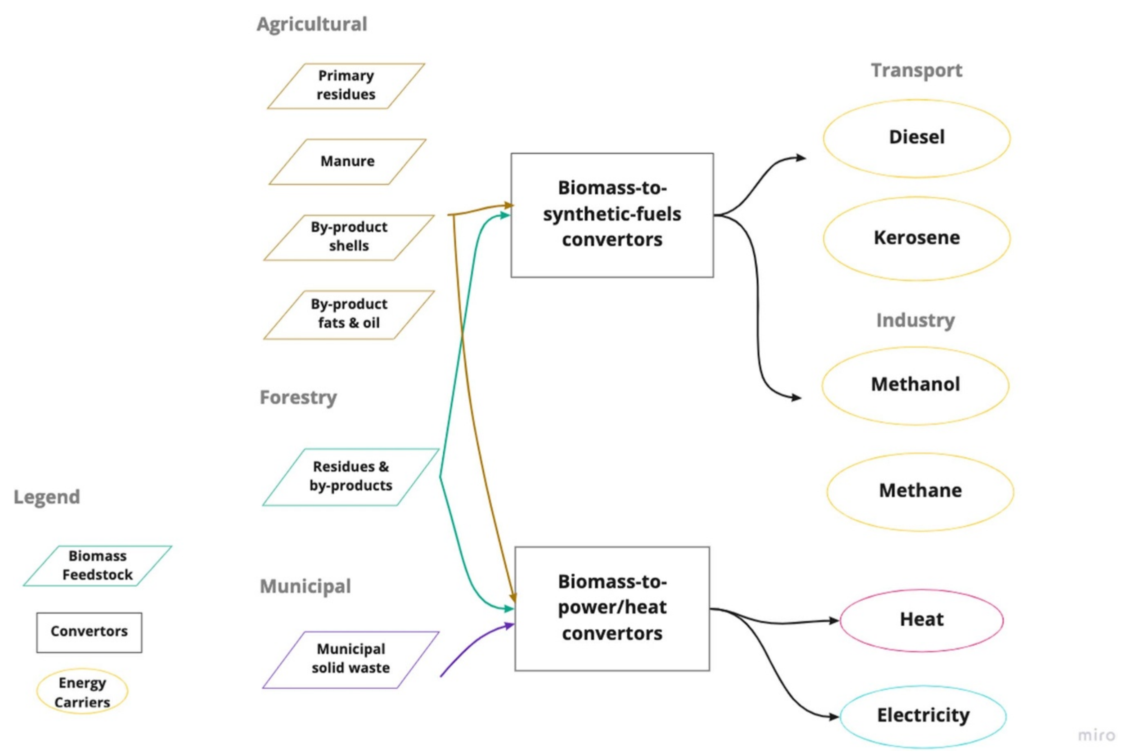

Figure 1. Ancillary biomass conversion pathways.

feeding. We run the model at national resolution (35 European countries). We update SOLm with crops-to-residue shares from the latest 2019 Intergovernmental Panel on Climate Change (IPCC) refinement ('Ratio of above-ground residue dry matter to harvested yield' in Volume 4, chapter 11) (Masson-Delmotte *et al* 2018). For a detailed description of SOLm, one may refer to its latest documentation (Müller *et al* 2020). For our assumptions and data processing of ancillary biomass potential, see appendix A for a detailed description.

2.2. Sector-coupled energy system optimisation model—Euro-Calliope

We model the European energy system in 2050 with a national resolution, sector-coupled energy system model modified from the Sector-Coupled Euro-Calliope model, which we hereafter refer to as Euro-Calliope (Pickering *et al* 2022). Euro-Calliope is a representation of demand and available supply technologies in all energy-consuming sectors (household and commercial heat, passenger and freight transport, industrial process heat and feedstocks, and all other sectors, including agriculture) across 35 European countries. The model is designed to be linearly optimised in the Calliope energy modelling framework v0.6.8 (Pfenninger and Pickering 2018).

The original version of Euro-Calliope (Pickering *et al* 2022) models all biomass feedstocks as one energy carrier, which is compatible for all bioenergy conversion technologies. Instead, we add more detailed bioenergy feedstocks data from SOLm and pair every biomass feedstock with compatible bioenergy conversion technologies (figure 1). With the modified and more detailed AB module in Euro-Calliope, we name our model AB-Euro-Calliope (for the detailed AB costs and technologies data, please refer to appendix B; for codes and data files to reproduce all model runs, see our GitHub repository (Wu 2022) and (Bryn 2022)). In AB-Euro-Calliope, we run all scenarios with a two-hour resolution for a full year, and assume that the annual biomass potential can be used arbitrarily throughout the year (i.e. it can be stored and used when needed).

2.3. Supply, demand, and common assumptions among scenarios

Overall, we consider and model a self-sufficient pan-European energy system, including self-sufficient bioenergy supply (i.e. no energy imports or transmission from outside of Europe). We assume the national autarky of both synthetic fuels demand and biomass supply in 2050 Reference (table 1).

For the future ancillary biomass supply data, we model the agricultural sector using SOLm and adopt the forestry and municipal waste potential from JRC-EU-TIMES (Ruiz *et al* 2015). This is because there is in principle no food/feed/land conflicts when we source forestry residues or forestry by-products and municipal solid waste, so for those feedstocks, there is no need to re-estimate the potential with strict exclusion of food/feed/land conflicts. There are many estimates of future residue data available from the literature (table A6 in appendix A), but they either

Table 1. Common assumptions and constraints for all scenarios in this study.

	Common assumptions/constraints	Explanation/reference (if applicable)
Supply (2018 weather year)	Carbon-neutrality	Assuming ancillary biomass as carbon-neutral with zero biogenetic emissions. Others are same as in Euro-Calliope—considering all energy technologies deployed as carbon emissions-free (Pickering *et al* 2022)
	Sustainable potential of ancillary biomass	As detailed in appendix A
	Conversion technologies of bioenergy	As detailed in appendix B
	Nuclear power plants and capacity range	Expected 2050 national nuclear capacity from JRC open power plant database (Kanellopoulos *et al* 2019) Assuming a minimum capacity (nuclear plants as planned towards 2050) that the model has to meet and a maximum capacity (as planned plus under consideration) that cannot be exceeded. Same as in Euro-Calliope (see table S7 in Pickering *et al* 2022)
	Bioenergy carbon capture and storage (BECCS) or carbon capture and utilisation (CCU)	No BECCS by default and assuming biomass is carbon neutral. Allowing BECCS only in scenario *AllBECCS* where all ancillary biomass is used for negative emissions at stationary plants (appendix C) Direct air capture and utilisation technologies are available (CCU) for providing industrial CO_2 feedstock, e.g. 'Power-to-X'—same as in the Euro-Calliope (Pickering *et al* 2022)
	Land-use footprint of renewables (not used to constrain the model; but for ex post analysis when comparing different scenarios)	Onshore wind: 0.125 km^2 MW^{-1}; open-field photovoltaics (PV): 0.0125 km^2 MW^{-1}; no land uses for other renewables. Same as in Euro-Calliope (Pickering *et al* 2022)
Transmission	Power grid transmission	High-voltage electricity grids are available between neighbouring countries. Same as in Euro-Calliope (Pickering *et al* 2022)
	Synthetic fuels are self-sufficient within every country ('national autarky' hereafter)	All countries must supply their low-carbon fuel demand with domestic energies. No transnational trade or transport allowed (different from Euro-Calliope (Pickering *et al* 2022) and *BioDistribution* scenario (section 2.4))
Demand (today's demand)	Shipping and aviation fuel and decarbonisation	Assuming marine shipping and aviation cannot be electrified in 2050 and can only be decarbonised by synthetic fuels
	Other transportation demand, electricity and heating demand	Allowing both electrification and synthetic fuels for other transportation (apart from shipping and aviation) and let the model decide the optimised solution
	Industry feedstocks (methane and methanol)	Assuming this can only be met by synthetic fuels
	Full incineration and utilisation of municipal solid waste	Assuming all municipal solid waste is incinerated (today's levels of waste)

have aggregated agricultural feedstocks with different energy properties (i.e. not suitable for the same conversion technology) or do not completely rule out feed/food conflicts. Therefore, we use SOLm and its FAO 2050 Business-as-usual scenario (Muller *et al* 2017) to model the more detailed and stringent agricultural ancillary biomass potential, i.e. we first extract only the non-food/feed shares of (a) by-/co-products (16 types of shells and three types of fats and oil with high energy density), (b) crop residues (114 types), and (c) animal manure. Moreover, we leave enough residues (50%) and manure (25%) on fields to keep enough soil fertility and nutrients. For the detailed assumptions and calculation of ancillary biomass potential data, please refer to table A4 and appendix A.

Next, we briefly introduce the common assumptions across all scenarios (table 1), using our baseline and reference scenario, hereafter referred to as the *2050 Reference* scenario. Overall, we consider and model a self-sufficient pan-European energy system, which assumption thus also applies to bioenergy supply (i.e. no energy imports or transmission from outside Europe). We assume the national autarky of both synthetic fuels demand and biomass supply in *2050 Reference* (table 1). For non-bioenergy renewable supply options, we have solar (open-field and rooftop), wind (off-shore and on-shore), hydro (run-of-river and reservoir), biomass (six categories of ancillary biomass as in figure 1) and nuclear (only the capacity in operation or planned towards 2050) to produce carbon-neutral electricity, heat, or synthetic fuels. Solar and wind constitute the predominant supply sources, i.e. their capacity reaches 2.23 TW and 3.32 TW in the optimised *2050 Reference* scenario. Meanwhile, hydro reservoir, biomass, and nuclear can provide comparably minor but flexible supply. The national difference is pronounced in terms of renewable energy capacity and supply structure (table D2 in appendix).

On the demand side, we adopt today's demand profiles by default—the same hourly demand profiles as in Euro-Calliope (Pickering *et al* 2022). This implies several key assumptions about demand-side decarbonisation (table 1). First, we assume the marine shipping and aviation cannot be electrified in 2050 and can only be decarbonised by synthetic fuels (diesel and kerosene). Second, for other transportation (road and rail, light, and heavy duty), heating, and electricity, both electrification and carbon-neutral fuels are allowed. Third, the industrial demand for methanol and methane feedstocks can only be met by synthetic fuels generated by biomass or hydrogen. Overall, we report the primary energy supply in PJ (section 3.1) and final energy consumption in TWh (sections 3.2–3.5) for differentiation.

2.4. Scenario descriptions and additional constraints

Apart from the *2050 Reference* scenario, we examine two sets of counterfactual and near-optimal scenarios (i.e. total system costs, or the optimisation objective, are no more than 10% above the optimal solution in *2050 Reference*) to explore different strategic uses of AB. Table 2 specifies the difference among these scenarios, marked in bold and italic when they deviate from *2050 Reference*.

For the first set (different utilisation cases), we explore the possible roles for AB when it can be utilised optimally, fully utilised (*FullUtiAll*), or not utilised at all (*NoUti*). This is realised by adding additional bioenergy utilisation constraints or infrastructure, where we change only one constraint per scenario. More specifically, first, for the *FullUtiAgr* and *FullUtiAll* scenarios, we force the 100% utilisation of agricultural (*FullUtiAgr*) or all kinds of ancillary biomass (*FullUtiAll*). Second, for *GasStorage,* we add existing underground methane storage facilities. This is based on the latest data on a national level, as documented in the Sector-coupled Euro-Calliope (Pickering *et al* 2022). Third, in the '*BioDistribution*' scenario, we deploy an additional distributing network (trail/road) connecting neighbouring European countries for transporting liquid synthetic fuels (see the third type of costs in appendix B). Lastly, *NoUti* disallows all biomass supply or conversion technologies, which provides a counterfactual scenario where Europe realises carbon-neutral energy systems in 2050 without utilising any bioenergy.

The second set explores alternative strategic use cases of AB—(a) adding or removing controversial low-carbon energy sources (*DedicatedBiomass:* allowing additional supply of dedicated advanced biomass (miscanthus) with additional land use; *NoNuclear*: disallowing all nuclear capacity); (b) forcing all AB to be used for negative emissions via stationary BECCS (*AllBECCS*). For the combined scenarios (e.g. *BioDistribution* + *FullUtiAll*) we change multiple constraints by combing assumptions, as indicated by the scenario names.

2.5. Land use, nutrients, and emissions estimation

Apart from modelling the energy flow (AB-Euro-Calliope) and mass flow (SOLm), we also conduct ex post analysis to compare three environmental metrics among scenarios—(a) land area used by the energy system (including onshore wind turbines and open-field PVs in all scenarios and the land used by miscanthus in *DedicatedBiomass* scenario); (b) agricultural nutrients lost through biomass incineration (via multiplying the Nitrogen and Phosphorus contents of biomass by their incinerated percent); (c) negative emissions potential of using all ancillary biomass at stationary BECCS plants (through their emission factors and CO_2 capture rate). For the detailed data source, assumptions, and calculation, please refer to appendix C in the supplementary material.

3. Results

3.1. Limited future potential of AB in Europe

The total potential of AB reaches 185 PJ (sustainable) and 798 PJ (technical) in 2050 in Europe. To minimise the environmental impact, we use only the sustainable potential of AB for comparing feedstock-wise availability and modelling all scenarios ('potential' refers to sustainable potential hereafter). Feedstock-wise, agriculture is the predominant sector for providing AB across Europe (81 PJ), accounting for over 56% of the total potential. Forestry potential (48 PJ) is the second highest, followed by municipal solid waste (33 PJ). For national potential of sector-wise ancillary biomass, please refer to figure D1 in appendix.

Compared to recent estimations including dedicated bioenergy (the middle block in figure 2), the potential of AB estimated here is reasonably limited (i.e. 3–6 times lower) given its stringent prerequisite—no land-use or food/feed competition. The more detailed and stringent estimation of AB

Table 2. Different assumptions among scenarios modelled in this study ('Y' for yes and '—' for no; difference from the 2050 Reference scenario is in bold and italic text).

Scenarios	Force full utilisation of agricultural biomass	Force full utilisation of all biomass	Underground methane gas storage technology	Synthetic liquid fuels distribution network	No biomass supply or conversion technology	Add dedicated biomass (miscanthus) with additional land use	No nuclear capacity	CCS available; all biomass is used for BECCS
2050 Reference	—	—	—	—	—	—	—	—
Different utilisation cases of ancillary bioenergy (section 3.2)								
FullUtiAgr	***Y***	—	—	—	—	—	—	—
FullUtiAll	—	***Y***	—	—	—	—	—	—
GasStorage	—	—	***Y***	—	—	—	—	—
BioDistribution	—	—	—	***Y***	—	—	—	—
GasStorage + FullUtiAll	—	***Y***	***Y***	—	—	—	—	—
BioDistribution + FullUtiAll	—	***Y***	—	***Y***	—	—	—	—
NoUti	—	—	—	—	***Y***	—	—	—
Strategic use cases of ancillary bioenergy (for higher societal acceptability, as in sections 3.3 — 3.5)								
DedicatedBiomass	—	—	—	—	—	***Y***	—	—
DedicatedBiomass + FullUtiAll	—	***Y***	—	—	—	***Y***	—	—
NoNuclear	—	—	—	—	—	—	***Y***	—
NoNuclear + NoUti	—	—	—	—	***Y***	—	***Y***	—
NoNuclear + FullUtiAll	—	***Y***	—	—	—	—	***Y***	—
AllBECCS	—	—	—	—	—	—		***Y***
NoNuclear + AllBECCS	—	—	—	—	—	—	***Y***	***Y***

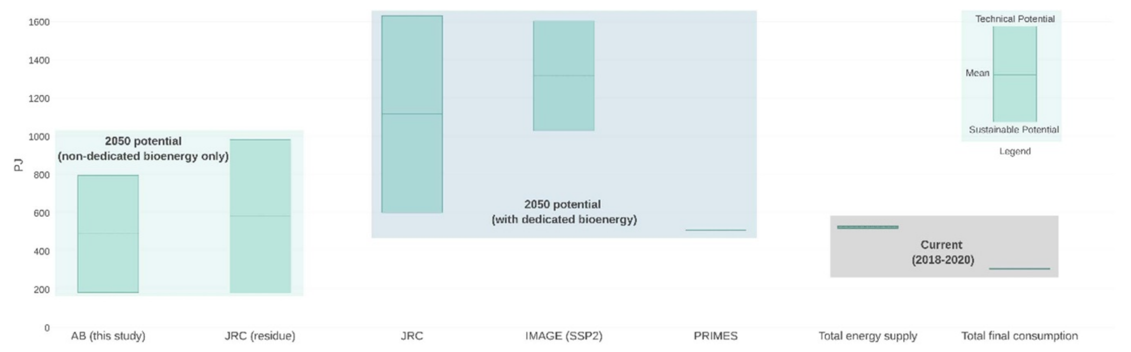

Figure 2. Europe-wide ancillary bioenergy (AB) potential modelled in this study compared to other models in 2050, and to the current supply and consumption in Europe (2019).

potential could better reveal its sustainable role in a fully renewable European energy system. The technical potential for AB is around 20% lower than that of residues from the high availability scenario of JRC-EU-TIMES. In figure 2, we display the lower bounds as sustainable potentials and higher bounds as technical potentials if applicable—for models without differentiating potentials, we use a line (e.g. price-induced market equilibrium system (PRIMES)). JRC (residue) and JRC are from the JRC-EU-TIMES model (Ruiz *et al* 2015). By non-dedicated bioenergy in JRC-EU-TIMES, we refer to the non-dedicated biomass from agricultural waste, manure, residues from landscape care, fuelwood residues, secondary forestry residues (woodchips and sawdust), municipal waste.; IMAGE (SSP2) is the bioenergy supply from the Shared Societal Pathway 2 scenario modelled by IMAGE (Huppmann *et al* 2019); for the PRIMES model, we use its input data of bioenergy potential in 2050 (European Commission. Directorate General for Energy *et al* 2016); the current supply and consumption of bioenergy is compiled from IEA World Energy Balances (International Energy Agency 2022).

We specifically subtract the non-dedicated bioenergy from JRC-EU-TIMES for comparison (the second-left bar—'JRC (residue)' in figure 2), as it is the closest to AB with overlapping forestry and municipal datasets. We further break down and compare the different agricultural biomass potentials between our results and the JRC data by feedstocks (table A5 in appendix) and spatial distribution (figure 3). Generally, our total agricultural ancillary biomass potential (185 PJ) is similar to the non-dedicated biomass considered in JRC-EU-TIMES model (182 PJ). However, the spatial distribution varies, especially when we break it down into sub-categories. There are three major differences. First, we consider additional by-/co-products feedstocks that are not included in JRC-EU-TIMES (i.e. (3) & (4) in figure 3—nuts shells and animal fats). Their amount is minor, but they have high energy density with strategic decarbonisation uses (e.g. producing kerosene and diesel for the hard-to-decarbonise aviation and shipping sectors for which regular agricultural residues do not qualify). Second, we embrace a wider variety of crops residues (114 types) compared to JRC (11 types) leading to a doubled potential (81 PJ in this study compared to 44 PJ in JRC-EU-TIMES). Third, we use the sustainable potential of manure without changing nutrient balance, livestock system, and food/feed system (e.g. 25% of all manure is left on fields), while JRC allows all wet manure (pig and cattle) to be available.

3.2. Roles for AB in a sector-coupled energy system

We first explore the possible roles for AB when it can be utilised optimally, fully utilised, or not utilised at all in our 2050 European energy system (figure 4). This section acts as the reference scenarios for comparing the following strategic use cases in sections 3.3–3.5. Hence, in this section we assume that (a) nuclear power is available, (b) dedicated biomass is disabled, and (c) no BECCS technologies are available to provide negative emissions.

Consumption-wise, the average European utilisation of AB is low and reaches only 38% in the optimised *2050 Reference* scenario (see the European and national utilisation rates in figure D1 in appendix), whereas 19 out of 35 European countries are below this rate. When adding bioenergy infrastructure (especially the continental distribution network of liquid synthetic fuels in *BioDistribution*), it can significantly boost the AB utilisation (by half) and alter sectoral uses (figures 4 and 5). Our optimisation results suggest different sectoral uses for bioenergy among scenarios (ancillary biomass only; solid colour bars in figure 4) compared to the current sectoral demand in Europe (dedicated biomass that is not optimised; the transparent bottom bar). In all scenarios, ancillary biomass is more attractive for decarbonising transport in 2050, instead of balancing variable renewable electricity supply or residential heating (the current major use of dedicated bioenergy in 2019).

In figure 4, the current (2019) data refer to the total final consumption of biofuels and waste in Europe from the International Energy Agency

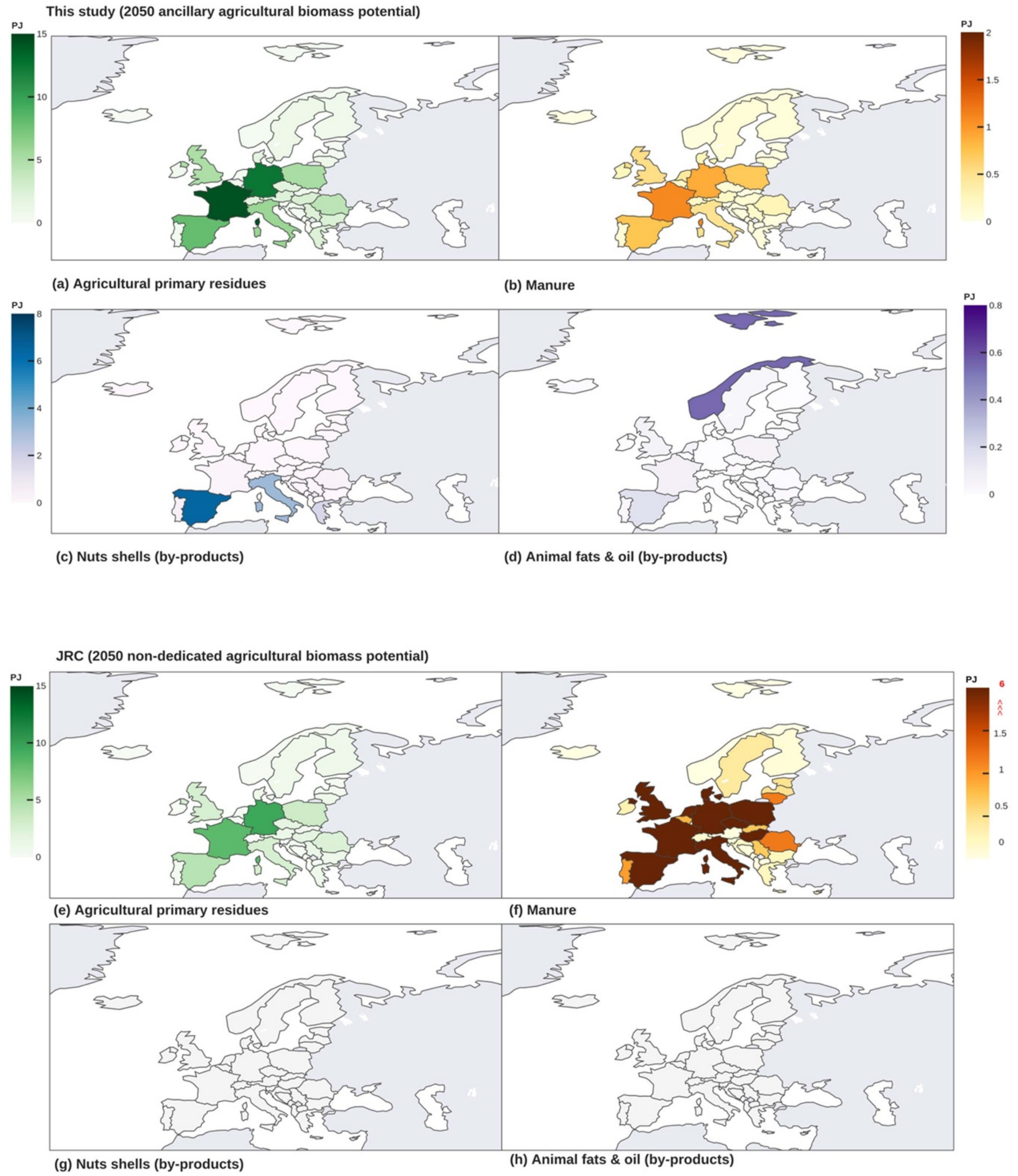

Figure 3. Comparing the (a)–(d) agricultural ancillary biomass 2050 potential in this study (SOLm model) and (e), (f) non-dedicated biomass from JRC-EU-TIMES (common agricultural policy regional impact model (CAPRI) model). By-products from nuts shells and animal fats are not available in JRC-EU-TIMES, so they are blank in maps (g), (h) (Ruiz *et al* 2015).

(IEA) Energy Balances, which includes dedicated biomass and is not cost-optimised (International Energy Agency 2022). 'Others' refer to the agriculture, commercial, and other sectors. For the detailed sectoral data, refer to table E1 in appendix. For scenarios difference, there are two additional kinds of infrastructure and/or forced full utilisation of AB—(a) underground methane gas storage facilities (for enhancing flexibility in scenario *GasStorage*) and (b) a liquid biofuels distribution network connecting European countries using wheel loaders and trucks for 0.64 €/km/ton (for realising pan-European autarky of fuels in scenario *BioDistribution*); (c) *FullUtiAgr* where all agricultural ancillary biomass is forced to be used and (d) *FullUtiAll* where all ancillary biomass is forced to be used. (e) We also combine *BioDistribution* and *FullUtiAll* scenarios into the fifth scenario (*BioDistribution* + *FullUtiAll*) as they can both substantially change strategic uses. We then compare them to the 2050 Reference scenario, which does not include either of two facilities.

When fully utilising AB, the total system costs barely increase (less than 1% in *FullUtiAgri and FullUtiAll*, table E2). But it can further decarbonise

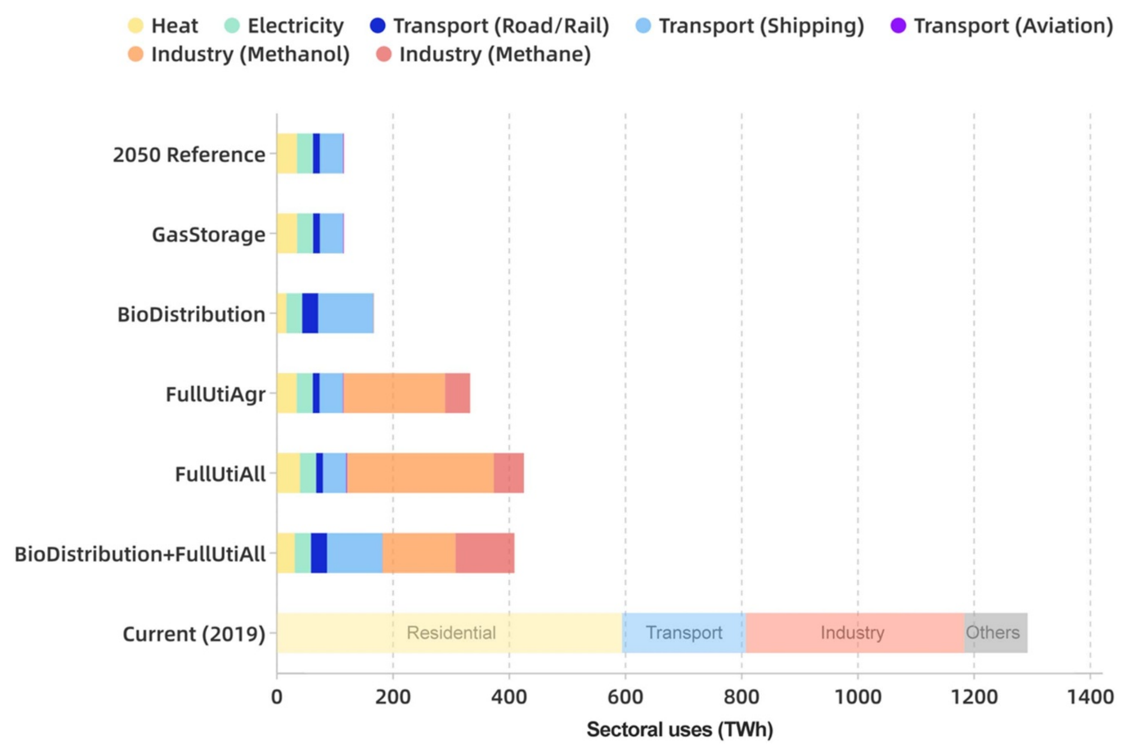

Figure 4. Sectoral final consumption of ancillary bioenergy differs among scenarios and from current uses including dedicated biomass.

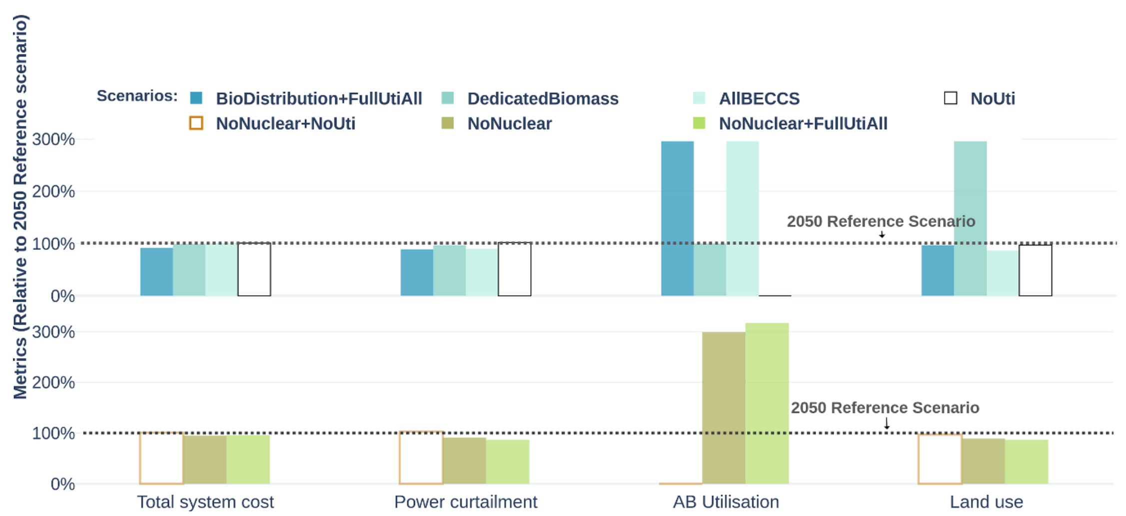

Figure 5. System-wide comparison of reference scenarios (power curtailment is the percentage of maximum available renewable electricity production from wind and solar photovoltaic technologies that is curtailed; AB utilisation is the percentage of the maximum available ancillary biomass potential which is used in a given scenario).

industry sectors by partially replacing hydrogen-based synthetic fuels, thus freeing up land (6% land footprint reduction) and reducing renewable power curtailment. This synergy is more pronounced when we combine the constraints of full utilisation and distribution network (*BioDistribution + FullUtiAll*, figure 5 and table E2), which leads to the highest reduction of total system costs (−8%) and power curtailment (−11%).

However, even with additional distribution and/or forced full utilisation, the attractiveness of AB is still uncompetitive in producing synthetic fuels in most European countries, compared to hydrogen (figure E1 in appendix). To further investigate the extent to which AB is necessary, in the *NoUti* scenario, we disallow all bioenergy supply, conversion, or consumption. Compared to *2050 Reference*, total system costs barely change (less than +0.6%) in

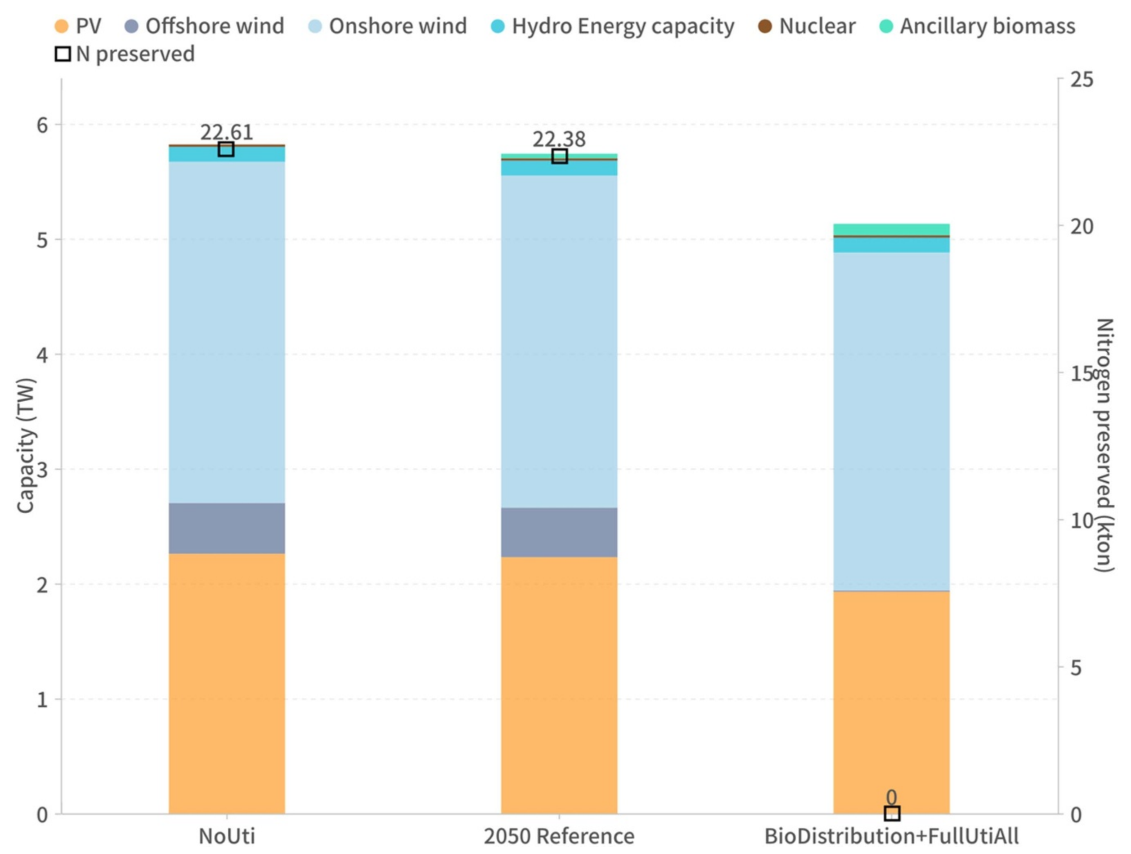

Figure 6. Different compositions of energy capacity and nitrogen nutrients preserved when the utilisation of ancillary bioenergy is zero (NoUti), optimal (2050 Reference), and full (BioDistribution + FullUtiAll).

NoUti—only the annual power curtailment slightly increases (+2%, see figure 5). However, compared to the highest utilisation case (*BioDistribution* + *FullUtiAll*), *NoUti* requires a drastically different solar-to-wind ratio to balance the system—substantially more offshore wind and rooftop PV and less onshore wind capacity (table 3). Note that even when comparing the two extreme utilisation cases here (full and zero utilisation of AB), their total system cost difference is still not significant, i.e. within 10%.

NoUti can lead to additional environmental benefits of preserving agricultural nutrients (figure 6). When AB is not incinerated for energy purposes, it can prevent up to 22.6 kiloton of nitrogen loss annually (equal to 2% of EU consumption in 2019). Similarly, it could be available as feedstock for other non-energy purposes without land/food/feed competition—for example, bio-based industrial materials, papers, and textiles.

3.3. Substituting dedicated biomass by enabling distribution network

When we add an abundant supply of dedicated biomass in the *DedicatedBiomass* scenario (via miscanthus with additional land use as described in appendix C), the total system cost does not change much (only 1% lower). This means that even the limited sustainable potential of ancillary biomass alone can contribute similarly to the energy system compared to the much larger dedicated biomass resource, while saving substantial areas of agricultural land (table 3). Although the attractiveness of bio-based diesel substantially increases by three times when adding dedicated biomass, we can achieve a similar attractiveness by fully utilising AB and by adding the distribution network (*DedicatedBiomass* vs *BioDistribution* + *FullUtiAll* in table 3). In other words, it is plausible that we replace land-intensive dedicated biomass with only limited but strictly sustainable AB for higher societal acceptance (via lower land use) and for higher attractiveness (for producing carbon-neutral fuels).

3.4. Phasing out nuclear by fully utilising AB

For a counterfactual nuclear-free European energy system (*NoNuclear*), we remove the enforcement of a minimum nuclear capacity in 2050. This inherently reduces the total system costs by removing the (assumed-to-be relatively high) capacity costs and operational costs of nuclear plants: the system is −5% cheaper than the *2050 Reference* (table 3). Without the balancing capacity from nuclear plants, intermittent offshore wind power and hydrogen production (via the power-intensive electrolysis technology) are less attractive, which results in their drastically reduced capacity (−36% less offshore wind and

Table 3. Comparison of system metrics when strategically using ancillary bioenergy for phasing out nuclear or dedicated biomass.

	DedicatedBiomass	BioDistribution + FullUtiAll	NoNuclear	NoNuclear + NoUti	NoNuclear + FullUtiAll	NoNuclear + AllBECCS	AllBECCS
System-wide metrics relative to the *2050 Reference* scenario							
Land use	+314%	−3%	−11%	−3%	−13%	−18%	−13%
Power curtailment	−3%	−10%	−9%	+3%	−13%	−9%	−10%
Total system cost	−1%	−9%	−5%[a]	+1%	−4%	+0.2%	+0.5%
Intermittent renewable energy capacity relative to the *2050 Reference* scenario							
Open-field PV	−3%	−13%	−7%	+2%	−10%	−8%	−9%
Rooftop PV	−15%	−3%	+12%	+93%	+29%	+78%	+69%
Offshore wind	−7%	−97%	−36%	+3%	−45%	−37%	−37%
Onshore wind	−2%	−2%	−3%	+4%	−6%	−4%	−6%
Hydrogen production capacity (electrolysis) and the percent of bio-base synthetic fuels (attractiveness)							
Electrolysis capacity (relative to the *2050 Reference* scenario)	−6%	−26%	−12%	+5%	−27%	−20%	−20%
% of bio-based Diesel (6% in *2050 Reference*)	19%	20%	38%	0%	38%	—	—
% of bio-based Methanol (1% in *2050 Reference*)	1%	11%	1%	0%	24%	—	—

[a] Note that we consider the capital cost of nuclear plants in our previous scenarios and constraint the minimum nuclear capacity according to national plans (table 1), so removing nuclear technology inherently reduces total system costs (i.e. −5% for *NoNuclear* as scaled by reference scenario).

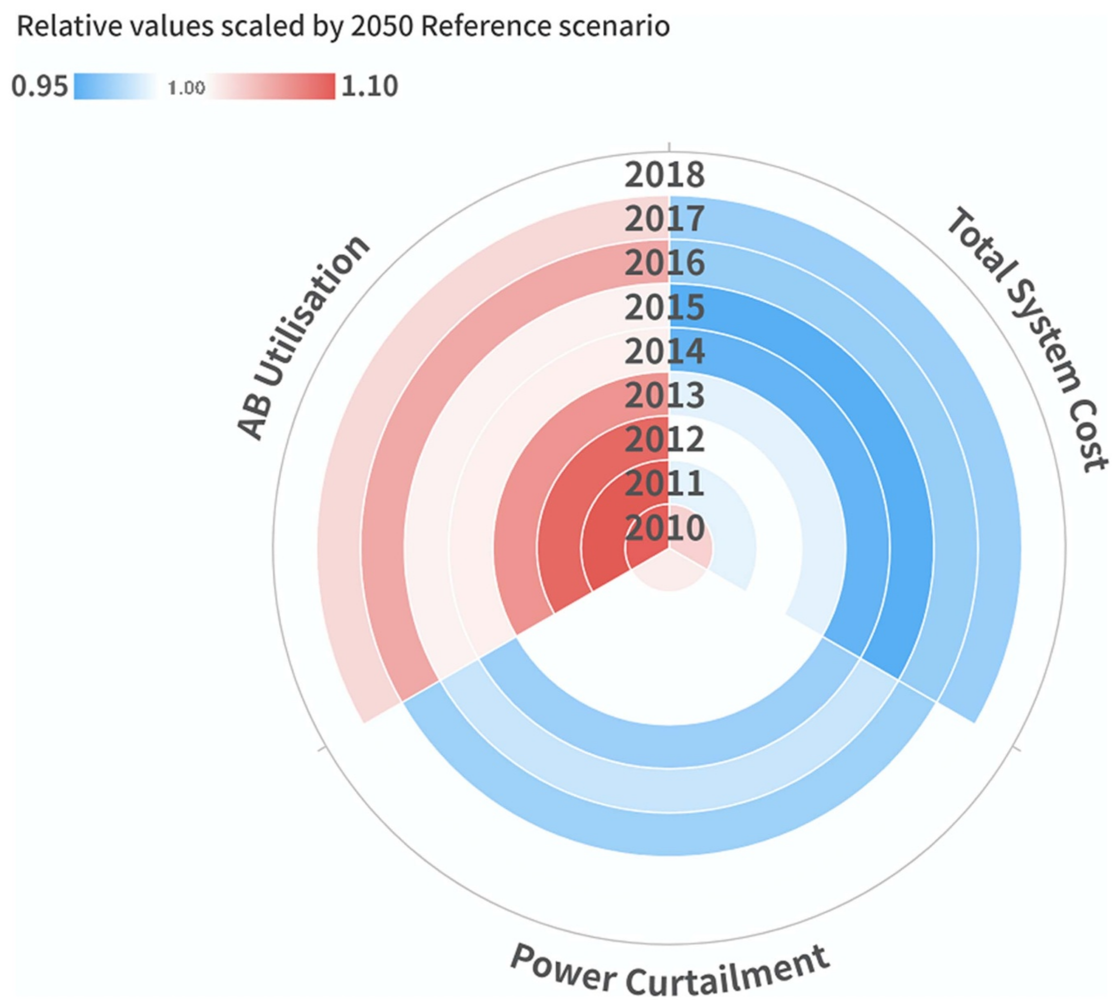

Figure 7. Sensitivity to the different weather years.

−12% less electrolysis capacity, *NoNuclear* in table 3). In this case, ancillary biomass becomes a strategic resource for balancing intermittent power (−9%–13% power curtailment) and for producing synthetic fuels (replacing the reduced capacity of hydrogen-based synthetic fuels). For instance, bio-based diesel accounts for 38% of the total diesel demand (*NoNuclear*), which is 6 times higher than its share in *2050 Reference* scenario with nuclear (first column in table 3). The strategic use of AB is more pronounced when we force the model to use them all in the nuclear-free scenario (*NoNuclear* + *FullUtiAll*)—bio-based methanol constitutes 24% of the total industrial demand, which leads to 13% lower land use as well as power curtailment at similar system costs (table 3).

In contrast, a biomass-free and nuclear-free energy system is lacking in both firm capacity (from nuclear) and dispatchable power (from biomass). The consequently higher power curtailment requires drastically more intermittent renewable energy, especially for the rooftop PV capacity (+93%). Moreover, the overall higher intermittent renewable capacity further increases total system costs (*NoNuclear* + *NoUti*). Hence, AB is especially critical in a nuclear-free and highly renewable European energy system as it can considerably reduce land uses and total system costs by balancing renewable intermittency.

3.5. Additional negative emission at similar costs

As a final alternative, the entire available AB potential could also be used exclusively in stationary applications with the intention of providing negative emissions (over and above our assumption of an already carbon-neutral energy system). This could be achieved by enforcing that all ancillary biomass is used either at stationary power plants or Fischer–Tropsch diesel plants, both of which would be coupled with CCS. This AB potential for negative emissions can contribute around 253–623 Mtons CO_2 eq yr^{-1}, which equals to 8%–21% of 2019 EU carbon emissions. We describe in detail how to calculate the negative emissions in appendix C.

We find that it is equally feasible to use all ancillary biomass for additional negative emissions with (*AllBECCS*) or without nuclear (*NoNuclear* + *AllBECCS*) at similar total system costs (less than 1%

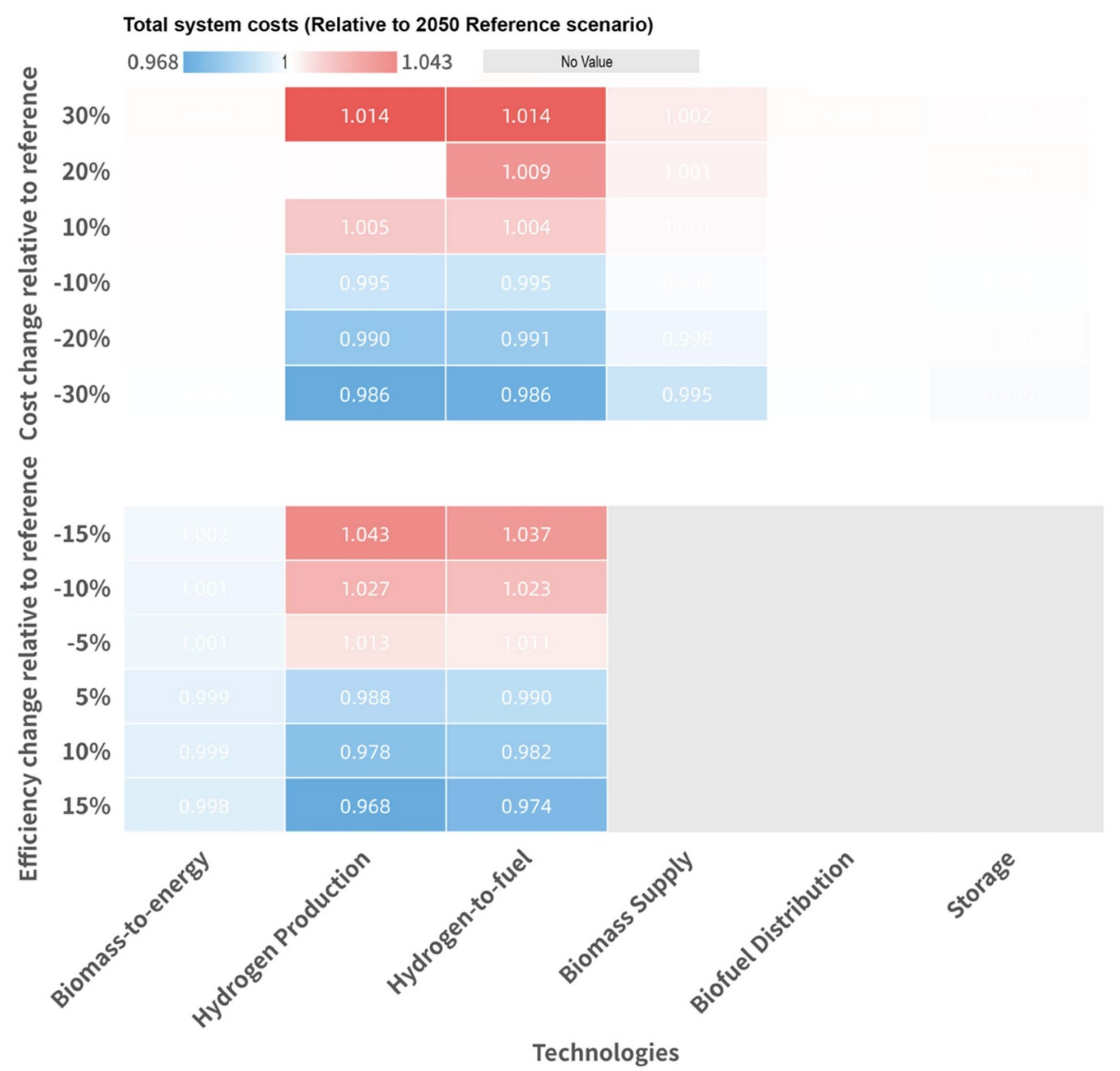

Figure 8. Sensitivity to technology costs and efficiency ('No Value', grey colour, represents that the uncertainty change is not applicable to the referred technologies; white colour (at the middle of colour scale) means the same system cost as in the 2050 Reference scenario, i.e. relative value = 1).

above *2050 Reference*). *NoNuclear + AllBECCS*, especially, can have the most synergies among all use cases (table 3)—additional negative emissions (goes beyond carbon-neutrality in the other scenarios), enhanced energy safety (no nuclear), and the highest land-use reduction (−13% to −18%).

3.6. Sensitivity analysis

Here we perform a sensitivity analysis to examine the robustness of our model and identify what may drive the total system cost reduction. We focus on the following uncertainties—inter-annual weather variability by varying the weather year modelled (figure 7) and the costs and efficiencies of future technologies related to or competing with bioenergy (figure 8). We carry out this sensitivity analysis using the *2050 Reference* Scenario.

First, energy system models may be sensitive to the inter-annual difference of various weather patterns (Zeyringer *et al* 2018). For a 2050-oriented energy modelling study, the future weather is uncertain, especially for estimating hourly PV and wind time series in the long term. This prediction also falls beyond the scope of our paper. However, we can examine historical weather years (from 2000 to 2018) to see how sensitive the model would be to observed variability. We check three aggregate results: AB utilisation, power curtailment, and total system cost. As shown in figures 7, 2018 is our reference weather used in all scenarios. Different weather-year runs comprise the corresponding time series data of solar photovoltaic, wind, and hydro hourly capacity factors, synthetic fuel demand profiles, and heating and transportation demand profiles. For the detailed data files of every weather year, please refer to our Data availability section.

Overall, these three global variables do not vary significantly between weather years (all within 10%), suggesting the robustness of our results to the choice of weather year. Total system costs and power curtailment are less sensitive to different weather years (changes <5%) compared to ancillary biomass utilisation (between 4% and 10%).

Second, we examine the future cost and efficiency uncertainty by changing the cost and efficiency of one technology category at a time (i.e. cost relaxations of ±30% in increments of 10%; efficiency uncertainty of ±15% in increments of 5%) and keep the rest unchanged (table F1 in appendix). These two uncertainty ranges (±30% and ±15%) are a reasonable estimate according to the Danish Energy Agency Technology Data for 2050 (Danish Energy Agency 2019). For technologies examined here, we look at bioenergy-related technologies (biomass supply, biofuels production and distribution, etc) and bioenergy-competing technologies (hydrogen production, synthetic fuels conversion, and storage) to identify under which circumstance it would render significantly cheaper total system costs. Overall, our results are not sensitive to technology cost relaxation or efficiency uncertainties, among which hydrogen technologies have the most perceivable effects on total system costs (around ±4%). Bioenergy-related technologies and storage options do not substantially alter total system costs in any case (less than 1%).

4. Discussion and conclusion

Our study has three important conclusions for energy research and implications for policy making. First of all, there will be an untapped (but limited) AB potential in the future Europe without land-use/food/feed competition (665–2873 TWh, or 2394–10 342 PJ), which is 3–6 times lower than recent estimation including dedicated biomass (Ruiz *et al* 2015, European Commission. Directorate General for Energy *et al* 2016, Huppmann *et al* 2019). Second, we find that fully utilising ancillary biomass could help reduce land uses at similar total system costs (i.e. by replacing land-intensive dedicated biomass or balancing intermittent renewables in a nuclear-free scenario), particularly if bioenergy-derived fuels are distributed with an additional distribution network. It is equally possible to use all ancillary biomass for additional negative emissions in a nuclear-free system (equal to 8%–21% of current EU carbon emissions in 2019). Third, leaving the AB potential completely unused has a minimal effect on total system costs but would preserve agricultural nutrients (equal to 2% of the EU demand for nitrogen nutrients in 2019). Overall, therefore, there are trade-offs between possible uses of Europe's AB potential (table 4), an understanding of which can provide guidance for bioenergy policymaking.

These conclusions imply novel insights for the EU bioenergy policy making, where dedicated bioenergy is receiving substantial subsidies but a long-term strategy is missing (European Parliament 2018). For national stakeholders, especially for the identified European countries where biomass is not economically attractive for producing synthetic fuels (e.g. costal countries such as the UK, Iceland, and Portugal in figure E1), further subsidies on dedicated bioenergy may not be economically sensible in the long run and can likely lead to carbon lock-in. Ultimately, if the European Union is to move towards a stringently sustainable bioenergy policy framework with nuclear energy, we can design different carbon-free supply mixes without any bioenergy to reach similar system costs, which saves more ancillary biomass feedstocks for non-energy usages, less agricultural nutrients loss, or more negative emissions potential. Alternatively, by providing substantial negative emissions potential while allowing the elimination of nuclear power, all the while not impacting land-use or agricultural sustainability, we find that AB can play a critical role in a strategic niche of the energy-land-carbon nexus to help achieve a fossil-free, carbon-neutral, and sector-coupled 2050 European energy system.

Our study is different from most carbon-neutrality scenarios that rely heavily on large-scale BECCS from dedicated biomass, especially in the latest IPCC AR6 reports—22 out of 32 carbon-neutrality-by-2050 AR6 scenarios deploy an average global capacity of 337 GW biomass for electricity with a growing trend towards 2100 (Byers, *et al* 2022). Among these 2050-neutrality scenarios, the highest biomass capacity (1553 GW) (Luderer *et al* 2018) can be six times higher than the lowest bound (260 GW) (Luderer *et al* 2022), which despite assuming high electrification and shares of renewables still requires substantial bioenergy capacity in power generation. Our study on the other hand reinforces the finding that bioenergy use can be much lower when high electrification and hydrogen integration are available in a fully renewable and carbon-neutral energy system (Mortensen *et al* 2020). Moreover, our work indicates that it is even possible to eliminate dedicated bioenergy, contradicting other work which found that a mass mobilisation of (dedicated) bioenergy resources would be required for a 100% renewable European energy system (Zappa *et al* 2019). This contradiction further supports our previous work that there is a broad manoeuvring space of drastically different pathways to a carbon-neutral European energy system (Pickering *et al* 2022), a finding which we refine through particular attention to the role of bioenergy.

There are some limitations in this study, in particular regarding assumptions made for biomass demand and supply. On the demand side, we assume all ancillary biomass is used for energy without considering its non-energy uses, like raw materials. More specifically, we simplify the industrial demand for biofuels into synthetic fuels or their equivalents, ignoring detailed chemical industry

Table 4. Synergies and trade-offs among use cases of ancillary bioenergy at similar total system costs, i.e. ±10% ('+' refers to whenever a scenario performs better than the 2050 Reference scenario; vice versa for '—').

Synergies (+)/trade-offs (−)		DedicatedBiomass	BioDistribution + FullUtiAll	NoNuclear	NoNuclear + NoUti	NoNuclear + FullUtiAll	NoNuclear + AllBECCS	AllBECCS
Energy	Attractiveness of biomass (% of bio-based fuels production)	+	+	+		+	+	+
	Power curtailment reduction	+	+	+	−	+	+	+
	Energy safety (phase-out controversial low-carbon energy)	−		+	+	+	+	
Land	Land-use reduction	−	+	+	+	+	+	+
	Agricultural nutrients preservation	−	−	−	+	−	−	−
Carbon	Negative emissions						+	+

processes that may require/generate more intermediate carriers/by-products for non-energy uses, thus changing operational costs. For instance, biomass gasification (Flow FT) technology can generate a small fraction of naphtha as by-product. Naphtha is mainly used for plastic production, which it is not part of our bioenergy demand portfolios, nor can it be produced by hydrogen. We divert naphtha equally into other synthetic fuels outputs from the same technology for simplification (i.e. diesel and kerosene). This implies that the actual demand for AB could be higher if non-energy uses, such as naphtha, were fully considered. On the supply side, we simplify the storage and domestic transportation of ancillary biomass, which may reduce the potential and increase the cost of biomass feedstocks (although our model is not sensitive to such uncertainty as in table F2). Specifically, we assume there are sufficient storage options to store biomass feedstocks over a full year to be used for the energy system whenever needed. Also, our model considers one country to be a single node, so the domestic transportation network is beyond our national modelling resolution. Besides, we do not capture the seasonal or inter-annual change of biomass availability, which is beyond the modelling resolution of SOLm; nor do we consider the impact of waste management improvement or additional cover crops potential, which should be minor to the total energy system given the small role of AB. We also do not consider energy crops from marginal or abandoned land, which does not fit into our definition of land-free AB. Moreover, there are also potential environmental downsides of using marginal/abandoned land for energy crops. For instance, clearing and tillage of long abandoned grasslands results in serious declines in soil carbon (Elbersen *et al* 2020). Also, converting unused land to biomass cropping implies more soil disturbance and thus higher risk for erosion and nutrients loss (Verheijen *et al* 2009). Future research could examine these points to improve the representation of bioenergy in energy systems modelling.

Data availability statement

The data that support the findings of this study are openly available. See https://github.com/wwwuFei/AB-Euro-Calliope and https://doi.org/10.5281/zenodo.6854685.

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