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Role of Bioenergy in Sustainable Energy and Food Systems

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FEI WU

MEng Environmental Engineering, Shanghai Jiao Tong University

born on *13.12.1994*

accepted on the recommendation of
Prof. Dr. Anthony Patt
Prof. Dr. Stefan Pfenninger
Dr. Adrian Müller
Prof. Dr. Birka Wicke

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Abstract

To combat climate change, the Paris Agreement established a global warming limit of 2℃ by the century's end. Numerous countries aspire to attain carbon neutrality by 2050, as evidenced by initiatives such as the European Union Green Deal. As the sole renewable energy that can provide negative emissions, bioenergy emerges as an appealing option yet with an unclear role in both long-term policy and current models.

The challenge of understanding sustainable roles of bioenergy stem from both supply and demand sides. Supply-wise, there are inconsistent definitions of “sustainable bioenergy” among models as well as between policy and models, among which land-use change is the major concern. Demand-wise, there are competing uses of bioenergy without a coherent strategy. Moreover, bioenergy uniquely serves as a bridge between the energy transition and food system sustainability where energy-land-food nexus may impose complicated trade-offs and synergies.

Accordingly, this thesis aims to model the potential roles of sustainable bioenergy, taking into account both energy and food systems, to contribute to a more cohesive bioenergy policy framework aimed at achieving climate neutrality. The thesis answers this overarching research question by three contributions that investigate (1) the challenges and opportunities of bioenergy deployment, (2) strategic uses of land-free ancillary bioenergy in a carbon-neutral Europe, (3) the option space and trade-offs between sustainable bioenergy provision and food system designs.

The first contribution examines the historical deployment, current policy support, and potential future roles of bioenergy in the European case. I identify three major challenges and proposes the corresponding opportunities. The first challenge pertains to the supply side, highlighting difficulties in securing bioenergy supply, particularly for liquid biofuels and countries with high per-capita bioenergy consumption. The second challenge addresses inconsistencies in the definition of "sustainable bioenergy" between modelling studies and EU policies. The third challenge is the conflicting uses for bioenergy from the demand side, which is lacking a clear long-term strategy in Europe. To address these challenges, future research could explore untapped bioenergy potential with low environmental impacts to enhance supply security. Establishing a clear and harmonized definition of "sustainable bioenergy" would facilitate conveying modelling results to policymakers. Additionally, this contribution proposes the land-free alternative “ancillary bioenergy” that rules out all land/food/feed conflicts with untapped potential from by-/co-products and residues from agricultural, forestry, and municipal sources.

The second contribution further explores the potential role of ancillary bioenergy based on energy system optimization modelling (sector-coupled energy system model Euro-Calliope). Findings reveal a limited future potential for ancillary bioenergy in Europe (2394-10,342 PJ, that is 3-6 times lower than other estimates including dedicated biomass). By modelling various use cases of ancillary bioenergy, this contribution finds that fully utilizing ancillary biomass could help phase out controversial nuclear or land-intensive dedicated biomass, potentially enhancing societal acceptability. Employing ancillary biomass as a negative-emissions source at stationary BECCS plants in a nuclear-free system provides added climate benefits. Leaving ancillary bioenergy unused slightly increases total system cost but preserves agricultural nutrients. This study concludes that strategic uses of ancillary bioenergy entail synergies and trade-offs, offering guidance for a more cohesive European bioenergy strategy.

The third contribution assess the trade-offs and option space between ancillary bioenergy and circular agroecology. The global mass-flow food-system model SOLm models the availability and environmental impacts of ancillary bioenergy by modelling 190 different future circular agroecological strategies combinations. Findings reveal a diverse option space for the future food and energy system, allowing for a similar range of ancillary bioenergy (60-70 EJ) across varied food systems, encompassing organic agriculture levels and waste and concentrate feeding reductions. Three trade-offs between food system sustainability and ancillary bioenergy provision emerge. First, a trade-off exists between nutrient recycling and negative emissions – providing negative emissions by using bioenergy with carbon capture and storage can make the food system incompatible with medium to high organic farming due to increased risks for nutrient deficits. Second, reducing feed from croplands impacts ancillary bioenergy production inversely based on organic agriculture share. Third, food waste reduction diminishes ancillary bioenergy provision. Overall, these embedded trade-offs could better assist in bridging the energy and food systems and in understanding the systematic role of sustainable bioenergy.

This thesis makes three contributions to the literature. Empirically, this thesis contributes to resolving the inconsistent definition of “sustainable bioenergy” by proposing a land-free alternative of “ancillary bioenergy”, along with identifying its strategic roles towards climate neutrality and its bridge between energy transition and food sustainability. In terms of data, this thesis provides the open dataset of further ancillary biomass potential covering over 120 biomass feedstocks at the national resolution for 2050 Europe. Regarding modelling, the thesis enhances the Euro-Calliope sector-coupled European energy system optimization model by providing a detailed representation of national-level bioenergy feedstocks paired with compatible conversion technologies. They contribute to the bioenergy modelling community by offering free, open, and reproducible data and model.

Correspondingly, this thesis provides policy implications both on the European and global scales. For the European energy system, this thesis provides sector-coupling insights to help bioenergy policymakers answer systematic questions, like when, where, and how to best utilize what bioenergy. The identified synergies and trade-offs of different bioenergy use cases can help enhance the coherence of bioenergy policy framework. For the global energy and food systems, this thesis identifies a diverse option space allowing policymakers to explore the potential economic/environmental/emission impacts of different policy mixes. This option space also implies the trade-offs between enhancing the sustainability of the food system and maximizing ancillary bioenergy potential for energy provision or negative emissions. However, higher ancillary bioenergy provision or additional negative emissions may conflict with food system sustainability through nutrient deficits. Thus, policymakers should align planning for sustainability in the energy system with planning for sustainability in the food system.

Zusammenfassung

Zur Bekämpfung des Klimawandels wurde im Pariser Abkommen eine Begrenzung der globalen Erwärmung auf 2℃ bis zum Ende des Jahrhunderts festgelegt. Zahlreiche Länder streben die Kohlenstoffneutralität bereits bis 2050 an, darunter in Initiativen wie dem Green Deal der Europäischen Union. Als einzige Quelle erneuerbarer Energie, die negative Emissionen verursachen kann, stellt die Bioenergie eine attraktive Option dar. Dabei bleibt ihre Rolle sowohl in der langfristigen Politikgestaltung als auch in den aktuellen mathematischen Modellen noch unklar.

Die Herausforderungen zum Verständnis einer nachhaltigen Rolle der Bioenergie liegen sowohl auf der Angebots- als auch auf der Nachfrageseite. Auf der Angebotsseite sind die Definitionen von "nachhaltiger Bioenergie" zwischen den Modellen sowie zwischen Politik und Modellen uneinheitlich, wobei die Veränderung der Flächennutzung das größte Problem darstellt. Auf der Nachfrageseite gibt es konkurrierende Verwendungen von Bioenergie ohne eine kohärente Strategie. Darüber hinaus dient die Bioenergie in einzigartiger Weise als Brücke zwischen der Energiewende und der Nachhaltigkeit des Lebensmittelsystems, so dass die Verknüpfung von Energie, Land und Lebensmitteln zu komplexen Zielkonflikten und Synergien führen kann.

Vor diesem Hintergrund ist es das Ziel dieser Arbeit, die potenzielle Rolle nachhaltiger Bioenergie zu modellieren und dabei sowohl Energie- als auch Nahrungsmittelsysteme zu berücksichtigen, um zu einem kohärenteren politischen Rahmen für Bioenergie zur Erreichung von Klimaneutralität beizutragen. Die Dissertation beantwortet diese übergeordnete Forschungsfrage mit drei Beiträgen zu den folgenden Aspekten: (1) die Herausforderungen und Chancen des Bioenergieeinsatzes, (2) die strategische Nutzung von flächenunabhängiger Bioenergie aus Nebenquellen ("ancillary bioenergy“) in einem kohlenstoffneutralen Europa, und (3) der Optionsraum und die Kompromisse zwischen nachhaltiger Bioenergiebereitstellung und Lebensmittelsystemkonzepten.

Im ersten Beitrag werden der historische Einsatz, die derzeitige politische Unterstützung und die potenzielle künftige Rolle der Bioenergie im europäischen Fall untersucht. Ich analysiere drei große Herausforderungen und führe auf, welche Möglichkeiten sich daraus ergeben. Die erste Herausforderung betrifft die Angebotsseite und hebt die Schwierigkeiten bei der Sicherung der Bioenergieversorgung hervor, insbesondere bei flüssigen Biokraftstoffen und in Ländern mit hohem Pro-Kopf-Verbrauch an Bioenergie. Die zweite Herausforderung betrifft die Unstimmigkeiten bei der Definition von "nachhaltiger Bioenergie" zwischen Modellstudien und EU-Politik. Die dritte Herausforderung ist die widersprüchliche Verwendung von Bioenergie auf der Nachfrageseite, für die es in Europa keine klare langfristige Strategie gibt. Um diese Herausforderungen zu bewältigen, könnten künftige Forschungsarbeiten ungenutzte Bioenergiepotenziale mit geringen Umweltauswirkungen untersuchen, um die Versorgungssicherheit zu erhöhen. Die Festlegung einer klaren und harmonisierten Definition von "nachhaltiger Bioenergie" würde die Vermittlung von Modellierungsergebnissen an politische Entscheidungstragende erleichtern. Darüber hinaus wird in diesem Beitrag die flächenunabhängige Alternative einer

"ergänzenden Bioenergie" vorgeschlagen, die alle Konflikte zwischen Land, Nahrungsmitteln und Futtermitteln mit dem ungenutzten Potenzial von Neben- und Reststoffen aus der Land- und Forstwirtschaft sowie aus kommunalen Quellen ausschließt.

Im zweiten Beitrag wird die potenzielle Rolle der ergänzenden Bioenergie auf der Grundlage einer Modellierung der Energiesystemoptimierung (sektorgekoppeltes Energiesystemmodell Euro-Calliope) weiter untersucht. Die Ergebnisse zeigen ein begrenztes zukünftiges Potenzial für Bioenergie aus Nebenquellen in Europa von 2.394-10.342 PJ, was 3-6 mal niedriger ist als andere Schätzungen, die reine Biomasse einschließen. Die Modellierung verschiedener Anwendungsfälle Bioenergie aus Nebenquellen zeigt, dass die vollständige Nutzung dieser zum Ersetzen umstrittener Kernenergie oder flächenintensiver dezidierter Biomasse beitragen könnte, , was möglicherweise die gesellschaftliche Akzeptanz erhöht. Der Einsatz Biomasse aus Nebenquellen als negativer Emissionsquelle in stationären BECCS-Kraftwerken in einem System ohne Kernenergie bietet zusätzliche Klimavorteile. Bleibt die Bioenergie aus Nebenquellen ungenutzt, erhöhen sich die Gesamtsystemkosten geringfügig, aber die landwirtschaftlichen Nährstoffe bleiben erhalten. Diese Studie kommt zu dem Schluss, dass die strategische Nutzung Bioenergie aus Nebenquellen Synergien und Zielkonflikte mit sich bringt und so eine Anleitung für eine kohärentere europäische Bioenergiestrategie bietet.

Der dritte Beitrag bewertet die Zielkonflikte und den Optionsraum zwischen Bioenergie aus Nebenquellen und Kreislaufagrarökologie. Das globale Massenfluss-Nahrungsmittelsystemmodell SOLm modelliert die Verfügbarkeit und die Umweltauswirkungen Bioenergie aus Nebenquellen durch die Modellierung von 190 verschiedenen Kombinationen zukünftiger agrarökologischer Kreislaufstrategien. Die Ergebnisse zeigen einen breit gefächerten Optionsraum für das zukünftige Lebensmittel- und Energiesystem, der eine ähnliche Bandbreite an Bioenergie aus Nebenquellen (60-70 EJ) in verschiedenen Lebensmittelsystemen ermöglicht, einschließlich des Umfangs der ökologischen Landwirtschaft und der Reduzierung von Abfällen und Kraftfutternutzung. Es zeigen sich drei Zielkonflikte zwischen der Nachhaltigkeit des Lebensmittelsystems und der Bereitstellung von Bioenergie aus Nebenquellen. Erstens besteht ein Konflikt zwischen Nährstoffrecycling und negativen Emissionen – die Bereitstellung negativer Emissionen durch den Einsatz von Bioenergie mit Kohlenstoffabscheidung und speicherung kann dazu führen, dass das Lebensmittelsystem aufgrund des erhöhten Risikos von Nährstoffdefiziten nicht mit einem mittleren bis hohen Anteil ökologischer Landwirtschaft vereinbar ist. Zweitens wirkt sich die Verringerung der Futtermittel aus Anbauflächen negativ auf die zusätzliche Bioenergieproduktion aus, je nach Anteil des ökologischen Landbaus. Drittens reduziert die Verringerung der Lebensmittelabfälle die Bereitstellung von Bioenergie als Nebenprodukt. Insgesamt könnten diese ineinandergreifenden Zielkonflikte dazu beitragen, die Energie- und Lebensmittelsysteme zu verbinden und die systematische Rolle der nachhaltigen Bioenergie zu verstehen.

Diese Arbeit ergänzt die Literatur in dreierlei Hinsicht. Empirisch gesehen trägt sie dazu bei, die bisher unklare Definition von "nachhaltiger Bioenergie" zu vereinheitlichen, indem sie die flächenfreie Alternative der "ergänzenden Bioenergie" vorschlägt und ihre strategische

Rolle für die Klimaneutralität sowie die Brücke zwischen Energiewende und Nahrungsmittelnachhaltigkeit identifiziert. Zudem stellt diese Arbeit einen offenen Datensatz über das Potenzial Biomasse aus Nebenquellen zur Verfügung, der über 120 Biomasse-Rohstoffe in nationaler Auflösung für Europa bis zum Jahr 2050 abdeckt. Im Hinblick auf die Modellierung erweitert die Arbeit das sektorgekoppelte europäische Energiesystem-Optimierungsmodell Euro-Calliope um eine detaillierte Darstellung von Bioenergie-Rohstoffen auf nationaler Ebene in Verbindung mit kompatiblen Umwandlungstechnologien. Sie tragen zur Bioenergiemodellierung bei, indem sie freie, offene und reproduzierbare Daten und Modelle anbieten.

Dementsprechend liefert diese Arbeit politische Implikationen sowohl auf europäischer als auch auf globaler Ebene. Für das europäische Energiesystem ergeben sich aus dieser Arbeit Erkenntnisse zur Sektorkopplung, die Entscheidungstragenden im Bereich der Bioenergie helfen, systematische Fragen zu beantworten – zum Beispiel wann, wo und wie welche Bioenergie am besten genutzt werden sollte. Die ermittelten Synergien und Zielkonflikte verschiedener Bioenergieanwendungen können dazu beitragen, die Kohärenz des politischen Rahmens für Bioenergie zu verbessern. Für die globalen Energie- und Nahrungsmittelsysteme wird in dieser Arbeit ein vielfältiger Optionsraum identifiziert, der es Entscheidungstragenden ermöglicht, die potenziellen Auswirkungen verschiedener politischer Maßnahmen auf Wirtschaft, Umwelt und Emissionen zu analysieren. Dieser Optionsraum impliziert auch die Abwägung zwischen einer Verbesserung der Nachhaltigkeit des Lebensmittelsystems und einer Maximierung des zusätzlichen Bioenergiepotenzials für die Energiebereitstellung oder negative Emissionen. Eine höhere Bereitstellung Bioenergie aus Nebenquellen oder zusätzliche negative Emissionen können jedoch durch Nährstoffdefizite die Nachhaltigkeit des Lebensmittelsystems gefährden. Daher sollten die Planung für Nachhaltigkeit im Energiesystem und die Planung für Nachhaltigkeit im Lebensmittelsystem in der politischen Gestaltung eng miteinander abgestimmt werden.

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Contents

1 Introduction

1.1 Motivation and problem statement

The world is heating up while seeking to provide more energy and food sustainably. We have been experiencing the warmest decade and we just witnessed the hottest month ever recorded on Earth in July 2023 (WMO 2023). On the one hand, the extremely warm weather impacts both energy and food systems – e.g., heatwaves boosts power demand while the induced droughts reduce both hydropower potential and crop yields (Nowell 2023). On the other hand, the energy and agriculture sectors collectively contribute to the most global greenhouse gas (GHG) emissions (85%, which is around 41Gt CO_2e in 2020), thus worsening the global warming (World Resources Institute 2023). **The double-edged challenge from both climate adaption and mitigation imposes unprecedented pressure on the energy transition and food sustainability simultaneously.**

One of the major international efforts to combat global warming, the Paris Agreement, set the global warming limit to 2 °C by the end of this century. Many nations correspondingly envision achieving climate neutrality by transforming their energy and food systems. For instance, the European Union (EU) aims to achieve carbon-neutrality by 2050. Meanwhile, the EU Green Deal sets the short-term 2030 targets of renewable energy shares of 42.5% and organic farming shares of 25% (European Commission. Directorate General for Communication. 2021).

Bioenergy, that is the energy recovered from biomass feedstocks, sits in between the energy and food systems as it provides energy sourced from the same resources as our food is sourced from. Moreover, biomass is the only renewable energy source that can occupy land used for feeding people or providing energy, thus linking the energy and food systems. This linkage is however often not duly addressed. The current EU policy, for example, specifies short-term bioenergy targets from the energy side, while the potential impacts of this on the food system is not an explicit topic in the policy agenda (MOUSTAKIDIS 2018). In the long term, there is no clear role of bioenergy in either energy or food policy towards 2050, at least in the case of EU (Wu and Pfenninger 2023). **Although bioenergy bridges energy and food policy, a clear long-term and coherent strategy is yet missing.**

The energy use of biomass, especially dedicated bioenergy crops grown from arable land, is seen critically because of its perceived lack of sustainability and competition with land use for food production (Muscat *et al* 2020). Recent policies have gradually recognized the pitfalls of dedicated bioenergy, especially the hard-to-quantify land uses. There is a stricter trend of bioenergy sustainability criteria, in particular with regards to indirect land-use change emissions (European Parliament 2018). The European Commission amended the first Renewable Energy Directive (RED-I) by guiding the estimation of indirect land-use change emissions from biofuels and capping conventional biofuels and promoting advanced biofuels (Panichelli and Gnansounou 2017, Cansino *et al* 2012). 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 refining bioenergy sustainability, an overarching long-term strategy of bioenergy deployment is missing, especially towards a highly renewable and carbon-neutral future energy system (Mandley *et al* 2020, International Renewable Energy Agency (IRENA) 2018).

Nevertheless, bioenergy is envisioned to play multiple roles in the energy system transition. Over 95% scenarios in the latest IPCC AR6 (the Sixth Assessment Report of the Intergovernmental Panel on Climate Change) deploy BECCS (bioenergy with carbon capture and storage) for reaching the 1.5 or 2℃ target (Byers *et al* 2022). Recent studies have also argued that biomass could supply "the final few percent" of renewable electricity, enhancing the short-term supply-side flexibility thanks to its dispatchable ability (Thrän *et al* 2015a, Kondziella and Bruckner 2016). Meanwhile, it can also supply hard-to-decarbonise sectors such as aviation or shipping in the short term (O'Connell *et al* 2019). Thus, bioenergy is envisioned to play multiple roles among competing energy usages, albeit its contentious availability and sustainability. In other words, **it remains unclear whether we will have enough sustainable bioenergy to fulfil its multiple roles in the energy transition**.

In a nutshell, bioenergy has a unique role in bridging the energy system transition and food system sustainability. Nevertheless, its long-term role in both systems is unclear from the policy side. It is therefore vital and timely to identify the sustainable roles of bioenergy aligning both renewable energy transition and food system compatibility. This thesis aims to model the possible roles of sustainable bioenergy considering both energy and food systems to support a more coherent bioenergy policy framework towards climate-neutrality.

1.2 State of the art and research gaps

This thesis asserts that sustainable bioenergy has a strategic but unclear role in energy transition and in relation to sustainable food systems. To further contextualize this assertion beyond the policy landscape, this section discusses the relevant state-of-the-art literature – namely the possible uses of bioenergy in the energy transition (demand side), and the modelling representation of bioenergy in energy system models in relation to food system models (supply side). Based on what is missing in the current literature, this section then identifies research gaps according to the state-of-the-art, which further leads to the research questions in the subsequent section.

1.2.1 Modelling the multi-sectoral demand for bioenergy.

On the demand side, there are multiple and competing uses of bioenergy feedstocks. As the future energy system approaches 100% renewables, bioenergy can be flexible in balancing fluctuations in weather-driven energy systems supplied by wind, solar, and hydropower (Thrän, 2015; Szarka *et al.,* 2013). From a negative-emissions perspective, bioenergy with carbon capture and storage is the sole renewable energy source that can provide negative emission (Byers *et al* 2022). Currently, bioenergy is mainly used for residential heating and transportation fuels in the case of EU (International Energy Agency 2022). However, most of these versatile uses of bioenergy can be sourced from the same bioenergy feedstocks, e.g., woody or crop residues, thus might cause competition among different sectoral uses of bioenergy.

The current literature has highlighted the potential competing uses of bioenergy feedstocks along the biomass supply chain. Daioglou et al explores the competing uses of biomass for energy and chemicals, focusing on the emission reduction potential (Daioglou *et al* 2015). They use the energy system model TIMER to examine different future scenarios where bioenergy is only allowed in one sector to identify what sectors are the most effective uses of bioenergy. This study emphasizes the effectiveness of bioelectricity in reducing emissions, especially when combined with carbon capture and storage and when a high carbon price is in place (>100/tC). The paper contributes to understanding the competing uses of bioenergy under specific circumstances, such as different land availability and technical improvement.

Nevertheless, the competition among bioenergy uses can also be altered by other non-bioenergy renewable carriers from a sector-coupling perspective, which is underexplored in the modelling literature so far. For instance, hydrogen is envisioned to be a competitor for bioenergy as they can both produce synthetic fuels, especially with the increased electrification and cheaper solar and wind power (Mortensen *et al* 2020). Moreover, the heat electrification and controlled electric vehicle charging can effectively lower the total use of biofuels (Pickering *et al* 2022). Therefore, the competing use of bioenergy remains unclear in a highly renewable energy system that is sector-coupled.

In short, bioenergy can serve multiple demand uses in the energy transition that other renewable energy sources cannot fulfil, among which the competition over limited bioenergy feedstock is highlighted in the literature. However, there is a lack of sector-

coupling perspectives to understand the optimal allocation of bioenergy competing uses, especially when other renewable energy sources become cheaper and more abundant.

1.2.2 Modelling the supply of contentious sustainable bioenergy.

On the supply side, the role of bioenergy is contentious among energy models and unclear between energy and food models. Within the energy modelling literature, the future potential and role of bioenergy exhibit variation across models, primarily stemming from inconsistent modelling assumptions regarding the "sustainable bioenergy supply."

By comparing the bioenergy representation in ten integrated assessment models (IAMs), Daioglou et al find that there is a significant bandwidth of results due to uncertainties in biomass feedstock supply and bioenergy conversion technology deployment (Daioglou *et al* 2020). Similarly, in the case of the EU, Mandley et al find out a wide rage of the future bioenergy supply projections by reviewing recent modelling studies. They identify a broad range of 9 to 25 EJyr-1 of the domestic bioenergy potential by 2050. The variation of bioenergy supply is mainly caused by uncertainties including land-use and surplus availability for agriculture or dedicated energy crops as well as energy crops yield assumptions.

These studies strive to compare the future supply of bioenergy and they both find significant bandwidths of disagreements within the literature. The varied future sustainable bioenergy potential, therefore, presents to be a common challenge in modelling studies. On the one hand, this controversy has led to the exclusion of bioenergy from certain widely cited energy systems modelling studies (Jacobson *et al.,* 2015; Pfenninger and Keirstead, 2015; Jacobson *et al.,* 2017). On the other hand, bioenergy with carbon capture and storage (BECCS) has been modelled as a crucial component to provide negative emission potential. In the most recent Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), over 95% of scenarios utilize BECCS to achieve the targeted global temperature limits of 1.5 or 2 degrees Celsius (Byers *et al.,* 2022). **Despite a general expectation that bioenergy will maintain a role in the energy transition, the nature of this role remains uncertain—whether it will be system-critical and whether it can fulfil such a role in an environmentally sustainable manner is still unclear.**

In addition to the unclear future role of sustainable bioenergy, bioenergy is also heatedly debated especially regarding to its land-use changes that is difficult to be quantified, which is often associated with carbon emissions.

From an emissions standpoint, Searchinger et al shows that the previously neglected indirect land use change can make the presumably carbon-neutral bioenergy footprints highly carbon positive. They find that the embodied greenhouse gas (GHG) emissions associated with bioenergy may surpass those of fossil fuels when converting carbon sinks into energy crop fields (Searchinger et al., 2008). Eric Johnson follows up on this topic and questions the carbon neutrality of bioenergy in his widely acknowledged paper entitled “Goodbye to carbon neutral: Getting biomass footprints right”. This study identifies the flaw in carbon-footprint guidance and proposes to use “carbon-stock change” line item instead. Such a remedy of bioenergy carbon footprint can make the national reporting practice more consistent with UNFCC reporting requirement. However, emissions are not the only contentious aspect associated with bioenergy-induced land-use change.

Besides the questionable emissions, the large-scale deployment of dedicated biomass supply also raises the concerns about potential land-use conflicts, especially in terms of forestry and agriculture. Recognizing the importance of land-use conflicts, there are recent efforts to eliminate the land-use conflicts and to better estimate the future supply of sustainable bioenergy. In the European context, for instance, the dedicated bioenergy crops are projected to constitute approximately 70% of the future energy supply (Ruiz *et al.,* 2015). Although Ruiz et al have modelled different forestry management to eliminate the land-use conflicts between bioenergy and forestry conservation, the potential impacts from the food system are not explored. Such a massive demand for dedicated bioenergy crops likely imposes additional pressure on agricultural land use, nutrients cycles, and other sustainability aspects of food systems.

Meanwhile, there are modelling efforts to explore the role of residual bioenergy to avoid land-use conflicts. Based on the modelling results from eight IAMs, Hanssen et al find that the residue bioenergy might provide a global potential around 55 EJ per year. Residual sources are anticipated to fulfil a substantial portion, ranging from 7% to 50% of the bioenergy demand by 2050 and 2% to 30% by 2100 (Hanssen *et al.,* 2020). Nevertheless, the possible contributions of agricultural residual bioenergy exhibit considerable variability across diverse models and scenarios.

Another recent attempt further eliminates the land-use conflicts by excluding land with significant biodiversity values, as well as by ruling out food and feed crops from sustainable bioenergy potential (Panoutsou 2021). This study assesses the future European bioenergy supply from agriculture, forestry, and waste that are consistent with the latest sustainability criteria in the European Renewable Energy Directive II (MOUSTAKIDIS 2018). Panoutsou 2021 also discusses different possibilities of enhancing bioenergy supply by improving the biomass mobolisaion and research and innovation measures.

All the aforementioned studies have collectively provided a holistic estimation of future sustainable bioenergy potential under different circumstances, contributing to a more coherent supply of sustainable bioenergy. However, these studies fail to capture the impact of future food system changes on bioenergy supply. Instead, the food system is usually simplified as the business-as-usual case without considering its transition towards a more sustainable system – e.g., from a conventional food system to a highly organic one, which can significantly impact the availability of sustainable bioenergy. **Therefore, the supply of sustainable bioenergy in relation to the food system changes is still unclear in the literature.**

1.2.3 Research gaps

The competing demand and contentious supply of sustainable bioenergy creates an opportunity to explore the optimal allocation of limited sustainable bioenergy in the energy transition, especially from a sector-coupling perspective. Beyond the energy transition, bioenergy also bridges the energy and food systems with an unexplored linkage.

Compiling the bioenergy policy status (Section 1.1) and the state-of-the-art literature (Section 1.2.1 and 1.2.3), this thesis identifies the following research gaps that are further linked to research questions presented in the subsequent section:

- **Unclear long-term roles of sustainable bioenergy in the renewable energy system considering its competing end uses and limited supply. (Research Question 1-2)**

- **Unexplored interactions between energy and food systems via bioenergy when the food system also transforms towards sustainability in the future. (Research Question 3)**

1.3 Research questions and contributions

Research questions. The overarching research objective of this thesis is to analyze the possible roles of sustainable bioenergy in the future renewable energy system. Identifying such roles of bioenergy are vital and timely for energy transition given the unclear bioenergy policy and inconsistent modelling assumptions. This thesis addresses the overarching research objective through the three interconnected research questions below.

(1) ***What is impeding the sustainable bioenergy deployment in reality and literature?*** The first and foremost research question is intended to depict the historical and holistic picture of the bioenergy deployment by comparing the literature, models, and policies. It points out what is challenging in the current bioenergy modelling and policy making. To tackle the identified challenges, it leads to the necessity of answering research questions (2) and (3).

(2) ***What roles can sustainable bioenergy play in a fossil-free and carbon neutral energy system?*** The second research question builds on the first question and focuses on the energy system alone. It is intended to identify the unclear future strategic roles of bioenergy among competing end uses while ensuring its sustainable supply in a business-as-usual scenario.

(3) ***What are the option space and trade-offs between energy and food systems while providing sustainable bioenergy?*** The third research question tells the unfinished story of question (2) – what if the future food system changed a lot and thus impacted the sustainable bioenergy provision? What would happen to bioenergy supply in the energy system and the environmental sustainability in the food system? This final question further investigates the role of sustainable bioenergy by integrating the important and unexplored impacts of the food system on the energy system and vice versa.

Synopsis of contributions. The three contributions presented in the thesis answer the aforementioned research questions sequentially and respectively. Here I briefly outline the synopsis of all contributions, focusing on the key findings and their interconnection. Their full versions are available in Sections 2-4. Their contribution to the literature, policy implications, and limitations are further discussed at the end of this thesis in Section 5.

Contribution I (Research question 1) identifies the challenges and opportunities faced by bioenergy in the case of Europe. This contribution untangle this picture from two sides (supply and demand) and three dimensions (historical national deployment, current policy support, and future possible roles) via qualitative literature review and quantitative data analysis. The main challenges include (1) biofuels supply insecurity, (2) inconsistent definitions of “sustainable bioenergy”, (3) and the lack of long-term strategy of competing end uses.

The corresponding opportunities lie in the (1) untapped bioenergy potential with low environmental impacts and high energy density that are not collectively captured by energy models (e.g., animal fats and other by-/co-products). (2) A clear and harmonized definition of “sustainable bioenergy”. (3) More strategies to understand where to best use the limited sustainable bioenergy.

Throughout all these challenges and opportunities, land use is the key issue hampering the sustainable deployment of bioenergy in models and policies. This contribution thus proposes the new concept of “ancillary bioenergy” without land/food/feed conflicts, which takes a step further than the existing inconsistent definition of “sustainable bioenergy” by completely ruling out any dedicated land use for bioenergy.

Contribution II (Research question 2) follows up the newly proposed concept of “ancillary bioenergy” and examines its strategic roles in a carbon-neutral and fossil-free European energy system. Such strategic roles are now missing in the EU long-term policy and are contested in the literature. This contribution fills in the gap through first investigating the future potential of ancillary bioenergy from agricultural, forestry, and municipal sources by combining the food system model SOLm and existing literature. Then I further model where and when to best use which ancillary bioenergy feedstock by soft-coupling the energy system optimization model Euro-Calliope. This contribution explores alternative futures with/without additional energy infrastructure, nuclear, bioenergy with carbon capture and storage, and dedicated energy crops.

Sector-wise, industry and transport appear to be the most sensible sectors for utilizing bioenergy with or without additional infrastructure (e.g., gas storage or biomass distribution network). Region-wise, the modelling results compare the attractiveness between biomass and hydrogen in producing different synthetic fuels (e.g., hydrogen is more economically sensible in wind-abundant costal countries such as the UK, Iceland, and Portugal in producing all synthetic fuels).

Finally, I conclude with the synergies and trade-offs among different strategic roles of ancillary bioenergy. Fully utilizing 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 ancillary bioenergy 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). This contribution provides modelling-based guidelines for a more flexible and coherent bioenergy policy.

(3) Contribution II (Research question 3) builds on Contribution II and further dives into the interaction between the energy and food systems via ancillary bioenergy. Such an interaction is vital for policy making yet unexplored in the literature. Both the energy and food systems have ambitious future goals, but they might clash with each other. The EU, for example, aims to achieve 25% organic farming by 2030 and carbon neutrality by 2050. The former requires more organic nutrient supply (including recycling residual biomass), while the later foresees considerable negative emissions from bioenergy that might consume massive nutrients without recycling. It remains unknow to which extent the energy and food system can have synergies or trade-offs while realizing their separate goals.

This contribution thus investigates the availability and environmental impacts of ancillary bioenergy from agricultural sources when varying future agroecological strategies using the global food-system model SOLm. On the one hand, it is possible to source a similar range of ancillary bioenergy (the option space within ±10% of the IPCC AR6 illustrative pathways median bioenergy supply) even from very different food systems (with 25% to 75% organic agriculture and various levels of waste and concentrate feeding reduction). On the other hand, there are embedded trade-offs within the option space, i.e., (1) negative emissions desired in the energy system come at the cost of nutrient deficits and less compatibility with sustainable agriculture (here exemplified with organic farming); (2) reducing feed from croplands increases the ancillary bioenergy production with low shares of organic agriculture and reduces it for high shares; (3) food waste reduction reduces ancillary bioenergy provision. In short, the findings illustrate how it is crucial to align sustainable energy system planning with sustainable food system strategies.

2 Contribution I: Challenges and opportunities for bioenergy in Europe

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Abstract

Bioenergy is currently a major renewable energy source in Europe but faces an unclear future because of conflicting modelling results and the lack of long-term policy. This paper identifies three challenges and potential opportunities by analysing bioenergy's historical national deployment, current policy support, and possible future roles in Europe. The first challenge is on the supply side. Calculating the supply-consumption dynamics and import dependency of EU bioenergy, we find that the security of bioenergy supply is challenging for liquid biofuels and those countries with the highest per-capita bioenergy consumption in Europe. Second, the definition of "sustainable bioenergy" in modelling studies is sometimes inconsistent with how EU policies label it. Third, on the demand side, there are unique but competing uses for bioenergy without a clear long-term strategy in Europe. We conclude with three opportunities to tackle these challenges for future research. First, utilising the untapped bioenergy potential with low environmental impacts could improve supply security. A clear and harmonised definition of "sustainable bioenergy" could better convey modelling results to policymaking. Finally, understanding where best to use limited sustainable bioenergy supply through sector-coupled energy system models can provide direction for a clearer EU bioenergy strategy towards 2050.

2.1 Introduction

Bioenergy, that is, the use of biomass feedstocks to supply energy, has become a growing renewable energy source in Europe. It is used not only in heating and cooling (increasing from 66% to 90% of the total renewable heat from 1990 to 2018) but also for bio-blending transportation fuels and subsidised bioelectricity (Banja *et al* 2019, International Energy Agency 2021). On the one hand, bioenergy is foreseen to play a role in the future EU energy system, including several 100% renewables scenarios in 2050 and the archetypal scenarios of IPCC SR1.5 (Masson-Delmotte *et al* 2018, Bogdanov *et al* 2019, Cornelissen *et al* 2012). Recent studies have also argued that biomass could supply “the final few percent” of renewable electricity, enhancing the short-term supply-side flexibility thanks to its dispatchable ability (Thrän *et al* 2015a, Kondziella and Bruckner 2016). Meanwhile, EU policy envisioned it to play a role in increasing EU energy self-sufficiency (European Commission 2018). With the recent surging natural gas prices in Europe (Davies 2022), domestic biogas could be a potential substitute with higher resilience to international trade shocks.

On the other hand, recent EU policies are ruling out biomass that was once “sustainable” by updating the sustainability criteria and phasing out subsidies. The latest EU Renewable Energy Directive II certification scheme introduces stricter sustainability criteria on all kinds of biomass by 2030 (European Commission 2019). Several European countries are also phasing out some national support for bioenergy (e.g., The Netherlands stopped subsidising biomass-fired power stations, and Switzerland banned transportation biofuel from mineral oil tax exemption as of 2020 (IEA Bioenergy 2018, DutchNewsNl 2020)). Naylor and Higgins (Naylor and Higgins 2017) argued that the rapid development of biodiesel would not have occurred without strong policy support, agricultural subsidies, and trade policies. Thus, the phased-out subsidies and stricter sustainability criteria may reduce bioenergy use in the near term, especially in transportation.

Moreover, bioenergy is hotly contested because of the questionable carbon neutrality and sustainability. Emission-wise, its embodied GHG emissions might be higher than those of fossil fuels when converting carbon sink into energy crops fields (Searchinger *et al* 2008). In addition, dedicated biomass can cause potential land-use conflicts between agriculture, forestry, and ecosystem restoration (Johnson 2009, Arevalo *et al* 2014, Söderberg and Eckerberg 2013). Hence, the contentious bioenergy has been excluded from some of the widely-cited energy systems modelling studies (Jacobson *et al* 2015, Pfenninger and Keirstead 2015, Jacobson *et al* 2017). While there is a general expectation that bioenergy will continue to play some role in the EU’s energy system, it is unclear whether that role will be a system-critical one and whether it can fulfil that role in an environmentally sustainable manner. By “environmentally sustainable manner”, we refer to the sustainability of embodied environmental impacts beyond just carbon neutrality, which are potentially inconsistent among models and policies (Wu *et al* 2023).For instance, there are potential land/food/feed conflicts when sourcing dedicated biomass crops (Muscat *et al* 2020) and possible soil erosion and nutrient losses when supplying energy crops from marginal land (Verheijen *et al* 2009).

Current literature has generally explored the role of bioenergy from only one of these concerns (e.g., political frameworks (Banja *et al* 2019), economics and markets (Alsaleh *et al* 2017, Alsaleh and Abdul-Rahim 2018), techno-economic modelling (Mandley *et al* 2020, Welfle *et al* 2020), or the environment and economics (Baležentis *et al* 2019)). However, few studies have investigated the interaction between two or more concerns providing more comprehensive and interdisciplinary insights. Moreover, the challenges and opportunities of EU bioenergy development may lie beyond these isolated aspects, shaped by interactions among historical deployment, current policy, and possibilities identified in modelling studies.

This paper intends to provide a more holistic picture of the status quo and potential of bioenergy in Europe, with a focus on these interactions. We consider not only the whole European region but also the national heterogeneity whenever necessary and possible. Although previous studies mostly investigated bioenergy deployment either on the whole EU level (Mandley *et al* 2020) or on single countries (Adams *et al* 2011, McDowall *et al* 2012, Szarka *et al* 2017), an EU-wide national breakdown is necessary. Because natural resource endowments, historical energy system structures, policies, and support schemes vary across member states. Such national heterogeneity may manifest different challenges and opportunities for bioenergy in Europe, hence providing local policymakers with varied implications.

Here we perform such an assessment to examine EU bioenergy from three areas – first, the spatiotemporal trends in terms of supply-consumption dynamics and energy security; second, EU level policies and national support schemes; third, unique roles for bioenergy discussed in the literature and modelled in decarbonisation scenarios for 2050. We conclude by synthesising challenges and opportunities for bioenergy in a fully renewable and sustainable European energy system.

2.2 Data and Methods

Here we adopt the International Energy Agency's (IEA) classification and dataset of biofuels and waste for energy – that is, world energy balance datasets, one widely-used database providing authoritative and up-to-date renewable energy statistics every year (International Energy Agency 2021). It includes major biofuels and waste for bioenergy, as shown in Figure 1, of which products are the finest level of available bioenergy data (e.g., solid biofuels, biogases, charcoal, industrial waste, etc.). Note that we do not intend to provide a detailed classification of all possible biofuels/biomass but to include major carriers with consistent European statistics as much as possible.

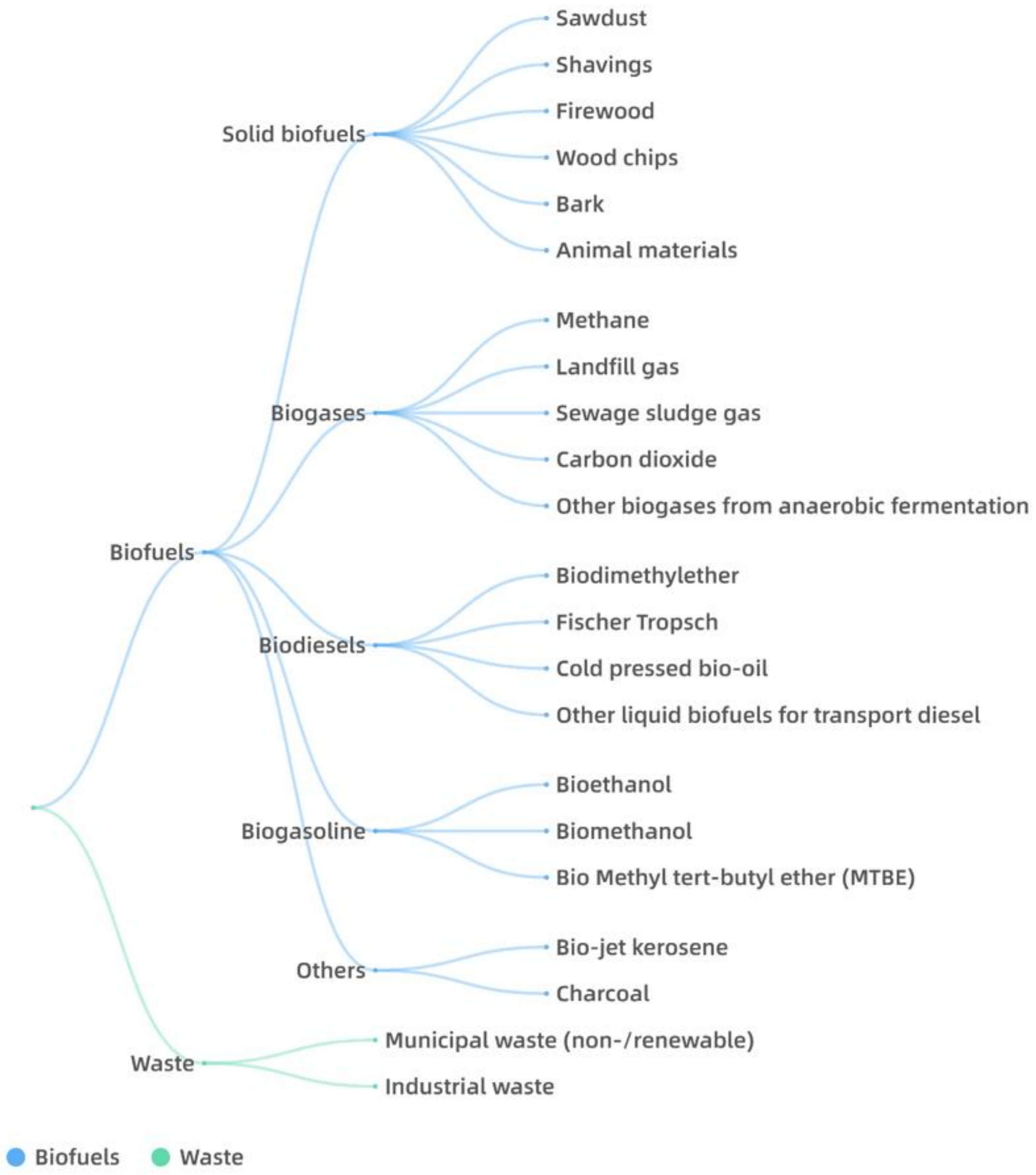

Figure 1: Classification of major bioenergy products and feedstock adopted from the IEA (Anon 2020a)

For the studied region and time span, we consider the EU-27 and the UK, excluding their overseas regions, and the timeframe from 2000 to 2018 (including 2019 and 2020 when available). 2018 is the latest year with complete records of energy balance tables from the International Energy Agency (IEA) (International Energy Agency 2021), which is our primary data source for exploring the spatiotemporal trends at the national level.

To analyse bioenergy policies and calculate national support schemes (Table 4), we draw on mixed qualitative and quantitative data sources. They include RES LEGAL Europe database (Anon 2020b) for feed-in and premium tariffs, and the International Energy Agency Bioenergy's national annual reports (IEA Bioenergy 2018) for bioenergy support levels and biofuel blending quotas. To calculate the shares of national subsidised bioelectricity (Table

2 and Figure 7), we extract subsidy data from the Status Review of Renewable Support Schemes in Europe from 2009 to 2017 by the Council of European Energy Regulators (CEER) (Council of European Energy Regulators (CEER) 2018), which is the only available open data on bioenergy subsidies. Considering the data availability of European bioenergy support schemes, we adopt the four kinds of support schemes from the CEER (Council of European Energy Regulators (CEER) 2018), including feed-in tariffs (FIT), feed-in premiums (FIP, sometimes also premium tariff, PT), green certificates (GC), and investment grants. A feed-in tariff is a fixed-price design regulating electricity prices through a given amount of per kWh payment to the generators depending on different technologies (irrespective of the wholesale prices), while a feed-in premium adds a bonus to the wholesale market price received by producers (Jenner *et al* 2013). Green certificates are tradable commodities generated with certain renewable electricity providers and may have minimum prices.

Modelling-wise, we select three distinct Shared Socioeconomic Pathways (SSPs) scenarios to compare how varied transition pathways would alter the roles for bioenergy within Europe. Specifically, we compare the sustainability, middle-of-the-road, and fossil-fuelled development SSPs and how their bioenergy supply and total primary energy supply in Europe vary in 2050. The modelling results are extracted from the IAMC 1.5°C Scenario Explorer 2.0 (Huppmann *et al* 2019) coming primarily from established integrated assessment models. We use the Shared Socioeconomic Pathways (SSPs) here also because they are among the few 2050 scenarios providing specific bioenergy data and Europe-wide results. All the data and the code for processing, analysis, and visualisations, are available on GitHub (see Data availability section).

2.3 Results

2.3.1 Historical deployment of bioenergy

2.3.1.1 Supply-consumption dynamics and import dependency

EU bioenergy has seen contrasting trends of increasing total supply volume and decreasing shares in total renewable supply since 2011. See the trends of EU bioenergy supply, consumption, and shares from 2000 to 2018 in Figure 2 (a). Meanwhile, total bioenergy final consumption has been stabilising, thus creating a growing “gap” between its total energy supply and total final consumption. This “gap” is primarily the bioenergy used for “Transformation processes” – converting primary biomass feedstocks into secondary/intermediate energy carriers (e.g., intermediate heat from CHP plants). In 2018, the transformation processes at heat, electricity, or CHP plants in Europe used over 2700 TJ bioenergy (top middle in (c), Figure 2), which are subtracted from the “total final consumption” in the world energy balances databases (International Energy Agency 2021).

The (b) and (c) of Figure 2 further illustrate the change of bioenergy supply and consumption flows by sectors. Product-wise, primary solid biofuels have remained the dominant source of bioenergy in all EU countries with a growing supply volume but with a falling share of overall bioenergy use (from 81% of all bioenergy in 2000 to 60% in 2017). Other products have growing shares, with biogas rising from 3% to 10% and biodiesel from 1% to 11%

during the studied period. The waste sector was minor and stable, constituting around 15% of the total supply, with a steadily decreasing share of industrial waste from 3.5% to 2.3%. Though dominated by primary solid biofuels, the EU's bioenergy supply structure has become more diversified. The majority of biofuels are domestically produced, while the rise of biodiesel has been primarily driven by imports, of which over one-third are from outside the EU (Figure 3). The EU has shifted from a domestic bioeconomy in 2000 to one heavily depending on sourcing liquid biofuels from overseas. The import dependency for biodiesels and biogasoline has risen from close to 0% to over 60% in less than 20 years (Figure 3), though these are primarily used for blending with and thus displacing imported fossil transport fuels.

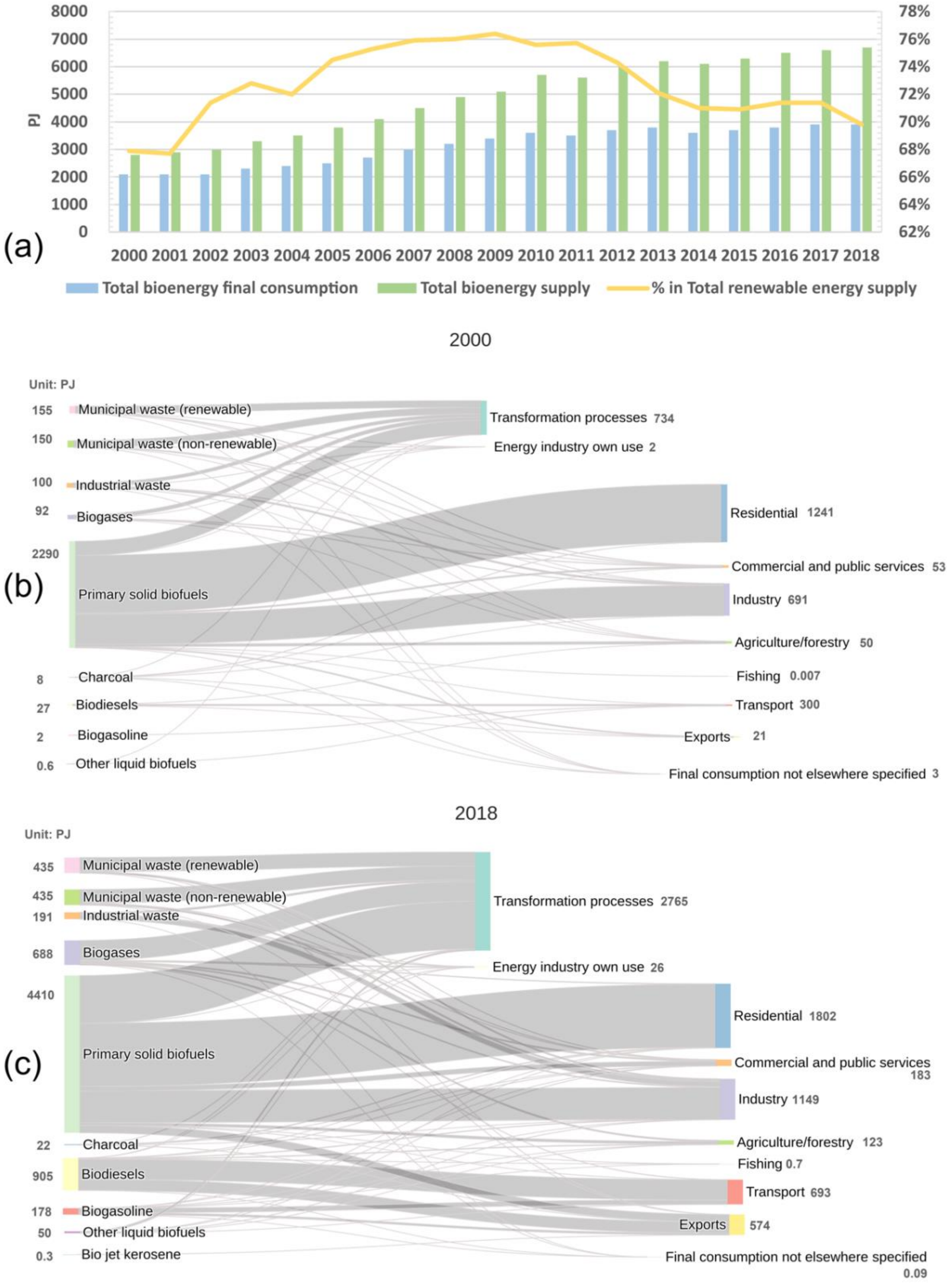

Figure 2. Overall EU bioenergy deployment. (a) Trends of EU bioenergy total consumption, supply, and its shares in renewables. (b) 2000 Energy flows of bioenergy supply, intermediates, and end-use sectors. (c) 2018 Energy flows of bioenergy supply, intermediates, and end-use sectors. 2018 is the last year with complete data records. Sankey diagrams (b) and (c) are in the same unit (PJ). To enable direct comparison between (b) 2000 and (c) 2018, the width of the coloured bars in the Sankey diagrams are in proportion to the energy flow.

On the consumption side, mirroring the rise of biogas and biodiesel, the share of residential (i.e., households) consumption dropped from 58% to 41% within this period. Driven by the legally binding EU-wide target of 10% renewable energy used for transportation (or even higher at the national scale, e.g., 20% in Finland), biofuels have had growing importance for the transportation sector, with the share of transportation in consumption dramatically rising from 1.5% to 14.7% by 2017. However, as most of the liquid fuels for transportation are imported – about 97% of the crude was imported in the EU in 2019 (International Energy Agency 2021) – transport biofuels currently replace one source of import dependency (imported fossil fuels) with another (imported biofuels). The potential of the clean energy transition to reduce import dependency thus remains unaddressed (Section 3.2).

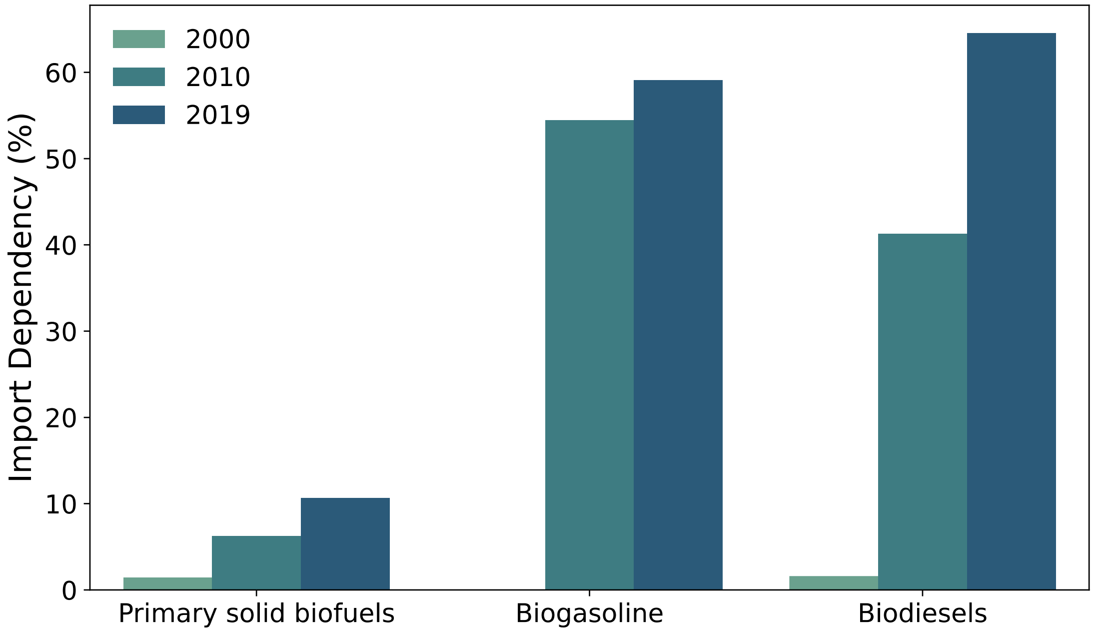

Figure 3. Changes in import dependency for the main biofuels (import dependency = imports/total energy supply per biofuel type).

2.3.1.2 Per-capita differences across countries

Sweden is notable for the highest proportion of bioenergy used for industry. In absolute terms, France and Sweden were the largest bioenergy supply countries in 2000, but were surpassed by Germany by 2017. However, considering the large population in Germany, bioenergy consumption per capita presents a rather different picture. As shown in Figure 4, the biomass used for power, heating, and transport per capita differs substantially across EU countries.

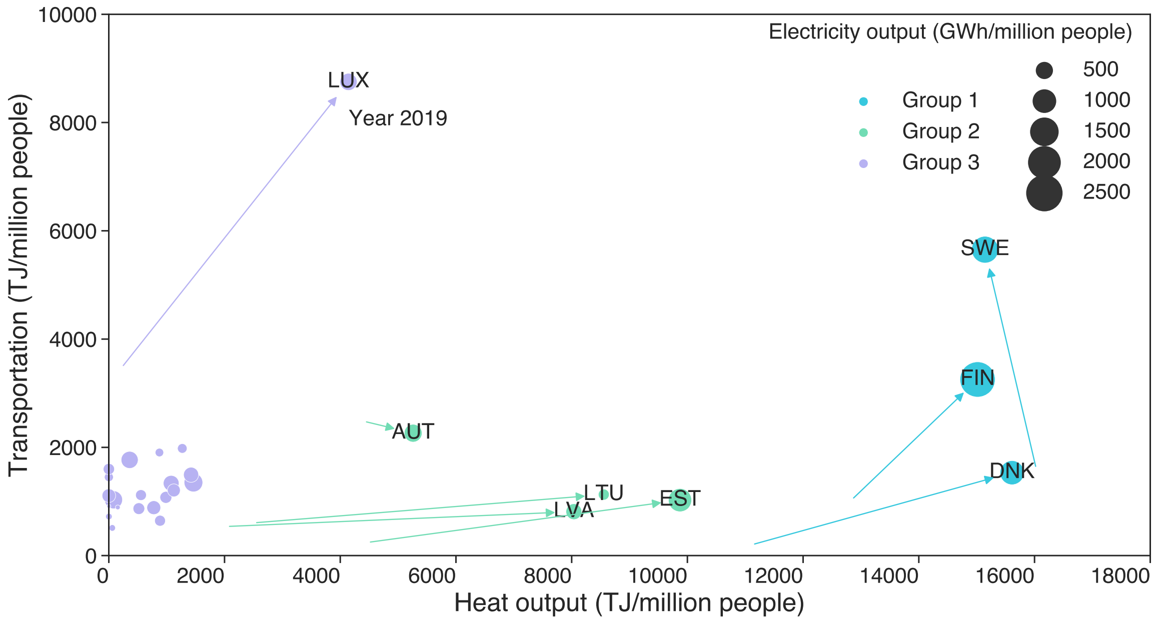

Figure 4. Changes in bioenergy per-capita consumption (transport, heat output, and electricity output per million people) from 2000 to 2019.

Three groups of nations stand out, of which the leading group consists of Finland, Sweden, and Denmark (Group 1). This group is characterised by high per-capita levels of bioenergy consumption (especially for electricity and heat) throughout the whole period. Though the per-capita levels of heat output in group 1 countries initially varied, they have converged by 2019. Group 2 consists of Estonia, Latvia, Austria, and Lithuania with higher per-capita heat from biomass. They start within the general mass of EU countries in 2000 but move towards Group 1 countries by 2019.

The remaining EU countries constitute Group 3, showing an overall low level of per-capita bioenergy consumption in all three sectors. However, one outlier is Luxemburg, where the per-capita biofuels for transportation have soared – it is now the number one country in the EU on that metric, despite its merely average biomass use for electricity and heat. This unique phenomenon is partly because the international work commuters contribute to transportation demand but not to the population or residential statistics.

2.3.2 Policy and support schemes for bioenergy

2.3.2.1 EU policy: stricter sustainability criteria yet unclear role of bioenergy

Overall, most bioenergy-related EU policies focus on the stricter sustainability criteria of bioenergy and mandate its growing targeted share in the transport sector or together with other renewables in the gross final energy consumption. Considering these two aspects, we list the major policies in chronological order along with the changing share of bioenergy products (Figure 5) and then compare these policies in Table 1.

In 2003, the European Commission (EC) issued the EU Directive on Biofuels, focusing on a first blending target (5.75% of biofuels by 2010) for the transportation sector (European Parliament 2003). Furthermore, to encourage the widespread use of bioenergy not only for transport but also for heating and electricity, the Biomass Action Plan (European Commission, 2005) first emphasised the importance of the bioenergy industry (Klink and Langniss 2006), specifying the general sustainability criteria of biofuels, including GHG reduction and biodiversity (Table 1). The EU strategy for biofuels issued in the following year further complements the Biomass Action Plan by a threefold objective with seven strategic policy areas –“further promotion of biofuels in the EU and developing countries, preparation for the large-scale use of biofuels, and heightened cooperation with developing countries in the sustainable production of biofuels” (European Commission 2005).

These earlier policies paved the way for the EU Renewable Energy Directive (RED-1) issued in 2009. RED-1 complemented the former plans with overall mandated goals, i.e., 20% renewables in the gross final energy consumption and 10% renewables in transport by 2020. This latter target is essentially met by transport biofuels alone (Panichelli and Gnansounou 2017). The directive further committed every country to set their annual breakdown of bioenergy shares by 2020 in the National Renewable Energy Action Plans (NREAPs) (Directive 2009). However, the RED-1 did not include life-cycle GHG emissions of biofuels caused by indirect land-use change, which could be even higher than those of fossil fuels when natural ecosystems with higher carbon stock are converted into agricultural land for energy crops (Searchinger *et al* 2008). Recognising this critical missing concern, the European Commission amended the RED-1 in 2012 by a legislative proposal that includes guidelines to estimate indirect land-use change emissions from biofuels (ANNEX V) (European Commission 1998, p 70) as well as capping conventional biofuels and promoting advanced biofuels (Panichelli and Gnansounou 2017, Cansino *et al* 2012).

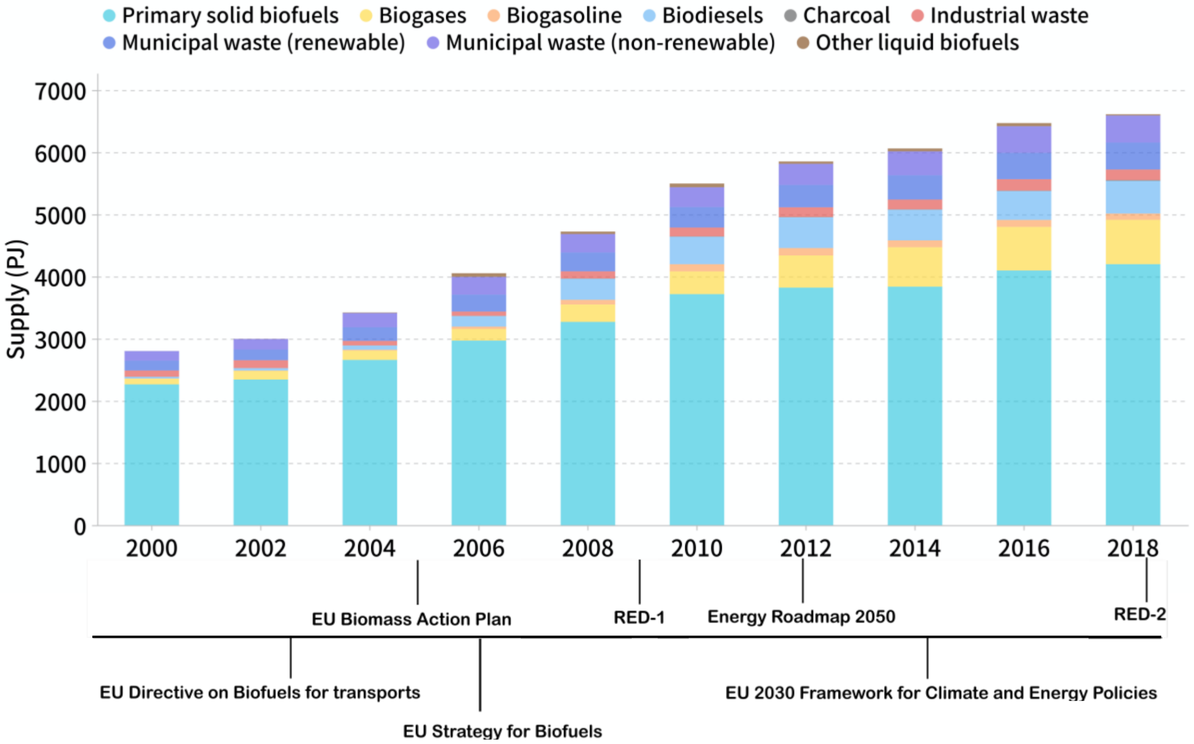

Figure 5. Timeline of major policies and the supply of bioenergy products in the EU from 2000 to 2018.

The Energy Roadmap 2050 (Union 2012) and EU 2030 Framework for Climate and Energy Policies (European Commission 2014) further proposed to increase the overall EU target of renewable shares and GHG reduction. However, no specific national bioenergy target has been suggested beyond 2020 or towards 2050. Most recently, the EU Renewable Energy Directive II recast (RED-2) sets an increased target of 32% renewables in the gross final energy consumption, along with a minimum goal of 14% renewables in transportation by 2050 (advanced biofuels double count and should reach 3.5%) (European Parliament 2018, International Renewable Energy Agency (IRENA) 2018). Furthermore, the sustainability framework of bioenergy is reinforced in RED-2 with (1) detailed GHG criteria and calculation rules for solid biofuels and biogas, (2) new sustainability criteria for forestry biomass, as well as (3) a new approach limiting biofuels with high indirect-land-use-change risk. For instance, palm oil, a traditional source of biodiesel, has more than 40% expansion on high carbon stock land, thus classified as a high indirect-land-use-change-risk biofuel feedstock (Dusser 2019). Therefore, it is likely that the supply of biofuels, especially the traditional biofuels from energy crops and forests, will see a decrease in response to the EU's stricter sustainability criteria.

Table 1. Development of major bioenergy-related policies and directives in the EU.

Policy/Directive	Year	Target (if applicable)	Sustainability criteria for bioenergy
EU Directive on Biofuels for Transport (European Parliament 2003)	2003	5.75% of biofuels in transport by 2010	Not specified
EU Biomass Action Plan (European Commission 2005)	2005	Not specified	Saving 35% GHG emissions compared to fossil fuels; Cannot be sourced from areas with high carbon stock & biodiversity
EU Strategy for Biofuels (European Commission 2006)	2006	Prioritising the role of biofuels in transportation by a threefold objective with seven policies areas	Not specified
EU Renewable Energy Directive (RED-1) (Directive 2009)	2009	20% renewables in the EU gross final energy consumption and 10% in transport by 2020 (Breakdown of bioenergy stipulated by every country in NREAPs)	Rising to 50% of GHG savings and 60% for new plants from 2018 and onwards (European Commission 1998, p 70)
Energy Roadmap 2050 (Union 2012)	2012	Bioenergy should contribute 22–28% of the	Not specified

Policy/Directive	Year	Target (if applicable)	Sustainability criteria for bioenergy
		EU gross inland energy consumption in 2050	
EU 2030 Framework for Climate and Energy Policies (European Commission 2014)	2014	A collective delivery and commitment to a 40% reduction in GHG emissions by 2030 (no bioenergy-specific target)	Not specified
EU Renewable Energy Directive II recast (RED-2) (European Parliament 2018)	2018	Increased shares of renewables to 32% and a minimum of 14% within the transport (3.5% of advanced biofuels) by 2030	A new criteria limiting biofuels with high indirect-land-use-change risk, e.g., Oil palm (MOUSTAKIDIS 2018)
2030 Climate Target Plan (European Commission 2020)	2020	A more ambitious target of 55% GHG emissions reduction by 2030 and carbon-neutrality by 2050 (no bioenergy-specific target)	Not specified
REPowerEU Plan (European Commision 2022)	2022	A revised target of 45% of renewable energy in power, industry, buildings and transport by 2030	Not specified

Contrary to RED-1, RED-2 generally commits nations to establish support schemes for expanding renewables in an “open, transparent, competitive, non-discriminatory, and cost-effective” way (European Parliament 2018), which does not specify what should happen with regards to bioenergy. The NREAPs and RED-1 terminated in 2021, and the new RED-2 is to come into force with no national binding targets or specific breakdown of bioenergy. Moreover, the EU is stepping up the 2030 and 2050 climate ambitions without clear policy targets on how to deploy bioenergy. The latest EU 2030 Climate Target Plan aims to cut GHG emissions by at least 55% by 2030 and become the first climate-neutral continent by 2050 (European Commission 2020). The following REPowerEU Plan further increases the renewable target to 45% by 2030 to rapidly reduce EU’s dependence on Russian fossil fuels (European Commision 2022). Neither of these include a bioenergy-specific target.

2.3.2.2 Low national subsidies in high per-capita bioenergy countries

Motivated by the collective EU targets, member states have set up different national support schemes for bioenergy used in power and heating sectors and mandated biofuel blending targets for transport. For the power sector, feed-in tariffs and premium tariffs are the primary support schemes encouraging biomass for electricity (Figure 6 and Table 4). The support schemes shown in Figure 6 represent financial support to industry involved in bioenergy, especially feed-in tariffs and premium to incentivise the use of agricultural waste, algae, and industrial biomass waste for bioenergy. All the subsidised bioelectricity is put into practical use in a sense that it can only receive subsidies after being fed into grids, i.e., paid by an electricity supplier or utility. After integrating into the power grid, all the renewable electricity is mixed without specifying the share from biomass. Therefore, as long as renewable/biomass electricity is subsidised (all countries in Table 2), it is part of the utility/supplier power grid.

Notably, the leading countries in terms of per capita bioenergy consumption (Group 1 identified in section 3.1) had low levels of unit support, which were 19.49 €/MWh (Finland), 12.80 €/MWh (Sweden), and 35.89 €/MWh (Denmark) in 2017 – they have been utilising the highest per capita level of bioenergy at the cost of low unit supports.

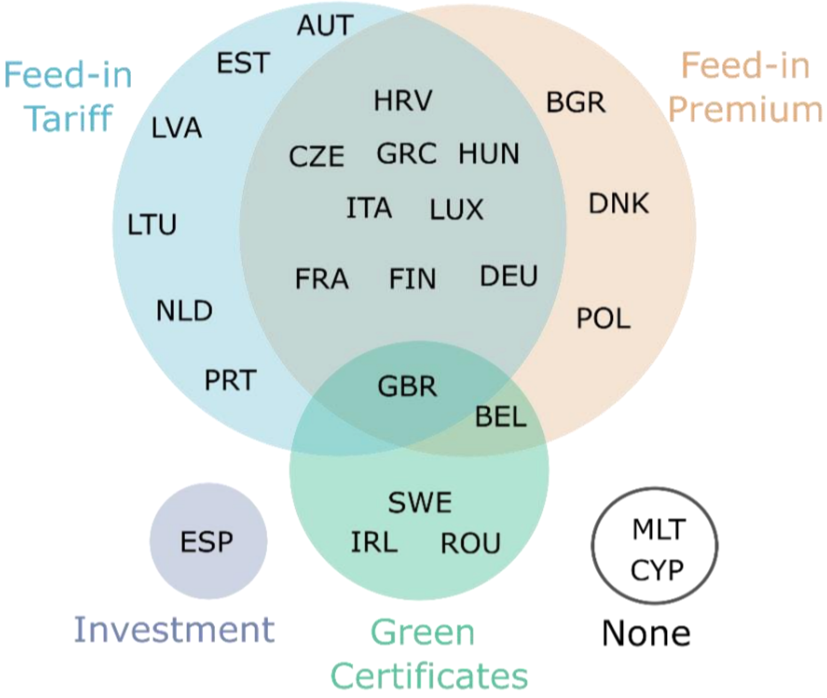

Figure 6. Support schemes for bioelectricity across the EU (2017).

As a consequence of this variety of supporting schemes, the subsidised bioelectricity share ranges from 2% (France, Lithuania, Portugal, and Romania) to over 30% (Ireland, UK) in 2017 (Figure 5 and Table 3). Overall, most member states have displayed an increasing trend of bioelectricity subsidies, with Ireland (35%), the UK (33%), and Germany (24%) having the highest shares of supported bioelectricity output in 2017, indicating the dominant role of support schemes for fostering the use of biomass in the power sector in these countries. Meanwhile, subsidies in nine countries declined, including Austria, Cyprus, Spain, Estonia, France, the Netherlands, Poland, Portugal, and Sweden. Sweden, Portugal, and Estonia, in particular, have seen a sharp drop in supported share by around half in the studied period. Sweden has one of the highest per-capita consumptions of bioenergy in the

EU, yet with low levels of financial support – both the shares of subsidised electricity and unit support cost are low.

Though there are fewer direct support schemes for biomass used in the heating sector, it may receive subsidies for CHP (combined heat and power) plants jointly with bioelectricity or gain connection priority in some countries (Council of European Energy Regulators (CEER) 2018). In addition to support schemes for CHP and district heating, other instruments for energy recovered from waste are also used. For Sweden, the taxation and charge for energy recovery from residual waste are increasing (e.g., SEK 75/tonne in 2020, SEK 100/tonne in 2021, to increase further) (Avfall Sverige 2020). As a result, however, the country recovers more energy from waste than any other European nation (3 MWh/tonne in 2019) (Avfall Sverige 2020).

Unlike in the power and heating sectors, biofuels for transportation have been indirectly mandated by the EU through the minimum of 10% renewables consumed by the transport sector in every Member State in 2020. Correspondingly, countries have adopted different minimum mandates for biofuel quotas (Table 3), which is another reason why the end-use of bioenergy has been soaring in the transport sector, apart from the general EU-wide target.

Table 2. Shares of subsidised bioelectricity in the EU. ("-" represents unavailable data. Author's calculation by compiling the annual Status Review of Renewable Support Schemes in Europe (Council of European Energy Regulators (CEER) 2018). 2012 is the earliest year, and 2017 is the latest update). 1 Group 1 and 2 Group 2 are countries clusters identified in section 3.1.

Country	2012	2017	Country	2012	2017
AUT[2]	4.00%	3.62%	HUN	2.61%	11.80%
BEL	12.00%	-	IRL	10.58%	34.61%
CYP	-	11.47%	ITA	10.23%	18.65%
CZE	5.46%	8.76%	LTU[2]	1.51%	2.21%
DEU	11.16%	23.56%	LUX	-	13.33%
DNK[1]	11.67%	14.68%	LVA[2]	-	3.06%
ESP	6.93%	5.21%	NLD	10.69%	9.59%
EST[2]	7.41%	4.43%	POL	8.85%	4.52%
FIN[1]	2.07%	4.18%	PRT	3.71%	2.71%
FRA	2.86%	2.27%	ROU	0.34%	2.02%
GBR	17.09%	33.36%	SVN	-	3.37%
GRC	1.38%	2.28%	SWE[1]	8.68%	4.00%
HRV	0.42%	3.95%			

The biofuels quota may slightly vary depending on the blending fuel type (e.g., 5% for E5, 10% for E10, and 7% for diesel in Belgium). Although most EU countries set blending targets around 10%, Finland has the highest goals of 20% by 2020 and 30% by 2030. As transport has been the second-largest CO2 emitter in Finland (2016), this could play a role in helping reduce CO2 emission outside the EU Emissions Trading Scheme (ETS) with cost-effective biofuels supply and ambitious quota obligations – but whether transport fuel blending is the most useful use of limited biofuel is nevertheless open question, to which we want to start turning our attention next.

Table 3. Levels of bioenergy support schemes in different sectors in the EU.

Country	Feed-in tariff for electricity (€ct per kWh)	Premium tariff for electricity (€ct per kWh)	Unit support level in 2017 (€ct per kWh)	Biofuel quota for transportation[1]
AUT	4.66 – 21.78		10.80	8.45%

Country	**Feed-in tariff for electricity (€ct per kWh)**	**Premium tariff for electricity (€ct per kWh)**	**Unit support level in 2017 (€ct per kWh)**	**Biofuel quota for transportation[1]**
BEL				5.00 – 10.00%
BGR				9.00%
HRV			9.95	10.05%
CYP			13.70	
CZE	5.60 – 13.00	7.20 – 11.50	10.50	4.10 – 6.00%
DNK		3.50 – 5.30	3.59	5.75%
EST			2.10	5.00%
FIN		8.35 – 13.35	1.95	20.00%
FRA	12.00 – 17.50		10.10	8.00 – 10.00%
DEU	5.71 – 13.32	5.66 – 23.14	11.83	6.30%
GRC	14.80 – 19.80	1.29 – 2.25	7.85	7.00%
HUN	4.04 – 11.05	9.89	2.13	6.4%
IRL	8.96 – 14.70		5.37	11.11%
ITA			15.40	6.50%
LVA			12.28	
LTU		1.11 – 1.34	5.66	
LUX	11.70 – 16.20	1.51 – 1.90	10.10	5.85%
MLT			10.80	10.00%
NLD		4.6 – 9.2		7.75%
POL				8.50%
PRT	10.20 – 11.90		9.95	10.00%
ROU			13.70	6.50%

Country	Feed-in tariff for electricity (€ct per kWh)	Premium tariff for electricity (€ct per kWh)	Unit support level in 2017 (€ct per kWh)	Biofuel quota for transportation[1]
SVK	7.03 – 9.22		10.50	8.20%
SVN			3.59	7.50%
ESP			2.10	8.50%
SWE			1.95	13.80%[2]
GBR	1.97 – 5.58		10.10	10.64%

[1] For countries with different biofuel quotas throughout the time, the latest one has been listed here if available (i.e., the target for 2020)

[2] Sweden no longer divides the renewable energy target into further targets per sector, so the projection in the NREAP is displayed instead.

2.3.3 Possible roles of bioenergy from modelling studies

2.3.3.1 Varied modelling assumptions of sustainable bioenergy supply

On the supply side, both the future potential and share of bioenergy varies among scenarios due to inconsistent modelling assumptions of "sustainable bioenergy". But one common consistency is that the stricter sustainability, the lower bioenergy potential/deployment. For instance, the Shared Socioeconomic Pathways scenarios present three future narratives – SSP1 (sustainable development with well-managed land systems and limited societal acceptability for Bioenergy with Carbon Capture and Storage, BECCS), SSP2 (a middle-of-the-road scenario where it follows historical societal and technological development), SSP5 (fossil-fuelled development with intensive resource and energy consumption mitigated through BECCS). Comparing the three distinct pathways from six models (Figure 7), the shares of bioenergy in primary energy supply relate to whether carbon capture and storage is restricted (SSP1) or intensively deployed (SSP5).

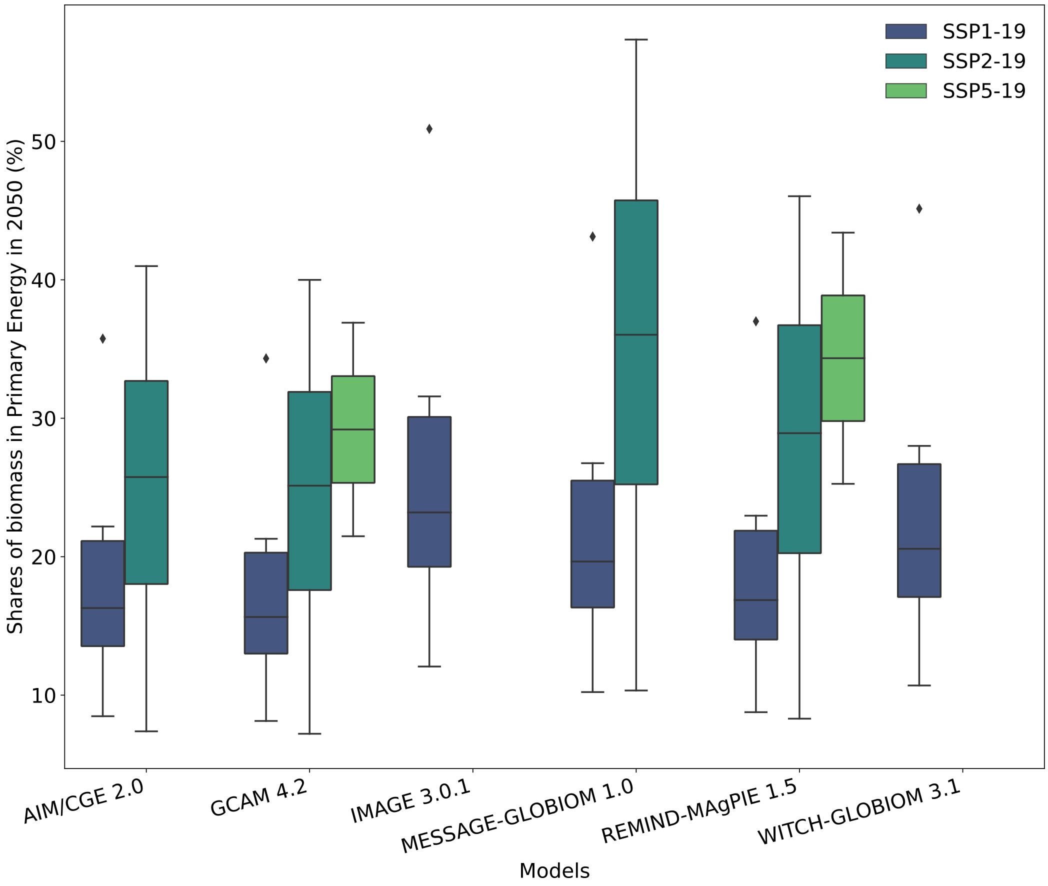

Figure 7. Different shares of biomass in primary energy in 2050 SSP (Shared Socioeconomic Pathways; SSP1 refers to a sustainability scenario, SSP2 is a middle-of-the-road one, while SSP5 depicts the fossil-fuelled development. “-19” refers to 19 is 1.9Wm^2, which is a proxy for 1.5C scenarios).

Even when comparing the same scenario, bioenergy potential still varies significantly among models (e.g., SSP1 in (Figure 7)). This is due to various modelling assumptions and definitions of what is “sustainable bioenergy” (Table 2). One major difference is how modellers consider different biomass feedstock types and their sustainable potential. Currently, most models have included dedicated energy crops or short-rotated forests (Ruiz *et al* 2015, Gernaat *et al* 2021). However, land-use change and environmental sustainability remain the key issues when sourcing bioenergy from dedicated conventional energy crops (Johnson 2009, Arevalo *et al* 2014). Therefore, some models prevent such concerns by excluding the dedicated energy crops and using waste and residues only (Hörsch *et al* 2018, Tröndle *et al* 2020), though the biomass supply may be limited and insufficient.

Table 4. Different assumptions of biomass feedstock and bioenergy potential in 2050.

Models (scenarios)	**European bioenergy potential in 2050 (TWh)**	**Biomass feedstock considered**
JRC-TIMES (Low or high availability scenarios)	2400–5869	Biofuel crops, dedicated perennial crops, residues from agriculture, forests, and waste (Ruiz *et al* 2015)
PRIMES	1837	Biomass and waste (Capros *et al* 2016)
IMAGE (SSP2)	3709–5775	Biomass from agriculture and forests (i.e., maise, sugar cane, switchgrass and miscanthus) (Gernaat *et al* 2021)
Euro-Calliope	2400	Wastes and residues from JRC-TIMES (Tröndle *et al* 2020)
PyPSA-Eur-Sec	2400	Wastes and residues from JRC-TIMES (Hörsch *et al* 2018)

2.3.3.2 Unique roles of bioenergy with competing end-uses

Bioenergy may play unique roles that other renewables cannot fulfil, such as balancing intermittency (Szarka *et al* 2013, Arasto *et al* 2017, Thrän *et al* 2015b), providing fuels for hard-to-decarbonise sectors (O'Connell *et al* 2019), allowing negative emissions (Muri 2018, Fajardy and Dowell 2017), and enhancing national energy diversity (European Commission 2018). When the European power system gets close to 100% renewables, bioenergy could help balance fluctuations in renewable power systems otherwise dominantly supplied by weather-driven wind, solar, and hydropower (Thrän 2015) (Szarka *et al* 2013). Technical options could be larger storage capacities of intermediate biomass, combined heat and power (CHP) biomass plants, or biogas upgrading to gas grids, e.g., bio-methane (Thrän 2015). However, the same biofuel could be used for other competing applications apart from power systems: e.g., methane is also a critical industry feedstock that is hard to decarbonise.

From the negative-emissions perspective, bioenergy is the only renewable source capable of carbon-negative power stations, making it a compelling component of energy systems transition otherwise primarily dominated by wind and solar power. Moreover, with carbon capture and storage technologies, BECCS (bioenergy with carbon capture and storage) is considered a "saviour" of feasibility for most explorative 1.5℃ and 2℃ climate mitigation pathways (Hanssen *et al* 2020, Muri 2018). This also resonates with the SSPs scenarios in Figure 7,where extensive carbon capture and storage deployment demand the highest bioenergy share. Nevertheless, if we consider the constraints of environmental sustainability, especially land-use impacts, the story may be very different. For example, the biomass supply suggested by 1.5℃ pathways would require additional land-use change causing net losses of carbon from the land and overuse of freshwater (Muri 2018, Harper *et al* 2018).

2.3.3.3 Substantial potentials from ancillary bioenergy

In contrast to the overall increasing trend in biomass for biofuels, the current utilisation of the municipal and industrial waste sector is relatively stable in Europe, constituting around 15% of the total bioenergy supply (Figure 2). However, recent studies suggest a considerable potential from municipal waste, agricultural residues, by-products, and co-products. All these studies provide a circular-economy perspective to reuse non-traditional feedstocks to provide bioenergy (Table 3).

Existing literature has well explored the separate potential of energy recovered from municipal waste, agricultural and forest sources (residues, co-products, and by-products), respectively, but without considering their combined potentials. All of these products share the common feature of recovering energy by reusing/recycling biomass of little or no value, which would otherwise be left to waste. Though the term “waste-to-energy” is well recognised for energy recovered from municipal waste, it cannot stand for the biomass from agricultural co-products or forest by-products, as waste and co-/by-products are different by definition.

To our best knowledge, there is no existing term to represent such non-dedicated bioenergy from the three different sources of human settlement, agriculture, and forests: we thus define it here as “ancillary bioenergy”. In contrast, we define those biofuels/biomass which are intentionally and specifically grown for energy utilisation (e.g., soybeans for biodiesel, corn grain for bioethanol, lignocellulose for renewable heat, etc. (Gent *et al* 2017)) as “dedicated bioenergy”. Ancillary biomass still has additional sources for domestic bioenergy without food competition or land conflicts, instead reusing resources in a circular-economy way. Some key feedstocks from ancillary bioenergy could be by-/co-products of high energy density that have not been included in major energy models (e.g., nuts shells, animal fats/oil, used cooking oil, etc.).

We provide an overview of different ancillary bioenergy potentials studied in separate papers (Table 6). Most of them look at the separate potential of a sub-category and are mainly based on historical or current spatial data.

Table 5: Overview of ancillary bioenergy potentials for different sources from the literature, along with the methods used to reach the estimation.

Feedstock	**Potentials**	**Methods/Models**	**Reference**
Agricultural residues, by-products, and co-products	18.4 billion tonnes of total potential in the EU28 (Animal ~31%, Vegetable ~44%, Cereal ~22%)	GIS and statistical analysis	(Bedoić *et al* 2019)
Agricultural residues, by-products, and livestock sewage	820,000 tonnes of feedstock per year can be used in small-scale CHP units to satisfy the thermal and electric demand of 116,000 households and 178,000 families in the Calabria region (Southern Italy)	Statistical estimation	(Algieri *et al* 2019)
By-products (fish fats)	20,000 tonnes of fish oil feedstock are available annually in Norway for producing 51.8 GWh bioenergy.	Statistical estimation	(Fernandes and Costa 2010)
Used cooking oil	13% of the biodiesel demand could be met by used cooking oil in Brazil.	Statistical estimation	(Monforti *et al* 2015)

2.4 Discussion

Biomass has grown in importance over the past two decades, but it remains a contentious renewable energy source in Europe, with an uncertain future. We identified challenges and potential opportunities for EU bioenergy by reviewing and analysing its historical national deployment (Section 3.1), current political support (Section 3.2), future modelling studies (Section 3.3), and how they are related to SDGs, as summarised in Table 6.

We identify three cross-cutting issues and opportunities in particular: supply security and untapped bioenergy potential, gaps between sustainability definitions in EU bioenergy policy and in modelling studies, and the question of optimal allocation in view of competing demand for limited resources. We now discuss these three challenges in turn.

Table 6. Summary of challenges in EU bioenergy national deployment, political support, and modelling studies.

Sections	**2.3.1 Historical National Deployment**	**2.3.2 Current Policy & Support Schemes**	**2.3.3 Future Modelling Studies**
Supply challenges	1a. Rising import dependency of liquid biofuels (Figure 3) 1b. National heterogeneity (Figure 4 and Figure 8)	2a. Stricter sustainability criteria & phase-out of biodiesel from palm (Table 1) 2b. No long-term bioenergy policy (Table 1)	3a. Varied sustainable potential & assumptions (Table 5 and Figure 7) 3b. Untapped potential of ancillary bioenergy (Table 5)
Demand challenges	1c. Growing consumption during transformation processes (Figure 2)	2c. Transport as the key mandated sector (Table 3)	3c. Unique but competing uses (Section 3.3.2)
Relevant SDG	Affordable and clean energy (SDG 7)		

2.4.1 Supply security and untapped bioenergy potential

First, although the EU initially designed bioenergy as an important alternative fuel for increasing energy diversity and self-sufficiency [8], over 60% of liquid biofuels were imported in 2019 (Figure 3). The rising import dependency of liquid biofuels (1a) reflects that on the supply side, there are simply not enough bioliquids from European oil crops. Partly, this is because they would require pesticides that are restricted by the European Commission (Scott and Bilsborrow 2019), for instance, for the oilseed rape used to produce the most vegetable oil in the EU. Then the EU pesticide laws came into force in 2013 (banning neonicotinoid seed dressings), which led to massive yield losses as well as the drop of land areas for growing oilseed rape. The shortage in oil crops supply has subsequently been replaced by imported bio-oils, like palm oil (Ortega-Ramos 2022). On the demand side, the EU has increased the renewable blending targets for transportation fuels (2b), which primarily relies on bioliquids to fulfil. The combination of scarcer supply and higher demand for bioliquids contribute to its increasing import dependency.

Moreover, the European Commission has recently proposed to amend the types of sustainable bioenergy feedstocks in the Renewable Energy Directive, which all require the feedstocks to be not fit for use in the food/feed chain (Annex IX amended in (European

Commission 2021)). It remains uncertain how much sustainable bioenergy will be available after accounting for biomass use in food, feed, or materials. Likely, supply will become more limited with the stricter sustainability criteria on all kinds of biomass coming into force (2a) in the EU. Domestic biomass supply will likely become even scarcer, thus challenging the security of bioenergy supply in Europe.

Second, the supply security also has national heterogeneity, especially in countries with high per-capita bioenergy consumption and low national subsidies (Group 1 and Group 2 countries, as identified in Figure 4). Figure 8 compares the three dimensions of nationwide bioenergy deployment among all EU countries (i.e., subsidised bioelectricity in orange, import dependency in red, and bioenergy supply shares in green). We classify countries using the same groups and colours as in Figure 4. Figure 8 shows a distinct picture of the three national groups compared to Figure 4. Generally, most EU countries (purple dots as Group 3) are moving towards a lower bioenergy share and higher subsidies (upper-right of the ternary chart). However, the consumption-leading Groups 1&2 have relatively low and decreasing subsidies at the cost of higher import dependency (blue and green dots moving to the bottom). Noticeably, Denmark (from Group 1) imported about 40% of its woody biomass from countries outside the EU in 2018, e.g., Russia (11%), the USA, and Canada (19%) (Statbank Denmark 2019). Therefore, the security of bioenergy supply is not only a common challenge just for imported liquids among the whole EU but also for the leading per-capita consumption countries.

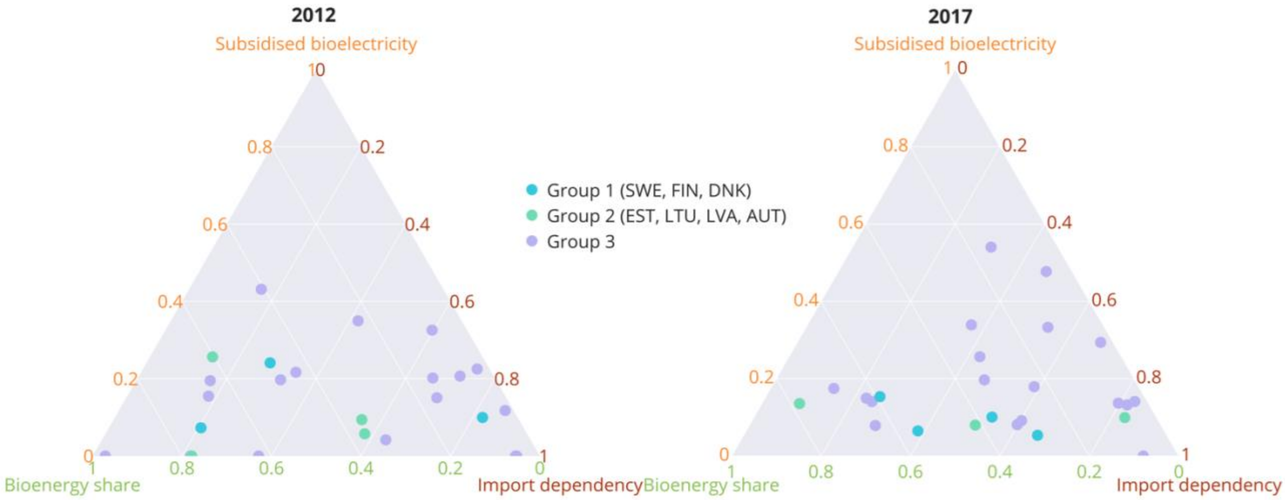

Figure 8. Comparing shares of bioelectricity received subsidies, bioenergy in total energy supply, and its import dependency (For bioenergy subsidy data, only the subsidised bioelectricity is available from 2012 to 2017 (Council of European Energy Regulators (CEER) 2018))

Third, one possible opportunity to combat this challenge could be exploring the “extra” or untapped bioenergy potential. Ancillary bioenergy, as proposed in Section 3.3.3., has substantially untapped potential, which could add to domestic supply without land-use competition. The collective potential of ancillary bioenergy (i.e., non-dedicated bioenergy from human settlement, agriculture, forests, and waste) is not systematically explored in the literature (Table 5)., nor has it been considered in future European energy scenarios so far (

Table 4). A systematical estimation of the collective potential of ancillary bioenergy for future energy systems is lacking.

In addition to ancillary bioenergy, abandoned land or dietary shifts could also provide "extra" biomass without food-/land- conflicts (Campbell *et al* 2008). For instance, modelling results suggest that reducing beef, lamb, and other land-intensive food would result in an extra land supply for biofuel crops without conflicting with food production (Haberl *et al* 2011). Moreover, replacing animal-based diets with plant-based ones could achieve a 70% reduction in land use and the associated GHG emissions (Aleksandrowicz *et al* 2016). However, all the untapped "extra" bioenergy is not a panacea, but a set of alternative futures with pros and cons. Whether it is economically sensible to collect ancillary bioenergy, how would waste reduction influence its availability, and how to sustainably allocate biomass on abandoned land – these research questions require more interdisciplinary modelling studies to provide plausible options for policymakers.

2.4.2 Supply sustainability: Gaps between EU bioenergy policy and modelling studies

Just as how versatile biomass feedstocks are, the definition of sustainable bioenergy or even just bioenergy varies. There is currently no unified classification for bioenergy in the literature. It can be categorised by fuel states (solid, liquid, and gaseous) (Guo *et al* 2015), by sources (e.g., FAO's classification from energy crops, agricultural residues, by-products, municipal waste, etc.), by generation (first-, second-, and third-generation biofuels), or through combined criteria for statistical purposes (e.g., IEA, IPCC). Some harmonised systems for classifying bioenergy and biomass inputs have also been advocated (e.g., (Rettenmaier *et al* 2008)), but no consensus has been reached. Similarly, "sustainable bioenergy potentials" are more varied among modelling studies (3a in Table 6). This is a common issue for modelling studies given their different assumptions of "sustainable" and various data sources.

However, this could be especially challenging for EU policymakers due to the gap of "sustainable bioenergy" definition between existing literature and ongoing policies. In other words, what energy modelling studies label "sustainable bioenergy" is not always consistent with how EU policies define it. For example, with the new EU bioenergy sustainability certification scheme (Annex IX in EU Renewable Energy Directive II, RED II (MOUSTAKIDIS 2018)), some 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). Meanwhile, the indirect land-use change and its embodied emissions are still poorly represented in some widely-cited 2050 modelling scenarios. E.g., the biomass supply suggested by 1.5℃ pathways would require additional land-use changes causing net losses of carbon from the land and overuse of freshwater when deploying extensive Bioenergy with

Carbon Capture and Storage technologies (BECCS) (Muri 2018, Harper *et al* 2018)). Since the BECCS is intensively advocated and deployed in most 1.5℃ and 2℃ climate mitigation pathways (Hanssen *et al* 2020, Muri 2018) and the Shared Societal Pathway 5 (Figure 8), whether the sustainable bioenergy supply is sufficient to support these negative emissions is contentious for policy implications.

Rather than adopting existing sustainability definitions from policy, energy modellers could take a step further by modelling higher sustainability bars for reaching a more sustainable energy system (SDG7), especially for ruling out indirect/undesirable land-use change. There is an opportunity here for clearing up the definitions of what “sustainable biomass supply” really is so that energy system studies can determine whether this sustainable biomass supply is sufficient for its intended purpose.

2.4.3 Competing demand and optimal allocation

Demand-wise, there are currently no sector-specific goals or nationally binding targets for bioenergy from 2021 onwards in Europe, except for the blending of transportation fuels. However, biomass has other possibly unique roles in a 100% renewable and zero-emissions energy system that other renewables cannot substitute, such as decarbonising industry and balancing power grids (3c in Table 6). Hence, the use of bioenergy for transportation fuel blending may remove feedstocks from other more strategically relevant uses in a renewables-based clean energy system. Moreover, there is the risk that bioenergy becomes locked-in to uses like fossil fuel blending without an overarching EU bioenergy strategy considering all energy sectors – what are the possible end-uses for different biomass feedstocks; how to optimise the limited sustainable feedstocks; where is bioenergy competitive over other renewable technologies in the long run?

In addition to the lack of EU bioenergy strategy, European countries have been responding differently through varied national support schemes. On the one hand, some sharply reduce the subsidies for bioelectricity (the highest reduction is over 50% in Sweden, see Table 2). On the other hand, some regions promote “coal-to-biomass” projects to extend the life span of fossil coal plants, thus benefiting from subsidies, as biomass is compatible with existing coal plants (Banja *et al* 2017, Reid *et al* 2020). The latter practice could provide cost-efficiency in the near-term pledge pathway (2030), as one can fulfil the targets of renewable shares and decarbonisation with renewable biomass (e.g., wood pellets are regarded as a zero-carbon feedstock in many nations, even when they are actually processed from imported stemwoods). But it might hinder the transition to superior alternatives with higher cost- and land-use-effectiveness towards 2050, especially when dedicated bioenergy power plants will still be operating given life spans of up to 60 years (Reid *et al* 2020).

Therefore, the challenge of competing bioenergy demand opens up a window for energy modelling studies, to consider the allocation of scarce sustainable bioenergy through sector-coupled energy system models.

2.4.4 Policy implications and future research directions

Our research has two-fold practical implications for both national and Europe-wide policymakers. First, more national policy should tackle the trilemma of biofuels supply security in consumption-leading countries – high import dependency, high bioenergy share, and the low subsidised level (especially in the Nordic region; see Figure 8). Apart from energy security regulations, stringent sustainability criteria or voluntary sustainable certificates should cover non-EU sourced biomass imports to prevent deforestation or environmental burdens in sourcing countries with lower sustainability standards. Future research could help local policymakers through modelling competing usages and local endowments. This research direction provides a better understanding of the most strategical use of bioenergy per country or even per region, assisting local policymakers to develop a more coherent bioenergy strategy towards 2050.

Second, EU policymakers and energy modellers should collaboratively close the gap of inconsistent sustainability assumptions and explore the realistic long-term role of bioenergy. Future research could consolidate bioenergy sustainability assumptions among models by checking and revising assumptions in existing models. Furthermore, more detailed land-food-industrial system modelling can reveal the embodied bioenergy environmental impacts overlooked by many carbon neutrality scenarios. Future research could investigate whether there will be enough nutrients to supply massive bioenergy crops for negative emissions or whether it is more environmentally friendly to prioritize biomass for energy or for high-value chemicals.

Technology-wise, there are also potential breakthroughs that may impact how we shape our bioenergy models and policies. For instance, the significant increase in biomass conversion efficiency (Ma *et al* 2018), scaling-up new feedstocks like algae (Chia *et al* 2022), or the commercialisation of bioenergy-competing technologies, such as solar fuels from just water and sunlight (Schäppi *et al* 2022). However, these novel technologies are still at the lab or demonstration level without sufficient data to support modelling or policymaking, so they remain as issues to be tackled by future research.

2.5 Conclusion

This study identified three challenges and opportunities for EU. First, the security of supply of imported liquid biofuels is questionable, particularly in countries with the highest per-capita bioenergy consumption in Europe. Second, the definition of “sustainable bioenergy” in modelling studies is sometimes inconsistent with how EU policies label it. Third, there are several unique applications competing for the limited bioenergy potential, yet there is no clear long-term strategy for making choices as to which of these to develop in Europe. We conclude with three opportunities to tackle these challenges for future research. First, utilising untapped European bioenergy potential with low environmental impacts could improve supply security. Second, a clear and harmonised definition of “sustainable bioenergy” would better convey research results to policymaking. Third, understanding where best to use limited sustainable bioenergy supply through sector-coupled energy system models can provide direction for a clearer EU bioenergy strategy towards 2050.

3 Contribution II: Strategic uses for ancillary bioenergy

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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 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 ancillary bioenergy 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 BECCS plants in a nuclear-free system provides additional climate benefits. It is also possible to leave the ancillary bioenergy 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 ancillary bioenergy, which can provide guidelines for a more coherent European bioenergy strategy. Although the 2050 potential of ancillary bioenergy is limited, our findings suggest that it could fill critical strategic niches for realising carbon-neutrality.

3.1 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 CCS (carbon capture and storage) (Muri 2018, Fajardy and Dowell 2017) 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 (Masson-Delmotte *et al* 2018, Bogdanov *et al* 2019, Cornelissen *et al* 2012). 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 (Panichelli and Gnansounou 2017, Cansino *et al* 2012). 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 (Mandley *et al* 2020, International Renewable Energy Agency (IRENA) 2018).

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, Huppmann *et al* 2019, European Commission. Directorate General for Energy. *et al* 2016) (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” 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 2023). Ancillary bioenergy 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, Mandley *et al* 2020, Panoutsou 2021, Elbersen and Voogt 2020), 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., ancillary bioenergy. To do so, we first systematically quantify the future potential of ancillary bioenergy 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 3.3.1). 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 (Section 3.3.2 - 3.3.5). Finally, we conduct a range of sensitivity analyses to examine the robustness of our model (Section 3.3.6).

3.2 Methods and Data

This study applies two models to first estimate ancillary bioenergy 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.

3.2.1 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 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 feeding. We run the model at national resolution (35 European countries). We update SOLm with crops-to-residue shares from the latest 2019 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.

3.2.2 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 9). With the modified and more detailed ancillary bioenergy module in Euro-Calliope, we name our model AB-Euro-Calliope (for the detailed ancillary bioenergy 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).

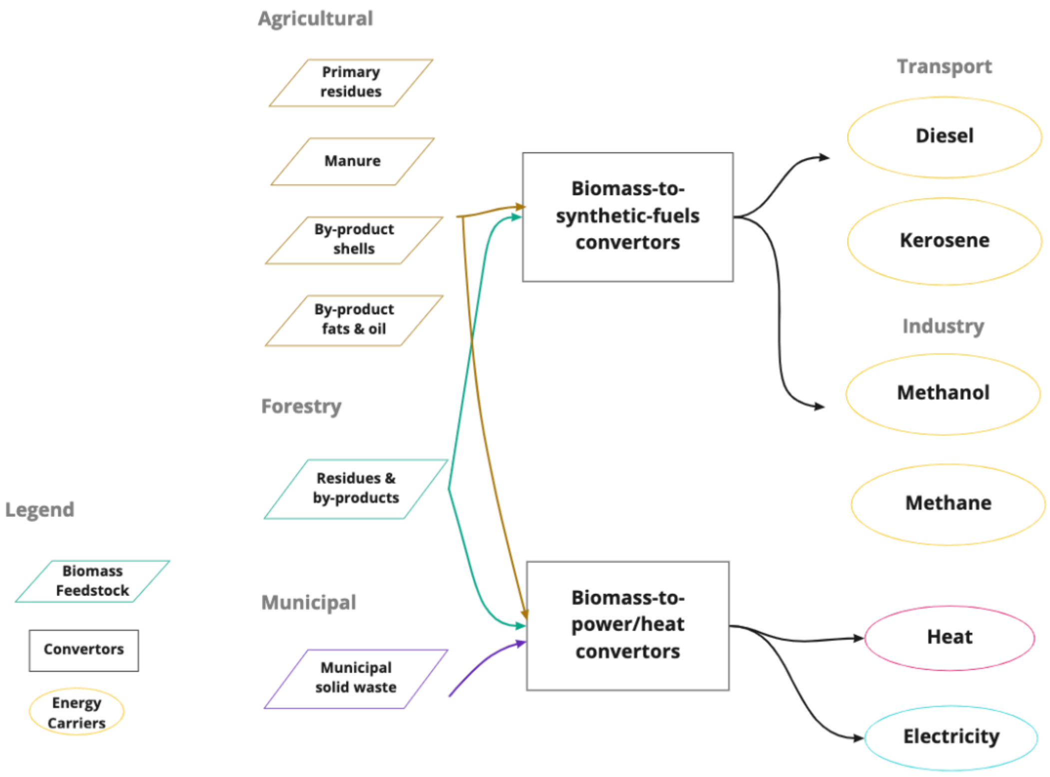


Figure 9. Ancillary biomass conversion pathways.

3.2.3 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 scenario (Table 7).

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 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 (1) by-/co-products (16 types of shells and three types of fats and oil with high energy density), (2) crop residues (114 types), and (3) 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 7), 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 7). 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 9) 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).

Table 7. 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; Open-field PV: 0.0125 km^2/MW; 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 3.2.4))
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)

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 7). 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 (Section 3.2-3.5) for differentiation.

3.2.4 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 ancillary bioenergy.

Table 8 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 ancillary bioenergy 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 ancillary bioenergy – (1) 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); (2) forcing all ancillary bioenergy 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.

Table 8. 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 (miscanthi-us) with additional land use**	**No nuclear capacity**	**CCS available; All biomass is used for BECCS**
2050 Reference	-	-	-	-	-	-	-	-
Different utilisation cases of ancillary bioenergy (Section 3.3.2)								
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 Section3.3.3 - 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***

3.2.5 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 – (1) 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); (2) agricultural nutrients lost through biomass incineration (via multiplying the Nitrogen and Phosphorus contents of biomass by their incinerated percent); (3) negative emissions potential of using all ancillary biomass at stationary BECCS plants (through their emission factors and CO2 capture rate). For the detailed data source, assumptions, and calculation, please refer to Appendix C in the Supplementary material.

3.3 Results

3.3.1 Limited future potential of ancillary bioenergy in Europe

The total potential of ancillary bioenergy reaches 185 PJ (sustainable) and 798 PJ (technical) in 2050 in Europe. To minimise the environmental impact, we use only the sustainable potential of ancillary bioenergy for comparing feedstock-wise availability and modelling all scenarios ("potential" refers to sustainable potential hereafter). Feedstock-wise, agriculture is the predominant sector for providing ancillary bioenergy 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 10), the potential of ancillary bioenergy 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 ancillary bioenergy potential could better reveal its sustainable role in a fully renewable European energy system. The technical potential for ancillary bioenergy is around 20% lower than that of residues from the high availability scenario of JRC-EU-TIMES. In Figure 10, 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., 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).

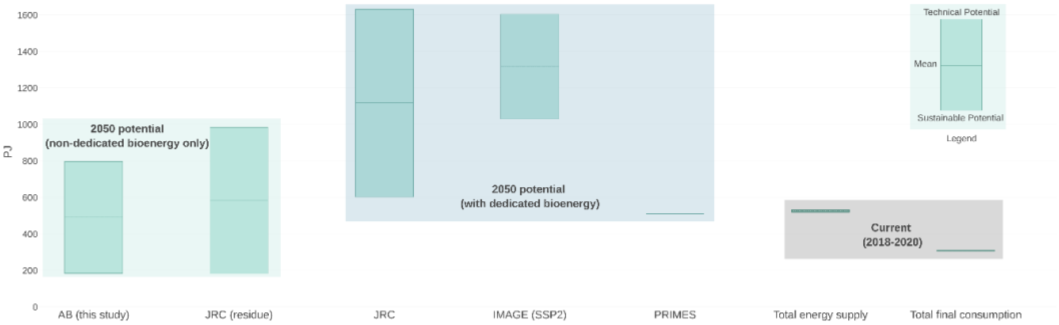
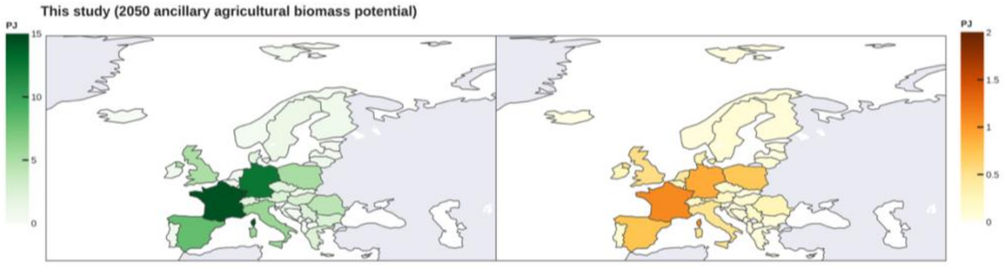


Figure 10. Europe-wide ancillary bioenergy (AB) potential modelled in this study compared to other models in 2050, and to the current supply and consumption in Europe (2019).

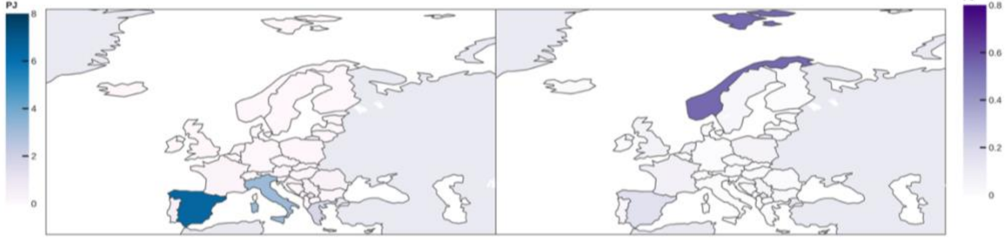
We specifically subtract the non-dedicated bioenergy from JRC-EU-TIMES for comparison (the second-left bar – “JRC (residue)” in Figure 10), as it is the closest to ancillary bioenergy with overlapping forestry and municipal datasets. We further break down and compare the different agricultural biomass potentials between our results and the JRC data by feedstocks (Table A5 in Appendix) and spatial distribution (Figure 11). 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 11 – 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.



This study (2050 ancillary agricultural biomass potential)

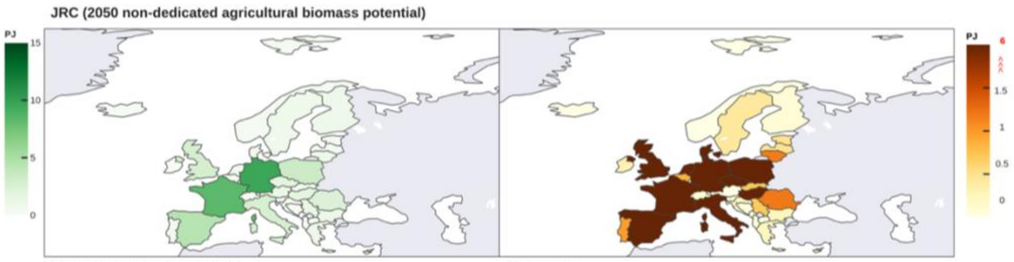
(a) Agricultural primary residues

(b) Manure



(c) Nuts shells (by-products)

(d) Animal fats & oil (by-products)



JRC (2050 non-dedicated agricultural biomass potential)

(e) Agricultural primary residues

(f) Manure

(g) Nuts shells (by-products)

(h) Animal fats & oil (by-products)

Figure 11. Comparing the (a-d) agricultural ancillary biomass 2050 potential in this study (SOlm model) and (e-f) non-dedicated biomass from JRC-EU-TIMES (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)

3.3.2 Roles for ancillary bioenergy in a sector-coupled energy system

We first explore the possible roles for ancillary bioenergy when it can be utilised optimally, fully utilised, or not utilised at all in our 2050 European energy system (Figure 12). This section acts as the reference scenarios for comparing the following strategic use cases in Sections 3.3.3 - 3.3.5. Hence, in this section we assume that (1) nuclear power is available, (2) dedicated biomass is disabled, and (3) no BECCS technologies are available to provide negative emissions.

Consumption-wise, the average European utilisation of ancillary bioenergy 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 ancillary bioenergy utilisation (by half) and alter sectoral uses (Figure 12 and Figure 13). Our optimisation results suggest different sectoral uses for bioenergy among scenarios (ancillary biomass only; solid colour bars in Figure 12) 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 12, the current (2019) data refer to the total final consumption of biofuels and waste in Europe from the IEA Energy Balances, which includes dedicated biomass and is not cost-optimised (International Energy Agency 2021). "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 ancillary bioenergy – (1) underground methane gas storage facilities (for enhancing flexibility in scenario *GasStorage*) and (2) 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*); (3) *FullUtiAgr* where all agricultural ancillary biomass is forced to be used and (4) *FullUtiAll* where all ancillary biomass is forced to be used. (5) 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.

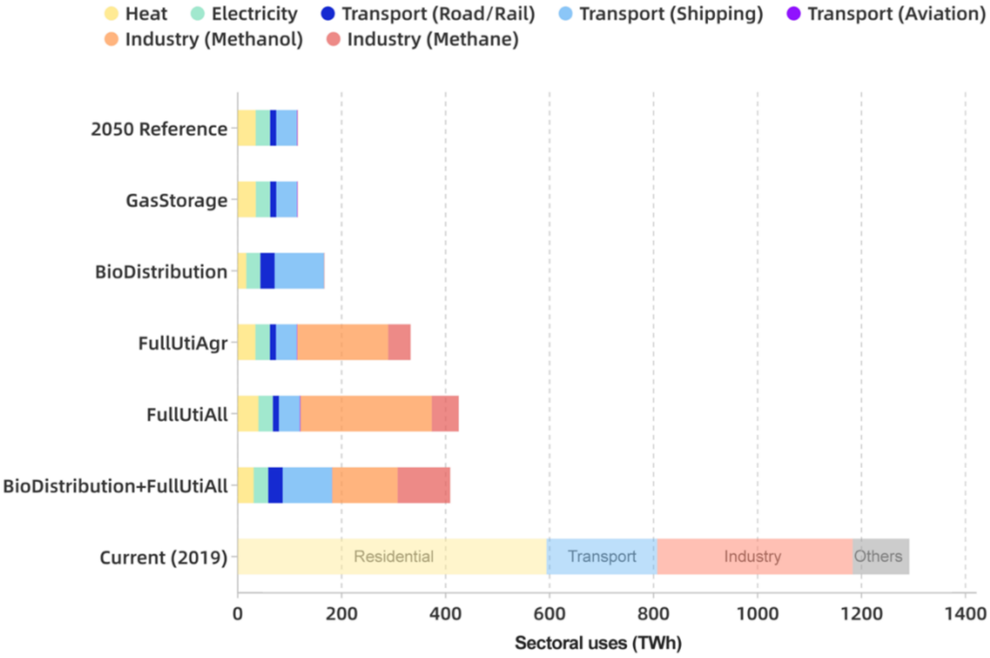


Figure 12. Sectoral final consumption of ancillary bioenergy differs among scenarios and from current uses including dedicated biomass.

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

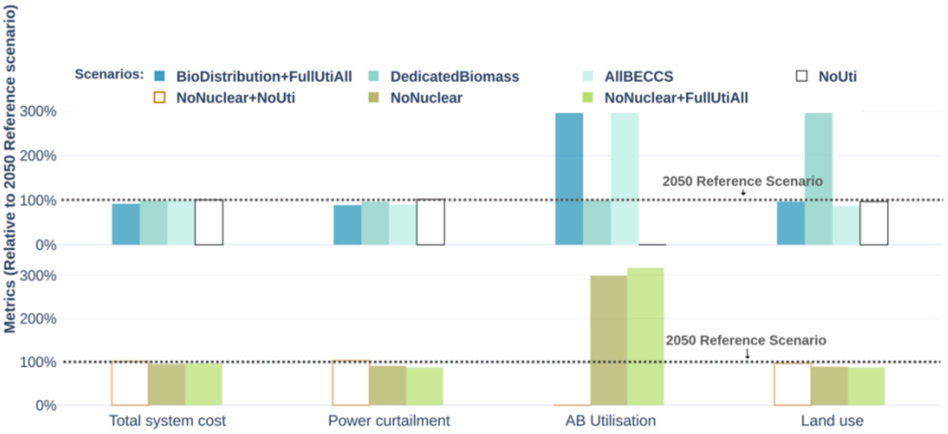


Figure 13. System-wide comparison of reference scenarios (Power curtailment is the percentage of maximum available renewable electricity production from wind and solar photovoltaic technologies that is curtailed; AB utilisation is the percentage of the maximum available ancillary biomass potential which is used in a given scenario).

However, even with additional distribution and/or forced full utilisation, the attractiveness of ancillary bioenergy 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 ancillary bioenergy 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 *NoUti* – only the annual power curtailment slightly increases (+2%, see Figure 13). 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 9). Note that even when comparing the two extreme utilisation cases here (full and zero utilisation of ancillary bioenergy), their total system cost difference is still not significant, i.e., within 10%.

NoUti can lead to additional environmental benefits of preserving agricultural nutrients. When ancillary bioenergy 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.

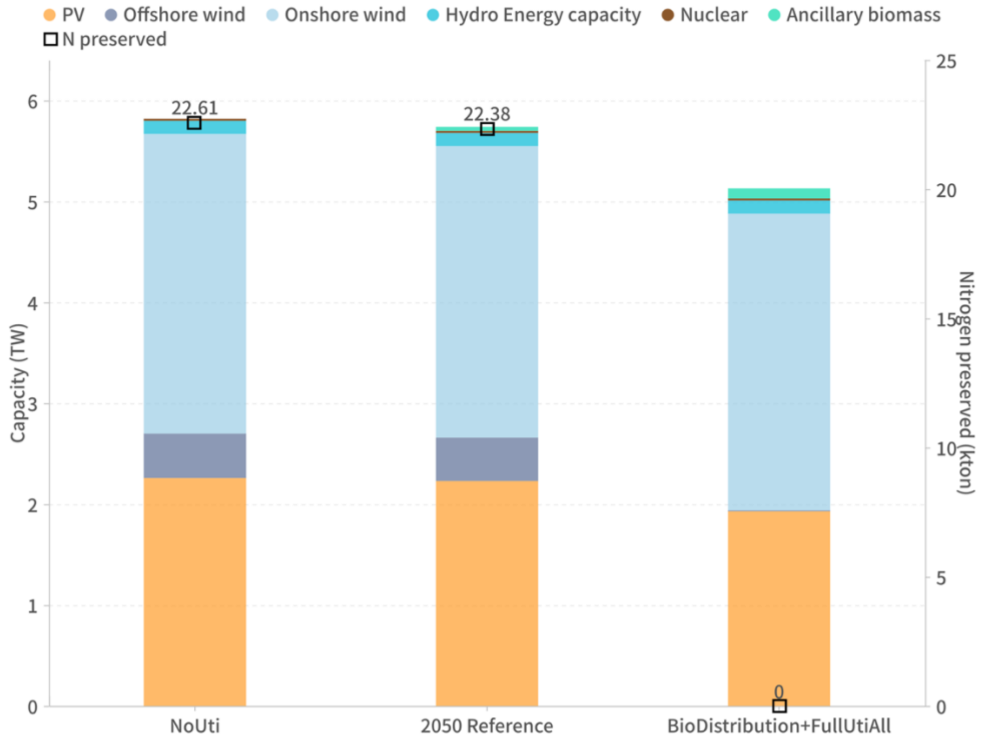


Figure 14. Different compositions of energy capacity and nitrogen nutrients preserved when the utilisation of ancillary bioenergy is zero (*NoUti*), optimal (*2050 Reference*), and full (*BioDistribution+FullUtiAll*).

3.3.3 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 9). Although the attractiveness of bio-based diesel substantially increases by 3 times when adding dedicated biomass, we can achieve a similar attractiveness by fully utilising ancillary bioenergy and by adding the distribution network (*DedicatedBiomass* vs *BioDistribution+FullUtiAll* in Table 9). In other words, it is plausible that we replace land-intensive dedicated biomass with only limited but strictly sustainable ancillary bioenergy for higher societal acceptance (via lower land use) and for higher attractiveness (for producing carbon-neutral fuels).

Table 9. Comparison of system metrics when strategically using ancillary bioenergy for phasing out nuclear or dedicated biomass.

	Dedicated Biomass	*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%[1]	+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%	19%	20%	38%	0%	38%	-	-

in *2050 Reference*)							
% of bio-based Methanol (1% in *2050 Reference*)	1%	11%	1%	0%	24%	-	-

[1] 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 7), so removing nuclear technology inherently reduces total system costs (i.e., -5% for *NoNuclear* as scaled by reference scenario).

3.3.4 Phasing out nuclear by fully utilising ancillary bioenergy

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 9). 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 -12% less electrolysis capacity, *NoNuclear* in Table 9). 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 9). The strategic use of ancillary bioenergy 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 9).

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, ancillary bioenergy 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.

3.3.5 Additional negative emission at similar costs

As a final alternative, the entire available ancillary bioenergy 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 ancillary bioenergy potential for negative emissions can contribute around 253-623 Mtons CO_2eq per year, 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% above *2050 Reference). NoNuclear+AllBECCS*, especially, can have the most synergies among all use cases (Table 9) – 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%).

3.3.6 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 15) and the costs and efficiencies of future technologies related to or competing with bioenergy (Figure 16). 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 timeseries 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: ancillary bioenergy utilisation, power curtailment, and total system cost. As shown in Figure 15, 2018 is our reference weather used in all scenarios. Different weather-year runs comprise the corresponding timeseries 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 4-10%).

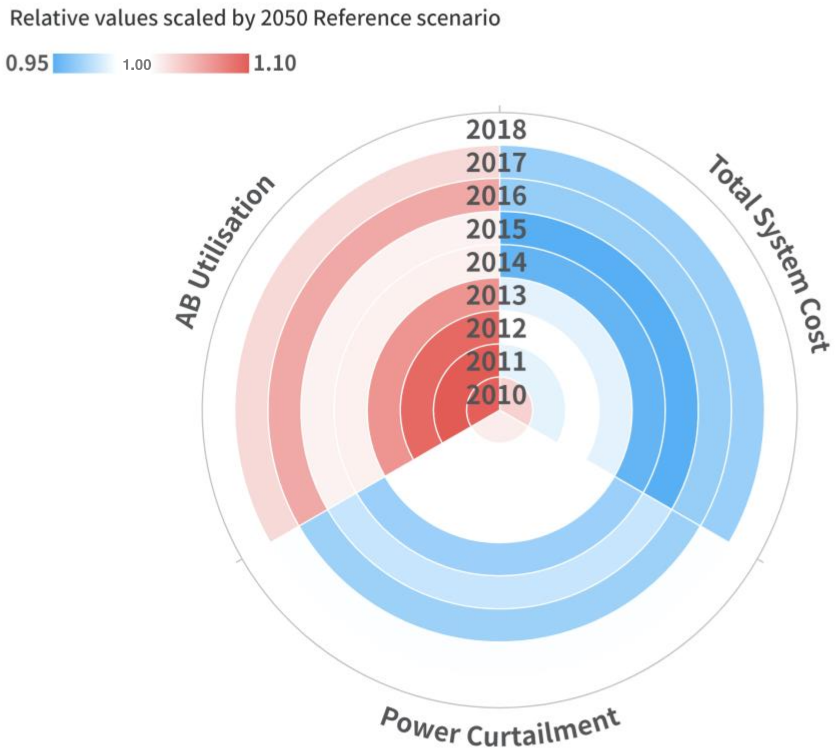


Figure 15. Sensitivity to the different weather years.

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%).

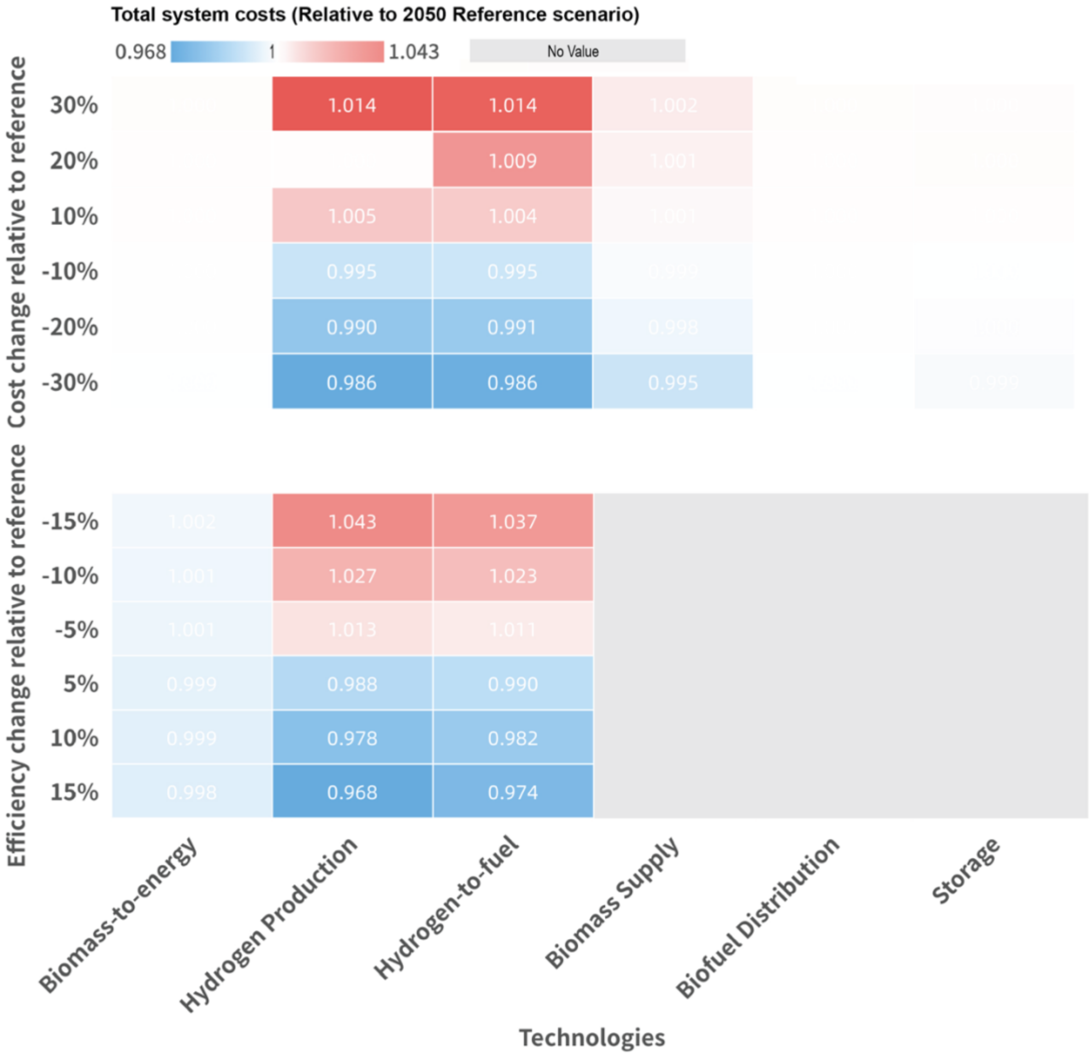


Figure 16. Sensitivity to technology costs and efficiency (“No Value”, grey colour, represents that the uncertainty change is not applicable to the referred technologies; white colour (at the middle of colour scale) means the same system cost as in the 2050 Reference scenario, i.e., relative value =1).

3.4 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) ancillary bioenergy 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, Huppmann *et al* 2019, European Commission. Directorate General for Energy. *et al* 2016). 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 ancillary bioenergy 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 ancillary bioenergy potential (Table 10), an understanding of which can provide guidance for bioenergy policymaking.

Table 10. 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**						+	+

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 ancillary bioenergy 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, Edward *et al* 2022). Among these 2050-neutrality scenarios, the highest biomass capacity (1553 GW) (Luderer *et al* 2018) can be 6 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 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 ancillary bioenergy 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 ancillary bioenergy. We also do not consider energy crops from marginal or abandoned land, which does not fit into our definition of land-free ancillary bioenergy. 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.

4 Contribution III: Land-free Bioenergy from Circular Agroecology

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Abstract

Bioenergy from energy crops is a source of negative emissions and carbon-neutral fuels in many 1.5/2℃ IPCC pathways. This may compete with other land uses. In contrast, ancillary biomass like by-products and waste is not primarily grown for energy and thus without land/food/feed competition. Here, we examine the availability and environmental impacts of ancillary bioenergy from agricultural sources under 190 circular agroecological strategies using the global food-system model SOLm for the year 2050. We find that there is a diverse option space for the future food and energy system, and it is possible to source a similar range of ancillary bioenergy even from very different food systems: 60-70 EJ, with 25% to 75% organic agriculture and various levels of waste and concentrate feeding reduction. We find three trade-offs between food system sustainability and ancillary bioenergy provision. First, there is a clear trade-off between nutrient recycling and negative emissions potential. 1.4-2.6 GTCO$_2$eq of negative emissions supplied through ancillary bioenergy with carbon capture and storage comes at the cost of nutrient deficits and resulting incompatibility with even a medium degree of organic farming. Second, reducing feed from croplands increases the ancillary bioenergy production with low shares of organic agriculture and reduces it for high shares. Third, food waste reduction reduces ancillary bioenergy provision. Hence, the sustainable transformation of the food system towards a less animal-based diet and waste reduction may conflict with a higher ancillary bioenergy provision, especially when the organic share is high as well. The policy implication of our results is that ancillary bioenergy can provide a similar range of future bioenergy as foreseen in IPCC AR6 illustrative pathways (±10%) without additional land use or compromising food availability. However, higher ancillary bioenergy provision or additional negative emissions compete with food system sustainability; hence, we recommend policymakers consider aligning energy system planning with the compatibility of sustainable food systems simultaneously.

4.1 Introduction

The Paris Agreement set the global warming limit to 2℃ by the end of this century. Many nations envision achieving climate neutrality by 2050, for instance, the European Union Green Deal (European Commission. Directorate General for Communication. 2021). As the only renewable energy providing negative emission potential, bioenergy appears to be an attractive option in most future carbon-neutral pathways. Over 95% scenarios in the latest IPCC AR6 (the Sixth Assessment Report of the Intergovernmental Panel on Climate Change) deploy BECCS (bioenergy with carbon capture and storage) for reaching the 1.5 or 2℃ target (Byers *et al* 2022). Yet, the contribution of dedicated and residual bioenergy varies significantly among models and scenarios. On the one hand, residues could meet 7 to 50% of bioenergy demand in 2050 and 2 to 30% towards 2010, according to the latest IAM (integrated assessment models) comparison (Hanssen *et al* 2020). In the case of European models, on the other hand, dedicated bioenergy crops are foreseen to constitute about 70% of the future energy supply (Ruiz *et al* 2015)). However, dedicated energy crops may compete with food and feed for arable land and water (Muscat *et al* 2020). Recent policies have gradually recognized the pitfalls of dedicated bioenergy. The European Commission, for example, has amended several types of sustainable bioenergy feedstocks in the Renewable Energy Directive, which requires the biomass feedstocks not to be fit for use in the food/feed chain (e.g., oil palms in Annex IX (Commission 2021)).

The land use or food/feed conflicts caused by sustainable biomass are difficult to quantify and are treated highly inconsistently when comparing policy goals and modeling studies (e.g., inconsistent definitions (Guo *et al* 2015) and differences between models (Wu *et al* 2023). Therefore, we proposed a land-free type of ancillary bioenergy and defined it as various non-dedicated bioenergy feedstocks recovered from residue and co-/by-products from agriculture, forests, and human settlements, which is sustainable in the sense that it does not cause competition for land, food, feed, or water (Wu and Pfenninger 2023).In our previous study, we found that ancillary bioenergy is important for realizing deep energy system decarbonization; for example, ancillary bioenergy can replace land-intensive dedicated biomass or balance intermittent renewable power in a nuclear-free scenario while achieving a similar total system cost (Wu *et al* 2023). The concept of ancillary bioenergy is different from previous literature mainly in two ways. First, it includes the embedded by-/co-products with high energy density (e.g., fish oil), which are not included in most residual/waste bioenergy studies/models like (Rosa *et al* 2021) and (Ruiz *et al* 2015). Second, ancillary bioenergy excludes food/feed/land conflicts that were not captured in previous studies (e.g., (Slade *et al* 2014) and (Bedoić *et al* 2019) proposed similar concepts without ruling out food/feed conflicts).

However, we simplified the agricultural bioenergy availability by assuming the business-as-usual case in the future food system. Nevertheless, when the food system evolves towards a more circular one, it is likely to alter the availability of ancillary bioenergy. A circular food system implies the reduction of waste and consumption of cropland-based livestock products, reuse of byproducts and waste, recycling of nutrients, and other circular practices to close mass or nutrient loops (Jurgilevich *et al* 2016). In relation to bioenergy and the energy system, for example, recycling food waste can yield more bioenergy with low opportunity costs (Breunig *et al* 2017). The increased organic farming leads to lower yields and less waste biomass for energy, which can impose a trade-off between bioenergy demand and sustainable agriculture (Siegmeier *et al* 2019, Muller 2009). Dietary changes may help reduce energy-system mitigation costs by 25% through the reduction of ruminant products (Bryngelsson *et al* 2017). It thus remains highly uncertain how much ancillary bioenergy will be available if we have fundamental changes toward a more circular global food system, especially when different and interrelated circular practices are in place.

Given the unsustainable food systems of today, significant changes in global production and consumption structures may be expected. Policy-wise, in the near term, the European Commission has already proposed to increase the share of organic production to 25% by 2030 in the context of its farm-to-fork-strategy and European Green Deal (Council 2023). Organic farming is not the only agroecological strategy toward a circular food system. Due to its generally lower yields, it also risks leading to increased land use, and complementary strategies are required to hedge against this (Muller *et al* 2017). In the long term, there are other circular practices available such as waste reduction, concentrate feeding reduction, reduced mineral fertilizer use, recycling nutrients in sewage sludge, etc (Muller *et al* 2017, Muller 2009). Such circular changes in the food system may alter ancillary bioenergy potential concurrently and significantly, both in quantities available and in its use as a nutrient source in agroecological production systems. In other words, the future global ancillary bioenergy potential will be well constrained by how we shape our future food system and vice versa, which is an unknown option space. It is hence vital to identify how ancillary bioenergy interacts with the various sustainability strategies for a more circular food system for timely policy advice.

Our research aims to answer the following questions. How do future circular agroecological strategies impact the supply of ancillary bioenergy from the food system, and does the resulting option space show any synergies or trade-offs? To answer these questions, we examine the option space for supplying ancillary bioenergy from agricultural sources under 190 circular agroecological scenarios using SOLmV6 (Müller *et al* 2020). Based on the FAO BAU 2050 scenario (Food and Agriculture Organization of the United Nations' Business-as-Usual 2050 scenario), we vary three parameters to explore the option space: organic agricultural share, concentrate feed reduction, and waste reduction. However, we do not model socioeconomic parameters or aim to capture the impacts of uncertain future food demand. Instead, we keep agricultural land use constant, i.e., we assume no more land than today is used.

This research contributes to the missing bridge between renewable energy and sustainable food system modeling, where both carbon neutrality and food sustainability are desirable but may have trade-offs between each other. The identified option space and trade-offs help both energy and agriculture policymakers to navigate the interplay between the two systems and make better decisions.

4.2 Methods and Data

4.2.1 Food system model and datasets

Our food system model SOLm is a mass- and nutrient-flow model of the global food system, which is by default calibrated with Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) data and categories of crops and livestock at the national level (Muller *et al* 2017, Müller *et al* 2020). Our baseline is the 2050 BAU scenario as provided by FAO in their Future of Food and Agriculture Report (FAO 2018), where there is no organic farming, waste reduction, or concentrate feeding reduction. We chose the year 2050 because that is when bioenergy is envisioned to provide massive negative emissions or carbon-neutral fuels in most energy transition pathways (Huppmann *et al* 2019). In the 6th version of SOLm (cf. the model documentation (Müller *et al* 2020)) that is used by this study here, the average from 2016 - 2020 FAOSTAT data serves as the baseline scenario.

4.2.2 Ancillary bioenergy potential

Using the definition of land-free ancillary bioenergy as in our previous study, we model the ancillary bioenergy potential from non-dedicated bioenergy feedstocks recovered from agricultural residue and co-/by-products that do not cause competition for land, food, feed, or water (Wu *et al* 2023)). We then aggregate hundreds of crop residues and commodity byproducts into six categories of ancillary bioenergy feedstocks (First column of Table G1 in Appendix G). Note that the system boundary of this research is the food system, so we do not include forestry and municipal biomass outside the food system. For detailed assumptions of ancillary bioenergy potential, please refer to Table G1.

4.2.3 Scenario assumptions

We model the three following agroecological practices. By combining the different shares of practices, we then have 95 circular strategies. Further driven by two bioenergy conversion pathways, we finally have 190 scenarios in total, as described below.

Agroecological practices. Changing agroecological strategies can significantly alter the availability of ancillary bioenergy and the corresponding environmental impacts. We depict different mixes of circular agroecological strategies by varying the three most central aspects of those in our model, namely (1) Organic agriculture: how food is produced, (2) Concentrate feeding: how animals are fed, and (3) Waste management: how much is wasted, and in consequence, which role animal source products play in human diets ("practices" hereafter). Another reason we choose these three agroecology practices is that they are supposed to change the food system, and thus bioenergy potential, in different ways that may compensate for each other.

Circular strategies. Strategies are correspondingly captured by varying and combining the following three agroecological practices. We explain in detail how they are captured in the model and how they alter ancillary bioenergy provision as follows:

(1) **Organic agriculture share** (captured by "Organic share": 0-100% that directly reduces the availability of primary crop residues and indirectly reduces the other residual, by-/co-product biomass potential). This is because a higher organic share is assumed to have lower

yields and less residue available for energy. We adopt a conservative and broadly accepted assumption on organic yields, assuming a yield gap between the organic and conventional systems, where organic yields are considerably lower in reference to the large meta-studies (Wilbois and Schmidt 2019). This then results in the corresponding decreasing effects on ancillary biomass availability. We admit there are cases when organic yields may improve gradually and surpass conventional yields in the long run (Gopinath *et al* 2023). However, one may expect conventional agriculture to develop further and thus keep up with the yield gap.

(2) **Food-competing feeding reduction**, as in the concentrate and other feed from cropland, such as forage maize (captured by "Concentrate feeding reduction": 0-100% that directly changes manure potential and frees-up land that is proportionally assigned to conventional/organic farming based on the organic share). Therefore, this practice can reduce manure biomass provision in response to the lower livestock numbers and increase the land used to cultivate crops, thus increasing/decreasing the crop production/residues based on the organic agriculture share changes.

(3) **Waste reduction** (captured by "Waste reduction": 0-75% including the end waste and the waste for food/feed purposes that directly reduces the secondary residues and byproducts for bioenergy provision). The combination of different practices hence creates an option space of possibly supplying similar ranges of ancillary bioenergy. Note that we keep the total land use constant and allocate all the freed-up land from concentrate feeding reduction to cropland. For detailed information on how we model organic agriculture, concentrate feeding reduction, and waste reduction, please refer to the previous paper using SOLm (Muller *et al* 2017) and the SOLm documentation (Müller *et al* 2020).

All three agroecological practices contribute to a more circular food system in terms of (1) reduced mineral fertilizer inputs, (2) less dedicated land for growing feed that frees up cropland for food, and (3) less waste. The intervals in which each strategy is implemented is 25% (i.e., 0%, 25%, 50%, etc. organic, etc.), which results in 95 strategies with different combinations of these agroecological practices. Note that the highest waste reduction we assume is 75%, as there will always remain some unavoidable share of waste from production to consumption (while the conversion to 100% organic production and 100% reduction of feed from cropland is possible in principle).

Bioenergy conversion pathways. We further model two different bioenergy conversion pathways driving the aforementioned circular strategies to depict how the energy system impacts the food system in return.

(1) ***NutrientFirst*** is the default bioenergy conversion pathway that preserves as many nutrients as possible by producing biogas via distributed anaerobic digestors. We optimistically assume that all nitrogen in digestible biomass can be recycled in this pathway to maximize nutrient circularity. However, we assume this pathway has the drawback of providing no negative emission potential since it deploys distributed digestors instead of centralized BECCS (bioenergy with carbon capture and storage).

(2) ***NegativeFirst*** is another plausible bioenergy conversion pathway, assuming all viable biomass (excluding manure) is used for stationary BECCS to maximize negative emissions but feeds no nutrients back to the food system. This pathway is also the prevailing use of dedicated biomass in most 1.5C AR6 scenarios(Byers *et al* 2022). To estimate the negative emissions potential that could be achieved through BECCS, we adopt the same method as in our previous study (Wu *et al* 2023). We assume the use of stationary power plants or Fischer-Tropsch diesel plants based on the viable biomass feedstocks. For BECCS technology cost and efficiency, we use data from the 2050 projection of biomass for electricity/liquids with CCS (carbon capture and storage) used in TIAM-Grantham (Grant *et al* 2021). We base the emissions factors of different biomass feedstocks on their default GHG emissions values (Ruiz *et al* 2015), and multiply the emissions by carbon capture rate (ranging from 90% to 99.5% for different BECCS technology chains (Rosa *et al* 2021).

4.2.4 Indicators for environmental impacts

Changing agroecological strategies inherently changes the environmental impacts of the food system. SOLm captures various environmental impacts as detailed in a previous study(Muller *et al* 2017) and the SOLm documentation (Müller *et al* 2020). The environmental impacts modeled in this study include (1) Irrigation water (scarcity adjusted according to (Pfister *et al* 2011); (2) Soil erosion; (3) Food availability (Calories per capita per day); (4) Food system GHG emissions based on Tier 1 and 2 methods (GWP100) from the IPCC 2019 (where applicable; otherwise IPCC 2006); (5) Nutrient balances (Nitrogen inputs, outputs, surplus, etc.). There are other impacts provided by SOLm but are not sensitive to different strategies, and they are all available in our open-access data repository for each scenario (Wu and Muller 2023). In addition to the environmental impacts modeled by SOLm, we also examine the negative emissions of ancillary bioenergy per scenario using the same emission factors and methods as in our previous study (Wu *et al* 2023).

4.2.5 Consistency check

We conduct a consistency check by comparing the model results for the baseline scenario to the same parameters from the established literature – i.e., FAOSTAT livestock numbers and production volumes, national UNFCCC (United Nations Framework Convention on Climate Change) GHG inventories (UNFCCC 2021) and OECD (Organization for Economic Cooperation and Development) nutrient balances (OECD 2022). Overall, there is no significant inconsistency between our baseline scenario and literature values (livestock numbers and production volumes are replicated, and there is no deviation of magnitude of total GHG emissions or Nitrogen balance). The consistency check consists of eight countries covering different world regions (South Africa, Brazil, Australia, Indonesia, China, the Netherlands, the United Kingdom, and the United States of America). Specifically, we compare the direct and indirect CH_4 and N_2O emissions (e.g., from dairy cattle enteric fermentation, managed soil, etc.) to the latest UNFCCC GHG inventories, and the Nitrogen flows to the OECD nutrient balance (i.e., total manure Nitrogen production per livestock, N in different harvested crops, etc.) whenever possible. One exception is for Brazil that the CH_4 emissions are unavailable from UNFCCC, so we use the Brazlin SEEG (Greenhouse Gas Emission and Removal Estimating System) database instead(Azevedo *et al* 2018).

4.3 Results

4.3.1 Similar bioenergy potential from diverse agroecological strategies

We find that a similar range of ancillary bioenergy potential from agricultural sources (around 60-70EJ) can stem from a diverse combination of agroecological strategies (25% to 75% organic farming Figure 1). This similar range of 2050 ancillary bioenergy potential is slightly higher than the current global production of total renewable biofuels and waste (57 EJ; 9% of the 2020 global energy supply) (Agence IEA, 2023). Compared to the 2050 primary bioenergy supply in the latest IPCC AR6 illustrative pathways, the range of similar ancillary bioenergy potential is around ±10% of their median value (67 EJ; 11% of the total primary energy supply) (Byers *et al* 2022). We thus use "±10%" and "a similar range" throughout the paper and figures to imply a similar range of ancillary bioenergy potential as in the AR6 illustrative pathways.

The reason behind this diverse option space is that the three agroecological practices are different in controlling the availability of various ancillary biomass feedstocks, which compensate for each other and result in a similar global potential (Figure 17). Here we analyze the trade-offs among different agroecological strategies – organic share, waste reduction, and concentrate feeding reduction, namely how they change the availability of various ancillary biomass feedstocks in different ways. In the following, we present results for the default biomass conversion pathway *NutrientFirst*. We subsequently discuss the results for the other pathway *NegativeFirst* in Section 4.3.3. For detailed explanations of the two pathways, please refer to Section 4.2.3.

First of all, the organic share is the driving factor in altering the total ancillary bioenergy potential because of its impact on agricultural productivity. The global ancillary bioenergy potential drops from around 100 EJ to 40 EJ when the organic share increases from 0% to 100% (Figure 17), regardless of the other agroecological aspects. Higher organic share reduces all crop yields and, hence, primary crop residues, which constitute the most ancillary bioenergy potential. Moreover, lower yields from organic farming also indirectly reduce the commodities available to produce secondary residuals and byproducts.

Second, waste reduction has a negative correlation with the total ancillary bioenergy potential by directly reducing the post-harvest feedstocks (i.e., end-use waste, secondary residues, and byproducts). Therefore, in combinations of high organic share with low waste reduction, the reduced primary crop residues can be compensated by the increased secondary residues and byproducts, which then barely changes the total ancillary bioenergy potential (e.g., Figure 17).

Third, concentrate feeding reduction directly reduces manure due to lower animal numbers and also frees up land for growing crops, indirectly increasing primary and secondary crop residues. Since the amount of freed-up land is fixed when the concentrate feeding share is constant, the same freed-up land provides less biomass when the organic share increases (i.e., more freed-up land is assigned to organic farming with lower yields). That explains why the concentrate feeding reduction has the highest impact on increasing the total ancillary bioenergy potential when there is 0% organic farming (i.e., all freed-up land is for conventional farming with the highest yields) and the impact reverses when the organic share increases (i.e., the same area of land is to organic agriculture with low yields plus the reduced number of livestock produce less manure).

Therefore, the three practices/central parts of circular agroecology alter ancillary biomass feedstocks in compensatory ways, which forms a diverse option space for sourcing similar bioenergy potential (Figure 17). Even within a similar range of global ancillary bioenergy potential, their feedstock compositions can be quite different due to the various agroecological strategies (Figure 17).

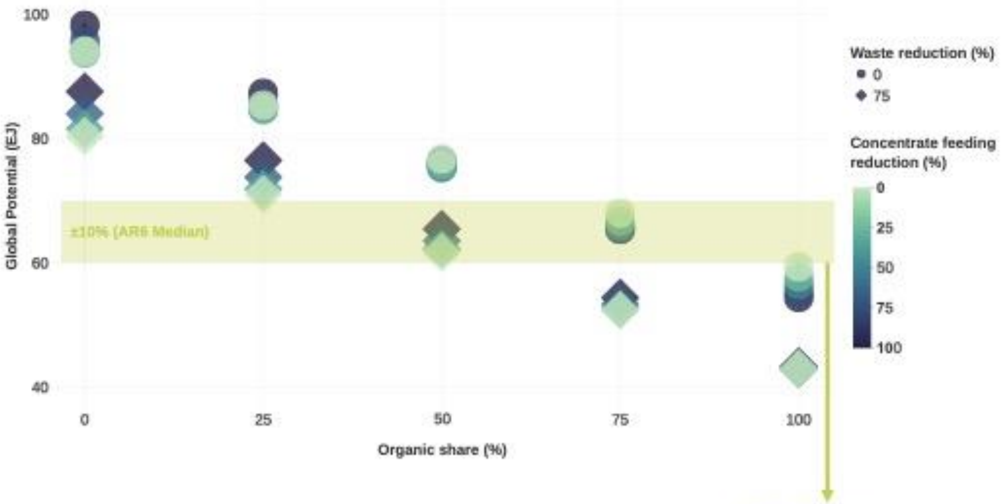
However, from a sustainability perspective, waste reduction clearly is a primary goal, and as in earlier assessments (e.g. on organic agriculture and global food security ((Muller *et al* 2017)), combinations of intermediate levels in all practices allow to meet potentially conflicting targets (e.g. bioenergy provision and sustainable food systems) to decent extents.

4.3.2 Varying environmental impacts from similar ancillary bioenergy potential

Focusing now on the 60-70 EJ range of ancillary bioenergy that the food system can provide to the energy system (the green shades in Figure 17), we can see that different strategies to provide this potential come with varying environmental impacts (Figure 18). On the one hand, we have a flexible option space to enhance certain environmental impacts for agroecology while providing a similar amount of bioenergy – a supposedly win-win situation for both the energy and food systems. On the other hand, one cannot improve all environmental impacts simultaneously; there are trade-offs between agroecological strategies and environmental impacts. For example, we find that the nitrogen deficit is the key challenge to a more organic and circular food system.

These results are supported by the same example of the ±10%ancillary bioenergy potential (Figure 18), where we identify the most varying environmental impacts in our option space. The two most varying aspects include the drastically different nitrogen balance (over -50% maximum) and a moderate variation of GHG emissions (±30%). The other environmental impacts do not vary significantly (within 20%). We also display the most varying environmental impacts of all scenarios in the Appendix (Table H1). Note that Figure 18 and Table H1 do not cover all the modeled environmental indicators, but the most varying ones. For the detailed results of all environmental indicators per scenario, please refer to our open-access data repository (Wu and Muller 2023).

(a) Global ancillary bioenergy potential from 95 strategies



(b) Example strategies with the most similar potential within the ±10% range

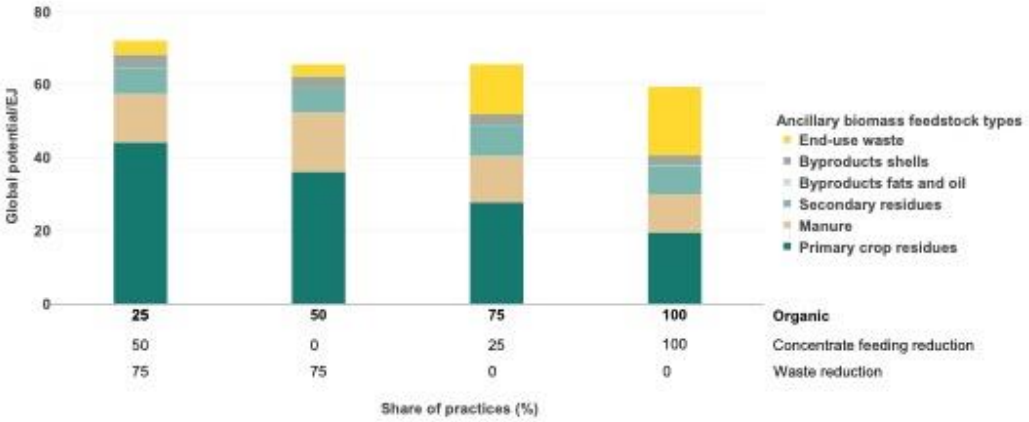


Figure 17. 2050 global potential of ancillary bioenergy varies in 95 strategies, but a similar range exists across low to high organic share (See Table B2 for all the numeric results; The ”±10% (AR6 Median)” refers to a ±10% range of 67 EJ, which is the 2050 primary bioenergy supply median value in IPCC AR6 illustrative pathways).

Comparing the similar ancillary bioenergy potential from medium- and high-organic scenarios (Figure 18), most environmental aspects improve with higher organic share (e.g., GHG emissions, irrigation water, soil erosion, etc.). Therefore, sourcing similar bioenergy potential from a more organic food system is generally more beneficial for the environment, albeit with reduced food availability and potential nutrient deficit as the trade-off. Meanwhile, waste reduction and concentrate feeding reduction can significantly increase food availability regardless of organic share, thus mitigating the trade-off between high organic share and food supply (e.g., an average of 20% higher calories per capita in (See Table H1). Hence, waste and concentrate feeding reduction strategies are necessary for a highly organic system if one prioritizes future food supply.

Nevertheless, the nitrogen deficit is the most challenging impact in a highly organic system because it is the only impact that cannot be sufficiently remedied by the other two practices (either waste or concentrate feeding reduction). Actually, the nitrogen deficit makes a fully organic system infeasible even when nutrients are all recycled back from bioenergy. I.e., when it is 100% organic, all options fall into the nitrogen deficit category (see the blue shades in Figure 19). Therefore, the nitrogen deficit is a key environmental impact constraining the food system from becoming fully organic while providing land-free ancillary bioenergy.

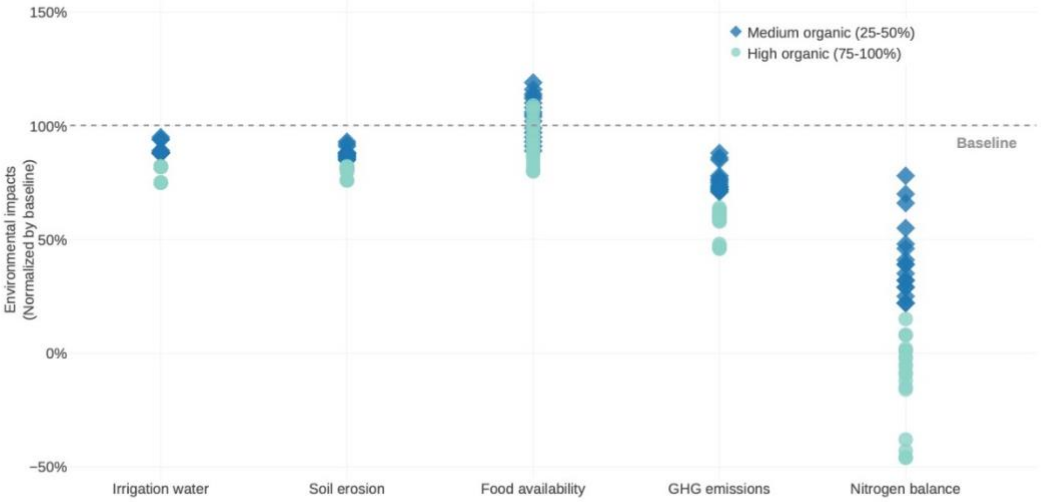


Figure 18. Comparison of varying environmental impacts when sourcing a similar potential of land-free bioenergy (”Similar potential” as in the ±10% of AR6 median in Figure 17. All values are normalized by the environmental impacts in the Baseline scenario where there are no agroecological or circular practices in place).

4.3.3 Changing bioenergy conversion pathways constrains the circularity of agroecology

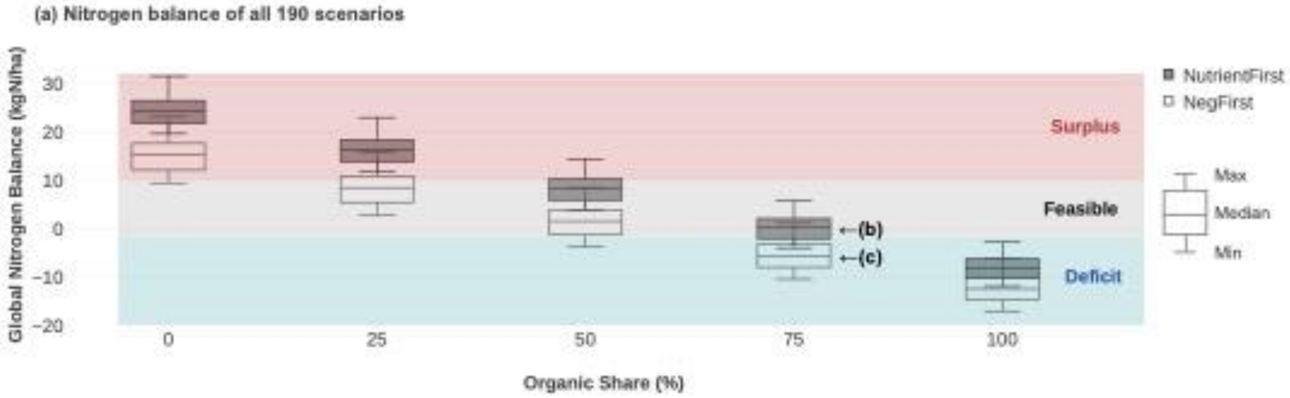
In the previous sections, we assume anaerobic digestors convert all ancillary bioenergy to biogas that maximizes the nutrients preserved for the food system (i.e., Pathway *NutrientFirst*; see detailed explanations of pathways in Section 4.2.3). Now we compare *NutrientFirst* to another plausible bioenergy conversion pathway maximizing the negative emission potential via stationary bioenergy with carbon capture and storage (BECCS) (i.e., Pathway *NegativeFirst*). How we design future bioenergy conversion pathways in the energy system alters the agroecological circularity. When massive nutrients are lost at BECCS, it can hinder the food system from being more circular and organic. Besides nutrient loss, we also find its trade-off with negative emission potential when choosing from different bioenergy conversion pathways.

Nutrient-wise, converting from *NutrientFirst* to *NegativeFirst* significantly reduces the nitrogen inputs that can be recycled from ancillary biomass and drags the nitrogen balance down by around 50% maximum (See Figure 19). To compare when nitrogen balance is surplus, feasible, or deficit, we adopt the same classification as in the previous study (Muller *et al* 2017), and plot the nitrogen balance with corresponding color codes in (a) Figure 19. When nitrogen balance surpasses 10 kgN/ha (red), it is "Surplus" (nitrogen is unsustainably high), between 10 kgN/ha and -2 kgN/ha is "Feasible" (grey), below -2 kgN/ha is "Deficit" (blue). It has to be emphasized that these numbers are very aggregate global average indicators of total nutrient surplus or deficit on agricultural land, which show considerable regional differences. Therefore, these indicators provide a risk measure for running into related problems of nitrogen surplus or deficit in the scenarios rather than displaying the actual number observed on a field.

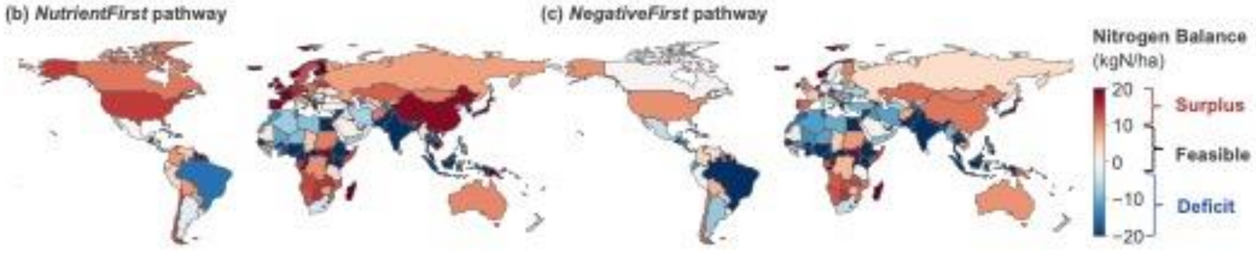
Nitrogen deficit makes deploying organic farming in such energy scenarios infeasible, as fewer chemical fertilizers are allowed when the organic share is higher. In the case of the *NegativeFirst* pathway, most 75% (and partially 50%) organic scenarios are no longer feasible due to the nitrogen deficit. However, they could work in the *NutrientFirst* pathway. In addition to the global scale, *NegativeFirst* also alters the national distribution of nitrogen balance. We identify what regions are more prone to nitrogen deficit when converting to *NegativeFirst*, such as Canada, the Latin American continent, Nordic regions, and central Europe (See the example in (b) and (c), Figure 19).

Emission-wise, *NegativeFirst* mitigates biogenic CO_2 emissions (i.e., emissions from biologically based materials like biomass, but not from fossil-based resources) both in energy and food systems that *NutrientFirst* does not. First, BECCS plants can provide additional negative emission potential for the energy system (1.4 to 2.6 $GTCO_2eq$, which is around 10-20% of the total food system GHG emission), while localized biogas digestors do not. Second, *NegativeFirst* also prevents a small proportion of emissions from processing and digesting ancillary biomass in the food system (about 2-5% of the total food system GHG emissions).

Compared to the default *NutrientFirst* pathway, where all nutrients can be recycled yet without negative emissions, we identify the trade-offs between worse nutrient deficit and additional negative emissions in the *NegativeFirst* pathway. For the detailed results of nutrient balance, negative emissions, and bioenergy potential in both pathways, please refer to Table H3 and Table H4 in Appendix H.



(a) Nitrogen balance of all 190 scenarios



(b) *NutrientFirst* pathway

(c) *NegativeFirst* pathway

Figure 19. Changing bioenergy conversion pathways alters global and regional nitrogen balance. (a) is the global nitrogen balance of all scenarios comparing two bioenergy conversion pathways. (b) and (c) are the national distribution of nitrogen balance when the same example strategy switches from (b) *NutrientFirst* to (c) *NegativeFirst* pathway. (The example strategy has organic share: 75%, concentrate feeding reduction: 25%, waste reduction: 0% as annotated in (a)).

4.4 Discussion

4.4.1 Trade-offs and policy implications

Compiling the aforementioned results, we find that there are trade-offs between two different goals: increasing the sustainability of the food system and increasing the ancillary bioenergy potential (for energy provision or for negative emissions). We use three example strategies and their corresponding pathways to illustrate the trade-offs when sourcing a similar range of ancillary bioenergy potential (Figure 20). All three examples lie within ±10% of ancillary bioenergy potential compared to the median value in AR6 illustrative pathways, and the green and blue scenarios have the same ancillary bioenergy potential (65 EJ).

First, there is a clear trade-off regarding nutrient recycling and negative emissions (the middle bar charts from two pathways in Figure 20). This trade-off can be particularly challenging for carbon-neutral scenarios with massive deployment of BECCS. For now, most 1.5/2℃ pathways rely on biomass conversion technologies that barely preserve any nutrients. For instance, over 95% of the latest IPCC AR6 scenarios deploy BECCS for negative emissions (Byers *et al* 2022), in which case all nutrients are lost during the conversion process. Only two mature bioenergy conversion technologies can preserve nitrogen – (1) bioethanol that can recycle only 3% of the nitrogen from its stillage byproduct (Gómez-Monedero *et al* 2018) and (2) biogas via anaerobic digestors that preserve most nitrogen. Unfortunately, these two technologies are unfavorable (biogas is not even viable) in most large-scale carbon-neutral scenarios (Byers *et al* 2022).

Policy-wise, there is so far no regulation on how to convert bioenergy strategically that recycles sufficient nutrients back to agroecology. This could potentially threaten a medium-to-high organic food system in the future, where fewer chemical fertilizers are available. Therefore, such a trade-off implies policy suggestions that bioenergy conversion pathways that allow for maximal nutrient recycling are important not to compromise sustainable agricultural production. We thus urge energy policymakers to consider nutrient deficit when designing the future carbon-neutral energy system, which is subtly connected to the food system via the nutrient cycle. Otherwise, we might achieve carbon neutrality, yet at the cost of deteriorating the food system's sustainability.

Moreover, the sustainable transformation of the food system towards a less animal-based diet and waste reduction may conflict with large-scale ancillary bioenergy provision. Reducing feed from croplands can increase the ancillary bioenergy potential in combination with a low organic food system, yet it reduces ancillary bioenergy production when there is a higher share of organic farming (See the blue and green example scenarios in Figure 20 and the Figure 17). Such a trade-off can be more prominent between waste reduction and ancillary bioenergy provision where there is a negative correlation – less waste reduction is required to ensure a similar ancillary bioenergy availability when the organic share is high (See the yellow and green example scenarios in Figure 20 and Sectio 4.2.2). From a sustainable food system perspective, it is inefficient to keep waste levels or cropland-based livestock numbers high for a higher ancillary bioenergy provision. Importantly, it has to be kept in mind that a change towards less cropland-based livestock results in considerable dietary change (Muller *et al* 2017), which necessitates corresponding consumer-focused strategies for implementation.

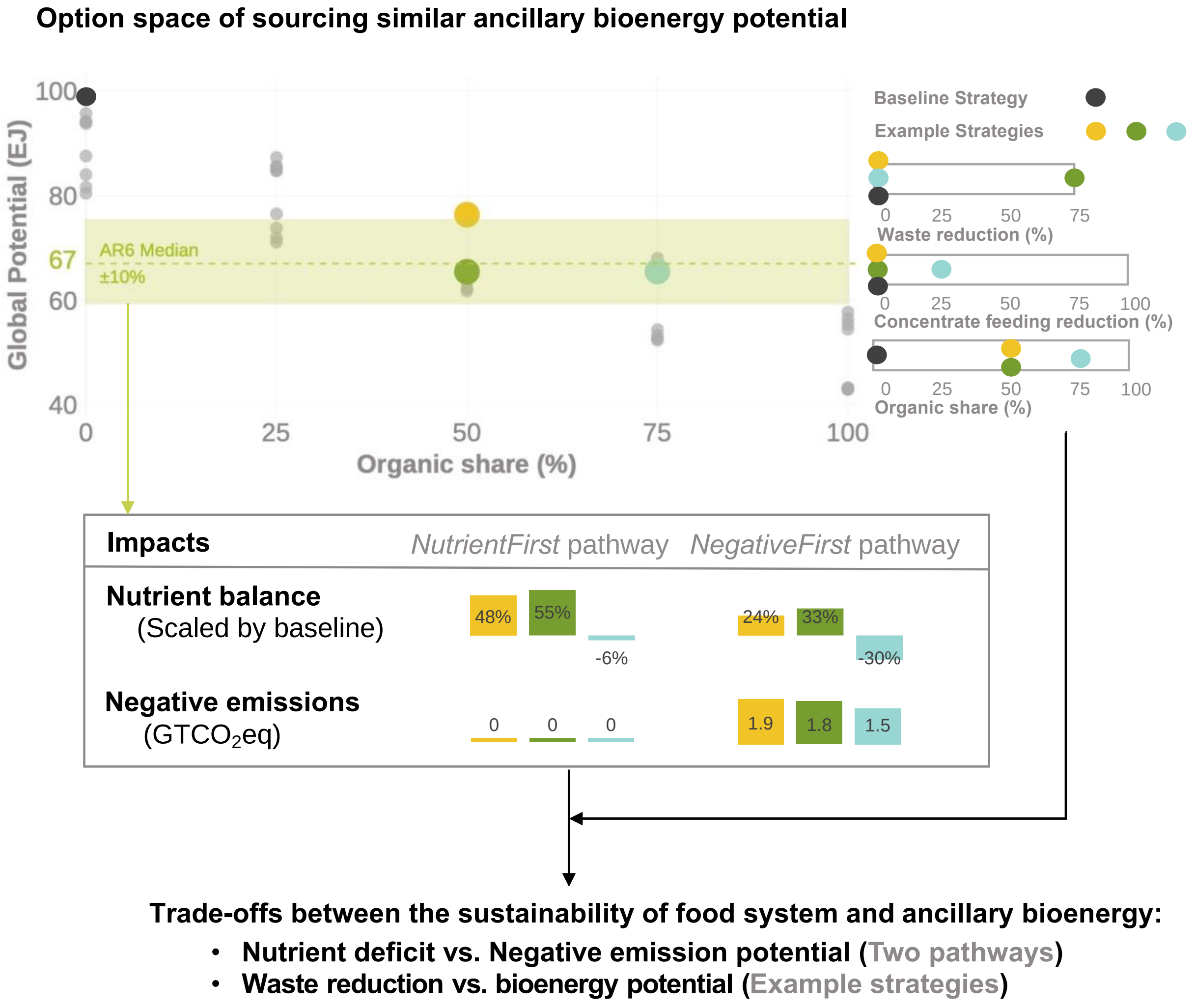


Figure 20. Option space and trade-offs between the sustainable food system and ancillary bioenergy illustrated by three example scenarios. The ”±10% AR6 Median” refers to a ±10% range of 67 EJ, which is the 2050 primary bioenergy supply median value in IPCC AR6 illustrative pathways.

Hence, it is crucial for policymakers to avoid one-sided solutions and consider balanced food and energy policy strategies. For instance, the combinations of intermediate levels in all practices allow to meet potentially conflicting targets while providing a similar range of ancillary bioenergy close to the median supply in AR6 illustrative pathways (Figure 17). This provides timely policy guidance, especially for the European Union, where both the targets of carbon neutrality (by 2050) and organic farming (25% by 2030) are to be met simultaneously (Council 2023).

Lastly, we briefly discuss and summarize the reasons behind the option space and trade-offs. This diverse option space is because the three agroecological practices differ in driving the availability of various ancillary biomass feedstocks (Section 4.2.3), which compensate for each other and result in a similar global potential (Figure 17). The same reason holds for the trade-off between the ancillary bioenergy provision and food system transition. As for the other trade-off of nutrients and negative emissions, the essential reason is more straightforward. With the same amount of bioenergy, food and energy systems tend to prefer different bioenergy conversion technologies – one to prioritize nutrient balance and the other to negative emissions –without considering the other system.

4.4.2 Comparing ancillary bioenergy potential to other studies

Compared to previous studies on the global potential of sustainable bioenergy in 2050, our agricultural ancillary bioenergy availability fits into their average estimated range of 40-160 EJ (Daioglou *et al* 2016, Haberl *et al* 2011, Searle and Malins 2015). Even under medium-high organic scenarios, our 2050 ancillary bioenergy potential can still reach around 60-70 EJ (See Figure 17). This range of ancillary bioenergy potential is very close (±10%) to the median value of the 2050 primary bioenergy supply in the latest IPCC AR6 illustrative pathways (67 EJ) (Byers *et al* 2022), where no organic farming is considered and dedicated bioenergy is included.

Nevertheless, unlike the dedicated energy crops predominantly deployed in these studies, our ancillary bioenergy requires no additional land use. In other words, we find that ancillary bioenergy may have the potential to provide a similar range of renewable energy as estimated in the existing literature, albeit with no land expansion when additional organic farming is in place.

4.4.3 Limitations and future directions

Our research has the following limitations that can be advanced in future studies. Assumption-wise, we model the three central practices of circular agroecology in a simplified way. However, other sustainable food strategies may also indirectly alter the bioenergy potential, nutrient cycle, and emission. For instance, the shift towards more agroforestry practices (Sharma *et al* 2016) and plant-based diets (Aleksandrowicz *et al* 2016) (although our concentrate feeding reduction strategy also leads to fewer animal source products and the corresponding dietary changes). Moreover, we also assume the total land use in the food system to be constant, and we do not consider any marginal land for cultivating dedicated energy crops in order to avoid additional land expansion and to align with the "land-free" principle of ancillary bioenergy. The assumption of constant land use also reflects the necessity that land use must not further increase in sustainable food systems. The focus here is thus on how much ancillary bioenergy is available from sustainable (e.g., also organic) production systems that, in particular, do not use more land than today and less on food security in organic systems (that then may use more land), as e.g., in (Muller *et al* 2017). The results then deliver the viability of scenarios regarding food supply by indicating whether enough calories and protein to feed the whole population are available or not.

The challenge regarding nitrogen deficits in high-organic-share scenarios also relates to how we modeled organic agriculture. We used crop rotations as collected in Barbieri et. al., 2021 (Barbieri *et al* 2021), which could be further optimized by adding off-season legume crops, etc., that would reduce the potential nitrogen deficiency. Due to the lack of data, for instance, regarding their yields and water requirements, this was not included, adopting a rather conservative view regarding organic agriculture.

For the *NegativeFirst* bioenergy conversion pathway, we do not consider the transportation or collection of biomass feedstocks to BECCS plants, as they are beyond our system boundary. We encourage future research to incorporate this biomass supply chain that may cause additional emissions, labor, and energy consumption. Another future research direction could be looking beyond ancillary bioenergy and investigating the dedicated energy crop production in large-scale carbon-neutral scenarios (e.g., IPCC AR5 and AR6), especially on how it interacts with the food system in terms of nutrient requirements and losses, land competition, food availability, and their trade-offs.

4.5 Conclusion

Our results show that there is a diverse option space between the future food and energy systems to supply land-free ancillary bioenergy. By varying the food system from 0% to 100% organic, we can source 40 to 100 EJ ancillary bioenergy (Figure 17), albeit with the issues of nutrient deficiency or food security identified in (Figure 18). Compared to the future supply of bioenergy in IPCC AR6, it is possible to source a similar range of ancillary bioenergy from very different food systems (i.e., 60-70 EJ of ancillary bioenergy when it is 25% to 75% organic and various shares of waste and concentrate feed reduction). This range is about ±10% of the median primary bioenergy supply in IPCC AR6 illustrative pathways, although they include dedicated biomass and do not consider organic farming. The negative emission potential ranges from 1.4 to 2.6 $GTCO_2eq$ across this option space. Thus, ancillary bioenergy has considerable potential to contribute to bioenergy futures while not compromising sustainable food systems.

For this, it is however important to hedge against the most challenging trade-offs, and balanced policy strategies for ancillary bioenergy provision and sustainable agriculture are needed, avoiding one-sided solutions. The following key messages can help to support this, as illustrated also in Figure 20. First, there is a trade-off between sustainable agricultural production and ancillary bioenergy production regarding nutrient recycling and supply (both national and global, as depicted in Figure 19). Bioenergy pathways that allow for maximal nutrient recycling are important not to compromise sustainable agricultural production. This is a particular challenge for bioenergy scenarios with negative emissions, as these energy conversion pathways go along with low or absent nutrient recycling. Second, reducing feed from croplands increases the potential for ancillary bioenergy production in combination with low organic agriculture and reduces it for high shares of organic agriculture. Hence, the thorough transformation of the food system and dietary patterns towards animal source food reduction as required for sustainable food systems may conflict with large-scale ancillary bioenergy provision. Third, waste reduction, another key strategy in circular sustainable food systems, negatively correlates with ancillary bioenergy provision. Finally, from a sustainable food systems perspective, it is inefficient to keep waste levels and cropland-based livestock numbers high for higher ancillary bioenergy provision. Given the sustainability impact of current food systems and the envisaged role of ancillary bioenergy in future energy systems, it is thus important to align ancillary bioenergy provision with what is compatible with sustainable food systems and not to maximize ancillary bioenergy supply to only then adjust food system sustainability.

5 Discussion and Conclusion

5.1 Contributions to the literature

The contributions of this thesis to the field of bioenergy research can be summarized into three categories, namely empirical, data, and modelling contributions as below. Each publication contributes to one or more of them as listed in Table 11.

5.1.1 Empirical contributions

There are three sequential empirical contributions to the existing literature of sustainable bioenergy. First, there is no consensus on the definition of “sustainable bioenergy” in the current literature and policy framework. The inconsistent assumption of sustainability impedes the comparison and interpretation of bioenergy modelling results, causing the mismatch between policy and models (as identified in Section 2.4.2). However, land uses and food/feed competition are in the center of most debates (Section 2.5). This thesis thus contributes to the definition of “sustainable bioenergy” by proposing a stricter concept of “ancillary bioenergy” that is free from any land/food/feed conflicts (Section 2.3.3.3). I then advance the definition of ancillary bioenergy by identifying, reclassifying, and quantifying the untapped by-/co-products of biomass with high energy density (Section 3.3.1).

Second, this thesis unravels the strategic roles of ancillary bioenergy in a future carbon-neutral and fossil-free energy system (Section 3.3.2). Although the land-free ancillary bioenergy has a more limited potential than the “sustainable bioenergy” in mainstream models (Figure 10), it can play different strategic roles when it is fully, optimally, or not utilized. Its full utilization can help phase out controversial nuclear or land-intensive dedicated biomass at a similar total system cost, so might achieve higher societal acceptability (Figure 13). It is also possible to leave the ancillary bioenergy potential completely unused, which barely increases total system cost, but would preserve agricultural nutrients (Figure 14). This empirical contribution can support national and European-wide stakeholders planning the missing goals of long-term bioenergy deployment.

Third, I identify and bridge the missing link between sustainable energy and food systems via ancillary bioenergy provision (Section 4). Sustainable bioenergy plays a role in both energy and food systems, yet each system is transforming towards sustainability without potential interactions with each other that are unexplored in the literature or covered in policy. I contribute to this field by identifying the option space and trade-offs of bioenergy provision when the food system becomes more circular and sustainable. This contribution thus reveals the embedded impacts of bioenergy provision on the food system, and vice versa. I find that negative emissions and nutrient recycling are the most prominent trade-off when sourcing ancillary bioenergy from the food system, which is ignored in most energy system models or integrated assessment models.

5.1.2 Data contributions

This thesis has two major data contributions to the energy system modelling and food system modelling field. First, for the energy system, I contribute the first open dataset of future ancillary biomass potential from untapped and detailed feedstocks and convert them into unified energy units by pairing their heat values (Wu 2022). This dataset consists over 120 types of biomass feedstocks data at national resolution in 2050 Europe. Second, for the food system, Section 4 contributes the open dataset of 190 different global food system designs and the correspondingly global potentials of ancillary bioenergy as well as the environmental impacts (Wu and Muller 2023). These open data datasets contribute to the bioenergy modelling community via free, open, and reproducible new data sources.

5.1.3 Modelling contributions

Built on the empirical and data contributions, I further contribute to the bioenergy modelling both for energy and food system modelling. On the one hand, I advance the sector-coupled European energy system optimization model (Euro-Calliope) with the detailed representation of bioenergy feedstocks at the national level that are paired with the compatible conversion technologies (See the open-source repository of AB-Euro-Calliope (Wu 2022). With the help of the documented scenario assumptions and overrides files, one can easily reproduce or build their own bioenergy scenarios – e.g., constraining the capacity of biomass distribution network in certain regions of interest or modify the transport cost. For the food system, Section 3 and 4 update the food system model SOLm by implementing the new module of modelling the land/food/feed-free ancillary bioenergy. On the one hand, we model the bioenergy provision (for the energy system) and capture the altered food system sustainability when 190 agroecological designs are in place. On the other hand, we also update SOLm by capturing how different bioenergy conversion pathways (from the energy system) impact the nutrients recycling and GHG emissions in the food system (Section 4.2.3).

Table 11. List of contributions related to each section in the thesis.

Contribution	**Methods**	**Contributions to the field**		
		Empirical	**Data**	**Modelling**
I	Literature review	Identifying the challenges and opportunities of bioenergy deployment and correspondingly proposing the stricter concept of “ancillary bioenergy”, which is free from land-use, food, or feed conflicts	/	/
II	Euro-Calliope (Energy system optimization))	Depicting the strategic roles of ancillary bioenergy by sectors, regions, and infrastructure	Open datasets of future European ancillary biomass potential from untapped and detailed feedstocks (Wu 2022)	Open-source model AB-Euro-Calliope with the detailed representation of national bioenergy supply paired with conversion technologies (Wu 2022)

III	SOLm (Mass-flow food system modelling)	Unraveling the unexplored option space between energy and food systems and their trade-offs via bioenergy provision	Open datasets of global potentials of ancillary biomass when 190 different agroecological policies are in place (Wu and Muller 2023)	New coding modules and scenario assumptions of modelling ancillary bioenergy in SOLm (Modelling results are available in (Wu and Muller 2023))

5.2 Policy implications

This thesis has specific policy implications for the European Union, particularly from the case studies in Contribution I and II. The thesis identifies the main challenges faced by the EU bioenergy development (as detailed in Section 2.4), and the policy implications for utilizing ancillary bioenergy (see Section 3.4), of which the most crucial ones are discussed here.

First, the current EU bioenergy policy lacks coherence and clarity, particularly in the interpretation and implementation of "sustainable bioenergy," where land-use change remains to be the key element. Additionally, bioenergy has an increasing share in realizing a carbon-neutral and highly renewable Europe while its sustainability criteria has become stricter, potentially leading to a mismatch between the decreasing supply and increasing demand for bioenergy. In view of these entangled challenges of “sustainable bioenergy”, this thesis proposes a land-free alternative – “ancillary bioenergy” – that is sourced from biomass not primarily grown for energy and without land/food/feed competition. The strategic use cases of ancillary bioenergy provide insights for its potential sustainable roles while minimizing land-use changes and land-energy trade-offs.

Second, this thesis also provides implications on how to improve EU bioenergy policy coherence, considering both the sector-coupling of energy system and the integration of food system. The sector-coupling of energy system can provide a more holistic picture to help local policymakers answer systematic questions, like when, where, and how to best utilize what bioenergy. Sector-wise, industry makes the most sense to utilize ancillary biomass (Figure 12). Spatial-wise, compared to hydrogen in producing synthetic fuels, ancillary bioenergy is the most attractive for producing diesel in central Europe and the Nordic region when a distribution network exists. Hydrogen remains more attractive over biomass in producing methane and kerosene in every European country, regardless of infrastructure. Overall, the identified synergies and trade-offs of different bioenergy use cases can inform policymakers about the potential gains and loss of alternative futures (as listed in Table 10).

This thesis also offers policy implications on a global scale, particularly concerning the integration of energy and food policies. The identified option space allows policymakers to explore the potential economic/environmental/emission impacts of different policy mixes (Figure 20). This option space also implies the trade-offs between enhancing the sustainability of the food system and maximizing ancillary bioenergy potential for energy provision or negative emissions. Currently, there is a lack of policy/regulations guiding strategic bioenergy conversion that considers optimal nutrient recycling. To avoid compromising food sustainability, policymakers should consider bioenergy conversion pathways that allow nutrient recycling. We urge policymakers to consider nutrient deficits when designing carbon-neutral energy systems, highlighting the possible connection to the food system through the nutrient cycle. By addressing these gaps, policymakers can foster more holistic and effective approaches to the interplay between energy and food sectors, fostering sustainability and strategic utilization of bioenergy.

5.3 Limitations and outlook

As the closure of this thesis, I outline the overall methodological limitations and discuss the potential research topics that can be extended in the future. Since each individual paper has presented its unique limitation and outlook, here I focus more on the integrated outlook considering all papers together and briefly summarize the overarching limitations of this thesis.

5.3.1 Limitations

Overall, there are three major limitations in modelling the sustainable role of bioenergy throughout the thesis – (1) cascading uses of biomass, (2) land-use change assumptions, and (3) the simplification of biomass potential.

First, there are cascading uses of biomass other than the energy purpose modelled in this thesis – e.g., chemical products or materials (both in Contribution II and III). Cascading uses refer to the efficient utilization of recycled/residual biomass for material use to extend the total resource availability (BTG *et al* 2016). For instance, we can first use the residual woody biomass for producing paper and then for energy rather than using it straight for energy to extend its total availability. There is guidance on the cascading use of woody biomass feedstocks (e.g., the best practice in the EU (Directorate-General for Internal Market 2018)), however, there is no consensus on the cascading uses of specific residual biomass from agricultural or municipal sources. The absence of cascading assumptions can impact the modelled biomass availability which assigns more biomass for energy that could be better used for other cascading uses. Therefore, I adopt a more conservative and generic assumption to assign as much biomass for cascading uses as possible. For example, I assume 42.5% primary crop residues as loss and cascading uses in the food system, (Table G1). Also, I disable all the woody biomass that could be used for materials to enter the energy system. My conversative assumption of cascading uses can lead to a lower bioenergy potential, so the modelled ancillary bioenergy potential can be higher when more specific cascading data are available.

Second, ancillary bioenergy is land-free itself. However, there are possible land-use changes associated with (1) other renewable energy technologies (Contribution II) and (2) within the food system when we model different agroecological practices (Contribution III). On the one hand, for the energy system, there are only two technologies assumed to have an exogenous land-use footprint – onshore wind turbines and open-field PV (Table 7 in Contribution II). Besides, the model Euro-Calliope does not specify where the land-use change should happen within the country/modelled polygon. Therefore, our energy scenarios still imply land-use change, although this is not from bioenergy. To better verify the feasibility/constraints of these land-use changes, one could overlay the land-use map with the modelled capacity, although the land uses remain uncertain towards 2050 in any case. One possibility could be matching the spatial data of marginal land with the modelled renewable capacity. On the other hand, the food-system study assumes the total land use to be constant in all scenarios (Section 3.2.5 in Contribution III). This principal assumption ensures that there is no land expansion, but it can come at the cost of lower food availability that is outside the research scope but could be improved by future research. For example, one could run another set of same scenarios by constraining food availability and allowing land expansion.

Third, there are simplified assumptions regarding the potential of biomass in terms of its energy potential and negative emission potential. Energy-potential-wise, I simplify the supply chain of biomass – collection, pretreatment, storage, and distribution – by using an aggregated cost estimation per biomass supply capacity (e.g., 27.78 €/MWh for crop residues; Appendix B). Then I use sensitivity analysis to show how higher costs or lower bioenergy potential would slightly change the modelling results (Table F2). However, I do not consider the labor costs or additional emission along the supply chain, which can impact the bioenergy availability or its negative emission potential. Emission-wise, the lack of soil carbon in the food model SOLm can also alter the emission potential of ancillary bioenergy. This can impact the nitrogen circle at the same time as soil carbon sequestration requires nitrogen, which further consumes nitrogen inputs in the food system and can reduce the nitrogen sufficiency in our modelling results. I further discuss how future research can help improve the representation of soil carbon in the next section.

5.3.2 Outlook

Considering the aforementioned limitations, there is a compelling need for future research to broaden the research scope and enhance the understanding of modeling sustainable bioenergy. First, the next step following the modelling studies in this thesis could be engaging with stakeholders to bridge the gaps between idealized models and the reality, especially in less developed agricultural regions like Africa and Brazil, where the data availability and consistency is more limited.

Second, the absence of soil carbon in the SOLm model introduces uncertainty about its potential impact, both in terms of carbon and nitrogen circles. Nitrogen, crucial for sequestering soil carbon, involves complex interactions within the food system and might imposes further trade-off with negative emissions. Future research could examine other nitrogen fixing strategies, like incorporating legume crops that might address nitrogen deficits.

In addition to land-free ancillary bioenergy, the further investigation into dedicated bioenergy with carbon capture and storage (BECCS) involving marginal land utilization, and the associated nutrient flows can provide a more diversified policy implication. The integration of BECCS can critically reflect on the prevailing climate pathways (e.g., IPCC AR6 where over 95% scenarios deploy BECCS to reach 1.5 or 2℃ targets) where massive dedicated bioenergy crops are necessary for climate-neutrality, but its impact on the food system sustainability remains unknown. The potential research agenda includes, for instance, the altered nutrient circle in different BECCS pathways and its interaction with organic agriculture.

Lastly, expanding the focus beyond biomass, there is a need to identify and understand other resources constraining the sustainable energy transition, considering factors such as critical raw materials. Designing energy systems embracing more resource sustainability and resilience emerges as a vital avenue for future research.

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Supplementary material to contribution II

The reproducible model and code used in this study is available online:

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Appendix A: Ancillary biomass potential data

In contrast to “2^{nd} generation bioenergy” or “waste-to-energy”, ancillary bioenergy refers to all non-dedicated biomass, that is, residues, by-/co-products, and waste, from human settlement, agriculture, and forests, where there is no land-use or food competition. We use this definition to compile the data on ancillary biomass potential. In addition to excluding first-generation or dedicated bioenergy feedstocks (e.g., energy crops or short-rotation forests), it is vital to identify untapped by-products with high energy density that are not explicitly available from previous studies (e.g., animal fats and nutshells with high energy density). Although there is detailed data of forestry and municipal ancillary biomass, the agricultural ancillary biomass potential is unknown in 2050, especially for the agricultural by-products. Therefore, we use SOLm and its FAO 2050 Business-as-usual scenario (Muller *et al* 2017) to model the agricultural ancillary biomass potential. The key assumption is to extract ancillary biomass without compromising the agricultural and food system – i.e., using only the non-food/feed shares of (1) by-/co-products, (2) crop residues, and (3) animal manure and keep enough soil fertility.

More specifically, (1) for agricultural by-/co-products during food processing, we identify nuts shells and animal fats & oil with high energy density and use only their non-food/feed competing shares (Table A3). (2) For primary agricultural residues, we embrace a much wider and more detailed category of crop types than previous studies (114 types in our study compared to 11 types in other studies, as in Table A1). To set aside enough agricultural residues for retaining soil fertility, we assume 50% is left on or returned to the fields (implicitly also allowing for the share to be used as bedding materials, which later can return via manure), and hence only 50% is for energy use). Our conservative removal rate (50%) equals the European average value that the sustainable removal rates vary from 35% to 90% per feedstock (Panoutsou 2021). (3) For animal manure, we use only 75% of all dry and wet manure and keep the nutrient balance, livestock system, and food/feed system unchanged.

We then convert all manure into dry matter quantities, which does not change the energy content but assumes the same transportation costs of all manure feedstock (Table A2). For the sustainable removal rates of residues and manure, we take an average of 50%

For a detailed description of how SOLm deals with left-on-field residues and by-products for feeding, please refer to its latest documentation (Müller *et al* 2020). In this way, we can assume that our ancillary biomass potential avoids food/feed and land-use competition, and insufficient nutrient cycles at our best efforts, allowing us to define this as a sustainable ancillary bioenergy potential.

For forestry and municipal waste, there is in principle no food/feed/land conflicts when we only source forestry residues, by-products, and municipal solid waste, and the ancillary biomass potential is readily available from JRC-EU-TIMES (Ruiz et al 2015). Specifically for the forestry sector, we only use the forestry residues and by-products (sawdust and woodchips) – excluding roundwood, stem wood, and other dedicated biomass/commodities, which might have prior uses for high-value biochemicals, materials, or manufacturing products (Dessbesell et al 2017). Therefore, we adopt this part of forestry and municipal biomass potential from the low availability scenario results (ENS-Low) from JRC-EU-TIMES (Ruiz et al 2015). By adopting this conservative estimation of sustainable potential, we can ensure it is most consistent with our agricultural ancillary biomass potential from SOLm's FAO BAU 2050 scenario. Note that even when we take the most conservative estimation of forestry and municipal ancillary biomass, they still account for around one third of the total potential. This ratio is even higher in Nordic countries which have abundant forestry resources (see Figure D1 for national potential of sector-wise ancillary biomass).

There is only one exception of allowing non-ancillary (or dedicated) biomass in our *DedicatedBiomass* scenario as comparison, where we enable the sustainable potential of miscanthus with additional land use (1096 PJ/year; using the same low availability scenario results (ENS-Low) from JRC-EU-TIMES) (Ruiz *et al* 2015)..

The aforementioned procedures are for the sustainable potential estimation. For the technical potential, we use the high availability scenario results (ENS-High) from JRC-EU-TIMES for forestry and municipal ancillary biomass. Then we add the agricultural part from SOLm without saving any residues on field (i.e., 0% are left on field) as the technical potential of ancillary biomass. Note that we only use the sustainable potential for energy system modelling, while the technical potential is for the cross-model comparison in Section 3.1.

Based on these ancillary biomass potential data (dry matter in mass flows, unit: ton), we then convert them into energy flows according to their different energy density per commodity. For agricultural feedstocks, we use the low heating values (unit: MJ/kg) from the Phyllis2 database (TNO Biomass and Circular Technologies 2022); for forestry and municipal sources, we use the ones from JRC-EU-TIMES for consistency (unit: MWh/Ton). Finally, we convert all ancillary biomass potential data into energy flows and feed them into the AB-Euro-Calliope.

Table A1. Agricultural primary residue from crops and their Nitrogen contents modelled in this study by SOLm model compared to those in JRC-EU-TIMES.

No.	**11 general types from JRC-EU-TIMES** (Ruiz *et al* 2015)	**114 types modelled in this study**	**2050 Sustainable Potential, this study (Ton in Dry Matter)**	**Nitrogen contents, this study (Ton)**
1	Apples and pears	Apples	31810.03	21.63
2	Citrus	Anise, badian, fennel, coriander	1308.09	8.63
3	Cereal straw	Almonds, with shell	2263.58	5.66
4	Cherries and other soft fruits	Apricots	1345.14	0.91
5	Grass and maize for biogas	Artichokes	872.67	2.61
6	Olives and olives pits	Asparagus	390.23	1.17
7	Oils seeds rapes and sunflower	Avocados	73.48	0.05
8	Rice straw	Bananas	216.61	0.15
9	Sugar beet	Barley	525977.05	3129.56
10	Stubbles	Beans, dry	4822.16	40.99
11	Vineyards	Beans, green	14275.76	74.92
12		Beets For Fodder	3225.01	11.27
13		Berries nes	153.84	0.18

14	Blueberries	60.48	0.07
15	Broad beans, horse beans, dry	17060.88	116.01
16	Buckwheat	1909.90	4.77
17	Cabbages and other brassicas	10171.33	30.41
18	Canary seed	49.93	0.32
19	Carobs	64.98	0.04
20	Carrots and turnips	10881.80	32.54
21	Cauliflowers and broccoli	3586.43	10.72
22	Cereals, nes	14563.61	112.14
23	Cherries	1388.28	0.94
24	Cherries, sour	395.27	0.27
25	Chestnut	895.80	8.96
26	Chick peas	885.85	6.02
27	Chicory roots	717.79	2.15
28	Chillies and peppers, dry	118.52	0.35
29	Chillies and peppers, green	3534.40	10.57
30	Cow peas, dry	510.44	3.47
31	Cranberries	1.04	0.00
32	Cucumbers and gherkins	4493.51	13.44

33	Currants	344.03	0.41
34	Dates	15.36	0.01
35	Eggplants (aubergines)	1077.69	3.22
36	Figs	92.31	0.06
37	Fruit, citrus nes	43.53	0.03
38	Fruit, fresh nes	599.20	0.41
39	Fruit, stone nes	44.62	0.03
40	Fruit, tropical fresh nes	38.08	0.03
41	Garlic	423.63	1.27
42	Gooseberries	113.08	0.14
43	Grain, mixed	34063.59	262.29
44	Grapefruit (inc. pomelos)	85.48	0.06
45	Grapes	31047.68	37.26
46	Groundnuts, with shell	88.81	1.21
47	Hazelnuts, with shell	913.00	2.28
48	Hempseed	895.34	5.73
49	Hops	325.55	2.15
50	Kiwi fruit	535.62	0.36
51	Leeks, other alliaceous vegetables	1859.70	5.56
52	Lemons and limes	1099.34	0.75

53	Lentils	899.61	6.12
54	Lettuce and chicory	8268.72	24.72
55	Linseed	7198.85	46.07
56	Lupins	500.07	17.51
57	Maize	607072.18	3096.07
58	Maize For Forage+Silage	27648.57	104.40
59	Melons, other (inc.cantaloupes)	1735.55	5.19
60	Millet	1304.96	7.76
61	Miscanthus	0.00	0.00
62	Mushrooms and truffles	575.26	1.72
63	Mustard seed	640.57	4.10
64	Nuts, nes	99.75	0.84
65	Oats	76163.29	453.17
66	Oilseeds nes	3948.68	25.27
67	Okra	15.10	0.05
68	Olives	133351.46	333.38
69	Onions, dry	7965.90	23.82
70	Onions, shallots, green	2763.07	8.26
71	Oranges	5562.94	3.78
72	Peaches and nectarines	3067.09	2.09

73	Pears	6821.49	4.64
74	Peas, dry	59312.56	403.33
75	Peas, green	15141.91	79.46
76	Peppermint	8.96	0.06
77	Persimmons	156.63	0.11
78	Pineapples	1.98	0.00
79	Pistachios	82.83	0.21
80	Plums and sloes	2863.18	1.95
81	Poppy seed	2505.43	16.03
82	Potatoes	88453.38	218.48
83	Pulses, nes	12296.77	83.62
84	Pumpkins, squash and gourds	2520.80	7.54
85	Quinces	98.39	0.07
86	Rapeseed	426310.41	2572.78
87	Raspberries	424.63	0.51
88	Rice, paddy	25848.45	232.64
89	Roots and tubers, nes	21.28	0.06
90	Rye	88955.08	378.06
91	Safflower seed	447.86	19.17
92	Seed cotton	16738.82	41.85

93	Sesame seed	50.37	0.32
94	Sorghum	5310.46	13.28
95	Soybeans	27161.21	184.70
96	Spices, nes	79.75	0.53
97	Spinach	1749.16	5.23
98	Strawberries	1668.14	2.00
99	String beans	3557.80	18.67
100	Sugar beet	233601.57	665.76
101	Sugar cane	8.51	0.10
102	Sunflower seed	125982.70	1133.84
103	Tangerines, mandarins, clementines, satsumas	2806.64	1.91
104	Taro (cocoyam)	1.44	0.00
105	Tea	0.31	0.00
106	Tobacco, unmanufactured	6146.00	40.56
107	Tomatoes	6073.85	18.16
108	Triticale	136509.14	696.20
109	Vegetables, leguminous nes	2419.78	12.70
110	Vetches	1156.24	7.86
111	Walnuts, with shell	5177.75	43.49
112	Watermelons	3032.13	9.07

113	Wheat	1480885.16	7552.51
114	Yams	0.20	0.00
Total (Ton)		4412900.33	22605.97
Total (kiloton)		4412.90	22.61

Table A2. Agricultural manure (Dry matter) modelled in this study by SOLm model.

No.	**Livestock types**
1	Buffaloes
2	Cattle
3	Chickens
4	Goats
5	Pigs
6	Sheep
7	Pigeons, other birds
8	Geese and guinea fowls
9	Rabbits and hares
10	Turkeys

Table A3. Agricultural by-products modelled in this study by SOLm model (16 types of shells and 3 types of animal fats and oil).

No.	By-products types
1	Almond shells
2	Apricot kernel shells
3	Cherries – kernels
4	Groundnut shells
5	Hazelnut shells
6	Peaches and nectarines – kernels
7	Pistachio shells
8	Plums and sloes – kernels
9	Pressed olive residues
10	Walnut shells
11	Apricot kernel shells
12	Cherries – kernels
13	Cherries, sour – kernels
14	Peaches and nectarines – kernels
15	Plums and sloes – kernels
16	Walnut shells
17	Fish, Body Oil
18	Fish, Liver Oil

19	Offals

Table A4. Ancillary biomass categories and sources considered in this study.

Sectors	**Ancillary biomass feedstocks**	**Sustainable potential**	**Technical potential**	**Convertible bioenergy carriers**
Agriculture	Agricultural crops primary residues	SOLm (2050 BAU scenario) *50% (50% left on fields)	SOLm (2050 BAU scenario)	Methanol, methane
	Animal manure	SOLm (2050 BAU scenario) *75% (25% left on fields)	SOLm (2050 BAU scenario)	Methane, electricity
	By-product animal fats and oil	SOLm (2050 BAU scenario)	SOLm (2050 BAU scenario)	Kerosene, diesel
	By-product shells	SOLm (2050 BAU scenario)	SOLm (2050 BAU scenario)	Diesel, methanol, methane, heat, electricity
Forestry	Residues and by-products (sawdust and wood pellets)	JRC (Low availability scenario) (Ruiz *et al* 2015)	JRC (High availability scenario) (Ruiz *et al* 2015)	All (i.e., electricity, heat, and four biofuels – diesel, kerosene, methanol, and methane

Human settlement	Municipal solid waste	JRC (Low availability scenario) (Ruiz *et al* 2015)	JRC (High availability scenario) (Ruiz *et al* 2015)	Heat, electricity

Table A5. Agricultural ancillary bioenergy potential modelled in this study compared to the non-dedicated bioenergy in JRC-EU-TIMES.

Ancillary biomass considered in this study	FAO 2050 Business-as-usual scenario from SOLm model (TWh)	Low availability scenario from JRC-EU-TIMES (TWh)	Non-dedicated biomass considered in JRC
Agricultural crops on-site residues (50% availability; see Table A1 in Appendix for 120 crop types modelled); same category as in FAOSTAT[1]	292.54	156.69	Primary agricultural residues comprising 11 general types (see Table A2 for detailed comparison)
Manure without changing nutrient cycle, livestock system, and food/feed system (75% availability; see Table A2 for the 10 livestock types modelled)	26.69	176.69	All manure produced on farms with >500 livestock units (Ruiz *et al* 2015)
By-product animal fats and oil (see Table A3 for 3 types modelled)	4.27	None	-
By-product shells (see Table A3 for 16 types modelled)	46.40	None	-

Total	369.90	333.38	Total

Table A6. Comparing the non-dedicated agricultural biomass potential data and assumptions in the literature.

	Total non-dedicated agricultural biomass in Europe (2050)	**Food/feed conflicts ruled out?**	**Nutrients preservation considered?**	**Potentially mixed energy properties?**	**Additional by-/co-products?**
This study	103 PJ	Yes	Yes	No	Yes (19 types of nuts shells and animal fats & oil)
(Ruiz et al 2015)	92 PJ	No for residues (Secondary residues can be used for feed, e.g., soybean cakes)	Not mentioned	Yes (Aggregated first and secondary residues)	Not mentioned
(Panoutsou 2021)	291 million tonnes	Yes	Partially (Yes for crops but not mentioned for manure)	Yes (Aggregated industrial residues including both animal and plant-based biomass)	Only animal fats (No nut shells data)
(Daioglou et al 2016)	No country-level or European data	Yes	Partially (by replacing nutrients with fertilizer)	Yes	Not mentioned

				(Aggregated first and secondary residues)	
(Elbersen and Voogt 2020)	No complete European data	Not mentioned	Not mentioned	Yes (Aggregated first and secondary residues)	Not mentioned

Appendix B: Ancillary bioenergy costs and technologies data

There are three types of bioenergy costs considered in this study (i.e., supply, conversion, and distribution). First, we assume the ancillary biomass supply is free of charge, as they are either left to be wasted or of little value by definition. But their collection and logistics costs still matter. We adopt the cost estimation for manure supply as 3.36 €/ton from the Danish energy agency (Danish Energy Agency 2019). For the other feedstocks, there is no specific estimation available – we use 27.78 €/MWh as adopted in JRC-EU-TIMES (Ruiz *et al* 2015). As collecting extra by-products and agricultural residues would increase labour fees or may cause supply chain loss, we further explore how the potentially higher supply cost and slight lower potential of biomass may change our modelling results (Table F2).

Secondly, we deploy bioenergy conversion technologies and pair them with the compatible types of ancillary biomass (see the convertible bioenergy carriers in Figure 1). Based on the 2050 costs estimation from Danish energy agency (Danish Energy Agency 2019), we update the Sector-coupled Euro-Calliope with 14 bioenergy conversion technologies (Table B1).

The third type of cost is for distributing synthetic liquid fuels among European countries (i.e., methanol, diesel, and kerosene; we assume no methane gas pipelines as a simplification). Meanwhile, we do not assume any international transport of ancillary biomass feedstock to minimise its supply cost and carbon emissions. In other words, biomass feedstock cannot be transported, but biomass- or hydrogen-derived synthetic liquid fuels (methanol, diesel, and kerosene) can be transported.

This additional biofuel distribution network is enabled in the "*BioDistribution*" scenarios to model how transport availability would alter ancillary bioenergy utilisation. We assume that this network connects neighbouring European countries using road/rail transport. To include the distribution costs, fuels, and emissions, we use the carbon-neutral synthetic fuels produced in departure regions to fuel the transport (1.23 L diesel per km per ton) (Ruiz *et al* 2015). More specifically, we use the constraints of costs and fuels consumed per distance per MWh to represent the distributing costs and energy consumption. The distributing cost and efficiency vary depending on different supply chain modes. There are two common supply chain modes for liquid synthetic fuels ((1) telescope loaders, trucks, and trailers for 0.34 €/km/ton; (2) wheel loaders and trucks for 0.64 €/km/ton) (Ruiz *et al* 2015). We adopt the more expensive one as a conservative estimation, although the cheaper distribution network does not significantly change total system costs or bioenergy consumption (i.e., within 0.1%). This distributing network is disabled in our reference scenario, where every country must be self-sufficient for ancillary bioenergy.

Table B1. Biomass conversion technologies implemented in this study. Costs and efficiency data is from the Danish Energy Agency technology catalogue 2019 (Danish Energy Agency 2019). BECCS data is from the model inputs of TIAM-Grantham (Grant et al 2021). Detailed parameters are available in the model files. Note that these technologies are different from the biomass-related technologies in the original Euro-Calliope.

	Technology	**Main Inputs**	**Main outputs**	**Capital Cost (M€2015/MW_output)**
Biofuels	Biofuel to liquid fuels converter	Forestry biomass	Diesel / Kerosene	3.46
	Biofuel to vehicle fuel converter	Forestry biomass / Shells	Diesel / Kerosene	0.93
	Biofuel to methanol converter	Forestry biomass / Shells / Agricultural residual biomass	Methanol	1.46
	Biofuel to methane converter	Forestry biomass / Shells / Agricultural residual biomass	Methane	1.5
	SNG from biogas	Biogas (from manure)	Methane	0.45

	Diesel from animal fats & oil	Animal fats & oil	Diesel	0.84
	Diesel from animal fats & oil and hydrogen	Animal fats & oil & Hydrogen	Diesel	0.58
	Jet fuel from animal fats & oil and hydrogen	Animal fats & oil & Hydrogen	Kerosene	0.71
Heat and Electricity	Biogas engines (spark ignition)	Biogas (from manure)	Electricity	0.85
	Biomass boiler	Forestry biomass / Shells	Heat	0.445
	Combined heat and power plants	Forestry biomass / Shells	Electricity / Heat	0.52
		Methane		1.1
		Municipal solid waste		7.3
BECCS[1]	Combustion of biomass with CCS	Forestry biomass / Agricultural residual biomass / Manure / Shells / Animal fats & oil	Electricity	3.93

Fischer-Tropsch Diesel from biomass with CCS	Forestry biomass / Agricultural residual biomass / Shells	Diesel	2.62

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[1] Disabled by default. Only available in scenarios *AllBECCS* and *NoNuclear+AllBECCS* as a counterfactual comparison.

Appendix C: Land use, nutrients, and emissions estimation

First, for land use estimation, there are two aspects. Amongst electricity generation technologies we assume only onshore wind turbines and open-field PV have a measurable land use footprint (onshore wind turbines: 0.125 km^2/MW and open-field PV: 0.0125 km^2/MW) (Pickering *et al* 2022). Our ancillary bioenergy resource has “zero” land use in the sense that it is a by-product, and so do the other renewables sources. The only exception is the *DedicatedBiomass* scenario where we add miscanthus as a comparison to ancillary bioenergy. Miscanthus is a dedicated short rotation grass which is frequently modelled as a sustainable and advanced source of biomass in mainstreaming IPCC 1.5C scenarios, e.g., illustrative pathways in the recent AR6 report (Soergel *et al* 2021, Luderer *et al* 2022). We take its 2050 European potential (1096 PJ/year; heating value as 12.54 TJ/ton) from the low availability scenario of JRC-EU-TIMES (Ruiz *et al* 2015). For estimating its land use, we base its 2050 productivity in Europe (16.332 t DM/ha) from MAgPIE (Soergel *et al* 2021), which leads to its land use of 5351 ha, or 53.51km^2.

Second, to estimate nutrient loss, we make a counterfactual estimation for the agricultural residues that can be left on fields as compost without additional cost. We extract their nitrogen (N) and phosphorus (P) contents from SOLm (Table A1). Then we multiply their nutrient contents by the percent of biomass incinerated as the nutrient loss (i.e., we consider all nutrients as fully lost during biomass incineration, but not for biogas composition / anaerobic digestion). We assume that these nutrients could have been fully preserved if they were left on agricultural fields for soil fertility. Note that this is a conservative estimation, and the actual nutrient loss could be higher as we do not account for the other biomass that could not be left on the agricultural fields for composition within a year (i.e., forests, human settlement, nuts shells, and animal facts). The corresponding reasons including that (1) it takes longer than a single year to decompose forestry residues, which is beyond our modelling time span; (2) all municipal solid waste is assumed to be incinerated in all cases anyway; (3) it requires additional procedures and costs for composting animal facts and shredding nut shells other than just leaving them on fields. Moreover, it usually takes more than a single year as well to compost woody-like nut shells.

Table C1. Negative emission potential of using all ancillary bioenergy for BECCS.

Feedstocks	**Default emission factors (gCO2eq/MJ)**		**CO2 capture rates (%)**	**Negative emissions potential (Mtons CO2eq per year)**	
	Lower bound	**Higher Bound**		**Lower bound**	**Higher Bound**
Animal manure	1	7	0.995	0.96	6.69
Agricultural crops primary residues	4	32	0.995	41.92	335.32
By-product animal fats and oil	8	13	0.9	1.11	1.80
By-product shells	4	32	0.9	6.01	48.10
Residues and by-products (sawdust and wood pellets)	36	42	0.9	203.12	236.97
Total	**-**	**-**	**-**	**253.10**	**628.88**

Third, we estimate the additional negative emissions potential that could be achieved through BECCS by using all ancillary biomass at stationary power plants or Fischer-Tropsch diesel plants coupled with (*AllBECCS* in Section 3.5). For BECCS technology costs and efficiency, we source them from the 2050 projection of biomass for electricity / liquids with CCS, which are inputs of TIAM-Grantham (Grant et al 2021). We then base the emissions factors of different biomass feedstocks from their default GHG emissions values (European Commission. Joint Research Centre. Institute for Energy and Transport. 2015) and then multiple the emissions by CO_2 capture rate (ranging from 90% to 99.5% for different BECCS technology chains (Rosa et al 2021)). Note that the default values of total biomass GHG emission vary due to different transport distances and conversion pathways (e.g., open digestate or close digestate biogas). We thus adopt the range of lower and higher bounds for each feedstock and estimate the corresponding range of negative emissions potential (Table C1).

Appendix D: Energy system modelling results of the reference scenario

Here we discuss the results from the *2050 Reference* scenario without any additional infrastructure or constraints on bioenergy (*2050 Reference* hereafter). We use the ancillary bioenergy potential data in AB-Euro-Calliope as constraints on the maximum bioenergy supply potential. The energy system model can choose to use any amount of biomass feedstock within that maximum national potential to fulfil national demand while minimising total system cost (i.e., national autarky of all synthetic fuels). Overall, biomass only constitutes less than 1% of the total energy capacity in our *2050 Reference* scenario, which predominantly consists of wind and solar capacity. At national scales, biomass capacity ranges from 55% (LTU) to 0.1% (IRL). See all national and European energy system composition details in Table D2.

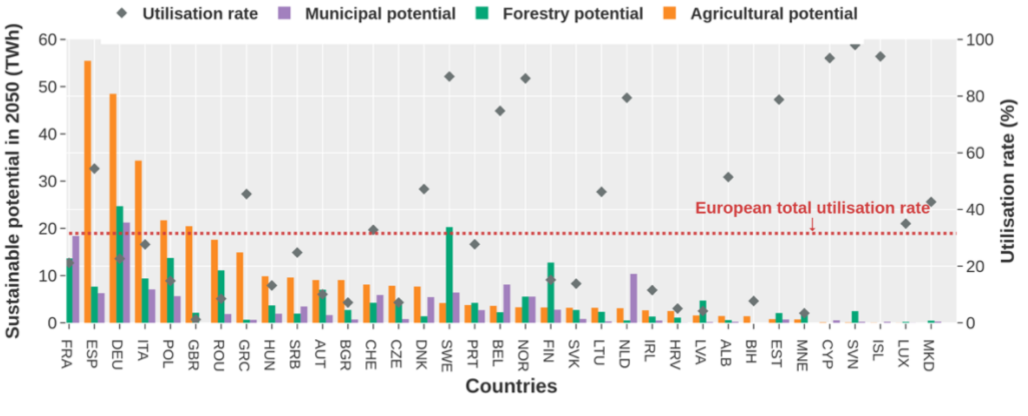

Figure D1. National potential (left axis) and utilisation rates (right axis) of ancillary bioenergy in 2050 Reference scenario (Utilisation rates = Bioenergy feedstocks consumed in optimisation scenarios / the total sustainable potential available)).

Country-wise, different national endowments of ancillary biomass feedstocks and demand portfolios result in varied national potential (left axis in Figure D1) and utilisation rates (right axis), respectively. The bioenergy utilisation rate refers to the percentage of the maximum available ancillary biomass potential which is used in a given scenario.

The average European utilisation of ancillary bioenergy reaches 38% (red line in Figure D1), whereas 19 out of 35 European countries are below this rate. Most countries still have substantial untapped ancillary bioenergy with low land/environmental impacts in the optimised *2050 Reference* scenario. The linear optimisation model chooses the least cost energy supply mix to meet the demand profiles (as described in the model overview of Euro-Calliope). Therefore, for countries with cheaper alternatives (e.g., cheaper abundant PV/wind for hydrogen production and thus cheaper hydrogen-to-fuels pathways), bioenergy becomes less attractive, which renders low utilisation rates in the *2050 Reference* scenario. That said, higher potentials of ancillary bioenergy in some countries or for certain feedstocks may not necessarily lead to high utilisation when we design an energy system to minimise total system cost (e.g., DEU has the third highest ancillary biomass potential but its utilisation rate is only 23%, as in Figure D1; agricultural residues has the highest potential among all ancillary feedstocks but its utilisation rate is the lowest, as in Table D1).

Feedstock-wise, poorly-utilised crop residues and manure share one thing in common – they cannot be directly converted into transport biofuels (i.e., they require multiple conversion technologies with higher costs compared to the other feedstocks), especially for shipping and aviation where we have a fixed demand in every country that cannot be electrified. Instead, they can produce heat, electricity, and methane, where cheaper alternatives are available from other renewables (i.e., heat pumps, PV, hydrogen-to-methane converter, etc.). In contrast, both agricultural by-products have a small potential with a high utilisation rate – shells reach over 72%; fats and oil are almost entirely used (over 99%). They both have high energy density and can be converted to transport biofuels (diesel and kerosene). Food-system-wise, we extract the untapped potential of both by-products that is not conflicting with either food or feed uses, so their opportunity cost is near zero. See Table D1 for the utilisation rate of every feedstock.

Table D1. Consumption and utilisation rate for all sources of ancillary biomass.

Sector	**Ancillary Biomass Feedstock**	**Consumption (TWh)**	**Utilisation Rate (%)**

Agriculture	**Agricultural crops primary residues**	0.29	0.10%
	Animal manure	0.17	0.63%
	By-product animal fats and oil	4.27	100%
	By-product shells	38.43	82.82%
Forestry	**Residues and by-products (sawdust and wood pellets)**	60.04	34.48%
Human settlement	**Municipal solid waste**	120.94	100% (fixed)[1]

[1] We enforce that all municipal solid waste is incinerated in our scenarios to reflect common practice in Europe (as stated in the scenario description in Section 2.3).

Table D2. National renewable energy capacity in the optimised 2050 Reference scenario (MW).

Country	**Solar Capacity**	**Wind Capacity**	**Hydro Capacity**	**Nuclear Capacity**	**Biomass Capacity**	**Biomass Capacity Percent (%)**
Sum (TW)	**2.23**	**3.32**	**0.14**	**0.02**	**0.04**	
Sum (MW, hereafter)	**2227491.78**	**3324262.97**	**139466.57**	**19124.34**	**37140.26**	**0.65%**
ALB	10476.46	22.52	2122.52	-	144.27	1.13%

AUT	75824.38	37.31	9713.54	-	533.73	0.62%
BEL	152524.66	63007.33	71.75	-	1221.84	0.56%
BGR	46982.27	117.06	1521.94	1.29	124.73	0.26%
BIH	482.32	44.01	1665.5	-	27.19	1.23%
CHE	35303.73	9.63	13200.21	-	715.2	1.45%
CYP	9630.82	6681.37	0	-	75.35	0.46%
CZE	125.54	152589.33	751.71	6230	1164.4	0.72%
DEU	529412.29	254177.45	3735.7	-	3189.63	0.40%
DNK	28.3	161694.02	0	-	801.98	0.49%
ESP	377942.05	231262.1	8511.24	-	5342.54	0.86%
EST	45.78	44932.15	0	-	337.86	0.75%
FIN	35.39	99465.66	2685.95	1.34	566.19	0.55%
FRA	243406.82	545226.66	15800.97	1.64	2374.81	0.29%
GBR	29.92	597689.32	1372.48	8900	142.45	0.02%
GRC	98329.72	45576.95	2696.52	-	882.69	0.60%
HRV	120.06	26544.82	1606.29	-	41.73	0.15%
HUN	39.03	212216.79	47.7	2400	264.89	0.12%
IRL	20.3	76398.59	217	-	77.48	0.10%
ISL	13.1	12033.47	0	-	31.28	0.26%
ITA	540107.12	90.7	11430.2	-	4824.03	0.87%

LTU	178.1	75.1	101	-	426.29	54.62%
LUX	255.19	11774.89	0	-	27.25	0.23%
LVA	61.77	57.19	1526.1	-	172.61	9.50%
MKD	2792.29	15.26	490.6	-	46.76	1.40%
MNE	4817.89	23.26	675.32	-	21.01	0.38%
NLD	39371.68	256479.48	0	-	2097.6	0.70%
NOR	25.86	100954.06	31754.31	-	1445.28	1.08%
POL	57029	114125.77	426.91	-	5067.83	2.87%
PRT	815.92	100173.85	2950.9	-	347.53	0.33%
ROU	78.48	104809.54	6143.93	650.04	327.62	0.29%
SRB	788.91	693.23	2090.3	-	447.09	11.12%
SVK	328.69	53299.61	1433.33	940.02	401.95	0.71%
SVN	27.25	26.89	1053.61	-	330.27	22.97%
SWE	40.73	51937.59	13669.06	-	3096.88	4.50%

Appendix E: Different utilisation cases and their modelling results

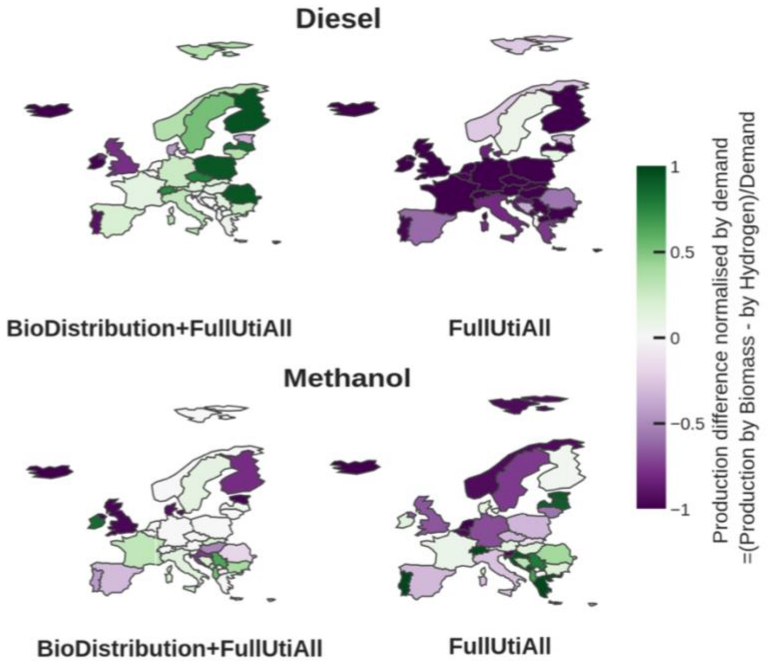

Figure E1. Change of attractiveness between ancillary biomass and hydrogen for producing the same synthetic fuels.

On the spatial side, distribution network increases the attractiveness of biomass over other competing renewables when producing the same fuels (i.e., Figure E1 E1). In the *BioDistribution+FullUtiAll* scenario, the total energy system demand and all sectoral demand profiles are unchanged while more ancillary biomass is utilised. What changed is the attractiveness of ancillary bioenergy over other competing renewables when producing the same energy products, like diesel. Hydrogen is the predominant biomass-competing renewable energy when producing synthetic fuels, while biofuels for transport and industry are the major use of ancillary bioenergy.

We identify where ancillary bioenergy is more attractive than hydrogen in producing different synthetic fuels (Figure E1). In green regions, ancillary biomass is more attractive in producing the specified fuel type, while in purple regions, hydrogen prevails. Fuel-wise, diesel is the most attractive use for ancillary biomass, especially in central Europe and the Nordic region only when a distribution network is available. Biomass for methanol maintains attractive in Middle-

South Europe irrespective of infrastructure. For the other synthetical fuels (methane, and kerosene), hydrogen maintains attractiveness in every country with or without infrastructure or forced utilisation.

Table E1. Sectoral consumption for ancillary biomass among scenarios (unit: TWh).

Sectoral consumption (TWh)	**2050 Reference**	**GasStorage**	**BioDistribution**	**FullUtiAll**	**FullUtiAgr**	**BioDistribution +FullUtiAll**
Heat	34.49	34.76	16.46	39.77	34.04	30.80
Electricity	27.67	27.6	27.09	27.86	27.83	27.88
Transport (Road/Rail)	11.66	11.66	27.48	11.66	11.66	27.69
Transport (Shipping)	40.08	40.08	95.01	40.08	40.08	95.14
Transport (Aviation)	0.83	0.83	0.07	1.2	0.83	0.21
Industry (Methanol)	0.34	0.27	0.28	252.77	175.02	125.68
Industry (Methane)	0.66	0.45	0.6	51.77	43.18	101.45

Table E2. System-wide comparison among scenarios (all metrics scaled by the 2050 Reference scenario)

	2050 Reference	***GasStorage***	***BioDistribution***	***FullUtiAgr***	***FullUtiAll***	***BioDistribution+FullUtiAll***	***NoUti***

Total system cost	1	1	0.91	1	1.01	0.92	1.01
Ancillary biomass utilisation	1	1	1.56	2.52	3.17	3.17	0
Land use	1	1	0.99	0.99	0.94	0.97	0.97
Power curtailment	1	1	0.92	0.97	0.96	0.89	1.02
Storage capacity	1	12.34	1	1	1	1	1.01
Offshore wind capacity	1	1	0.07	0.94	0.92	0.03	1.03
Onshore wind capacity	1	1	1.05	0.98	0.97	1.02	1.03
Open-field PV capacity	1	1	0.89	0.96	0.95	0.87	1.02
Rooftop PV capacity	1	1.13	0.73	1.14	1.24	0.97	1.73
Electricity LCOE	1	1	0.99	1.03	1.05	1.03	1.03

Heat LCOE	1	1	0.91	1	1.01	0.92	0.99
Methanol LCOE	1	1	0.89	1	1.01	0.9	1.01
Methane LCOE	1	1	0.91	1	1.01	0.92	1.01
Kerosene LCOE	1	1	1.35	1.01	1.01	1.36	1
Diesel LCOE	1	1	1.16	1	1.01	1.17	0.94

Appendix F: Sensitivity analysis

Table F1. Technology costs and efficiency uncertainty considered in sensitivity analysis.

Sensitivity analysis	**Cost relaxation ±30%, run every 10%**					
	Efficiency uncertainty ± 15%, run every 5%			**(Efficiency not applicable)**		
Technology category	**Biomass-to-energy**	**Hydrogen production**	**Hydrogen-to-fuel**	**Biomass supply**	**Biofuel distribution**	**Storage**
Technology name	Biofuel to liquid fuels converter	Electrolysis	Hydrogen-to methanol convertor	Manure supply cost	Synthetic fuels distributing costs	Battery storage costs

	Biofuel to vehicle fuel converter	Hydrogen to methane convertor	Agricultural residues cost	Hydrogen storage costs
	Biofuel to methanol converter	Hydrogen to liquids (kerosene and diesel) convertor	Agricultural by-products nuts shells costs	
	Biofuel to methane converter		Agricultural by-products animal fats costs	
	SNG from biogas		Forestry ancillary biomass supply costs	
	Biogas engines (spark ignition)		Municipal solid waste costs	
	Biomass boiler			
	Combined heat and power plants			

Table F2. Sensitivity analysis of biomass supply cost and potential when biofuels distribution network is available (all metrics scaled by the 2050 Reference scenario).

	BioDistribution		
	No change	**Biomass potential reduced by 20%**	**Biomass cost increased by 20%**
Total system cost	0.91	0.91	0.91
Ancillary biomass utilisation	1.56	1.55	1.55
Land use	0.99	1.04	1.01
Power curtailment	0.92	0.92	0.92
Storage capacity	1	0.99	0.99
Offshore wind capacity	0.07	0.07	0.07
Onshore wind capacity	1.05	1.05	1.05
Open-field PV capacity	0.89	0.89	0.89
Rooftop PV capacity	0.73	0.69	0.71

Supplementary material to contribution III

The reproducible codes and results files from this study are openly available online:

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Appendix G: Ancillary biomass feedstock and management assumptions

We refine the agricultural residue management assumptions in addition to our previous study (Wu *et al* 2023) in two ways, as shown below.

First, we differentiate how organic and conventional agriculture systems treat the primary residue and manure to supply enough organic fertilizer (by allocating around half of the primary residues and manure to compost in organic systems).

Second, we subtract the possible losses (from collection, storage, and transportation) and cascading uses (biochemicals and materials) to more conservatively estimate sustainable ancillary biomass potential without competing uses.

Compared to the existing literature, our assumption of loss, cascading uses, compost, and the lefton-cropland ratio is close to their average sustainable removal rates (around 50%) (Ruiz *et al* 2015; Panoutsou 2021). Sustainable removal rates are the only common management assumption among studies, as most energy system models do not consider food/feed competition per feedstock or other cascading uses of biomass. For the detailed ancillary bioenergy potential and management assumptions, please refer to Table G1. For the energy and carbon content of ancillary biomass feedstocks, we adopt the same estimation method from our previous study (Wu *et al* 2023) (See its Appendix). Generally, all of our low heating values are from the Phyllis2 database , (TNO Biomass and Circular Technologies 2022) and the default GHG (greenhouse gas) emissions values are from (Ruiz *et al* 2015).

Table G1: Ancillary bioenergy potential and management assumptions

AB feedstock	Production system	Management assumptions	Nitrogen recyclable?
Primary crop residues	Conventional	5% Left on croplands	Y
		42.5% Bioenergy	Y
		42.5% Loss and cascading uses‡	N
	Organic	5% Left on croplands	Y
		50% Compost	Y
		22.5% Bioenergy	Y
		22.5% Loss and cascading uses	N

Manure§	Conventional	100% Bioenergy	Y
	Organic	50% Bioenergy	Y
		50% Compost	Y
Secondary residues, byproducts fats, & end-use waste	Conventional & Organic	All non-feed/food uses plus 80% of remaining waste for energy	Y
Byproduct shells	Conventional & Organic	All used for bioenergy	Y

‡ A conservative estimation including a post-harvest loss at 20% (handling, storage and transportation) and cascading uses 30% (bio-chemicals and materials) of the remaining 95% primary crop residues not left on the field, i.e., (20+30)%*95% = 42.5% of the total primary crop residues

§ We use only the manure not left on grassland for local/on-site use, thus no loss. We leave those on grassland as it as (i.e., for pasture, range, orpaddock).

Appendix H: Scenario assumptions and results

Table H1: Environmental impacts scaled by Baseline in all scenarios (*NutrientFirst* pathway). For scenario names, OrgX = Organic farming share; ConcRedX = Concentrate feeding reduction share; WasteRedX = Waste reduction share. Baseline is Org0 ConcRed0 _WasteRed0.

Scenarios	**Irrigation water**	**Soil erosion**	**Food availability**	**GHG emissions**	**Nitrogen balance**
Org0 ConcRed0 WasteRed0	100%	100%	100%	100%	100%
Org0 ConcRed0 WasteRed25	100%	100%	102%	101%	107%
Org0 ConcRed0 WasteRed50	100%	100%	104%	102%	114%
Org0 ConcRed0 WasteRed75	100%	100%	107%	103%	121%
Org0 ConcRed25 WasteRed0	100%	99%	107%	97%	88%
Org0 ConcRed25 WasteRed25	100%	99%	109%	98%	95%
Org0 ConcRed25 WasteRed50	100%	99%	111%	99%	102%
Org0 ConcRed25 WasteRed75	100%	99%	114%	100%	109%
Org0 ConcRed50 WasteRed0	101%	97%	113%	95%	80%
Org0 ConcRed50 WasteRed25	101%	97%	116%	96%	87%
Org0 ConcRed50 WasteRed50	101%	97%	118%	97%	94%
Org0 ConcRed50 WasteRed75	101%	97%	120%	97%	100%

Org0 ConcRed75 WasteRed0	101%	96%	119%	94%	76%
Org0 ConcRed75 WasteRed25	101%	96%	121%	95%	82%
Org0 ConcRed75 WasteRed50	101%	96%	124%	96%	89%
Org0 ConcRed75 WasteRed75	101%	96%	126%	97%	96%
Org0 ConcRed100 WasteRed0	102%	95%	125%	94%	76%
Org0 ConcRed100 WasteRed25	102%	95%	127%	95%	83%
Org0 ConcRed100 WasteRed50	102%	95%	129%	96%	89%
Org25 ConcRed0 WasteRed0	94%	94%	93%	87%	67%
Org25 ConcRed0 WasteRed25	94%	94%	96%	88%	74%
Org25 ConcRed0 WasteRed50	94%	94%	98%	89%	81%
Org25 ConcRed0 WasteRed75	94%	94%	100%	90%	88%
Org25 ConcRed25 WasteRed0	94%	93%	100%	85%	56%
Org25 ConcRed25 WasteRed25	94%	93%	102%	86%	64%
Org25 ConcRed25 WasteRed50	94%	93%	104%	87%	71%
Org25 ConcRed25 WasteRed75	94%	93%	106%	88%	78%
Org25 ConcRed50 WasteRed0	94%	92%	107%	83%	49%
Org25 ConcRed50 WasteRed25	94%	92%	109%	84%	56%
Org25 ConcRed50 WasteRed50	94%	92%	111%	85%	63%
Org25 ConcRed50 WasteRed75	94%	92%	113%	86%	70%
Org25 ConcRed75 WasteRed0	95%	91%	113%	82%	45%
Org25 ConcRed75 WasteRed25	95%	91%	115%	83%	52%
Org25 ConcRed75 WasteRed50	95%	91%	117%	84%	59%
Org25 ConcRed75 WasteRed75	95%	91%	119%	85%	66%
Org25 ConcRed100 WasteRed0	95%	90%	119%	82%	45%
Org25 ConcRed100 WasteRed25	95%	90%	121%	83%	52%
Org25 ConcRed100 WasteRed50	95%	90%	123%	84%	59%
Org50 ConcRed0 WasteRed0	88%	88%	87%	74%	34%
Org50 ConcRed0 WasteRed25	88%	88%	89%	76%	41%
Org50 ConcRed0 WasteRed50	88%	88%	91%	77%	48%
Org50 ConcRed0 WasteRed75	88%	88%	93%	78%	55%

Org50 ConcRed25 WasteRed0	88%	88%	94%	72%	25%
Org50 ConcRed25 WasteRed25	88%	88%	95%	73%	32%
Org50 ConcRed25 WasteRed50	88%	88%	97%	75%	39%
Org50 ConcRed25 WasteRed75	88%	88%	99%	76%	46%
Org50 ConcRed50 WasteRed0	88%	87%	100%	71%	18%
Org50 ConcRed50 WasteRed25	88%	87%	102%	72%	25%
Org50 ConcRed50 WasteRed50	88%	87%	104%	73%	32%
Org50 ConcRed50 WasteRed75	88%	87%	105%	74%	39%
Org50 ConcRed75 WasteRed0	88%	86%	106%	70%	15%
Org50 ConcRed75 WasteRed25	88%	86%	108%	71%	22%
Org50 ConcRed75 WasteRed50	88%	86%	110%	72%	29%
Org50 ConcRed75 WasteRed75	88%	86%	112%	73%	35%
Org50 ConcRed100 WasteRed0	89%	85%	112%	70%	15%
Org50 ConcRed100 WasteRed25	89%	85%	114%	71%	22%
Org50 ConcRed100 WasteRed50	89%	85%	116%	72%	29%
Org75 ConcRed0 WasteRed0	82%	82%	80%	62%	1%
Org75 ConcRed0 WasteRed25	82%	82%	82%	63%	8%
Org75 ConcRed0 WasteRed50	82%	82%	84%	64%	15%
Org75 ConcRed0 WasteRed75	82%	82%	86%	66%	22%
Org75 ConcRed25 WasteRed0	82%	82%	87%	60%	-6%
Org75 ConcRed25 WasteRed25	82%	82%	89%	61%	1%
Org75 ConcRed25 WasteRed50	82%	82%	90%	63%	8%
Org75 ConcRed25 WasteRed75	82%	82%	92%	64%	15%
Org75 ConcRed50 WasteRed0	82%	81%	93%	59%	-12%
Org75 ConcRed50 WasteRed25	82%	81%	95%	60%	-5%
Org75 ConcRed50 WasteRed50	82%	81%	96%	61%	2%
Org75 ConcRed50 WasteRed75	82%	81%	98%	62%	9%
Org75 ConcRed75 WasteRed0	82%	81%	99%	58%	-16%
Org75 ConcRed75 WasteRed25	82%	81%	101%	59%	-9%
Org75 ConcRed75 WasteRed50	82%	81%	103%	60%	-2%

Org75 ConcRed75 WasteRed75	82%	81%	104%	62%	5%
Org75 ConcRed100 WasteRed0	82%	80%	106%	58%	-15%
Org75 ConcRed100 WasteRed25	82%	80%	108%	59%	-9%
Org75 ConcRed100 WasteRed50	82%	80%	109%	60%	-2%
Org100 ConcRed0 WasteRed0	75%	77%	74%	49%	-32%
Org100 ConcRed0 WasteRed25	75%	77%	76%	50%	-25%
Org100 ConcRed0 WasteRed50	75%	77%	77%	52%	-18%
Org100 ConcRed0 WasteRed75	75%	77%	79%	53%	-11%
Org100 ConcRed25 WasteRed0	75%	76%	80%	48%	-38%
Org100 ConcRed25 WasteRed25	75%	76%	82%	49%	-31%
Org100 ConcRed25 WasteRed50	75%	76%	83%	51%	-24%
Org100 ConcRed25 WasteRed75	75%	76%	85%	52%	-17%
Org100 ConcRed50 WasteRed0	75%	76%	86%	47%	-43%
Org100 ConcRed50 WasteRed25	75%	76%	88%	48%	-36%
Org100 ConcRed50 WasteRed50	75%	76%	89%	49%	-29%
Org100 ConcRed50 WasteRed75	75%	76%	91%	51%	-22%
Org100 ConcRed75 WasteRed0	75%	76%	92%	46%	-46%
Org100 ConcRed75 WasteRed25	75%	76%	94%	47%	-39%
Org100 ConcRed75 WasteRed50	75%	76%	96%	49%	-32%
Org100 ConcRed75 WasteRed75	75%	76%	97%	50%	-25%
Org100 ConcRed100 WasteRed0	75%	76%	99%	46%	-46%
Org100 ConcRed100 WasteRed25	75%	76%	101%	47%	-39%
Org100 ConcRed100 WasteRed50	75%	76%	103%	49%	-32%

Table H2: Global ancillary bioenergy potential and nitrogen balance in all scenarios (*NutrientFirst* pathway)

Organic share (%)	**Concentrate feeding reduction (%)**	**Waste reduction (%)**	**Global potential (EJ)**	**N balance per ha (kgN/ha)**
0	0	0	98.2	26.0
0	0	25	94.8	27.7
0	0	50	91.3	29.6

0	0	75	87.6	31.5
0	25	0	95.7	22.8
0	25	25	92.0	24.7
0	25	50	88.1	26.5
0	25	75	84.0	28.4
0	50	0	94.2	20.7
0	50	25	90.1	22.5
0	50	50	85.9	24.3
0	50	75	81.6	26.1
0	75	0	93.8	19.6
0	75	25	89.5	21.4
0	75	50	85.0	23.2
0	75	75	80.4	25.0
0	100	0	94.1	19.7
0	100	25	89.6	21.4
0	100	50	85.0	23.2
25	0	0	87.3	17.4
25	0	25	83.8	19.2
25	0	50	80.2	21.1
25	0	75	76.5	22.9
25	25	0	85.6	14.7
25	25	25	81.8	16.5
25	25	50	77.9	18.4
25	25	75	73.8	20.2
25	50	0	84.7	12.7
25	50	25	80.6	14.6
25	50	50	76.4	16.4
25	50	75	71.9	18.2
25	75	0	84.8	11.7
25	75	25	80.3	13.5

25	75	50	75.8	15.3
25	75	75	71.1	17.1

25	100	0	85.4	11.8
25	100	25	80.8	13.6
25	100	50	76.0	15.3
50	0	0	76.3	8.9
50	0	25	72.9	10.6
50	0	50	69.2	12.5
50	0	75	65.4	14.4
50	25	0	75.6	6.5
50	25	25	71.7	8.3
50	25	50	67.7	10.2
50	25	75	63.5	12.0
50	50	0	75.3	4.8
50	50	25	71.1	6.6
50	50	50	66.8	8.4
50	50	75	62.3	10.2
50	75	0	75.7	3.8
50	75	25	71.2	5.6
50	75	50	66.6	7.4
50	75	75	61.7	9.2
50	100	0	76.7	3.9
50	100	25	71.9	5.7
50	100	50	66.9	7.4
75	0	0	65.4	0.3
75	0	25	61.9	2.1
75	0	50	58.2	3.9
75	0	75	54.4	5.8
75	25	0	65.5	-1.7
75	25	25	61.6	0.2
75	25	50	57.5	2.0
75	25	75	53.3	3.8
75	50	0	65.9	-3.2
75	50	25	61.6	-1.3

75	50	50	57.2	0.5
75	50	75	52.6	2.3
75	75	0	66.7	-4.1
75	75	25	62.1	-2.3
75	75	50	57.3	-0.5
75	75	75	52.4	1.3
75	100	0	68.0	-4.0
75	100	25	63.1	-2.2
75	100	50	57.9	-0.5
100	0	0	54.5	-8.3
100	0	25	50.9	-6.5
100	0	50	47.2	-4.7
100	0	75	43.3	-2.8
100	25	0	55.4	-9.9
100	25	25	51.5	-8.0
100	25	50	47.4	-6.2
100	25	75	43.1	-4.4
100	50	0	56.5	-11.1
100	50	25	52.1	-9.3
100	50	50	47.6	-7.5
100	50	75	42.9	-5.7
100	75	0	57.7	-12.0
100	75	25	53.0	-10.2
100	75	50	48.1	-8.4
100	75	75	43.0	-6.6
100	100	0	59.3	-11.9
100	100	25	54.2	-10.2
100	100	50	48.9	-8.4

Table H3: Global negative emission potential and nitrogen balance in all scenarios (*NegativeFirst* pathway). The ancillary bioenergy potential is the same as in Table B2.

Organic share (%)	**Concentrate feeding reduction (%)**	**Waste reduction (%)**	**N balance per ha (kgN/ha)**	**Negative emission ($GTCO_2eq$)**
0	0	0	16.2	2.6
0	0	25	18.5	2.5
0	0	50	20.8	2.5
0	0	75	23.1	2.5
0	25	0	13.0	2.5
0	25	25	15.3	2.5
0	25	50	17.6	2.5
0	25	75	19.9	2.4
0	50	0	10.7	2.5
0	50	25	13.0	2.5
0	50	50	15.3	2.4
0	50	75	17.6	2.4
0	75	0	9.5	2.5
0	75	25	11.8	2.4
0	75	50	14.0	2.4
0	75	75	16.3	2.4
0	100	0	9.4	2.5
0	100	25	11.7	2.4
0	100	50	14.0	2.4
25	0	0	8.9	2.2
25	0	25	11.2	2.2
25	0	50	13.5	2.1
25	0	75	15.8	2.1
25	25	0	6.1	2.2
25	25	25	8.4	2.1

25	25	50	10.7	2.1
25	25	75	13.0	2.1
25	50	0	4.0	2.2
25	50	25	6.3	2.1
25	50	50	8.6	2.1
25	50	75	10.9	2.1
25	75	0	2.9	2.1
25	75	25	5.2	2.1
25	75	50	7.4	2.1
25	75	75	9.7	2.0
25	100	0	2.8	2.1
25	100	25	5.1	2.1
25	100	50	7.3	2.1
50	0	0	1.6	1.9
50	0	25	3.9	1.8
50	0	50	6.2	1.8
50	0	75	8.5	1.8
50	25	0	-0.8	1.8
50	25	25	1.5	1.8
50	25	50	3.8	1.8
50	25	75	6.1	1.7
50	50	0	-2.7	1.8
50	50	25	-0.4	1.8
50	50	50	1.9	1.8
50	50	75	4.2	1.7
50	75	0	-3.8	1.8
50	75	25	-1.5	1.8
50	75	50	0.8	1.8
50	75	75	3.1	1.7
50	100	0	-3.8	1.8
50	100	25	-1.6	1.8
50	100	50	0.7	1.7

75	0	0	-5.7	1.5
75	0	25	-3.4	1.5
75	0	50	-1.2	1.5
75	0	75	1.1	1.4
75	25	0	-7.7	1.5
75	25	25	-5.4	1.5
75	25	50	-3.2	1.4
75	25	75	-0.9	1.4
75	50	0	-9.3	1.5
75	50	25	-7.1	1.5
75	50	50	-4.8	1.4
75	50	75	-2.5	1.4
75	75	0	-10.4	1.5
75	75	25	-8.1	1.5
75	75	50	-5.8	1.4
75	75	75	-3.5	1.4
75	100	0	-10.5	1.5
75	100	25	-8.2	1.5
75	100	50	-5.9	1.4
100	0	0	-13.1	1.2
100	0	25	-10.8	1.1
100	0	50	-8.5	1.1
100	0	75	-6.2	1.1
100	25	25	-12.4	1.1
100	25	50	-10.1	1.1
100	25	75	-7.8	1.1
100	50	0	-16.1	1.2
100	50	25	-13.8	1.1
100	50	50	-11.5	1.1
100	50	75	-9.2	1.1
100	75	0	-17.0	1.2
100	75	25	-14.8	1.1
100	75	50	-12.5	1.1
100	75	75	-10.2	1.1
100	100	0	-17.1	1.2

100	100	25	-14.8	1.1
100	100	50	-12.6	1.1