Bioenergy in the European energy transition

Integrated assessment of the long-term position of bioenergy within the context of climate targets

Steven James Mandley

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Steven James Mandley, November, 2022

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Bio-energie in de Europese energie transitie

Geïntegreerde analyse van de positie van bio-energie op lange termijn binnen de context van klimaatdoelstellingen

(met een samenvatting in het Nederlands)

Proefschrift

Ter verkrijging van de graad van doctor aan de Universiteit Utrecht

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Copromotoren

dr. V. Daioglou

'Models are not true or false but lie on a continuum of usefulness.'

Barlas and Carpenter (1990)

'Change is the only constant.'

Heraclitus (500 BCE)

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ABBREVIATIONS

1G	First-generation
2G	Second-generation
ABT	Advanced Bioenergy Technologies
BECCS	Bioenergy with Carbon Capture and Storage
BEE	Biomass Energy Europe
BIGCC	Biomass Integrated Gasification Combined Cycle
CAPRI	Common Agriculture Policy Regionalised Impact model
CCS	Carbon Capture and Storage
CHP	Combined Heat & Power
COP	Climate change Conference Of the Parties
EC	European Commission
EF	Emission Factor
EMF-33	33rd study of the Stanford Energy Modeling Forum
EU	European Union
FT	Fischer-Tropsch
GDP	Gross domestic product
GHG	Greenhouse gas
IAM	Integrated Assessment Model
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IMAGE	Integrated Model to Assess the Global Environment
I-O	Input-Output
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
LCOE	Levelized Cost Of Electricity
LNG	Liquified Natural Gas
LPJml	Lund-Potsdam-Jena managed Land
LULUCF	Land Use, Land-Use Change and Forestry
LUC	Land Use Change
MF	Mitigation Factor

MRV	Measurement, Reporting and Verification
MS	Member State
NDC	Nationally Determined Contributions
NECP	National Energy and Climate Plan
NREAP	National Renewable Energy Action Plan
NUTS	Nomenclature of territorial units for statistics
O&M	Operation & Maintenance
PCI	Project of Common Interest
PRIMES	Price-Induced Market Equilibrium System
PV	Photovoltaics
RCP	Representative Concentration Pathway
RED II	Renewables Energy Directive recast to 2030
RES	Renewable Energy Source
SRC	Short Rotation Coppice
SSP	Shared Socioeconomic Pathway
TEN-E	Trans-European Network-Energy
TIMER	Targets IMage Energy Regional
TPED	Total Primary Energy Demand
UNFCCC	United Nations Framework Convention on Climate Change
VRES	Variable Renewable Energy Sources
WEM	World Energy Model
WEO	World Energy Outlook

CHAPTER 1

Introduction

1. INTRODUCTION

1.1 Climate and energy system targets to 2050

In 1992, the world agreed on the United Nations Framework Convention on Climate Change (UNFCCC) to prevent dangerous climate change. Since then, stabilising greenhouse gas (GHG) emissions has been pushed to the forefront as one of the most challenging issues confronting the international scientific and policy communities. Current energy-related GHG emissions are estimated to be at the highest level recorded at 40.8 $GtCO_2eq.yr^{-1}$ [1], and are responsible for 74% of total global anthropogenic GHG emissions, with the remainder resulting from agriculture and land management [2]. This contribution to global temperature rise from energy purposed for human activities has been known for some time with increased coordinated efforts emerging in global policy.

At the global scale, climate policy is steered by the UNFCCC. Since its formation at the Earth Summit of 1992, landmark treaties that introduce quantitative GHG reduction targets into legislation include the Kyoto Protocol and the Doha amendment. Interestingly, the more recent Paris agreement did not focus on emission reductions but set a targets for global mean temperature increase, to keep this well below 2°C and striving for 1.5°C [3]. As part of this global legislative body and born out of a necessity for understanding the requirements of and progress towards achieving overarching climate targets and how to adapt to impacts, it has become commonplace for climate change decision support to depend on projections of future energy, land, and emissions pathways.

The Intergovernmental Panel on Climate Change (IPCC) is the international body for assessing the science related to climate change. IPCC assessments provide a scientific basis for governments to develop climate-related policies that underlie negotiations at the UN Climate Conference. The assessments are policy-relevant but not policy prescriptive. Presented projections for future climate change explore different scenarios highlighting the risks that climate change carries and deliberate the implications of response options but are not intended to tell policymakers what actions to take. IPCC assessments, particularly those of Working Group III focusing on climate change mitigation, are supported by the analysis of Integrated assessment models (IAMs).

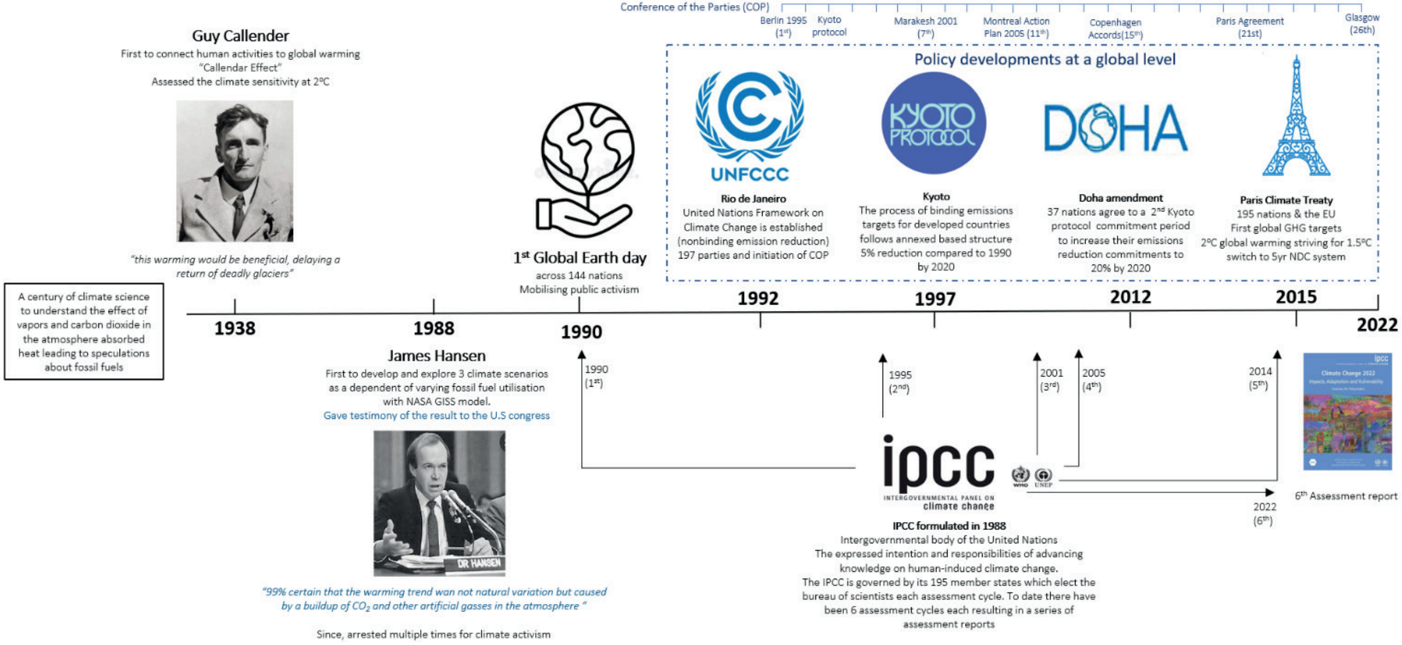

Fig.1.1: A brief history of milestones in the global energy-climate-policy interface

IAMs are numerical models that represent and capture the interactions between natural and human systems inside a single integrated framework. They are deployed to generate quantitative projections surrounding the long-term evolution of these interactions, focusing specifically on climate change, to inform policy decisions [4,5]. Both global and national IAMs exists and they can be complex (covering many emission sources) but also relatively simple and transparent (mostly focused on the main dynamics). The IPCC, as part of the sixth assessment report published in 2022, has compiled GHG emission trajectories from the scientific literature, presented in Fig.1.2, highlighting that despite current policy commitments, projected global emission trajectories are too high to limit to the minimal 2°C global warming targets. This suggests that a significant increase in action is needed in the coming decades to accelerate GHG reductions [6].

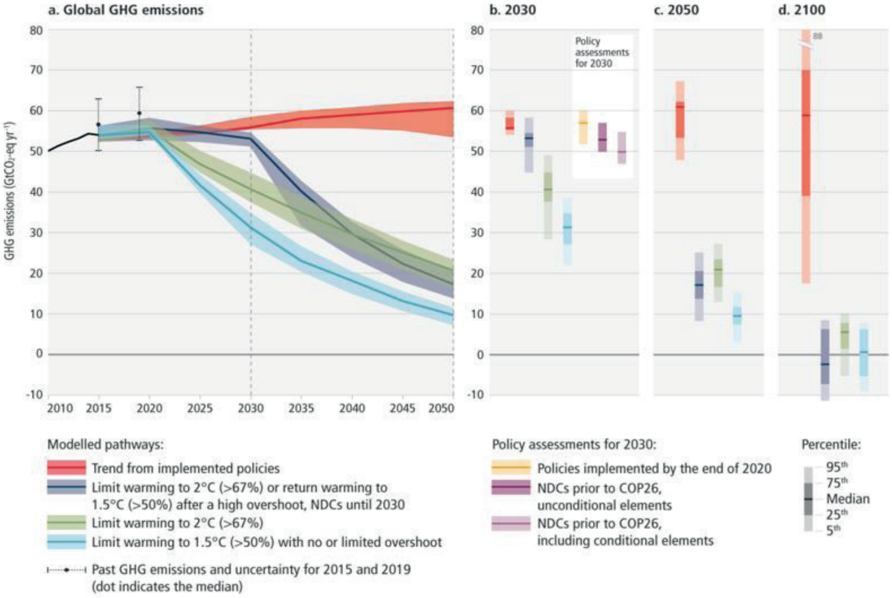

Fig.1.2: Global GHG emissions of modelled pathways as reported in the IPCC 6th Assessment Report[6]

- funnels in Panel a
- associated bars in Panels b, c, d & emission outcomes from near-term policy assessments for 2030 (Panel b).

Adopting the Paris agreement requires coordinated efforts from all world regions implemented through an embedded nationally determined contributions (NDCs) approach, which are national climate action plans for domestic mitigation measures reported in 5-year cycles. This approach effectively combines top-down international agreement with bottom-up elements committing nations and supranational regions such as the European Union (EU) to assess their independent carbon budgets and create and communicate actionable measures to achieve them. Essentially this system is designed to foster domestic and transitional policies that create increasingly ambitious commitments and place accountability at the state level.

For the EU, under the strategic European Green Deal [7] and legislative European climate law [8], constituent Member states (MS) committed to turning the EU into the first climate-neutral continent by 2050. The EU has set ambitious GHG reduction targets of 55% by 2030 compared to a 1990 baseline and net-zero emissions by 2050. In the build-up for EU adoption of these targets within the communication 'A clean plant for all' [9], the European Commission presented a sector-wide distribution of emissions reductions required at the EU-level towards a net-zero 2050 under a shared long-term strategic vision, shown in Fig 1.3. The magnitude of mitigative efforts to 2050 across the EU energy-system are large-scale and present especially significant challenges for electricity, transport, and heat within industry and the built environment which combined currently emit 3.3 $GtCO_2eq.yr^{-1}$ representing 85% of current EU emissions when excluding land-use, land-use change and forestry (LULUCF) at present [10].

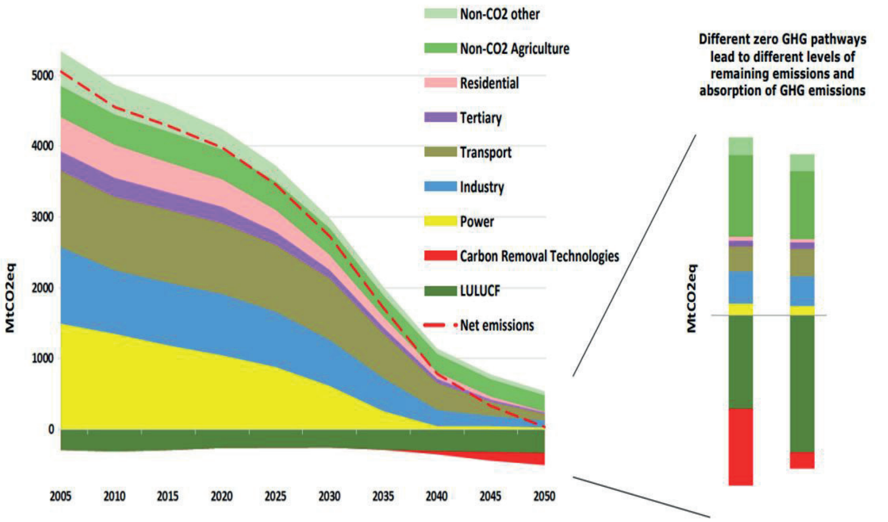

Fig.1.3: GHG emissions trajectory to 1.5°C for the EU to 2050 a long-term strategic vision [9]
– Right-hand bars represent the EC 7th and 8th scenarios respectively which both aim for net-zero by 2050. Scenario 8 follows the same measures as 7 but strengthens circular economy and land-use sink strategies

The required mitigation efforts at EU-scale shown in Fig.1.3 are not a solution but rather a guiding vision for the remaining carbon budget to mid-century. Through this guidance, the European Commission aims to facilitate and encourage both nations and sectors to draw up indicative voluntary roadmaps to plan their transition towards achieving the Union's climate-neutrality objective by 2050. In response, there has been an extensive array of sectoral and cross-sectoral (EU-level) decarbonisation pathways presented as transitional scenarios that, in general, aim for a cost-effective route to net-zero [11–13]. These projections rely on regional-level energy system models that can hold improved geographical and technological resolution for national purposes than IAMs and can adapt quickly to incorporate regional-specific climate and energy policy directions within their scenario assessment. These modelling approaches are briefly introduced below in section 1.3

Whilst the GHG reduction target is consistent between different scenarios meeting the required climate targets (i.e. <2°C), pathways to reaching it and the fuel and technological mixes can vary widely [14]. Mitigative scenarios may ascribe different socioeconomic contexts, policy mechanisms, resource and energy efficiency assumptions, and technological progress that may all steer the energy mix across sectors and along different pathways. Furthermore, scenario choices can change the emissions trajectory by allowing intermediatory overshoot or delaying emission reductions that may be offset via carbon dioxide removal (CDR) technologies in the long-term. In Fig.1.4, the energy mix as projected under the EU reference scenario, which aims to show development under present adopted policy and trends, is compared to a green deal compliant scenario the fit for 55 scenario 'FF55mix' for the year 2050.

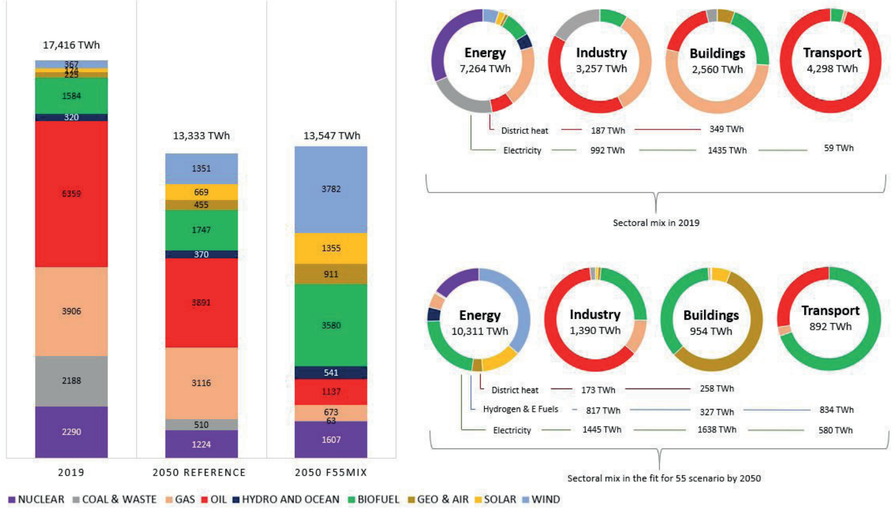

Fig.1.4: Projected gross available energy mix at EU and sectoral level for a mitigative trajectory in line with EU Paris agreement commitments under the Fit For 55 package [TWh of final energy]– Adapted from [15]

- The EU reference scenario reflects current policy and trends and does not meet GHG mitigation targets
- The Fit for 55 Mix scenario is one of three core policy scenarios developed to deliver the European green deal; it serves as a midweight to represent a transition driven by a combination of a strong carbon price signal in the format of an EU ETS and intensification of energy and transport policies

As presented above, a notable feature across all successful <2°C scenarios at EU-level and globally is the build-out of a large portfolio of renewable and low-carbon technologies to replace incumbent fossil fuels. A prominent feature amongst long-term climate scenario strategies is the large-scale deployment of more mature technologies, wind and solar power, for direct electrification of end-use sectors via, for instance, heat pumps and electric vehicles. Currently, wind and solar power represent 20% of the EU's electricity supply, with a significant upsurge in installed capacity in recent years [16]. While variable renewable energy sources are a key driver for the decarbonisation of electricity production, they may also be indirectly used to produce hydrogen and E-fuels for other challenging to electrify end-use sectors, particularly heavy industry and transport. However, the technical challenges of integrating non-dispatchable sources increase as their share in power generation grows, and renewable hydrogen production is almost absent in the EU at present. Bioenergy provides an alternative non-variable low-carbon energy option that offers flexibility for use across all major end-use sectors. Furthermore, in conjunction with carbon capture and storage (BECCS) can offer CDR potential but carries with it implementation concerns for its associated environmental impact.

Modelling future energy-mix projections has a heuristic nature that relies on real-world techno-economic data and climate policy interventions that happen today. This can create notable differences in assessments over time. For instance, technological breakthroughs and rapid cost reductions may develop differently than expected trends (this has happened recently for solar power), meaning cost assumptions that dictate competitivity are outdated and previous assessment cycles obsolete [17]. The sway of political will to support future energy carriers also affects model outcomes. For instance, renewable hydrogen has been positioned center-stage within the European commission's decarbonisation agenda in recent years, owing largely to a 60% drop in production costs [18]. A decade ago, the maximum potential for hydrogen in the EU's energy supply was deemed 4% within the EU's Energy roadmap to 2050 [14]. The European green deal released in 2019 made three mentions of hydrogen [7]. Last year the REPowerEU plan [19] incorporated within the European commission's Fit for 55 package set a target of 10 Mt of domestic renewable hydrogen production and 10 Mt of renewable hydrogen imports by 2030.

Meanwhile, the EU's climate chief Frans Timmermans recently stated that "Europe is never going to be capable of producing its own hydrogen in sufficient quantities" and will rely on imports, a feature regarded as detrimental for other more mature renewable sources. His statements reflect the fact that this demand is to be met by a very immature market that presently produces 40Kt globally [20]. The point of this analogy is to highlight that understanding decarbonisation scenarios can be complex. The feasibility of projections is directly affected by the formulation of incorporated exogenously set policy targets within regional modelling assessments that may prove to be overly ambitious or defunct within future assessments. This further fuels the overarching debate of do strategies align with expectations and questions the role of strategic policy targets within energy-climate modelling scenarios.

The EU has committed to decarbonising its energy system, **but** the pathway to get there remains uncertain. This thesis explores the position of '*modern bioenergy*' as a decarbonisation option through deployment within the EU's energy mix to 2050 when following the Paris agreement climate targets and seeking a low-cost transition. For this, we investigate the methodological differences across available energy-system models and their ability to capture key energy-carrier-specific considerations pertaining to bioenergy competitivity to support policy decisions at the EU-level. The ability to capture bioenergy considerations within modelling approaches can be influenced by both geographical and technological representations, which can affect the accuracy of projections for supply and demand dynamics, ultimately steering the formulation of bioenergy deployment strategies. This thesis confines its focus to *modern bioenergy* constituting biological materials used as energy carriers in conjunction with modern end-use technologies, thus, omitting traditional small-scale wood-burning applications for heating and cooking purposes.

1.2 Bioenergy as a mitigation option within the current EU context

Substituting fossil fuels with modern second-generation and advanced bioenergy sources, i.e. those that utilise non-food feedstocks and residue/waste streams or metabolic by-products, offers an option for decarbonising the EU energy system. At an EU-level, bioenergy currently contributes a large share of total renewable energy (60%), standing at 6.7 EJyr^{-1} primary bioenergy [21], representing 9% of gross inland final energy consumption. From a sourcing perspective, the majority (96%) of the biomass used is EU-sourced, with 89% consumed in the member state (MS) that produces the biomass. However, over the past decade, the EU has been the largest global importer of modern bioenergy carriers [22]. Total EU imports are expected to increase in the decades ahead as decarbonisation strategies intensify [23–25]. This is especially true when focusing on higher-quality and cheaper modern bioenergy carriers [26]. Expansion of overseas sourcing adds further complexities to the bioenergy deliver-chain that must be adequately monitored, verified and reported to ensure mitigation is occurring.

Bioenergy holds notable advantages over other mitigative options that support the case for further integration into the EU energy system. Key features include (i) Versatility for the dispatchable generation of electricity and cross-sectoral application for heat in industry and biofuels for the transportation sector and chemical manufacture; (ii) relatively low cost if biomass residues are used in conjunction with adapted fossil (power) plants; and (iii) the potential to provide CDR through BECCS, which offers a buffer space for delayed climate actions.

Combustion of biomass results in carbon emissions like fossil fuels; however, this biogenic carbon emission can be re-sequestered provided it is offset by net growth. This requires prudent selection of biomass feedstocks, management across the delivery-chain (see 1.4), and full life-cycle accounting of emissions points, including LULUCF and forgone sequestration of harvested lands, to ensure a sustainable loop of growth and use. These critical safeguards are needed to guarantee emission reductions are transpiring but are complex to put into practice, and standardised accounting methods are still largely developing. Progress can be seen within the EU-wide enforcement of the Renewables Energy Directive recast (RED II) [27], which stipulates mandatory sustainability and GHG reduction criteria and accounting guidance for major end-use applications compared to a fossil fuel comparator. However, uncertainty has led to scepticism within national governments of the EU, pausing or even swaying away from commitments for future bioenergy investment and subsidy provision [28]. The debate has carried over into the European parliament which in September of 2022 have voted within the updated RED III formulation to continue to count primary woody biomass as carbon neutral, however, with a (to be specified) cap intended to hold contributions at their current level.

Despite the inherent benefits of bioenergy, inadequate implementation of sustainability criteria across the delivery chain, especially necessary for imported bioenergy carriers, can jeopardise attached GHG performance. The risks and real-world operational failures in implementing regulatory frameworks for sourcing appropriate low emission factor feedstocks have received considerable attention at the EU level in recent years within academic, societal and political debate. Opposition to bioenergy is centered around several core arguments. (i) The carbon payback period, i.e., the regenerative time for absorption of atmospheric levels of carbon dioxide by new biomass growth, can be substantial and does not align with climate urgency [29,30]. (ii) There is disagreement surrounding the supply potential of suitable feedstocks, especially regarding imports, where monitoring of the supply chain is more challenging, less transparent and can lead to other possible negative environmental and socioeconomic impacts such as deforestation, degradation, biodiversity loss, localised air pollution and land-grabbing [31,32]. (iii) Bioenergy conversion facilities can be expensive to build and operate and have low efficiency compared to other renewable sources, with considerable operation and maintenance costs, including extracting, transporting, and storage [33]. (iv) Use of arable lands for the production of energy crops directly raises concerns for food security and reduced capacity for direct carbon sequestration, for instance, through afforestation [34,35].

The mitigative effect of bioenergy (i.e. the attached mitigative factor per unit of energy provided) can range anywhere from a net reduction in emissions if energy system emissions are reduced under favourable terrestrial carbon sequestration to a net increase in emissions when land use and upstream emissions are higher than the fuel mix they are intended to substitute. Thus, it is crucial to hold a holistic account of major emission flows across the entire delivery chain including imports and evaluate supply potential under regional regulations such as RED II. Moreover, for regional EU-level projections, the scale of deployment potential can vary widely depending on the techno-economical performance of end-use applications and feasibility of key decarbonisation technologies such as BECCS. These considerations for bioenergy are both complex and dynamic/context specific in nature, variable over: time, scale and pace of expansion, geographically and technological availability, making a long-term systematic-level assessment of the mitigative potential within energy systems challenging. Existing projections for bioenergy at the EU level to 2050 tend to neglect or lack detailed representation for considerations across the full bioenergy delivery-chain which fail to adequately address the aforementioned concerns.

1.3 Modelling approaches for long-run bioenergy developments

Models can provide important quantitative insights regarding alternative designs for energy systems through both direction and simulated road-testing of policy. Therefore, models explore and reduce the persistent uncertainties of different energy-system configurations and improve informed decision-making. As mitigation targets become increasingly urgent, challenges within the energy system to integrate a growing number of low-emission technologies with increased complexity of performance demands have led to an equivocal growth in modelling approaches [36]. A wide array of approaches and methodologies may be used to assess the potential role of bioenergy within climate mitigation efforts over the decades ahead. Whilst modelling efforts strive for the common goal of a comprehensive quantitative assessment that captures major considerations and drivers/barriers, they vary in complexity, system boundaries and scope. Prominent differences between approaches include spatial and temporal scopes, representative resolutions for critical delivery-chain components such as logistical and technological infrastructure, and capabilities to capture wider environmental, economic and social themes. Classification of modelling approaches is notoriously complex [37,38]. However, they can be generally categorised as: 1) bottom-up assessments, 2) top-down assessments and 3) integrated assessments. We will briefly discuss these three categories.

Bottom-up assessments

Bottom-up assessment approaches for bioenergy assessments vary in scope from resource-focused assessments that aim to provide data-driven estimates of future biomass supply through to impact assessment of specific conversion technologies. Bottom-up models and tools focus on specific aspects, processes, technologies or agents, often incorporating accurate, current performance data relevant to a defined analysis boundary and parameter details. These approaches afford highly detailed, tailored assessment of bioenergy developments for specific technologies, feedstocks or impacts. Bottom-up assessment methodologies include: Biomass resource and land use management models [39,40]; life cycle assessment modelling and multi-criteria assessments [41,42]; Process-based technical models and Techno-economic analysis [43]; Process-based biophysical models and geographic information systems [44,45]. These approaches are often applied to explore technological or supply-chain development at a case-study level. Such studies have highlighted bio-based systems' environmental and economic performance for energy applications, including mitigative potential. However, these approaches apply narrow system boundaries that are limited to focused outputs, thus, are unable to capture wider effects, both indirect or induced, such as interactions with the economic market via price responses, competition and replacement effects or technological or structural changes [46]. Unlike other prominent renewable technology options, the sustainability of bioenergy is intrinsically linked to multiple natural systems and industry sectors. Therefore, modelling bioenergy systems presents unique challenges which need to capture interaction and feedback loops between systems. Restricted system boundaries mean bottom-up tools are less suitable for the long-term scope of climate mitigation strategies and policy impact assessment.

Top-down assessments

Top-down assessment approaches often stem from economic framework models and can be deployed to investigate mid-long term market development and policy effects for (bio)energy deployment. The benefits of top-down approaches stem from their encompassing representation of economic markets, simulating the correlations between the economy and the energy system. Within this model branch, two major approaches are widely applied. (i) Computable general equilibrium (GCE) models focus on market balancing holding a representation of the entire economy, which may vary in geographical scope (global or regional/national), but attempt to represent all economic sectors. GCEs are highly useful for assessing the impacts of bioenergy deployment over the short-mid term and the wider impacts of policy interventions across multiple sectors. Applications include analysis of bioenergy developments on food markets [47], land use change [48], and GHG emission trajectories [49]. (ii) (ii) Partial equilibrium (PE) models are similar in framework but are limited in sectoral coverage, often focused on a single sector and adopted to investigate specific sectoral research lines. Such research includes allaying the economic impact of a developing bioeconomy for the Netherlands [50] and maximising the mitigative value of specific feedstocks [51]. Top-down approaches often hold detailed, disaggregated, regional-specific representation for demand-side aspects such as technological and policy representation and are well suited to evaluate the mitigative potential of bioenergy across multiple economic sectors. However, they lack biophysical representation and the capacity to capture the interlinked impacts between the energy system and environment nexus, such as the effects on water, land-based carbon stocks, and climate. Furthermore, they neglect the complex interlinkages between international energy and food markets, which are imperative for a meaningful account of bioenergy import availability.

Integrated assessments

Integrated assessment models (IAMs) are developed to evaluate the feasibility of achieving targets when exploring the potential evolution of the global energy system when incorporating the interlinkages between human and natural systems under varying policy interventions. Simplified stylized modules are embedded within an IAM framework to represent the most pertinent systems, which commonly include land use, resource availability, energy-system supply and demand, climate, commodity trade and economy. Represented biopsychical processes are often spatially explicit within IAM frameworks, whilst human systems such as economies and technological developments are aggregated commonly at a regional level. Most analyses using IAMs are conducted globally, allowing for an enhanced representation of large-scale bioenergy dynamics encompassing interregional delivery chains. Some research streams have begun to apply IAM frameworks at the national scale [52,53], whilst other efforts focus on regional assessments from downscaling macro-regional outputs of global IAMS [54]. The benefit of a regional application is an enhanced value for policy-decision making which often occurs at the national or supranational level. Global IAMs are well-positioned to explore the role of specific energy options such as bioenergy at a macro-regional scale from a supply and demand perspective. They can account for international import availability and resource competition in the context of limited emissions budgets and consider the complex and dynamic interactions between global biophysical systems. Due to the large breadth of parameters considered, IAMs tend to restrict data aggregation to world macro-regions, e.g. Europe, in order to maintain transparency. Critically, this coarse spatial, infrastructure and technological aggregation brings significant challenges for understanding bioenergy integration and contribution at a more granular level.

These different categories of models are designed based on varying overarching objectives that influence the model's scope, inputs and calculation approach, hence, characterise the capability, strengths and weaknesses. Assessing the limitations and suitability of a model for a given task is critical for long-term projections. No individual modelling approach can encompass all of the relevant nuances required for a precise assessment of the bioenergy delivery-chain. However, there is significant scope to refine current approaches and develop frameworks that leverage the benefits of multiple approaches to increase the robustness of assessments.

1.4 Critical considerations and knowledge gaps in bioenergy delivery-chains

The formulation of climate mitigation strategies, energy-mix portfolios and steering policies are conducted at the national or supra-national level for the EU. Therefore, evaluation of bioenergy's climate mitigative 'role' in energy-system transitions is most useful for decision-support at a systems level, i.e. the entire EU energy system. For bioenergy, a system-level assessment presents more challenging considerations than for other renewable energy sources where diffusion rates are the primary determinant.

The techno-economic, environmental performance, and total mitigation potential of EU bioenergy depends on a complex delivery-chain that will likely extend beyond Europe's borders to include multiple and diverse import streams for scaled-up deployment which means attached emissions are partly reliant of the production systems of and interactions with other world regions.

These delivery-chain considerations have been enveloped below in Fig.1.5 as a 'Root-Chute' assessment. They can be broadly dichotomised along two axes: (i) supply and demand dynamics and (ii) geographical resolution, i.e. global or regional scale. Considerations are often tightly inter-linked but may be thematically divided across **PESTEL** categories (**P**olitical, **E**conomic, **S**ocial, **T**echnological, **E**nvironmental and **L**egal)

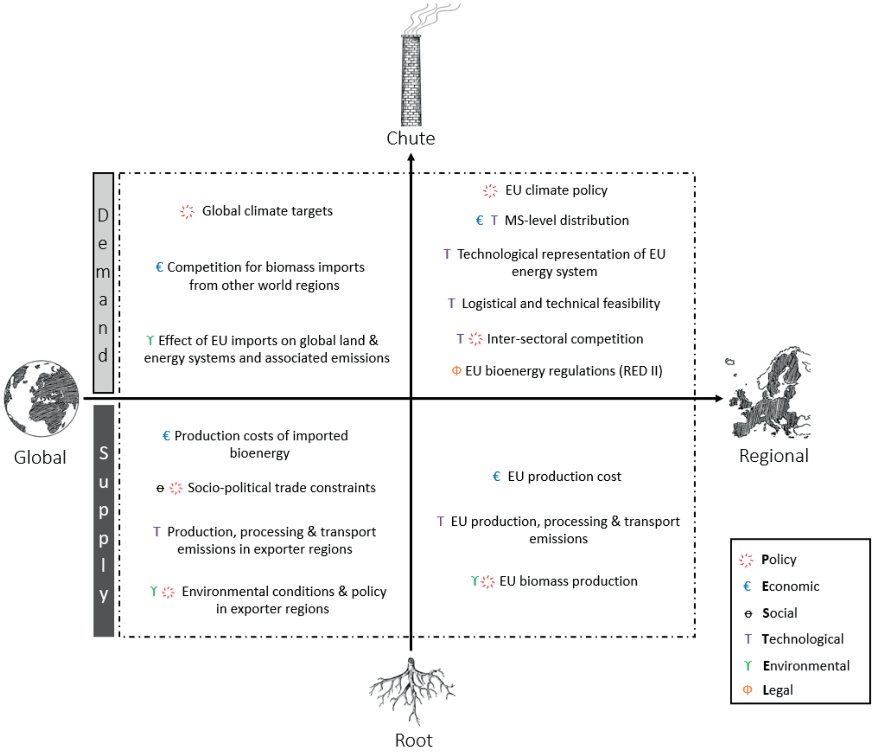

Fig.1.5: Consideration within systematic-level 'Root-Chute' assessment of Global-European bioenergy delivery-chains.

- Considerations at both global and regional level that are further dichotomised along the supply vs demand axis may pertain to market dynamics. This is especially true of economic considerations which can be steered by both supply and demand forces. Hence, positioning within the schematic above are motivated by subjective weighting but are in part arbitrary.

Global considerations

Assessing inter-regional dynamics of bioenergy delivery-chains are essential for informed evaluation of the mitigative potential of bioenergy at the EU scale. Global considerations dictate both the attached emissions factor of imported resources and the scale of deployment within the energy-system.

Demand: For demand dynamics, global climate targets play a direct role in affecting EU climate policy. They also hold the potential to intensify economic competition between world regions for low-emission bioenergy, which must be accounted for when projecting EU import availability. This may be in the form of large producing regions increasingly servicing their own needs in response to tightening mitigation obligations or increased import demand within importing regions from the international market.

Patronage of the international resource base to the EU could affect not only EU mitigation potential but that of other competing regions that are priced out, potentially leading to greater global emissions due to a displacement of the resource away from less developed, more emission intensive regional energy-systems.

Supply: For supply dynamics, assessment must consider a global context for import availability that considers the evolving costs of biomass production in emerging exporter regions. The production and export capacity in regions that currently do not supply the international market requires large scale investment and logistical challenges to mobilise meaningful trade [24]. The challenges associated with expanding production within exporting regions are only being tackled at demonstration scale with large associated capital costs [55].

Part of these costs stem from the transportation from exporter regions and the production and processing technologies available therein. For instance the fuel-mix within national shipping fleets and local land management practices. Such regional technological parameters dictate the emission factor (GHG emission per unit of energy provided) of produced bioenergy carriers which can widely vary dependent on spatial-specific conditions.

Part of the environmental impact of EU sourced imports (represented above under global demand) are borne out of regional environmental policy decisions within exporter regions. Some of which may be classified as socio-politically driven. Feasibility of sustainable supply must be considered when sourcing bioenergy imports. Concerns have been raised regarding the negative impacts of increased bioenergy demand in regions with poor governance and regulatory accountability, where issues such as deforestation, land tenure insecurity and inequitable supply chains are present [56–59]. Furthermore, the formulation of bilateral trade agreements with emerging exporting regions face increased competition from other world regions

Regional considerations

There are EU specific considerations that can effect bioenergy mitigation potential across the PESTLE categories. It is important to capture these with as much regional specificity as possible to better inform modelling efforts.

Demand: EU wide demand considerations should aim to include EU-level climate and energy targets and the trajectories of these which will strongly influence the rate of mitigative efforts and scale-up of low-emission fuels, for instance, an adherence to net-zero by 2050.

Given the complexities of the EU energy system, and the diversity of possible bioenergy uses, in order to properly understand its mitigation potential within the energy and material systems we need to have improved representation of demand technologies. This requires MS-level technological representation to refine estimates on the techno-economic competitivity of the technology and capture the heterogeneity of MS-level energy mixes dynamically over time. Assessing demand using MS-level technological representation allows for feasibility assessment of bioenergy demand distribution at MS-level for aspects such as logistical requirements and BECCS deployment that may be overlooked (overoptimistic) at coarser levels.

Inter-sectoral comparison for net climate benefit is required to determine optimal use among alternative energy services electricity, heating, transport and chemicals. This inter-sectoral deployment may additionally be unintuitive to economic forecasting methods where regional policy such as RED II may steer bioenergy deployment via setting bioenergy specific targets or caps for specific sectors e.g. transport.

From a legislative perspective, EU specific regulatory measures such as RED II need to be introduced into assessments because they may constrain the potential of the resource base eligible to be used in the EU, which in turn may influence both European consumption and global bioenergy trade regimes.

Supply: At the EU level, the cost of domestically produced bioenergy carriers can interplay with that of the international market when production volumes exceed those fulfilled by cheap residues leading to imports. This interaction plays a defining role in EU sourcing strategies, which can affect all deployment decisions. Considerations for attached emissions also hold for domestic production, with an explicit requirement to address how bioenergy can be logistically distributed across MS's and if it complies with legislative criteria in the form of RED II. To assess the emission factor of EU produced bioenergy requires assessment of the environmental impacts related to production, especially important for projections that observe large scale-up, but also the incorporation of regional policies that may impact the EU's ability to domestically produce sufficient quantities such as caps on primary woody biomass for energy use as proposed under RED III.

The global scope of IAMs means they rarely are used for regional assessment of specific energy carriers. However, such global scale assessment is imperative to capture the global considerations captures above whilst retaining the ability of IAMs to capture the environmental impacts and interlinkages with other natural systems. Scenario development offers the solution space to incorporate some of the complex considerations within a Root-Chute assessment into IAMs such as introduction of feasibility dimensions or regional technological constraints such as BECCS or regulatory constraints such as RED II. However, IAMs remain hindered by a lack of regional geographical and technological representation they decrease the ability to capture regional considerations. At the same time regional scale modelling holds similar flaws for global considerations. The current body of bioenergy assessments rarely use global IAMs for regional assessments and do not provide in depth provide insights into bioenergy dynamics that are considered vital for climate mitigation and raised within EU policy debate, including BECCS deployment, sectoral demand, and feedstock category demand.

Projections stemming from IAMs for EU bioenergy developments certainly hold space for improvement in their detail and testing of narrative constraints. However, to broaden the regional considerations to widen assessment to 'Root-Chute' indicatively calls for a novel approach. For this we need to increase the granularity for geographical and technological resolutions which relies on the linkage of modelling approaches for a more robust assessment.

1.5 Thesis objectives, research questions and outline

This thesis aims to advance the assessment of the future role of bioenergy as a climate mitigation option for the EU to mid-century. This is achieved by improving EU-level projections at a systematic level via accounting for the critical considerations within supply and demand dynamics across global and regional scales, traversing the full delivery-chain and attached emissions. To achieve this aim, the following research questions are addressed:

1. What do quantitative assessment approaches project for the role of Bioenergy within EU decarbonisation strategies?
2. How consistent are modelling assessments for representing EU-level bioenergy and climate policy targets and capturing Root-Chute considerations?
3. To what extent can global bioenergy competition for the resource base and trade constraints shape EU mitigation potential from bioenergy and vice-versa?
4. How feasible are long-term projections for EU bioenergy deployment and mitigative potential from the perspective of logistical supply, scale-up, management practices and technological advancements?

To answer these questions requires a step-wise tactic to progressively improve current approaches' ability to capture the breadth of 'Root-Chute' considerations.

Chapter 2 initiates the thesis by constructing a foundation to build upon through a review-based analysis of leading biomass resource assessment, demand-driven and integrated approaches for EU-level projections over the mid (2030) to long term (2050) when following a <2°C climate target. This assessment allows us to identify what 'Root-Chute 'considerations are included across approaches. Key drivers and underlying assumptions that cause inter- and intra-approach bioenergy deployment variances are evaluated. Finally, projections are synthesised to identify absolute ranges, determine cohesion with policy and draw insights on the implications for the scale of development, trade and energy security.

Following this, **Chapter 3** provides a first step into incorporating 'Root-Chute' considerations within 2050 bioenergy projections. This study explores the fringes of Integrated assessment model work through producing regional results from a global IAM models. We utilise IMAGE to produce a detailed regional European-level assessment in the global-context when considering technological limitations, including the prohibition of all bioenergy or biomass paired with carbon capture and storage. Projected key developments include bioenergy demand, feedstock availability, interregional trade requirements and sourcing regions, emission optimal sectoral allocation and mitigation potential. This approach serves as an important intermediate step to explore optimal end-use strategies and for a point of comparison to validate IAM regional level climate trajectory representation and credence that finer resolution data leads to improved assessment.

Expanding on regional-focused assessment in a global context, **Chapter 4** examines Europe's access to interregional bioenergy imports towards the year 2050 using the IAM IMAGE. We develop a scenario protocol that describes plausible future developments for European bioenergy carrier sourcing from the international marketplace. Developed trade scenarios are representative of the challenges faced to overcome bi-lateral trade negotiations in emerging exporter regions, feasibility of techno- and socioeconomic challenges for international supply chains, and EU regulatory requirements in the form of GHG criteria prescribed in the Renewable Energy Directive. Additions are made to the model to allow for the enhanced allocation of emissions across the entire delivery-chain (Root-to-Chute) per unit of European imported bioenergy and enforcement of RED II. The projections provide insight into how assessed trade constraints affect EU and global mitigation targets and shape EU sourcing strategies.

Chapter 5, provides a significant step in incorporating Root-Chute considerations for this thesis along the horizontal (global-regional) axis in Fig.1.5. Here we develop a soft-linked multi-model model framework that includes incorporates the global IAM IMAGE, EU energy system model PRIMES and EU-level bioenergy dedicated least-cost energy system model RESolve-Biomass to explore EU27 & UK bioenergy deployment following a 2°C climate scenario. The approach allows examination of IAM macro-regional supply and demand projection feasibility through the lens of regional energy system models that hold improved energy system and internal trade representation. . Bridging this divide for technological and geographical resolutions permits a deeper assessment for national-level implications and feasibility concerns for trade logistics, cost-optimal processing and conversion routes for end-use sectors, and scale-up of BECCS deployment.

Chapter 6 based on the insights of the preceding chapters of the thesis, this chapter provides a synthesis and discussion of the main findings and conclusions within the context of the overarching research questions. The synthesis chapter offers reflection of the methodologies used throughout the thesis and proposals for how these may be expanded to formulate future research avenues alongside key recommendations for policy decisions.

Table 1.1: Thesis chapter overview and contribution toward the outlined research questions

Title		**RQ1**	**RQ2**	**RQ3**	**RQ4**
2	EU bioenergy development to 2050	+++		++	
3	Integrated assessment of the role of bioenergy within the EU energy transition targets to 2050	+	+	++	
4	The implications of geopolitical, socioeconomic and regulatory constraints on European bioenergy imports and associated GHG emissions to 2050		+++	++	+++
5	EU bioenergy supply-chain projections to 2050 using a multi model framework	+		++	+++
6	Thesis synthesis	**X**	**X**	**X**	**X**

1.6 Models used within this thesis

1.6.1 Image

IMAGE is an integrated assessment modelling framework developed to describe the relationships between humans and natural systems and the impacts of these relationships on the provision of ecosystem services to sustain human development [60]. IMAGE has been principally developed, maintained and operated by the Netherlands Environmental Assessment Agency (Planbureau voor de Leefomgeving, PBL) since the 1980s, with the latest model version used in this thesis being IMAGE 3.2. A detailed description of the modelling framework, individual modules and components are available in Stehfest *et al.* (2014) [60]. The model represents planetary boundaries, including resources, stocks, and flows of the agricultural, forestry, water and energy systems, and represents their interactions and the effect of climate change, policy, and socio-economic developments for 26 world regions with a modelling horizon of 2100. Human system impacts in the form of emissions and land-use change are communicated to dedicated earth system modules for land, atmosphere and ocean. Natural system modules are represented on a grid size of 5x5 arcminutes. IMAGE has been applied for many purposes pertaining to the exploration of long-term dynamics including a key role in assessing climate mitigation stratergies at global-level, inluding developing and assessing global socio-economic development pathways [61,62] used within IPCC reports. Model characteristics and specific alterations to model operations used in this thesis and pertaining to bioenergy are provided in the following sections and specified where relevant within the thesis chapters.

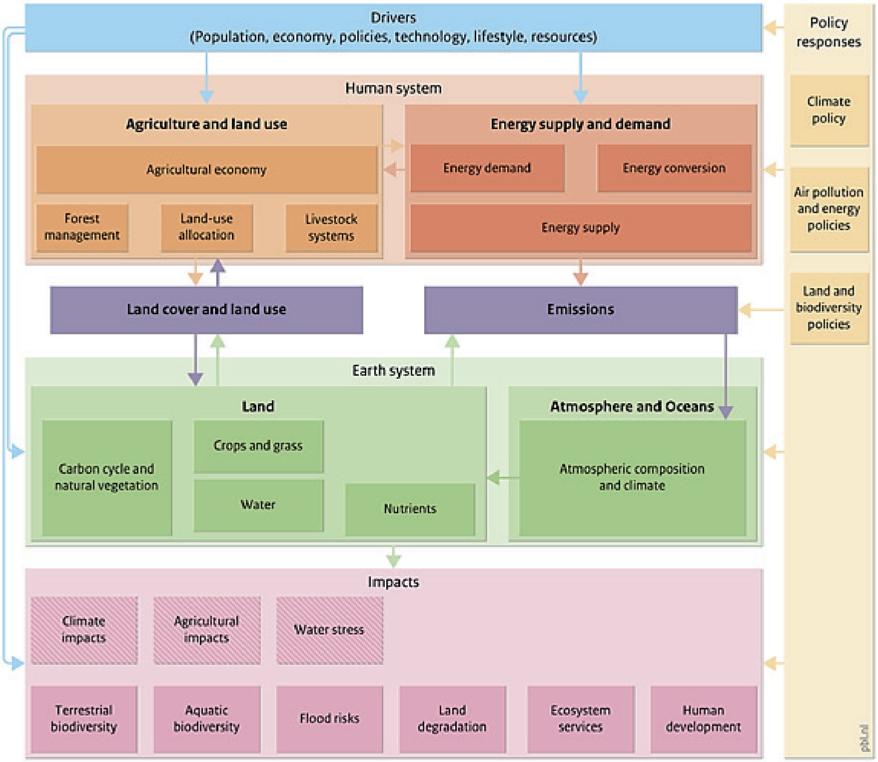

Fig.1.6: IMAGE framework (PBL) as presented in [60]

Description of the TIMER energy system module in IMAGE

The energy module of IMAGE 3.2, TIMER, is a recursive dynamic (i.e. no-foresight) energy system model representing the global energy system, disaggregated across 26 global regions, with projections till 2100 [60]. It includes fossil and renewable primary energy carriers (coal, heavy/light oil, natural gas, modern/traditional biomass, nuclear, concentrated/photovoltaic solar, onshore/offshore wind, hydropower, and geothermal). Primary energy carriers can be converted to secondary and final energy carriers (solids, liquids, electricity, hydrogen, heat) to provide energy services for different end-use sectors (heavy industry, transport, residential, services, chemicals and other). The model projects future (useful) energy demand for each end-use sector (industry, transport, residential, commercial, and other) based on relationships between energy services and activity, the latter of which is primarily related to economic growth – but also environmental effects (i.e. required cooling or heating, population density) and behavioral parameters.

For each demand sector, secondary energy carriers (including solid and liquid biofuels) compete based on relative costs with each other to meet the useful energy demand. TIMER also includes demand elasticity with respect to carbon prices. This is represented via two distinct mechanisms: (i) Investment in energy efficiency, and (ii) reduced demand in energy services (i.e., reducing consumption and foregoing activities and amenities which demand energy/emissions). The former is represented via technological options (i.e., invest in insulation, more efficient technologies, etc.) and the latter is represented based on econometric data. Energy prices are based on supply curves of energy carriers [63,64]. For non-renewable sources, these are formulated in terms of cumulative extraction; while for renewable sources, these are formulated in terms of annual production [65–67].

All investments in the TIMER model (including fuel use, technology choices, and insulation levels) are based on the Multinomial Logit function. This assigns market shares to different options fulfilling a service based on their relative costs, where the cheapest option gets the largest market share, the 2nd cheapest the 2nd largest market share, and so on. This implies that TIMER follows an optimization formulation, since non-optimal technologies also maintain a certain market share to meet a given energy service. The Market Share (MS) allocation is calculated according to:

$$MS_R = \frac{e^{-\lambda C_{R,D,Q,tech}}}{\sum_{Ntech} e^{-\lambda C_{R,D,Q,tech}}}$$

Where λ is the logit parameter, an elasticity representing the importance of relative costs. C is the final costs of different technologies and tech is an index of technologies. The Multinomial logit is used for all investment decisions, so tech could be a list of energy carriers, insulation levels, or heating technologies.

To meet climate targets, the model is used to determine the required value of carbon prices. The application of this price has two effects on the energy system (i) The price of energy carriers increases depending on their carbon content. This leads to increased competitiveness of renewable energy carriers, including biomass, and, (ii) Aggregate energy prices increase, leading to reduced energy demand due to behavioural change or investment in energy efficiency measures. For further reading on model representation of integration constraints and differences in regional energy-systems within IAMs please see [68–71].

Bioenergy dynamics in IMAGE

Below is a brief summary of the representation of biomass, bioenergy, and the associated emissions in the IMAGE 3.2 model, as used in this analysis. For more details on the supply of bioenergy and conversion technologies, please refer to [67,72].

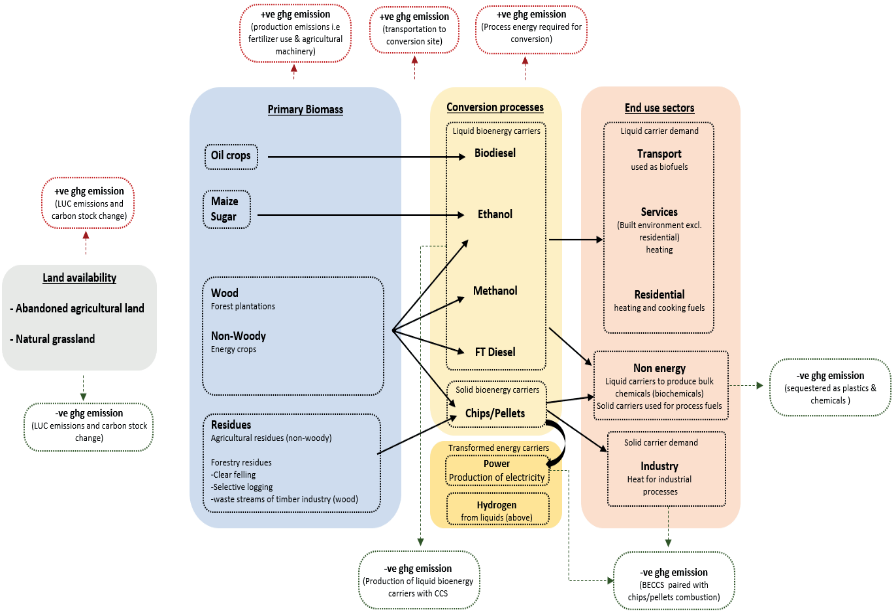

Fig.1.7: Schematic of biomass feedstocks production, feedstock categories, transformation to bioenergy carriers and end-use sectors. Points of negative and positive emissions in the bioenergy supply chain are highlighted.

Primary biomass production: Biomass can be grown as energy crops on either abandoned agricultural or natural grasslands (including forest plantations in the form of short rotation forestry). To ensure that bioenergy supply does not interfere with major environmental and social criteria, specific areas are excluded from bio-energy production, including urban areas, nature reserves, forests and areas used for food production. In this sense, the model assumes a 'food first 'principle [73]. Other biomass streams for bioenergy are in the form of residues which may be as waste-streams of the agricultural and timber Industry or from forestry management [74]. Potential bioenergy supply within the IMAGE 3.2 framework is determined at the grid level by the dynamic vegetation model LPJml, which describes crop growth based on local biophysical and climatic conditions [75].

Feedstock categories are represented by six primary feedstock categories: maize, sugarcane, oil crops, woody (short rotation production of eucalyptus or willow), Non-woody (switchgrass and miscanthus), and residues (which can be agricultural or forestry residues).

Conversion process: This primary biomass can be converted into either liquid or solid secondary bioenergy carriers. These include 1st generation biofuel production of biodiesel from oil crops or bioethanol from dedicated energy crops (i.e. sugar & maize). Bioethanol, Biomethanol and FT diesel can be produced from 2nd generation conversion routes utilising grasses or woody crops. Solid bioenergy (pellets) can be further converted to electricity, hydrogen, or directly combusted for heat. Techno-economic details for all conversion technologies are available in Daioglou et al. (2020)[72].

End-use sectors: Bioenergy carriers may enter five key economic end-use sectors; Industry, transport, residential, services and 'other'; they may additionally be used as a feedstock for the non-energy sector to produce materials such as plastics and chemicals.

Emissions: Emissions from biomass production are represented and accounted for throughout the complete supply chain.

LUC emissions	In this thesis, land-use change emissions from the conversion of abandoned agricultural and natural grasslands to land used to produce bioenergy crops are included. These are based on spatially explicit emission factors for bioenergy production, accounting for LUC emissions as well as emissions arising from "foregone sequestration" [76]. These emissions also include so-called "foregone sequestration, i.e. carbon sequestration that would have happened in the absence of bioenergy production via the growth of natural vegetation is accounted as an emission from biomass production. This explicitly assumes that the land would have reverted to natural land cover in the absence of biomass production, and thus forms a pessimistic assumption concerning LUC emissions.
Growth cycle	Biogenic carbon uptake during the growth of all primary biomass (including residues) is considered a sink (i.e. a negative emissions source on the LULUCF side).
Primary Production	Emissions occurring during growth stage management (i.e. fertiliser application, agricultural machinery fuel consumption) are accounted for as a positive emissions source.

Conversion & Transportation	Process emissions relating to the transportation of primary biomass and bioenergy carriers are accounted. The process emissions resulting from the energy requirements for conversion are also accounted for as a positive emission source.
CCS & BECCS during the conversion of biomass to final energy carriers	CCS during the conversion of primary biomass to electricity, hydrogen, liquid bioenergy carriers, or in industrial processes is accounted for as a negative emissions source. Capture rates of BECCS vary depending on the various conversion routes are applied.
Combustion to final energy	At the point of combustion to final energy (or conversion to final energy carriers, i.e. heat and electricity), the carbon content of the bioenergy is accounted as a positive emission source. This is offset by the equivalent biogenic uptake in the growth cycle.
Non-energy applications	Alternative use of bioenergy carriers into the non-energy sector for materials allows for the sequestration of biogenic carbon (equal to the reduction within the growth cycle, i.e. the embodied carbon). It is assumed that a portion of carbon embedded in non-energy products is permanently stored [77,78].

Bioenergy trade representation in IMAGE

The IMAGE model projects bilateral bioenergy trade across 26 macro-regions. The trade of secondary bioenergy carriers is facilitated based on the regional production cost of bioenergy and associated transport costs. Regional cost supply curves of primary biomass are projected by determining and ordering spatially explicit biomass costs based on yields and land prices. These regional bioenergy supply curves and regional demand are used to determine the optimal bilateral trade. A region imports bioenergy when imported bioenergy cost (export region production cost plus international transport cost) is lower than domestic production or alternative fuel sources to match the equivalent secondary energy demand.

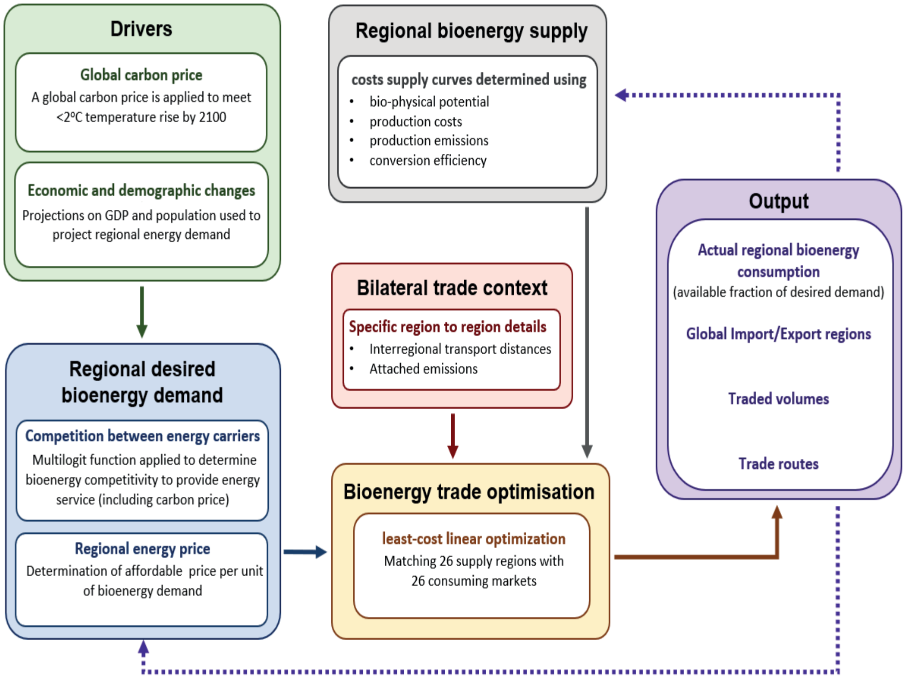

Fig.1.8: Schematic of the drivers, constraints, and formulation of bioenergy trade within IMAGE 3.2. Dashed lines indicate feedbacks from modelled trade and final consumption.

1.6.2 PRIMES

The Price-Induced Market Equilibrium System (PRIMES) model can be generally classified as a partial equilibrium energy system model, however, it is a distinctive model as it holds a mixed approach via including both bottom-up (engineering, technologically rich) and top-down (macroeconomic behaviour) formulation. The model determines the equilibrium by finding the prices of each energy form such that the quantity producers find best to supply matches the quantity consumers wish to use. The equilibrium is static (within each time period) but repeated in a time-forward path, under dynamic relationships. The model provides comprehensive projections of energy demand, supply, market prices, system costs and investment, covering the entire EU energy system at MS-level detail and the related emissions with a time horizon to 2070. Primes runs with a five-year time step from 2005 to 2070 with historical calibration to Eurostat statistics from 2005 to 2015. The model consists of several inter-connected sub-models that are used to express decentralised decision making and ensure market equilibrium conditions and explored policy constraints.

The decision process is forward-looking assuming perfect or semi-perfect foresight according to the specificities of each sector of the energy system. PRIMES model includes various policy instruments, such as targets concerning emissions, renewables, energy efficiency and others, price or market-based policies, e.g. energy taxation, subsidies and non-market based and behaviour-oriented policies, e.g. regulations and policies addressing market failures.

The PRIMES biomass model solves for cost minimisation from the perspective of a biomass supply planner, with perfect foresight for demand, fuel prices, biomass costs and technology improvement potentials. The model determines: a) the optimal use of biomass/waste resources, b) the investments in technologies for biomass conversion to bio-energy commodities, c) the use of land, d) the imports from outside the EU and the intra-EU trade of feedstock and bio-energy commodities, e) the costs and the consumer prices of the final bio-energy products as well as f) the GHG emissions resulting from the bio-energy commodities for EU production. The decision on investment for the secondary and final transformation processes is endogenous. Improvements in each technology are described by one learning-by-doing curve for each technology, uniform for all Member States of the EU; therefore learning-by-doing effects spill over to the whole EU [79].

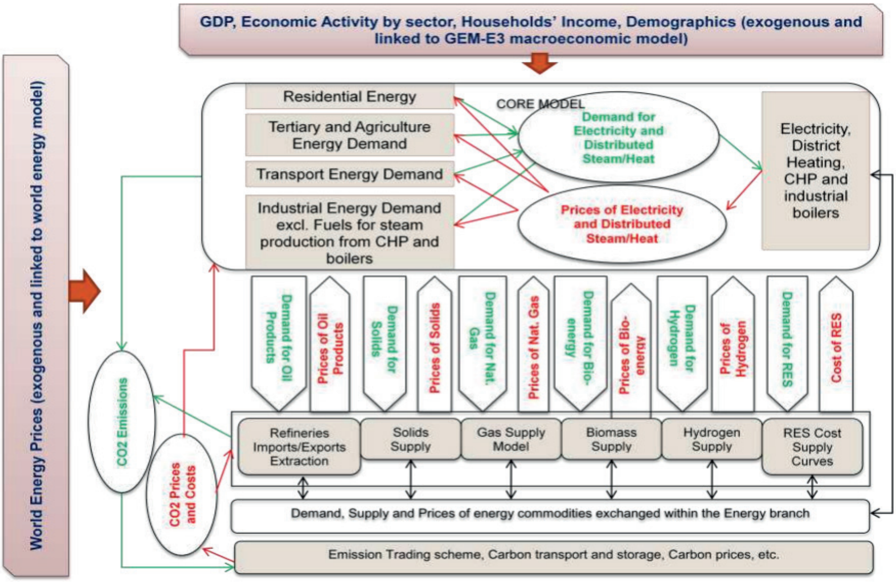

Fig.1.9: PRIMES framework [79]

1.6.3 RESolve-Biomass

RESolve-Biomass is a dedicated bioenergy, least-cost energy-system model with a spatial resolution at MS-level for the EU27 & UK. The model can determine the least-cost configurations of the bioenergy supply-chain when provided with external projections for energy demand, supply, and technological progress. Exogenous sectoral demand for bioenergy is treated as a potential target, where allocation of bioenergy also considers competition to fulfil energy services from reference fossil fuel commodities. Hence, the model optimises the choice of technology alternatives concerning total system costs to find the least-cost path to meet the demand projections for energy services. It considers the cost-supply curves of various biomass feedstocks and conversion technologies [80]. End-use sectors for biomass represented in the model include bioelectricity, bioheat, biofuels for transport and biochemicals. A prominent feature of the model is the high level of detail regarding bioenergy conversion technologies, related feedstocks and in-between logistics [81]. Within this thesis, RESolve-Biomass representation coverage extends to 38 primary feedstock categories, 37 intermediate conversion processes, 30 secondary bioenergy carriers (+ 2 chemicals) and 67 final bioenergy conversion technologies. An additional notable feature of the model is the capacity to inter-link MS-level bioenergy production and logistics networks, hence internal trade dynamics can be captured [82]. EU-wide trade of feedstocks and final products is represented by three transport modes, trucks, trains and short sea shipments; extra-EU imports are hauled via ocean tankers [80].

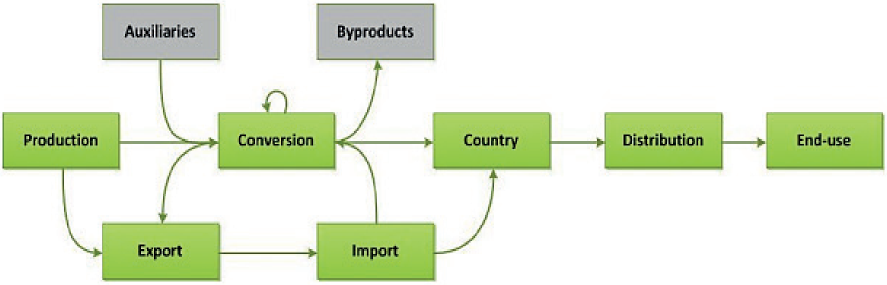

Fig.1.10: RESolve-Biomass framework [80]

CHAPTER 2

EU bioenergy development to 2050

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2. EU BIOENERGY DEVELOPMENT TO 2050

Abstract

Bioenergy is the EU's leading renewable energy source at present. Understanding bioenergy's contribution to the future EU energy mix is strategically relevant for mid to long term climate targets. This review consolidates recent projections of both supply and demand dynamics for EU bioenergy to 2050, drawing from resource-focused, demand-driven and integrated assessment approaches. Projections are synthesised to identify absolute ranges, determine cohesion with policy and draw insights on the implications for the scale of development, trade and energy security. Supply side studies have undergone methodological harmonisation efforts in recent years. Despite this, due to assumptions on key uncertainties such as feedstock yields, technical potential estimates range from 9–25 $EJyr^{-1}$ of EU domestically available biomass for energy in 2050. Demand side projections range between 5-19 $EJyr^{-1}$ by 2050. This range is primarily due to variations in study assumptions on key influential developments such as economic competitivity of bioenergy, EU energy efficiency gains within the power sector, flexibility for meeting mitigation targets and technological portfolios. Upper bound technical supply estimates are able meet future demand wholly from the domestic resource base, holding the potential to reduce total EU primary energy import dependency 22 percent points from the current EU roadmap trajectory. However, due to part of this domestic resource base being deemed economically inaccessible or of insufficient quality, interregional imports are projected to increase from current 4% to 13-76%. Emergence of non-energy applications are projected to compete for at least 10% of the biomass needed to fulfil bioenergy demand in 2050.

2.1 Introduction

At global scale, approximately half of the total renewable energy consumption in 2017 was derived from modern bioenergy. This leading contributory role is projected to continue over the short term and expected to remain the sole largest renewable energy source (RES) until 2023, accounting for 30% of renewables growth over the next five years [83]. At EU level, bioenergy is the most flexible and heavily used RES, with current consumption standing at 5.6 $EJyr^{-1}$ accounting for 64% of RES consumption [84]. Of this, 96% of biomass used for energy is EU-sourced and 89% is derived from the member state (MS) it is consumed in [85], with EU biomass production exceeding that of domestic gas or coal [86]. Switching to biomass thus provides the EU with an option to improve its energy independence. From a policy perspective, bioenergy is also recognised as a fundamental contributor in efforts to decarbonise the EU's energy system. Immediate milestones that place urgency on the contribution from biomass can be seen in many of the National Renewable Energy Action Plans (NREAPS) [87].

Considering future EU bioenergy development, mid-term (2030) binding targets are defined for the EU within the 2030 energy and climate framework, stating a continued commitment to bolster the share of RES up to 32% in an attempt to cut GHG emissions to 40% of 1990 levels [88]. At present, targets for 2030 at MS level are absent, thus national-level energy mixes and quantitative bioenergy contributions are somewhat unclear. There are no long-term (2050) binding targets for RES or bioenergy apart from a commitment to emissions reductions of 80-95% by 2050 as part of climate mitigation efforts required by developed nations as a group [89]. Under the European Commission's 2018 strategy release 'A clean planet for all', reaping the full benefits of the bio-economy and maximising the deployment of RES to fully decarbonise the EU energy supply by 2050 with improved security of supply are highlighted as key strategic building blocks [90]. Furthermore, bioenergy, especially when combined with carbon capture and storage (BECCS), is increasingly relied upon for scenarios exploring stricter climate mitigation efforts that limit temperature rise to 1.5-2°C [91]. However, the supply and demand dynamics for EU bioenergy in the long-term (2050) are not well understood, which may have implications on both EU energy security and trade should demand outstrip supply. Furthermore, the demand between the aforementioned end-use sectors and emerging advanced non-energy end uses (e.g. bioplastics, biochemicals) could create a potential mismatch between feedstock supply and end-use requirements.

Considering the importance of bioenergy within future supra-national EU climate targets, it is essential to understand the quantitative scales at which an EU bioenergy sector could develop. To achieve this it is imperative to understand both the supply and demand dynamics at play and the leading estimations thereof. There are three common and distinguishable approaches that are employed to estimate future biomass development, namely; ***resource-focussed***, ***demand-driven*** and ***integrated***. Each of the assessment approaches holds both advantages and disadvantages within their ability to estimate future bioenergy development, with their issues and suitability of models to answer major policy questions being addressed within assessment/model comparison studies [46,92,93].

Comparative reviews on recent bioenergy assessments at an EU scale are available. However, the existing knowledge base (including standalone studies and reviews) of projections for EU biomass supply and bioenergy demand is limited on one or more of the following dimensions;

Time horizon not extending to 2030-2050: Based on the perceived importance of continued contribution towards the UNFCCC's 1.5-2°C global temperature rise target, projections on EU bioenergy at these time horizons become increasingly important. Over the past few years, efforts have been published on the harmonisation on supply-side resource-focussed assessments and demand-side model inter-comparison projects. These efforts have yielded estimations for the mid-long term. An up-to-date review of potentials at these time horizons is absent within the current literature base; with previous reviews carried out +5yrs ago [94].

Most studies focus on one biomass stream. Bioenergy supply potentials tend to focus on one of the available biomass feedstock streams (i.e. Energy Crops [95,96], Forestry [97,98], Agricultural Residues [99,100] and waste streams [101]). In doing so, these studies are not able to determine the total bioenergy potential available to contribute to the future EU energy mix.

Another limitation relates to previous **studies only utilised one of the three available approaches**. The current literature base provides standalone single study estimates on bioenergy development as projected from a single approach or reviews of projections that investigate either the supply [102,103] or the demand side [104,105] separately. IAM's do take both supply and demand into account simultaneously, however, their outcomes have not been compared directly to those of the other two approaches.

Besides the lack of inter-approach comparisons, previous studies have **not reflected on recent policy aspirations**. Whilst estimations from deploying each of the three approaches often place ‘sustainability’ constraints to limit supply (e.g. land use limits/change) or influence demand (e.g. emission levels, CO_2 taxes), they do not draw a direct comparison to long term policy with proposed binding targets. Due to their agility, IAM’s are able to incorporate recent policy developments. However, included policy considerations are often outdated, not transparent how they are applied or lacking [93].

Given the limitations within the existing literature identified above, this review aims to consolidate the current knowledge base by providing a holistic, up-to-date and quantitative understanding of EU bioenergy development over the mid (2030) to long term (2050). This study takes an integral approach via incorporating leading estimations from the three available assessment approaches, i.e. resource-focussed, demand-driven and integrated, and compare these projections to EU climate policy ambitions. The study specifically assesses both EU-domestic available biomass supply and bioenergy demand estimations simultaneously, providing absolute ranges (bandwidths) both intra/inter-approach to identify to what extent total supply matches total demand, and to identify the major causes of uncertainties in future development between the studies included. The review then aims to provide insight into the feasibility of EU policy ambitions for bioenergy as a climate mitigation option and assess if projections interfere with or bolster EU climate strategy. We also highlight implications at varying levels of EU bioenergy development for: i) EU bioenergy interregional trade, ii) EU energy security, iii) Potential mismatch in EU domestic feedstock supply to demand requirements, and iv) Competition from an emerging biomaterials & biochemicals sectors.

2.2 Methodology

2.2.1 Characteristics of the reviewed assessment approaches & study inclusion parameters

Resource-focussed approaches

When envisaging the development of bioenergy deployment to 2030 & 2050, one approach is to estimate biomass availability via carrying out a Resource-focussed assessment which considers that a bio-based transition is limited by natural systems (e.g. land availability and land use impacts). Such assessments can produce theoretical, technical, economic, implementation or sustainable potential on biomass availability, otherwise known as the hierarchy of opportunity [106]. This approach is a bottom-up assessment, which aims to provide estimates of the bioenergy resource base (supply side), with most studies applying a food first principle and accounting for resource competition from established industries (e.g. timber). This approach also takes key macro socio-economic drivers into account (e.g. population growth & consumption trends). Within this approach, there are two common methodologies: i.) Statistically derived estimations derived from calculations utilising often (high level) aggregated biophysical data (e.g. land use, agriculture, yield productivity, etc.), and ii.) Spatially explicit analysis using geodata to provide more accurate region-specific information and distribution.

Existing resource assessments tend to focus on sole biomass types i.e. forestry, energy crops, waste or residues explicitly, with few studies capturing all biomass streams. To align with the objectives of this review, only studies that represent all of these major streams are included. Furthermore, only resource-focussed assessment projections identified as conferring to the technical bioenergy supply potential are incorporated. Within this approach sustainability (e.g. environmental policy), economic (e.g. crop profitability) and implementation (e.g. harvest/yield rates) constraints are explored through scenarios.

Demand-Driven approaches

The demand-driven approach is commonly used to assess the cost and effectiveness of policy options. Conversely to the resource-focussed assessments, they aim to estimate future bioenergy demand rather than supply. This assessment approach utilises either energy-economics or energy system models. However, most demand-driven studies do include some (often unspecified) feasibility estimation of the supply side, but there are no land-use or crop growth biophysical modules with feedbacks built into the (energy) modelling framework [107]. These models must include assumptions on biomass price and availability. Future demand is estimated based on either cost-supply analysis and bioenergy's economic competitiveness with other energy supply technologies or determination of the deployment of bioenergy required to meet exogenously fed in targets such as RES contribution or climate mitigation. The two are often intertwined (e.g. models calculate the lowest cost energy mix available at a given carbon price), hence they do not preclude the option (i.e. energy mix) to meet the goal. These prices are also influenced by other market end uses for biomass such as increased food demand and materials. Within this approach, population and economic trends are principle factors that stimulate bioenergy demand [107] with climate and energy policy inclusion crucial [92].

Bioenergy demand-driven projections included within this review evaluate the economic potential of bioenergy. Due to the nature of the approaches, their potential assessed is not the same as the technical potentials arising from the supply side but are the closest fitting on the hierarchy of opportunity [106], hence, the most suitable selections for direct comparison of supply (technical) vs demand (economic). Demand-driven approaches can also include sustainability constraints (e.g. varying levels of climate policy) and implementation constraints (e.g. technology availability/learning rates) through the exploration of scenarios. Demand-side models are generally globally orientated.

Integrated approaches

IAM's are designed, among other purposes, to assess policy options aiming to limit climate change through the exploration of different mitigation scenarios. To achieve this, they have extended system boundaries to address the activities and complex interactions between human and natural systems. IAM's architecture then commonly interlinks separate modules to formulate an energy-land-climate nexus [17]. The energy system represents both supply and demand dynamics with projections of future energy use (including bioenergy, fossil fuels, nuclear and other renewables) driven by the projected demand. IAMs are often used to project energy and land-use strategies which would be consistent with specific GHG emission levels [5,92].

A key distinction between the demand-driven approach and IAM's is the use of bi-directional interconnected modules representing both natural/geophysical and socio-economic systems including their feedbacks. The environmental impacts of this demand are further assessed within the natural system modules and feedbacks (e.g. land-use impacts, water scarcity, climate impacts) are communicated to the social/economic modules again. Thus, IAM's can take into account the effect of demand onto available supply dynamically unlike pure demand-driven approaches.

2.2.2 Framework of the review

To enable a systematic evaluation of EU bioenergy assessments, a review framework is constructed in a manner which allows for 1) The quantitative comparison of total bioenergy projections stemming from each of the three aforementioned assessment approaches, 2) Comparison between approaches, and 3) Cohesion with policy. A detailed assessment of methodological differences internally within each of the approaches assessed is beyond the scope of this review and has been covered to a large extent elsewhere [108–110]. Building on previous reviews, this framework focuses on highlighting bandwidths (absolute primary energy ranges) of EU bioenergy development to 2050 with a reflection on their implications for EU policy intentions.

As noted by others [110], frequently throughout the fields of bioenergy assessments (all approaches) it can be observed that the type of biomass potential reported is unclear and often blends into another (e.g. techno-sustainability). This is largely due to the exploration of limiting factors within scenario analysis that reduce the overall potential, applied through the lens of the author on a study by study basis. This results in a situation in which study outcomes do not conform to the common biomass potential definitions [92] and are prevalent within this review. Thus, for the comparative purposes of this review, we dilute the classical definitions of potential types and simplify them as follows. Resource (supply-side) assessments lead to a technical potential, whereby sustainability, economic and implementation constraints can be applied. Demand-driven estimations produce economic potential estimations that can apply either sustainability or implementation constraints. Fig.2.1 provides a schematic of the review framework.

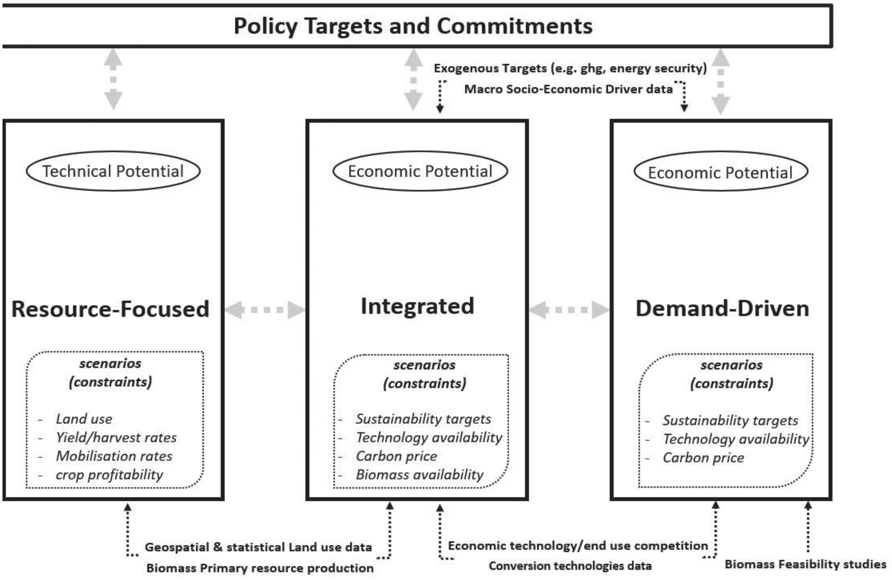

Fig.2.1: Framework of the review, highlighting key characteristics of bioenergy assessment approaches.

2.3 Bioenergy projections to 2050

2.3.1 Policy overview

Bioenergy related policy for EU to 2030

Major EU policies that affect the development of bioenergy are tied to renewable energy as a whole. The EU 28 as a political union is currently party to the United Nations Framework Convention on Climate Change (UNFCCC)'s Kyoto protocol, which after the extension for a second commitment period through the Doha agreement is set to expire post 2020 [111]. Beyond this point, the EU 28 is committed to the UNFCCC Paris agreement with the intended response of steering global temperature rise below 2°C above 1990 levels, with each of the EU MS (Member states) set to announce nationally determined contributions (NDC's) for which next round preparations began in 2018. The EU 28 have agreed on a collective delivery and committed to a 40% reduction in GHG emissions by 2030 [88], acknowledging that increased uptake of RES into the energy sector as the key climate strategy. If the current momentum of renewable energy development within all end-use sectors (heat, electricity, and transport) is maintained as projected in the short-term (2018-2023) market analysis for the IEA [83], renewables would attribute about 18% of final energy consumption in 2040. This is significantly below the absolute RES energy mix required to follow exploratory development scenarios aligned to achieve climate mitigation targets established within the Paris Agreement such as the IPCC's pathways to curb global warming to 1.5°C [112] and the IEA's Sustainable development scenario which projects a needed RES mix of 28% by 2040 [105]. The renewable energy directive II recast [27] has increased the EU targeted RES contribution from 27% to 32% by 2030 with a minimum of 14% within the transport with a strict cap of 7% placed on conventional biofuels. Bioenergy used in heating and electricity end-use sectors must comply with a mandatory 70% GHG saving compared to fossil incumbents from 2021 and 80% post 2026 with a stringent list of sustainability constraints [27].

In order to meet these ambitious mid-term targets, the EU energy system must swiftly transition to low-carbon fuels. The pathways to achieving such a transition are unique per member state and will become clearer with the release of the 2020 NDC's. The EU 28 currently sources approximately 74% of gross available energy from fossil fuels with individual member states deploying varying national strategies to achieving an energy transition to low carbon fuel mixes, largely based on the geographical resources at their disposal and economic ability, with some countries reliant on a substantial share of fossil power generation. 59% of renewable gross inland energy consumed in the EU is derived from bioenergy with some MS's relying on biomass almost entirely, >80% of renewables consumed (Czechia, Estonia, Latvia, Lithuania, Hungary, Poland, and Finland) only Norway has <25% of renewable consumption from bioenergy. At present the largest absolute bioenergy consuming nations are France [0.67 $EJyr^{-1}$], Italy [0.52 $EJyr^{-1}$], UK [0.52 $EJyr^{-1}$], Sweden [0.5 $EJyr^{-1}$] and Finland [0.41 $EJyr^{-1}$][113].

Bioenergy related policy for EU to 2050

At COP 24, the European Commission strengthened its 2050 aspirations for bioenergy within its 'long-term vision for a prosperous, modern, competitive and climate neutral economy' acknowledging the bio-economy and natural carbon sinks as one of seven strategic action areas [90]. On a longer-term scale, there are no binding targets for RES or bioenergy apart from a commitment to emissions reductions of 80-95% by 2050 as part of the efforts required by developed nations as a group [89]. As this study is aimed at quantitative comparisons of EU bioenergy to 2050 data is drawn from the European Commission's adopted communication 'Energy Roadmap 2050' (Fig.2.2) and the envisioned decarbonisation scenarios to bring about 85% domestic energy related GHG emission reductions below 1990 levels without reliance on international carbon offsets. The roadmap aims to provide the EU with a set of alternative energy system development pathways that align with the UNFCC Paris agreement limiting global temperature rise. It is the only policy strategy at EU level that provides quantitative energy mix proposals and gives an indication of the bioenergy contributions required to meet targets under varying climate policy packages. The modelling framework employed is documented within the impact and scenario analysis publication [114]. The roadmap explores a reference scenario incorporating energy system relevant policies adopted by 2010 with the current policies scenario including updated measures proposed at the time of publication (2012). The decarbonisation strategies are designed to investigate the EU energy mix when steered to varying degrees by policy facilitating the EU's 2050 key routes to a competitive and secure energy system; energy efficiency, renewable energy, nuclear energy, and carbon capture and storage [14]. Facilitation policies for bioenergy include agricultural policies stimulating the production of energy crops, increased residue collection, and/or increased yield of crops.

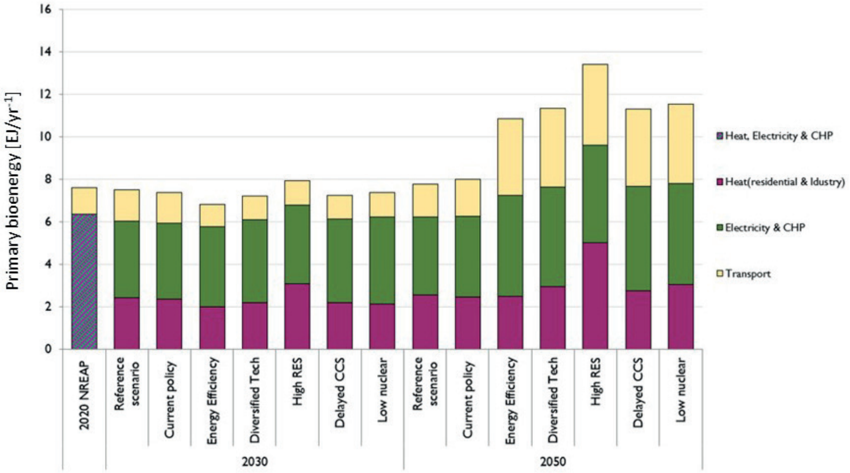

Fig.2.2: Evolution of Absolute Domestic EU Primary bioenergy within major end-use sectors. Own calculations using data from the EU Energy Roadmap 2050 [14]

Fig.2.2 indicates all decarbonisation pathways are characterised by a significant growth by 2050 in bioenergy for transport fuels when compared to the reference and current policy projections. It should be noted that BECCS is not included within the technology portfolio assessed – while fossil CCS is. Biomass used for heat only sees a noticeable growth under the 'High Res' policy pathway with bioelectricity generation observing a small growth. The roadmap indicates that by 2050 under the policy pathways assessed, the EU would require an increased primary bioenergy consumption of 3.3-5.8 $EJyr^{-1}$ (+ 43-76%) compared to the 2020 EU combined NREAP bioenergy consumption target. This correlates to a bioenergy contributing (22-28%) of EU gross inland energy consumption in 2050 throughout the decarbonisation pathways. Key reasons that bioenergy holds a substantial share throughout the decarbonisation scenarios assessed within the EU2050 roadmap is due to its versatility across the three end-use sectors of heat, electricity, and transport and its dispatchable characteristics, especially within the electricity sector.

2.3.2 Resource assessments (Supply)

Current resource assessments at an EU level present a strong variation in the future projection of domestic feedstock. For the purposes of this review and to improve accuracy when comparing projections, studies included are drawn from the Biomass Energy Europe (BEE) project [92]. The BEE project, concluding in 2010, focussed on harmonising leading resource assessments and found there to be large disparities at a supranational EU level due to underlying factors such as inconsistent definitions, varying system-external factors that influence production (i.e. land use), and inconsistent data between assessments on parameters such as productivity and yield [109]. The focus of the project laid in the harmonisation of biomass type classification, approaches deployed, methodologies and underlying datasets via comparative analysis, used to distinguish the points of heterogeneity. Within this review, the outcome of three calibrated studies from the BEE project are included. The BEE project furthermore published a 'handbook' [115], outlining specific data sets and methodologies to promote harmonisation of future EU level assessments, thus increasing both accuracy and comparability. Since the publication of the BEE Project report, several EC Projects: Biomass Futures [116], Biomass policies and S2biom [117] have utilised and built on this state-of-the-art resource assessment approach. Post 2010 estimations included within this review utilise and expand on the generic approaches laid out from the BBE project and are reported to provide a current overview.

Despite the aforementioned efforts to reduce heterogeneity between estimations, there exist significant bandwidths of disagreements between the studies assessed as seen in

Fig.2.3. In the short-term to 2020 large differences appear in the amount of primary bioenergy available, ranging between 4.8-21.6 EJyr^{-1}, the mid-term 2030 show a range of between 8.6–25 EJyr^{-1}. For long-term estimates, only two studies were available, highlighting the lack of/difficulty for conducting resource-focussed assessments over this time horizon.

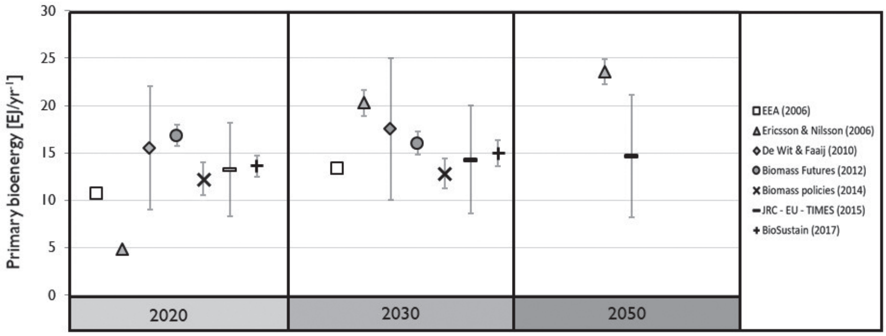

Fig.2.3: Total EU Domestic bioenergy production Technical Potentials 2020-2050
-As projected by the Resource assessment approach
*pre 2011 assessments are calibrated to EU level as part of the EC project BEE.

Variation in the estimates arise from one or more of three key uncertainties: 1) land use and surplus availability for agriculture or dedicated energy crops, 2) yield improvements and rate thereof for bioenergy crops, 3) mobilisation of forestry biomass through harvest rates and residue collection. Scenarios are utilised in a bid to explicitly account for the uncertainties encountered whilst modelling these key developments and highlight their influence on the total potential. Annex I.1 provides the general characteristics alongside key assumptions, constraints, and scenarios deployed within the analysed resource assessments.

An important observation to note is that studies conducted post 2010 display a tighter grouping between 8.6-20 EJyr^{-1}. This reflects the conclusions reached by Panoutsou [118] that between 2008-2016 collaboration, cross-sectoral cooperation, harmonisation of data sets and methodological choices have improved consistency within the field of resource assessments. The use of the Common Agriculture Policy Regionalised Impact model (CAPRI) is observed in all post 2010 studies included in this review. CAPRI is a partial equilibrium model used to project future EU agricultural land use and hence land release for dedicated bioenergy crops via maximising agricultural income at a NUTS 2 level with the baseline run utilised in all post 2010 studies assessed aimed to project the most probable future under status quo policy. CAPRI is also used within these studies to project future yields based on price elasticities. The methodologies behind the model are well documented [119]. Pre 2010, future land use and yield developments are more crudely estimated. A recent review on EU scale land and bioenergy potential studies [108] investigates the deficiencies of existing assessments ability to capture the environmental impacts of land intensification needed to enable energy cropping and higher yields, concluding that future assessment methodologies should incorporate sustainability constraints that utilise a more integrative approach and investigate a larger variety of intensification pathways.

The remaining key development influencing the total technical potentials reported is the mobilisation of forestry biomass. Nearly all studies included relied on the use of the EFISCEN model which simulates future projections on forest and roundwood extraction that can be sustained. However, different sustainability criteria can be exogenously fed into the model and this is tested within some of the later studies, for example 'biomass policies' solely evaluated the increased mobilisation of forestry biomass using the European Forest Sector Outlook Study (EFSOS) II [120] (medium mobilisation scenario) and projected an additional 137 Ktonnes of stem wood and residues are available in 2030. This results in an additional 2.9 $EJyr^{-1}$ of bioenergy. The 'JRC-EU TIMES' [121] study further investigates the (high EFSOS mobilisation scenario) which projects a bioenergy contribution of up to 9.9 EJ domestic EU production in 2050, roughly 50% of the total projected bioenergy as opposed to only 2.8 $EJyr^{-1}$ under the (low availability scenario). A general trend can be seen within resource assessments to move from a stand-alone, bottom-up inventory-based approach to utilising common datasets and scenario-based analysis to explore the sensitivity of estimates that account for the associated policy interface.

2.3.3 Demand driven

Methodological comparability of demand-driven estimates have received less attention than the resource-focussed approach. Alternatively, efforts are steered towards transparency of the underlying assumptions and setting of common climate-neutral energy supply policy targets, whilst utilising harmonised scenarios on key fundamental energy system drivers such as population/economic growth and portfolios of technology availability, especially to better represent the integration of variable renewables. These demand-driven assessments often engage simulation, optimisation, partial or general equilibrium models [122] and are based on cost-supply of aggregated resources [106].

This review indicates there is a lack of long-term projections stemming from the demand-driven approach with only four publicly available studies that meet the inclusion parameters (Section 2). Furthermore, only the world energy model (WEM), a global long-term hybrid simulation model, produced estimates of EU bioenergy demand post 2030 to the year 2040. Fig.2.4. presents the primary bioenergy contribution to the future configurations of the EU's energy system. In general, the studies estimate a moderate growth in bioenergy deployment from the 2020 levels toward 2040 but with a maximum deployment of about 12 EJyr^{-1}.

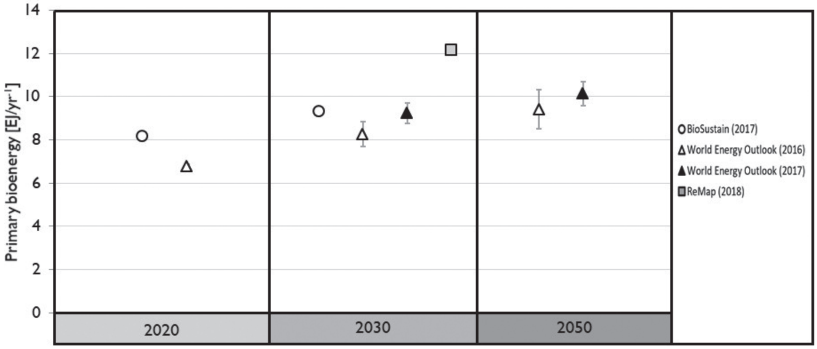

Fig.2.4: Total EU Primary bioenergy demand 2020-2050 - As projected through the Demand-driven approach

Within the Biosustain study bioenergy demand is projected through the EU regionalised partial equilibrium model Green-X, which takes into account both policy developments and sustainability criteria for bioenergy (i.e. sustainable forest management, conversion efficiency standards, iLUc reduction) [123]. Key macroeconomic assumptions including energy system specific developments such as efficiency gains and total primary energy demand per sector are based on the PRIMES reference scenario [124]. Bioenergy development is calculated through economic optimization via nationally specific dynamic cost-supply curves for all RES technologies. Projected demand is dictated by a target 40% GHG reduction and 27% RES share in gross final energy consumption by 2030. Despite the modest growth in bioenergy development between 2020-2030 the share of bioenergy within total RES for energy production falls overall due to a strong increase in the competitiveness of wind and solar.

IRENA's renewable energy roadmaps (REmap) projections show a substantially larger deployment of bioenergy by 2030. Total energy demand is determined through national energy plans and the use of the PRIMES reference scenario as seen for the Biosustain project [49]. RES integration is projected through the use of cost-supply curves and formulation of substitution costs compared to fossil counterparts through the employment of a unique technology and project cost dataset [125]. The REmap project aimed to exceed the RES 27% target in 2030 to 33% and technology options are ranked as the model projects the most cost-effective solution, with bioenergy making up all of the additional contribution (roughly 3% of TPED). Much of the increase is in liquid biofuels, with a significant proportion derived from advanced biofuels, that are judged to be a competitive option with large potential. The projections thus show that in the mid-term to 2030, bioenergy is key to exceeding minimum requirements as laid out in current EU policy. The REmap results additionally show that under a case in which only 27% RES is realised, 9.9 $EJyr^{-1}$ of bioenergy is demanded (falling closer in line with other projections in Fig.2.4). However, as seen across all demand-driven projections, bioenergy's relative stake in RES falls due to faster growth from PV and solar.

The results from the World Energy Outlook's (WEO) see growth in EU bioenergy deployment between the two annual releases (2016 &2017) projected by the IEA's WEM. Although a simulation model, specific costs play a crucial role in determining the share of technologies to meet energy demand [126]. The ranges displayed for both WEM annual outputs represent three scenarios namely: '*current policies scenarios*' in which climate orientated policies enacted at the time of publication are incorporated (lower range), 'new polices scenarios' additionally capturing the effects of announced policies e.g. COP21 pledges, and a '450 (2016 release)' or 'sustainable development goals (2017 release)' scenario conducive with mitigation efforts from the energy system required to limit long-term global warming to 2°C (higher estimate range) giving the energy sector a global cumulative CO_2 budget of 1,080 Gt CO_2 [126]. Projections within the WEO show an increase in deployment within the later 2017 projection for the years 2030 & 2040. This occurs even though final consumption in all sectors decreases due to energy efficiency improvements. Additionally, within the 2017 'sustainable development goals' scenario, bioenergy become costlier due to the need for post-combustion control to limit air pollution, which is additionally considered within the 2017 update [127]. There is a 20% increase in the projected power generation from bioenergy in 2040 under the '450 scenario' which overcompensates for decreases in direct consumption and is due primarily to stronger investments within bio-based power plants. The projections see the share of EU power generation capacity hold static for bioenergy where a tripling is observed for wind and PV taking their share to ≈33%. Part of this increase is due to substantial reductions in the levilised cost of electricity; both experienced in recent years and projected forwards. Additionally, 70% of subsidies are allocated to PV and wind and 20% to bioenergy to 2040 [127].

The close grouping of the projected developments over a span of 30 years is observed in Fig.2.4. This is partly due to their formulation under conditions that conform tightly to intermediate policy targets most notably a GHG reduction of 40% [88], RES shares of >27% [27] and an energy efficiency target of 30% accordance to the EC's energy efficiency directive and its proposed revision [128] by 2030. Furthermore, all projections follow a close total EU primary energy demand with <5% difference. 2030 projections are additionally closely banded due to economic competitivity between RES technologies witnessing less divergence (i.e. front runners) over a shorter framed temporal scope.

2.3.4 Integrated Assessment Models

Though IAM's are able to produce supply-side estimations, due to the inclusion of regionally focussed resource assessments with finer resolution, this review only leverages IAM projections for the demand of bioenergy. Within this review, we take harmonised projections of bioenergy demand attained from the 33rd study of the Stanford Energy Modeling Forum (EMF33) which aimed to quantitatively consider the development of bioenergy development towards climate targets consistent with the Paris Agreement [129]. The EMF33 project compares the results of 12 IAMs across harmonised scenarios of varying emissions reduction targets and portfolios of available bioenergy technologies (see Fig. 5).

IAM projections for the EU energy system are used, which adhere to a fixed global carbon budget of 1000 Gt CO_2 for fossil fuels and industry. This cumulative emission level was selected as it reflects the global efforts to limit mean global temperature increases to 2°C. Thus, it is also most consistent with the EU roadmap decarbonisation pathway projections [129] and is the most suitable scenario available for this review.

In addition to the harmonised emissions budget, scenarios testing the uncertainty relating to the varying future availability of advanced bioenergy technologies (ABTs, i.e. lignocellulosic biofuels and BECCS technologies) are explored. The technology availability scenarios are (i) all ABT's available (ii) exclusion of all ABTs, (iii) No conversion of lignocellulosic feedstocks into liquid fuels, and (iv) No BECCS technologies. A detailed description of the ABT scenario protocols is presented in Bauer et al. [129], it should be noted that constraints on technologies may make the carbon budget infeasible for specific IAM's and thus submissions for these technologically constrained scenarios are not present for every model.

While scenario parameters such as emissions budget, ABT availability and key socioeconomic drivers (i.e., population and economic growth) are harmonised, the models' projections of EU primary energy demand, food demand, biomass feedstock prices, price per unit energy for non-fossil energy sources (competitivity), and natural system parameters including biomass supply assumptions are independently and endogenously derived for each model. All IAM projections reported stem from globally focussed models whereby the imposed planetary carbon budget is spread across not only world regions but also sectors, which is determined endogenously per model. This is irrespective of regional policy or targets, thus bioenergy outcomes concerning the EU are not predisposed to a fixed regional emission cap or RES target. Fig.2.5 presents the projections of EU primary bioenergy demand for varying technology availability scenarios from the IAM's that participated within the EMF33 study.

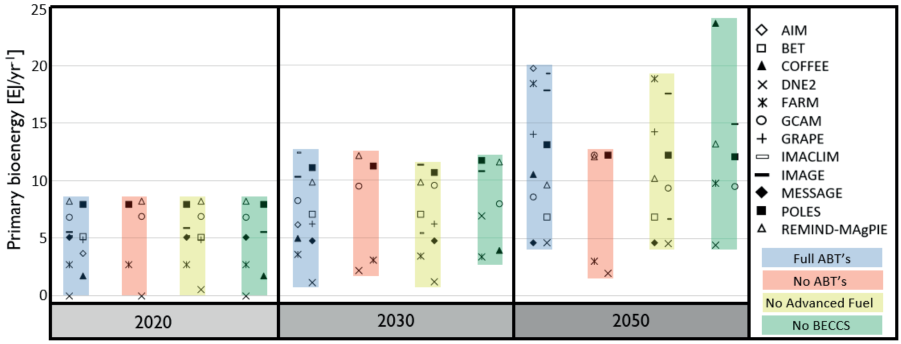

Fig.2.5: Total EU Primary bioenergy demand 2020-2050 - As projected by EMF33 participating IAM's - Under a harmonised global emissions constraints for varying bioenergy technology availability scenarios.

The projections on EU bioenergy demand from the collection of 12 IAM's displays a clear increase in bioenergy contribution when observed to 2050. The scale of bioenergy deployment when all ABTs are made available increases significantly between 2020-2030 with a model average increase of +60% (6%/yr) absolute primary energy demand. Between 2030-2050 as a collective, the suite of models follows the same trend in bioenergy demand +114% (6%/yr.) However, large differences are witnessed between the model outcomes with some models. For example, BET and GCAM show little to no increase as opposed to AIM and FARM which project a strong advance in bioenergy deployment within the region.

This divergence in model outcomes branches from the individual model structure including assumptions and methodologies concerning technological change and flexibility of the energy system, and key driving factors such as bioenergy's competitiveness vis-à-vis other low emissions technologies [72]. The model comparison shows under full ABT availability, bioenergy deployment will contribute between 7-34% of total EU primary energy consumption in 2050 with an average of 19% or just over the levels observed at present. This ranges between 5-20 EJ in 2050 when the set of advanced bioenergy technologies are available due to the increased flexibility to utilise bioenergy to a greater extent within all end-use sectors (heat, electricity & transport) and net negative emissions brought about by BECCS.

The absolute deployment of bioenergy as projected by the models is strongly linked with the models endogenously projected EU final energy demand. The greater final energy demand does not show a greater deployment of bioenergy by 2050, but there is a noticeable relationship between lower final energy demands and a decrease of bioenergy deployment. For instance both the BET and DNE model project a low EU final energy demand at 39 $EJyr^{-1}$ in 2050 compared to the model average 52 $EJyr^{-1}$ which is reflected in the comparatively lower bioenergy deployment seen in Fig.2.5. Other models that exhibit low bioenergy demand have assumptions in place that economically favour the conventional use of fossil fuels twinned with CCS over this time frame with both MESSAGE and DNE models meeting >75% of their EU primary energy demand through fossil fuels, with over 40% of this in combination with CCS. It must be noted that due to the nature of model runs to 2100 and the allowance of temporary over-shoot of the carbon budgets. Some models (particularly those with inter-temporal optimization) display a weaker take-up of low carbon technologies early on and proceed to have stronger growth of low carbon technologies in the latter half of the century to make up for this. This delay effect is partly due to projected decreasing costs relating to prominent low carbon technologies and the increasing costs of fossil fuels. A general observation is that models grouped towards the median of the suite tended to exhibit a more technologically balanced energy mix portfolio with competition between RES options.

Analysis of the availability of bioenergy technological options displays some unanticipated findings. For example, the NO BECCS scenario for both the REMIND-MAgPIE and COFFEE models show an absolute increase in bioenergy deployment compared to full ABT availability. This phenomenon is brought about due to the internal policy feedback effect i.e. CO_2 prices are increased to abide by the compliance level of emissions to reach climate targets. This, in turn, makes bioenergy more competitive when compared to fossil fuels and stimulates an overall increased deployment [129]. This is again evident within GCAM and REMIND-MAgPIE models for NO ABT's which stimulates a higher demand for non-advanced technologies due to a more limited energy technology portfolio reallocating the needed abatement and stimulating an increased deployment.

Within other models, the direct technology effect is more apparent. E.g. the total bioenergy deployment projected observes a reduction when technology constraints are applied and increases the demand for other renewable energy options in order to reach the required abatement levels. This leads to a more rapid scale-up in technologies such as PV and solar which in some cases exacerbates the decrease in bioenergy by outcompeting 'non-advanced' bioenergy demand in the electricity sector due to the inherent economic benefits of scale-up.

2.4 Synthesis

Drawing from the quantitative insights derived in the previous sections, Fig.2.6 presents an overlay for future EU bioenergy development. Within this section, the major inter-approach variances between projections are discussed. This is followed by observations into the supply-demand dynamics formed from the comparison. Finally, the implications of the ascertained ranges of bioenergy deployment levels are explored for the key aspects of an EU bioenergy transition outlined in the research objectives.

Inter-approach comparison and cohesion with developments envisaged in policy

From Fig.2.6 comparing the policy envisaged developments of the EU Roadmap we can see that the reference scenario in which RES reaches a 25% share of EU total primary energy demand (TPED) in 2050 (exploring current deployment trends and policy), strongly aligns with the lower-bound supply-side estimates. Thus, current policy intentions relating to EU bioenergy development may be considered conservative in relation to the technically realisable EU domestic bioenergy development. Bioenergy deployment as projected within the EU roadmaps' 'decarbonisation pathways' (projecting RES provides up to 60% of EU TPED) doesn't reach the average domestic supply levels attained from resource-focused studies, suggesting there could be a far greater technical potential for bioenergy than explored within strategies documented within the policy sphere.

The IAM projections show an average of 34% (max 50%) RES of EU total primary energy demand (TPED) in 2050. This is considerably lower than the 60% within the Roadmaps 'decarbonisation pathways' yet a notable proportion of the IAMs (5 out of 12 models, under full ABT scenario) project a greater bioenergy demand than seen in the 'decarbonisation pathways'. This can be partly explained by the deeper reductions achieved through efficiency gains within the 'decarbonisation pathways'. Additionally, an important finding is the similarity between the IAM projections in Fig.2.5 under no ABT with the decarbonisation policy pathways. Of the IAM models that do report for this scenario (no ABT), the majority show a clustering at a very similar level to those observed for the 'decarbonisation pathways' which also hold key assumptions that do not include these technologies (most notably BECCS). In 2050 the 'decarbonisation pathways' show a greater bioenergy deployment than the demand-driven forecasts. This is primarily due to these projections only being at 2040 levels (Fig.2.4, 2040 projection held static for 2050 within Fig.2.6 synthesis) and taking a more aggressive energy efficiency strategy, which closely aligns to the 'energy efficiency' decarbonisation scenario in Fig2.2 at 11 $EJyr^{-1}$ in 2050.

As shown in Fig.2.6, demand-side projections show variance between studies/models for both the demand-driven and IAM approaches in 2030 and 2050 (shown via error bars). This disagreement between outcomes using the same approach is larger for IAM's. This is partly because time-bound prescribed policy targets such as 30% reductions through energy efficiency measures and RES shares of 27% by 2030 are not necessarily closely obeyed within the IAM estimates. This flexibility then allows mitigation decisions within the IAM's to be taken at time points that are economically more favourable. Hence, deeper reduction efforts pertaining to low carbon technologies may scale-up after 2050. Furthermore, IAM's employ a global carbon budget, meaning that there is potential for variance in the regional EU GHG absolute reduction levels, as other world regions pursue weaker/stronger reduction strategies.

Supply-Demand dynamics

The synthesis indicates that bioenergy has an important role to play within the EU energy mix for scenarios consistent with the Paris Agreement climate targets. This observation is bolstered by the growing deployment of bioenergy to 2050 across demand-orientated assessments and the levels remaining within the projected upper boundaries of domestic supply. Furthermore, the average supply potential is able to meet the demand arising from all but four of the IAM projections. These four model results exhibit more aggressive reduction efforts within the 1st half of the century than most other model reduction paths and implement a more favorable carbon price earlier, inducing more substitution of fossil fuels (particularly into the liquid fuel market) by 2050, and additionally hold the assumption of ABT availability as discussed in section 2.3.4. The synthesis then lends itself to the conclusion that the EU bioenergy technical potential is likely to be feasible from the utilisation of domestic feedstock. However, the lower bounds of the projected supply potential would interfere with all demand projection except the roadmaps' reference scenario. Ultimately, this has large implications for the volumes of EU biomass/bioenergy trade, especially when considering non-technical considerations such as economic and sustainable constraints to utilise domestic sources. Whilst the EU (under conditions of the average technical supply potential in Fig.2.6) exceeds almost all demand projections investigated, a substantial share depends upon the active implementation of supply-side developments discussed in section 2.3.2, most notably the realisation of yield improvements and land availability for bioenergy dedicated crops and mobilisation of forestry biomass.

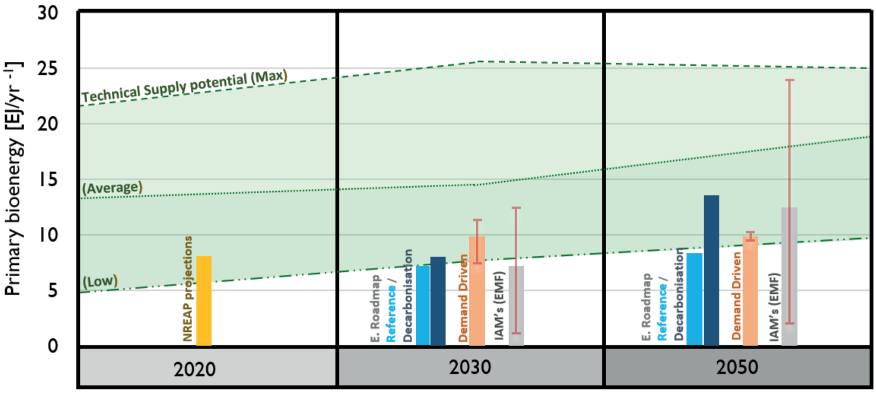

Fig.2.6: Comparative synthesis of assessment approaches and policy ambitions 2020-2050

Implications for trade

A comparison of the supply-demand dynamic provides an array of possible development patterns in relation to the EU's degree of ability to supply itself with domestic biomass for projected levels of bioenergy demand. Where shortage of supply implies the need for interregional import, the excess may be either exported to other world regions or utilised in the wider bio-based economy for non-energy purposes (outside of traditional industry e.g. building material, for which demand is already accounted for within the resource-focused assessments). Observations from the synthesis in Fig.6 central for EU bioenergy trade indicate the following possible developments (Box. 1).

A) Maximum EU domestic biomass supply is achieved: There is a surplus of ***2030*** 12.7-23.9 EJyr^{-1} and ***2050*** 1.3 -23.1 EJyr^{-1} of biomass available for energy purposes

(B) ***Average EU domestic biomass supply is attained:*** There is a surplus of ***2030*** 2.3-13.5 EJyr^{-1} and ***2050*** a maximum surplus of 17 EJyr^{-1} with a potential domestic deficit of up to 4.8 EJyr^{-1}.

(C) Minimum EU domestic biomass supply is realised: EU in a situation where there is a shortage of up to 4.7-17 EJyr^{-1} by ***2030*** and 15.1-17 EJyr^{-1} in ***2050***.

Box 1. Possible supply developments for EU biomass trade

Of the demand-projecting studies included within this review, several additionally reported projected net biomass trade. These are seen below in Fig.2.7 when compared with the possible supply developments (A-C, as defined in box 1).

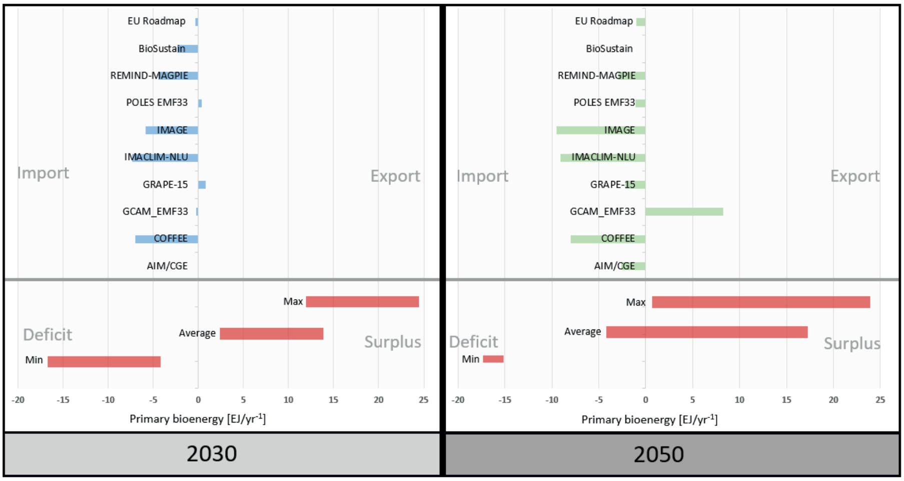

Fig.2.7: Comparison of annual net trade as projected by individual studies (upper panel) and possible trade developments (A-C) from box.1 (lower panel).

When comparing trade as reported by the studies focusing on future demand included within this review to the ranges of EU technical biomass supply *(A-C)*, interesting observations emerge. By 2030, only one model (GCAM) projects net EU inter-regional biomass export for energy purposes. This is due to the model assumption, in which the EU food demand is actually met through import. That is land availability for bioenergy increases to a point at which the EU exports bioenergy to the Middle East and Africa [72]. All other projections on 2030 biomass trade are for import, showing a closer alignment with the minimum biomass supply range *C*. This is caused in part by the fact that the models project biomass costs to be lower in other regions due to lower labor and land costs, thus making it more worthwhile for the EU to import. Furthermore, the supply characteristics of IAM's may project lower biomass availability in the EU due to primary feedstocks limited to energy crops and agricultural residues. Thus, in general, the trade projections disagree with the maximum biomass supply range *A* which shows a large technical potential for EU biomass net export.

By 2050, none of the studies project a significant level of export. This is in spite of the average technical supply potential indicating that the majority of the demand forecasts should leave a surplus of domestic biomass. In actuality, the studies project significant levels of biomass import, increasing in most cases from the 2030 volumes due to higher deployment of bioenergy within the EU energy system and fit better with the lower bounds of supply range *B* than they do with *C*. Concluding all demand forecasts assume a larger domestic supply potential is feasible than the lower estimates shown in Fig.2.6. The general trend of import dependency increasing to 2050 suggests that the majority of the demand-driven projections do not envisage a meaningful reduction in domestic bioenergy production costs within the EU by this point. The region is forecasted to be a large importer with the IAM's showing a range of 13-76% (excluding GCAM) of primary bioenergy demand met by import (av. 35%) and the EU roadmap 7.5%.

An unknown proportion of this EU domestic excess could be economically unavailable due to cheaper inter-regional biomass imports (and even fossil fuels depending on CO_2 price assumptions). Other studies investigating bioenergy trade in 2050 include Matzenberger et al. [25] which utilised global energy system models to explore bioenergy trade in world regions under different energy market scenarios, including varying CO_2 prices and economic trade barriers in a 2°C trajectory, which also identifies the EU as a large net importer of both solid and liquid bioenergy to 2050.

Implications for Energy Security

The current utilisation of bioenergy in the EU stands at 5.63 $EJyr^{-1}$ [84] of which 4% is imported. Upper range future demand projections (Fig.2.6) could see up to a doubling of this deployment by 2030 and a quadrupling by 2050. The studies that assess trade within this review indicate future EU bioenergy development could entail 0-60% to be met through imports by 2030 and 13-76% by 2050. At these volumes, which are somewhat unrepresentative due to net (rather than total) trade being reported, the logistics and infrastructure investment become more challenging. Furthermore, relatively stricter sustainability criteria on bioenergy, local demand developments in exporting regions, spot price and futures fluctuations for feedstock, fossil fuel price developments, and other low carbon technologies including CCS can all act as limiting factors, reducing the potential for cost-competitive available biomass for import to the EU [130,131]. As these import prices rise, a greater degree of domestic biomass sources becomes economically attainable. However, this future dynamic is little understood. Daioglou et al. [132] employs the same EMF33 IAM database as this review but further formulates indicators to assess the energy security implications. Their results indicate that the EU observes increased bioenergy import dependency when more ambitious climate mitigation is taken; yet does not reach the level of fossil fuels at present, thus increasing overall energy security when replacing fossil incumbents. A forecasting analysis of the EU bioenergy market import-export function to 2020 performed by Alsaleh et al. projects short term increases for the EU's international import of biomass due to economic determinants creating a growing gap between domestic production and total bioenergy consumption

A transitional shift away from imported fossil fuels towards RES is a key objective of the EU [114]. Improved utilisation of domestic bioenergy would aid in achieving EU energy security ambitions. Throughout the demand side projections, future TPED of the EU is envisaged at varying levels due to assumptions regarding the implementation of energy efficiency policy measures and energy intensity to GDP ratio. This makes meaningful insight into the energy security implications for bioenergy difficult to interpret. Perhaps most expressive is to demonstrate the potential contributory value under more certain circumstances. If we consider the case of the 'current policy initiatives' from the EU 2050 Roadmap to be representative of future development under current conditions, then EU TPED stands at 68 EJyr^{-1} (7 EJ from bioenergy) in 2030 and 68 EJyr^{-1} (8 EJ from bioenergy) in 2050; with 10-15% of this bioenergy from interregional imports. Fossils (oil, gas and non-renewable solids) represent a combined 47 and 43 EJyr^{-1} by 2030 and 2050 respectively, or 69 and 63% of EU TPED. With a fossil fuel import dependency of 81% in 2030 and 90% in 2050. The EU total import dependency is 58% in both years. In the following paragraph, we assess the quantitative potential of further exploitation of domestic EU bioenergy to alleviate EU import dependency under two hypotheses *(a)* average supply potentials are achieved (at economically competitive levels), *(b)* highest demand levels from the review can be achieved domestically.

> **(A)** If the average technical supply potential as envisaged by the resource focused assessment in Fig.2.6 were to be achieved, then domestic biomass would be technically able to substitute an additional 6.5-9.8 EJyr^{-1} (2030-2050). At these levels, domestic bioenergy reduces total EU import dependency from 58% to a maximum of 48% in 2030 and 44% by 2050. The degree to which this substitution lowers the import dependency is largely governed by the final application of the additional biomass, i.e. 100% CHP use would be required to achieve maximum reduction. Solely thermal electricity production would yield smaller reductions due to slightly higher conversion losses in biomass power plants compared to the EU fossil-fired average (with the average EU biomass fueled plant at 32% [133] and fossil-fired average 49.7%).

(B) At exploitation levels equivalent to the largest bioenergy deployment seen in Fig.2.6 as the upper IAM's projections for 2050, where advanced bioenergy technologies are available, EU import dependency could fall from 58% to 36%.

Potential Mismatch between feedstock supply and demand applications

Within the supply projections, potentials are simply reported in the broad categories of energy crops, agricultural residues, forestry, and waste. Similarly, demand side projections simply show total bioenergy demand, but not the amounts pertaining to key conversion pathways. This causes confusion to whether the supply is of sufficient quality or type to meet the end-use (e.g. forestry biomass is not efficient for biogas). Thus, detailed analysis into geographical miss-match of supply and demand is not possible within this review. However, at a higher level, patterns for combustion of woody biomass for electricity generation are projected and demand goes beyond the EU domestic supply from forestry for all of the resource-assessments except those that consider the explicitly increased mobilisation of woody feedstocks, which is eventually eclipsed by 2050. The European Biomass Association (Bioenergy Europe) estimated that in 2013, 70% of EU bioenergy demand was met through forestry feedstock and 17% from agriculture [103]. However, this review identifies local (domestic EU biomass) supply is composed of forestry (29-50%) and agriculture residues and energy crops (30-70%) in both 2030 & 2050. Thus, there may be a mismatch between EU domestic supply and EU demand unless imminent and significant structural changes in the EU bioenergy demand sectors occur that steer away from heavy reliance on forestry feedstocks.

The physical and chemical characteristics of the broad range of biobased feedstock are more challenging to homogenise than those for fossil fuels. Therefore, conversion systems need to be specifically designed to match feedstocks [134]. Not only does this directly exacerbate the need for security of supply; it also requires additional pre-processing. There has been a range of studies investigating environmental impacts arising from different biomass sources for various conversion routes through life cycle assessments. Thus, a ranking of different biomass types can be composed for final energy sources. Such studies could aid in the identification of domestic feedstocks that can be utilised most efficiently from a GHG perspective and alleviate inter-regional dependency.

Competition between different biomass applications

Next to bioenergy, the EU bioeconomy includes the substitution of fossil fuels for non-energy related purposes (biobased products). The current literature base whilst accounting for demand from traditional non-energy industries (e.g. furniture, paper & pulp) is scarce of future development projections for new advanced biobased products at EU level and their competition for feedstocks with bioenergy uses. This is due to the complex nature of the chemicals and plastics industries, with multiple interrelated chemical flows, making efforts to modelling them fraught with difficulties and adopting highly aggregated representations [77]. Furthermore, there are large uncertainties pertaining to the cost-effectiveness of feedstock processing, exploitability of lignocellulosic sources, efficiency of pre-treatment and conversion processes and capital expenditures for refining facilities within the EU [135]. Schipfer et al., [136] utilise top-down estimations of fossil-based products that are highly substitutable (surfactants, solvents, lubricants, plastics & bitumen) accounting for biobased capacities and targets within relevant sectors. Schipfer et al. explore two scenarios, i.e. a reference scenario in which a 40% substitution is assumed and a more ambitious transition scenario with a 70% substitution factor by 2050. At these levels, the EU non-energy sectors will demand between 0.56–2.3 $\mathrm{EJyr^{-1}}$ of primary biomass to facilitate the transitional switch [136]. Competition with bioenergy would at these levels become a reality; biomaterials would require at least 10% of the projected feedstock needed to fulfil bioenergy demand (Fig.2.6) and actually eclipses the lowest bioenergy demand estimates in 2050. In a situation where a remaining fraction of domestic biomass is inaccessible for bioenergy uses due to economic constraints (current situation), other sector non-energy uses that produce higher value goods may be able to unlock this potential, which may ultimately be eligible for bioenergy generation as cascaded tertiary residues.

Non-energy uses also contribute to overarching climate targets; however, their GHG reduction potentials in comparison to energetic purposes are not well understood at large scale and can vary widely between applications [137]. Daioglou et al., [77] developed a global model for non-energy demand, disaggregating demand over several key substitutable products and allow the biobased substitution to occur through economic competition. On a global scale, they project that 40% of primary energy utilised in the non-energy sectors can be competitively replaced by bioenergy by 2100, which brings about 20% reductions in the sectoral GHG emissions by 2100 but are not significant by 2050. This reflects bioenergy being a more efficient reduction option for 2050 targets due to its ability to directly replace fossil fuels whose carbon is emitted (as opposed to chemicals where most of the carbon is locked in, hence accumulated carbon is reduced heavily by 2050 but not emitted by then).

2.5 Conclusions

The review has presented an updated set of projections for future bioenergy developments at an EU scale for the mid – long term (2030-2050) under a consistent trajectory for climate mitigation to limit temperature rise to 2°C. The review covered projections from three types of assessments (Resource-focussed, Demand-driven, and Integrated), and policy pathways are synthesised and compared.

Inter-approach comparisons indicate bioenergy has an important role to play in the future EU energy mix regardless of sustainability and technology development. The demand projections arriving from policy pathways, demand-driven assessments and IAM's show a general trend of modest growth in EU bioenergy deployment to 2030 with significant scale up to 2050 driven by climate change mitigation efforts. Higher estimates (over a fourfold increase of current consumption) are conceived when advanced bioenergy technology availability is considered, allowing the conversion of readily accessible cheaper lignocellulosic biomass into liquid fuels and the deployment of BECCS to potentially allow for carbon dioxide removal in the power generation sector. However, the sourcing of primary biomass especially from the domestic forestry resource base must be carefully managed to achieve a net negative impact on global warming potential [138]. The projections for future EU bioenergy demand range between 5-11 EJyr-1 in 2030 and 5-19 EJyr-1 in 2050. With regards to the sustainability aspects incorporated into the resource-focussed (supply) estimates, only the very strictest sustainability constraints under conditions in which bioenergy is not afforded the possibility of expansion into surplus land interfere with demand developments as envisaged within the EU roadmaps decarbonisation pathways.

A significant untapped domestic potential presents an opportunity for the future development of the EU (bio)economy. The synthesis shows that domestic EU biomass may hold significant additional potential for meeting projected demand. Upper bound estimates for domestic supply exceed that of the demand range by 13-24 EJyr-1 in 2030 and 1-23 EJyr-1 by 2050. The extent to which this resource base can be exploited in the long term lies within its economic accessibility, which is governed by four factors: (1) price developments and availability of imports (demand projections do not envisage this as a barrier by 2050), (2) developments of other low-carbon technologies, (3) profitability in non-energy bio-products and (4) perhaps most importantly for climate targets enforced sustainability criteria for GHG reductions. The possible developments of these aspects and conditions in which the domestic resource base becomes attractive for different end uses should be explored to detect its potential for alleviating EU import dependency. The synthesis shows that domestic EU biomass in 2050 may hold significant additional potential for GHG reduction efforts of the EU towards its 2°C commitments than projected by the demand estimates. However, economic constraints provide a barrier to accessing this domestic potential.

Interregional trade of biomass for energy is projected to increase to 2050, but the implications on climate targets and total import capacity (security of supply) are uncertain. Limitations in the accessibility of feedstock from other world regions due to global demand could produce a case in which imported EU biomass is originating from less sustainable sources and requiring more complex supply chains, leading to a situation where lower GHG emissions savings are realised. This limits the potential for reductions when set against regional policy such as the renewable energy directive mandates which must perform markedly favourably in comparison to fossil counterparts. A deeper investigation is needed into the absolute scales at which bioenergy imports can contribute to EU demand whilst abiding by legislative reduction targets.

3

CHAPTER

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

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3. INTEGRATED ASSESSMENT OF THE ROLE OF BIOENERGY WITHIN THE EU ENERGY TRANSITION TARGETS TO 2050

Abstract

Bioenergy is considered an important component within the European Union (EU) energy transition to meet mid-century climate targets. Model assessments that have highlighted the role of bioenergy in decarbonising EU energy systems fail to account for the fact that mitigation strategies and bioenergy supply take place within a global decarbonisation effort. Thus, they do not account for inter-regional competition for the resource base that Europe may face. This study shows how bioenergy can contribute to EU climate targets, highlighting its possible role within the energy system and developments required to facilitate its scale-up. We use the global integrated assessment model IMAGE 3.2 to project bioenergy demand, sectoral deployment, feedstock, and inter-regional import for Europe to 2050. Employing a global model allows for projections of EU decarbonisation strategies consistent with global climate targets and captures the effects of biomass production and consumption in other world regions. Bioenergy is projected to account for up to 27% of total primary energy demand, increasing from the current 5EJ to 18EJyr^{-1}. To match this demand, the model projects imports of biomass to increase from 4% of its current supply to 60%. Bioenergy could provide up to 1GtCO$_2$ or 40% of the overall mitigation needed by the EU in 2050. This is based on large-scale use for power production, with the transport, industry and buildings sectors getting smaller shares. By 2050 it is projected that 55% of total EU bioenergy use is coupled with Bioenergy with carbon capture and storage (BECCS). Bioenergy supply comes primarily for agricultural and forestry residues, as these sources have low upstream greenhouse gas emissions. However, as demand increases, energy crops are increasingly used, especially in the provision of advanced liquid fuels. The results show that one route for achieving an EU energy transition is based on rapid deployment of BECCS and the mobilisation of sustainable imports of second-generation feedstocks.

3.1 Introduction

The goal of the 2015 Paris Agreement is to limit the global mean temperature increase to 'well below' 2°C and preferably 1.5°C [3]. Currently, energy production and use are responsible for more than 70% of global anthropocentric greenhouse gas (GHG) emissions [139]. Hence, complying with the Paris Agreement requires deep decarbonisation of the energy sector. The European Union (EU) has pledged to implement strategies that align with these global objectives, aiming for 55% reductions in EU GHG emissions by 2030 and net-zero by 2050 with respect to the 1990 levels [7].

The use of renewable energy resources is a crucial decarbonisation strategy, alongside other measures such as optimising energy efficiency and reducing demand. Bioenergy is considered a possible future option for attaining climate targets [112], with current EU consumption standing at 5.7 $EJyr^{-1}$ and accounting for 64% of renewable energy consumption [140]. This position is primarily due to biogenic carbon being considered climate neutral at the point of consumption. Furthermore, it can act as a flexible producer to balance the power system when paired with other renewables. It also offers versatility in end-use applications for heat, power and transport fuels. [140]

From a sourcing perspective, EU bioenergy demand is currently comprised of 60% forestry (woody) sources (split evenly between direct (fellings and residues) and indirect (industry by-products) sources), 27% agricultural residues and energy crops, and 13% waste streams [141]. A recent review of EU-wide biomass supply-side projections shows that future domestic EU biomass supply (2030-2050) is expected to consist of forestry biomass (29-50%); and agriculture residues and energy crops (30-70%) [142]. This indicates a projected mismatch between current demand and future supply for feedstock categories and agrees with other studies that suggest the greater the dependence on forestry biomass, the more the EU needs to import [39,143]. Future European feedstock demand composition has implications for interregional biomass trade and access to sustainable biomass. While currently 96% of biomass used for energy is EU-sourced, import is expected to increase to 2050 under scenarios meeting strict climate change mitigation targets [23,131].

Bioenergy with carbon capture and storage (BECCS) provides an opportunity to attain net-negative GHG emissions, which may compensate for emissions from more difficult-to-decarbonise sectors [144–146]. At EU-level, BECCS is targeted in 11 member states national energy and climate plans (NECPs) as an essential carbon removal technology. However, significant uncertainties remain regarding the techno-economic capabilities including storage capacity, investment costs and social feasibility [147,148]. This uncertainty propagates to future feedstock requirements, total biomass demand, and bioenergy's GHG emission mitigation potential.

Bioenergy, as a mitigation option, faces opposition in the global climate debate. Critique is built around several core arguments, including access to sustainable feedstocks, uncertainty surrounding bioenergy with carbon capture and storage (BECCS) deployment, dependency on subsidies and competition between different biomass end uses. The Renewables Energy Directive recast to 2030 (RED II) [27] partly addresses these concerns. RED II introduces stricter minimal GHG savings thresholds on biogenic energy sources, withdraws subsidies to electricity-only installations and promotes the cascading principle of biomass. Still, understanding the role of bioenergy in decarbonising Europe's energy system towards 2050 requires a better understanding of these critiques and uncertainties.

The multifaceted nature of bioenergy, from the supply, conversion, trade, and multiple final consumption possibilities, calls for an integrated approach when assessing its mitigation potential. Key aspects that need to be investigated include the access to appropriate feedstocks, sectors where bioenergy use should be prioritised, and the potential contribution of BECCS. Integrated Assessment Models (IAMs) are often used to study climate change mitigation strategies, including bioenergy deployment. These models describe the dynamics of energy and land-use system and their relationships with natural and human systems. Therefore, IAMs can be used to investigate the potential transition of the energy and land systems under varying degrees of policy intervention and can, for instance, explore mitigation pathways that meet exogenously defined climate targets [5].

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

This research aims to investigate projections of bioenergy demand, its contribution to climate change mitigation, and import dependency of the European region between 2020 and 2050. The analysis further aims to provide insights into bioenergy dynamics that are considered vital for climate mitigation and raised within EU policy debate, including BECCS deployment, sectoral demand, and feedstock category demand. This study uses existing baseline and RCP 2.6 projections from the IAM IMAGE 3.2 that illustrates the effects of a global <2°C mitigation pathway that seeks to bring about a least-cost energy transition. Counterfactual scenarios are formulated that explore the future European energy system when BECCS is prohibited and when bioenergy is absent. Using global modelling to produce regional results is a novel approach that allows the research to capitalise on the systemic effects of other world regions' production and consumption behaviour for bioenergy and subsequently the access to imports for Europe.

3.2 Materials and methods

3.2.1 Model overview

This study uses the global integrated assessment model framework IMAGE 3.2 [149], which simulates the environmental consequences of energy and land-use systems worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change and human wellbeing for 26 world regions. IAMs such as IMAGE 3.2 hold the benefit of modelling planetary boundaries including resources, stocks, and flows of the agricultural, forestry, water and energy systems, and represents their interactions and the effect of climate change, policy, and socio-economic developments. Human system impacts in the form of emissions and land-use change are communicated to dedicated earth system modules for land, atmosphere and ocean. Accordingly, IAMs are an appropriate tool for exploring mid-term climate change mitigation pathways that meet exogenously defined climate targets while considering systemic and global effects.

In the IMAGE 3.2 framework, the energy system is represented by the recursive dynamic global energy system model TIMER [69]. TIMER includes a representation of primary energy supply, including fossil and renewable resources, which can be converted to secondary and final energy carriers. TIMER is calibrated to IEA energy data for the period 1971-2018 to replicate observed fuel and electricity consumption trends [150]. From 2018 onwards, scenario settings are applied.

Demand for energy services is projected by linking socioeconomic drivers (e.g., population and economic activity) to five key economic sectors: industry (including cement, steel, paper, and chemicals), transport, residential, services, and 'others'. It includes fossil and renewable primary energy carriers, where primary energy carriers can be converted to secondary and final energy carriers (solids, liquids, electricity, hydrogen, heat) in order to provide energy services for different end-use sectors. Technological learning within TIMER is endogenously based on learning by doing, where investment and associated conversion costs are projected to decrease as a function of cumulative installed capacity. Competition between final energy carriers is based on their relative cost of providing energy services, formulated at regional and sectoral levels. Constraints on GHG emissions increase the competitiveness of low-carbon sources by applying an endogenously calculated price on fuels' carbon content. From this bioenergy's competitiveness in the power system is based primarily on its mitigation potential. However, other VRE sources suffer from integration curtailments (storage requirements, back-up and system load) that increase their relative cost as their shares increase. As a non-variable source bioenergy's competitiveness increases under these circumstances [70]. See section 1.6.1 for further details on the model, including a schematic overview of how bioenergy is treated.

Techno-economic assumptions of IMAGE3.2 (capital costs, conversion efficiencies, feedstock costs, Operation and maintenance costs, CCS capture rates, technology readiness, technology lifetimes and emission factors) are similar to those provided in the supplementary material of Daioglou et al. [72]. The development of the applied caron price, energy carrier price and levilised cost of electricity production for the mitigation scenarios presented in this study are available in Annex III.2.

3.2.2 Bioenergy dynamics within the model framework

The IMAGE3.2 framework covers all stages of the bioenergy value chain, accounting for feedstock production, associated land-use change, conversion to secondary energy carriers, international trade, and final consumption in end-use sectors [67]. Potential bioenergy supply within the IMAGE 3.2 framework is determined at the grid level by the dynamic vegetation model LPJml, which describes crop growth based on local biophysical conditions [75]. In order to ensure that bioenergy supply does not interfere with major environmental and social criteria, specific areas are excluded from bioenergy production, including urban areas, nature reserves, forests and areas used for food production [73]. The model additionally assumes a 'food first' principle, i.e., food demand is allocated first before biomass for energy. Consequently, primary biomass is grown on either abandoned agricultural areas or natural lands deemed available. Biomass supply is represented by six aggregated primary feedstock categories: woody crops, grassy crops, maize, sugarcane, and oil crops. Residues (agricultural or forestry residues) can be harvested from agricultural and managed timber operations. A disaggregation of feedstock flows is provided in section 1.6.1.

Primary biomass can be converted into liquid and solid bioenergy carriers. Liquids include 1st generation and advanced biofuels. Bioenergy carriers may also be used for non-energy purposes, such as the production of ammonia, methanol, and higher value chemicals [77]. Solid bioenergy carriers (i.e. chips and pellets) can be further converted to hydrogen or electricity. The delivery cost of bioenergy includes feedstock, conversion technology, labour, capital, and O&M costs, represented through dynamic cost supply curves [67].

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

BECCS is incorporated into the model during the conversion to secondary energy carriers (liquid fuels, hydrogen, electricity) and during heat generation within industry. For bioenergy emissions accounting, smokestack emissions during conversion that result from biogenic carbon are considered carbon-neutral. When paired with CCS, sequestered biogenic emissions are considered net-negative. Pre-combustion upstream process emissions include: land-use change, primary biomass production (including fertiliser production and application), transport of primary biomass to processing/conversion site, process energy for conversion into bioenergy/secondary carriers [76]. See section 1.6.1 for a schematic of modelled bioenergy GHG sinks and releases.

3.2.3 Scope, scenarios & indicators

Scope

This study represents the European region by combining IMAGE regions West Europe and Central & Eastern Europe [149]. The list of nations included within the modelled 'Europe region' is presented in Annex III.1. Although the geographical boundaries of this European region are not an exact match with the EU 27, the results are relevant for comparison of relative emission mitigation targets at EU-level. The results from this study focus on the modern applications of biomass only, i.e., excluding traditional uses (e.g., fuelwood for heating and cooking). Bioenergy developments included in the analysis are total bioenergy demand, sectoral level demand, feedstock demand, regional mitigation potential and interregional trade. Limitations of the approach are discussed in section 3.4.3.

Scenarios

Scenario analysis is performed to 2050 to explore the effects of introducing global-scale climate targets in line with the Paris agreement and the role of bioenergy and BECCS deployment within the European energy system. The scenario protocol is presented in Table 3.1 and outlined below.

A 'baseline scenario' is included that follows the Shared Socio-economic Pathway SSP2. The IMAGE projections of the SSP scenarios are described in van Vuuren et al. [150]. SSP2 is commonly referred to as a 'middle of the road' narrative and holds key assumptions concerning population growth, GDP, and technological trends that are in line with historical patterns [151,152].

A 'Global <2°C target' scenario projects achieving the Paris Agreement target via introducing a global carbon price from 2020 onwards. This is applied to all energy carriers based on their carbon contents. The carbon price mechanism is dynamic and promotes lower carbon fuel sources to ensure total emissions are in line with a cumulative global carbon budget ≈1,000 $GtCO_2eq$. The carbon price trajectory applied to scenarios aiming for a <2°C global target in this study is presented in Annex III.2.

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

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

Table 3.1: Scenario Protocol

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

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

Indicators

Table 3.2 describes the indicators used for assessing bioenergy developments in terms of total bioenergy demand, sectoral level demand, feedstock demand, regional mitigation potential and interregional trade.

*Table 3.2: Indicators used to report Europe's bioenergy development, grouped by the bioenergy developments analysed in this study. s = Sectors r = Regions, ec = Energy carrier, f = Feedstock, t = Technology, EF = Emissions Factor, scen = scenario. * Reported in primary energy (i.e., the energy content of biomass before conversion into secondary energy carriers). ** Reported in secondary energy (i.e., the energy content of ready-to-combust modern bioenergy carriers).*

Indicator	**Description**	**Equation**
Total demand		
Bioenergy demand * EU_bioD	Summation of primary bioenergy demand (*bioD*) across end-use sectors (*s*) in Europe only	$\mathbf{EU\_bioD} = \sum_s bioD_{\ s,r=EU}$
Bioenergy share of Total primary energy demand EU_bio%	The share of the EU's total primary energy demand (EU_*energyD*)) that is derived from bioenergy	$\mathbf{EU\_bio\%} = \frac{\mathbf{EU\_bioD}}{\sum_s \sum_{ec} EU\_energyD_{\ s,ec,r=EU}}$
Share of global bioenergy **Global_bio%**	The share of global primary bioenergy demand attributed to the EU	$\mathbf{Global\_bio\%} = \frac{\mathbf{EU\_bioD}}{\sum_s \sum_r bioD_{\ s,r}}$
Sectoral demand		
Sectoral bioenergy demand EU_SECT_bioD	Secondary bioenergy demand of feedstock (*FeedBiod*) within each end-use sector in Europe only	$\mathbf{EU\_SECT\_bioD} = \sum_f \mathrm{FeedBioD}_{\ f,s,r=EU}$
Feedstock demand		
Feedstock demand EU_FEED_D	Demand per feedstock type consumed in all sectors combined in Europe only	$\mathbf{EU\_FEED\_D} = \sum_s \mathrm{FeedBioD}_{\ f,s,r=EU}$

Indicator	**Description**	**Equation**
Mitigation		
Total GHG emissions **EU_Emis**	Energy system emissions of Europe under any given scenario run. An activity level (*energyD*) is determined per end-use, sector, technology and energy carrier. This is multiplied by the specific emissions factor (*EF*) for the corresponding activity.	$\mathbf{EU\_Emis} = \sum_s \sum_{ec} \sum_t energyD_{t,s,ec,r=EU} * EF_{\ t,ec}$
Mitigation from bioenergy **EU_BioMitig**	GHG mitigation contribution brought about by bioenergy deployment in Europe compared to a counterfactual (No bio) scenario	$\mathbf{EU\_BioMitig} = \mathrm{EU\_Emis}_{\mathrm{scen=2^oC}} - \mathrm{EU\_Emis}_{\mathrm{scen=Nobio}}$
Mitigation from BECCS **EU_BECCSMitig**	GHG mitigation contribution brought about by the deployment of BECCS in Europe compared to a counterfactual (No BECCS) scenario	$\mathbf{EU\_BioMitig} = \mathrm{EU\_Emis}_{\mathrm{scen=2^oC}} - \mathrm{EU\_Emis}_{\mathrm{scen=Nobio}}$
Trade		
Net trade of bioenergy EU_Trade	Net trade of bioenergy carriers between Europe and rest of the world. *r* refers for this indicator to all regions except Europe	$\mathbf{EU\_Trade} = \sum_r \mathrm{EUBioImport}_{\ r} - \sum_r \mathrm{EUBioExport}_{\ r}$

3.3 Results

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

Europe's primary bioenergy demand is projected to increase across the three scenarios explored (see Fig.3.1, Panel A). To 2030 bioenergy demand remains muted at approximately 5 EJyr^{-1} across scenarios. This stagnation is because Europe's total primary energy demand (TPED) is reduced from 72 EJyr^{-1} to 64 EJyr^{-1} (-12%) through the rapid adoption of measures with low marginal abatement costs. These include increased efficiency and price-induced energy demand-reduction.

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

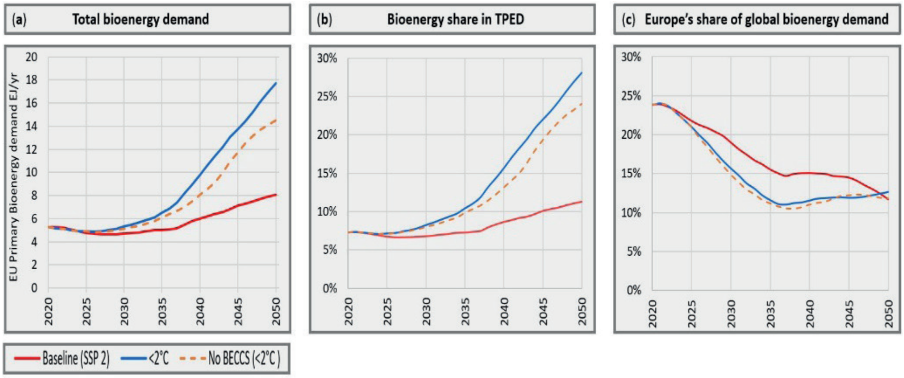

Fig.3.1: Climate mitigation and BECCS effects on the development of Europe's primary bioenergy demand (a), bioenergy's share in total primary energy demand (b), and Europe's share in global bioenergy demand (c)

In Fig.3.1 panel (B), the ‘Baseline’ scenario displays an increase (>5% points) for bioenergy contribution to TPED over the period. Projected system-wide energy efficiency improvements and activity reductions under the ‘<2˚C’ scenario leads to a substantial increase in bioenergy’s contribution to Europe’s TPED. Bioenergy demand rises to 27% of Europe’s TPED. Underpinning this development is the direct replacement of coal with bioenergy for electricity production and indirect oil displacement in the transport sector via bioelectricity and electric vehicles. To put this scale of bioenergy demand into context, at the projected contribution to Europe’s TPED, bioenergy would match the current oil and petroleum products contribution [10]. At the same time, Europe’s TPED reliance on fossil fuels falls from 82% to 58% over the period assessed. Comparison with the ‘No BECCS’ scenario indicates that BECCS can contribute 4.5% of Europe’s TPED by 2050, roughly equivalent to the shares provided by all other renewables combined at present [10].

Although bioenergy demand is projected to increase in Europe, as seen in Fig.3.1 panels (A & B), Europe’s share of global bioenergy demand decreases (panel C). This is due to a relatively greater increase in bioenergy uptake in other world regions, even in the absence of global decarbonisation targets. This dynamic is vital to consider because it has implications for interregional bioenergy supply as Europe faces stiffer competition in the global market. This increased global demand is driven by a growing global primary energy demand which increases 11% over the period assessed, increasing fossil fuel prices due to depletion (in the Baseline), decreasing costs of bioenergy due to learning, and increased efforts to decarbonise energy systems in the ‘<2˚C’ scenario. See Annex III.4 for projected global TPED developments.

3.3.2 Sectoral level demand developments

Fig.3.2 shows the demand for bioenergy for key sectors across the scenarios. In the ‘Baseline’ scenario, the small levels of bioenergy use in the power sector are phased out, becoming a less economically attractive option due to the absence of a carbon price. For power generation, in the ‘Baseline’, fossil fuels hold the majority share of production, with coal and natural gas consumption increasing towards 2050. Fossil fuels are increasingly used in the power system due primarily to their affordability in the absence of a carbon price. See Annex III.5 for a detailed breakdown of power sector consumption. Post-2035, there is a significant increase of bioenergy in the non-energy sector which has a higher demand in the baseline than in the mitigation scenarios, where biomass feedstocks provide a cost-competitive option to produce chemicals. This greater demand in non-energy applications within the 'Baseline' is due to three dynamics: i) a greater absolute demand (compared to mitigation scenarios) for non-energy sector products due to the absence of price induced demand-reduction, ii) bio-based energy carriers become economically competitive at replacing oil in chemical manufacture when as oil prices rise due to depletion, and iii) access to cheaper biomass feedstock and conversion technologies due to yield increases and learning-by-doing [67]. See Annex III.6 for detailed non-energy sector fuel demand.

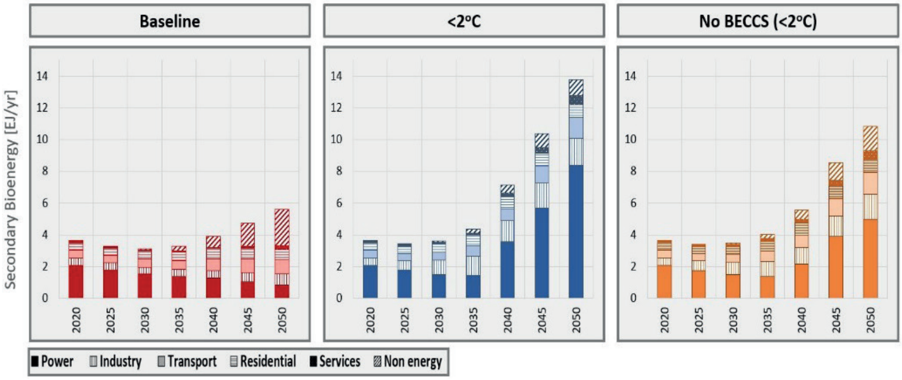

Fig.3.2: Sectoral secondary bioenergy demand in Europe under different scenarios.

The '<2°C' scenario projects a 2.5-time increase in total secondary bioenergy demand by 2050 compared to the 'Baseline'. There is an initial depression in power sector demand to 2035 because Europe's TPED decreases in line with the carbon price induced efficiency gains. Post-2035, bioenergy deployment increases in the power sector mainly in the form of BECCS (where 90% of bioenergy is paired with CCS by 2050). The ability to attain net-negative emissions and an increasing carbon price tilts BECCS technology into favour. This results in annual bioenergy consumption in the sector quadrupling from 2 to 8 $EJyr^{-1}$. The mitigation scenario's show an increase in bioenergy used for heat within the industry sector where other low-carbon technologies are costly, and bioenergy displaces coal (see Annex III.7 for sub-sector breakdown of industry). A similar trend occurs for the transport sector with a tripling in demand over the assessed period. Liquid biofuels displace conventional oil in freight, notably for land-based freight, and fulfil almost half of the fuel demand for marine freight. Passenger travel energy demand in Europe is met 50% by electricity in 2050, of which a third is generated via bioenergy. See Annex III.8 for a breakdown of energy carrier demand in the transport sector. Within the non-energy sector, consumption falls compared to the 'Baseline' scenario due to a re-routing of biomass and bioenergy into sectors (services, residential, transport or electricity production) where it can provide more significant mitigation for the same system cost.

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

3.3.3 Feedstock demand developments

Fig.3.3 shows the projected demand for secondary bioenergy carriers when disaggregated across biomass feedstock categories represented in IMAGE 3.2. See section 1.6.1 for details on feedstock categories composition and conversion routes. Liquid biofuels demand increases to 2050, doubling in the 'Baseline' and tripling in the mitigation scenarios. Over the period assessed, there is a transition away from 1st generation ethanol produced from sugar crops to higher-yielding sources. Particularly towards temperate region sourced advanced lignocellulosic fuels (woody and non-woody feedstocks). An increased liquid bioenergy demand is observed for the mitigation scenarios. This increase is caused by greater demand for biofuels in the transport sector (particularly for marine freight) produced from dedicated energy crops. See Annex III.9 for the sectoral deployment of liquids and solid bioenergy carriers.

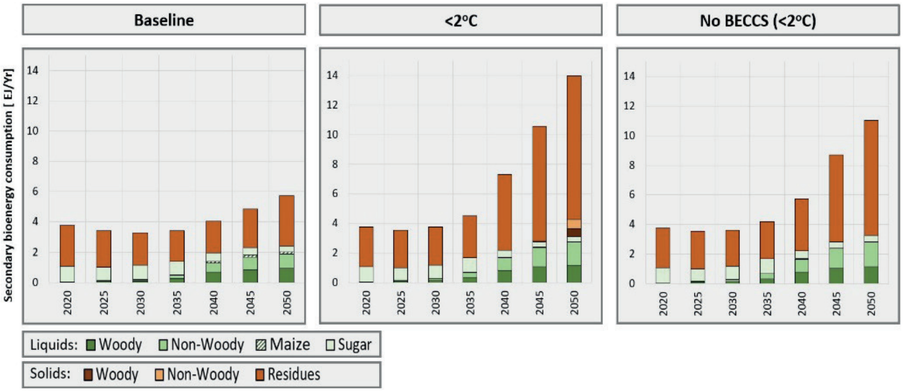

Fig.3.3: Demand for biomass feedstocks used to produce secondary bioenergy carriers for Europe

In all scenarios, demand for solid bioenergy carriers (chips/pellets) increases, driven by their increasing consumption in the power and industry sectors. Solid bioenergy carriers are almost exclusively sourced from residues as they are the cheapest feedstock. There is moderate growth of solid bioenergy carrier demand in the 'Baseline' scenario at 0.6EJyr^{-1} (+23%) by 2050. For the '<2˚C' scenario, residue uptake increases 7EJyr^{-1} (+260%). When BECCS is prohibited, residue consumption falls by 2 EJyr^{-1} (-20%) in 2050. Pellets from residues are primarily used for power generation and industry but also provide process energy for the non-energy sector. The large-scale deployment of electricity generation with BECCS in the '<2˚C' scenario reaches the limit of affordable residues supply for Europe by 2050, approximately 10 EJyr^{-1}. At these levels, other solid bioenergy sources, i.e. 'woody' and 'non-woody', become economically viable for power generation. This dynamic and the near-term importance of residues as a cheap resource aligns with other IAM results [153].

3.3.4 Mitigation potential of European bioenergy

Fig.3.4(A) projects the cumulative European-wide GHG emissions attached to each scenario. The SSP2 'Baseline' scenario projects Europe will emit 110 Gt CO$_2$eq cumulatively over 2020-2050. Under the '<2˚C' scenario, projections show Europe's energy system needs to limit cumulative emissions to 78 Gt CO$_2$eq over the same period to meet climate targets.

In the absence of BECCS, cumulative emissions reach 85 Gt CO$_2$eq by 2040. Thus, BECCS availability contributes 6.5Gt CO$_2$eq (20%) of the total projected mitigation required in the '<2°C' scenario. The complete absence of bioenergy in the 'No Bio' scenario results in cumulative emissions of 87 Gt CO_2eq. Thus, bioenergy as a whole is responsible for 27% (8.5 Gt CO_2eq) of total mitigation required in Europe to 2050. Non-bioenergy based mitigation is largely achieved through the increased uptake of natural gas combined with CCS. Key developments of the European energy system in the absence of bioenergy are shown in Annex III.10.

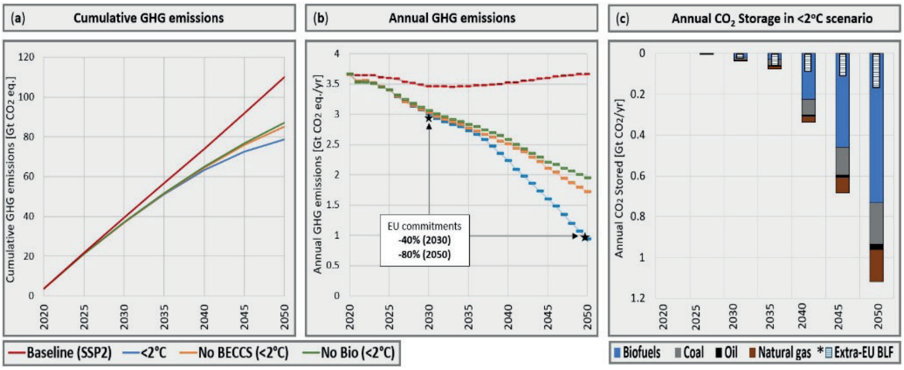

*Fig.3.4: Mitigation from bioenergy in Europe for 2020-2050 presented for total cumulative emissions (Gt CO_2 eq.) for all scenarios (a), annual GHG emissions (Gt CO_2.eq.yr^{-1}) for all scenarios (b), and annual mitigation from CCS in the <2°C scenario (Gt CO_2.eq.yr^{-1}) (c) . *'Extra-EU BLF' refers to CO_2 storage from BECCS for biofuel production outside of Europe.*

Concerning the '<2°C ' scenario, as seen in panel (B), there is a very tight fit to the current legislative EU regional emissions trajectory targets of 40% by 2030 and 80% by 2050 compared to 1990 baseline values [154]. Therefore the regional emission reduction trajectory projected within this study is in line with EU policy.

Panel (B) highlights the critical role of BECCS in achieving the '<2°C' scenario, showing accelerated reductions post-2035 whereby BECCS utilising residues for electricity generation allows for mitigation via net-negative emissions. In the year 2050, bioenergy without CCS provides an annual reduction of 0.23 Gt CO_2eq yr^{-1} in 2050, which is approximately the current annual emissions of Spain [155]. BECCS provides an additional 0.78 Gt CO_2eq yr^{-1}, approximately the current annual emissions of Germany [155]. BECCS is projected to account for 78% of annual bioenergy mitigation by 2050.

In panel (C), negative emissions resulting from CCS are displayed only for the '<2°C' scenario. By 2030 CCS technology is deemed too expensive for significant uptake. Only a small amount of BECCS occurs during the production of liquid biofuels from lignocellulosic sources and for process heat in industry. See Anex III.11 for projections of sectoral BECCS deployment in Europe. Post-2030, a combination of an increasing carbon price, emission credit for atmospheric CO_2 removal, and technological learning create a situation where rapid deployment of CCS technologies is possible. Total European CCS deployment increases from 0.03 to 1.12 $GtCO_2eqyr^{-1}$ between 2030-2050. In 2050, Europe is projected to capture 1.12 $GtCO_2eqyr^{-1}$ (54%) of emissions occurring within the energy system. Of this 0.73 $GtCO_2eqyr^{-1}$ (65%) is captured via BECCS due to its ability to deliver net-negative emissions and thus favourable carbon price, especially when delivered via residues. This combination steers BECCS deployment into the power sector. As annual residue supply for Europe reaches maximum capacity, applying CCS to power generation with coal and natural gas becomes increasingly important to reduce Europe's emissions further. The projected role of CCS technologies in the power sector is available in Annex III.5. In panel (C), 'Extra-EU BLF' refers specifically to BECCS during the production of imported liquid biofuels to Europe. Biogenic CO_2 emissions captured during biofuel production are allocated to the exporting country in IMAGE 3.2. Note that they are significant as almost all European liquid bioenergy is imported. They represent 3$EJyr^{-1}$ in 2050, with 46% refined with CCS. This equates to additional cumulative BECCS mitigation of 1.7 Gt $CO_{2.}$eq over the period 2020-2050.

3.3.5 Interregional bioenergy trade requirements for Europe

Fig.3.5 (A) displays the net interregional bioenergy trade between Europe and the rest of the world. The import requirement is projected to rise in tandem with total demand across all scenarios. To meet the '< 2°C' target, the model projects an increase in annual import from 1.4$EJyr^{-1}$ in 2020 to 8.4 $EJyr^{-1}$ by 2050. In the 'No BECCS' scenario, the demand for imports is 1.5 $EJyr^{-1}$ lower in 2050 due to a decrease in solid bioenergy carrier demand of BECCS. The breakdown of import and domestic supply for feedstock categories is provided in Annex III.12.

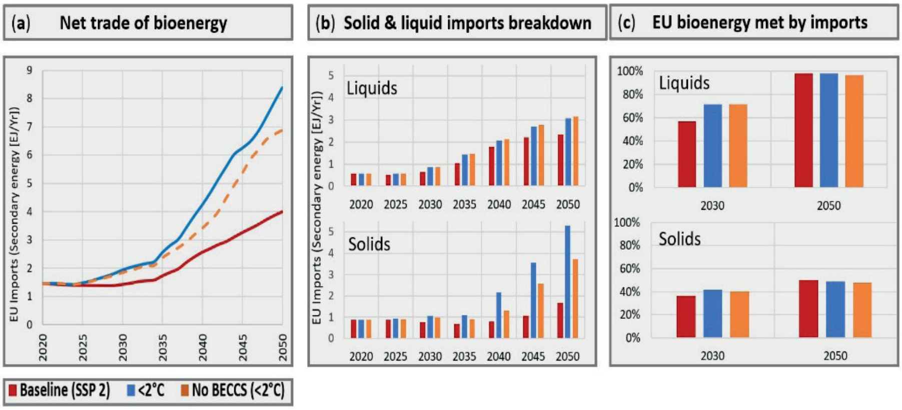

Fig.3.5: Europe's bioenergy trade with other world regions, shown for total net trade (a), solid and liquid imports breakdown (b), and share of Europe's bioenergy met by imports (c)

For liquid fuels, we see a steady rise in import demand across all scenarios. Cheap imported advanced lignocellulosic fuels outcompete European-produced 1st generation biofuels. They compete with fossil incumbents primarily in the transport, buildings (residential & services), and non-energy sectors. See Annex III.12 for a breakdown of domestic and imported bioenergy carriers. Post-2030, lignocellulosic biofuels become Europe's dominant supply and boost import dependency of liquid biofuels to >95% by 2050.

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

The major sourcing regions for Europe are projected to change over the period assessed. For solid bioenergy carriers, the U.S.A provides >80% of European imports in 2030, and by 2050 West Africa is projected to be the dominant supplying region providing 70%. For Liquid bioenergy carriers, 80% of European imports is supplied by Brazil in 2030, and by 2050 West Africa provides >80%. These projected sourcing regions hold favourable land availability and production costs making them important future bioenergy exporters according to the cost-optimisation formulation for inter-regional trade in TIMER. The drivers and implications of these trade projections are discussed in the context of an IAM intercomparison project for bioenergy trade [23].

3.4 Discussion

3.4.1 Observations and implications for European bioenergy dynamics

Bioenergy demand and sectoral deployment

For the '<2°C' scenario, secondary bioenergy can provide 4 $EJyr^{-1}$ in 2030, and 14 $EJyr^{-1}$ in 2050; this represents 50 and 70% of the required energy from renewables in Europe. The projected results show a complete restructuring from the current secondary bioenergy deployment within Europe's energy system. Currently, heating and cooling account for 2.9 $EJyr^{-1}$ (75%), electricity for 0.5 $EJyr^{-1}$ (13%), and transport for 0.5 $EJyr^{-1}$ (12%) [156]. In projections for 2050, we find heating and cooling use 4.2 $EJyr^{-1}$ (30%), electricity 8.3 $EJyr^{-1}$ (60%), and transport 1.4 $EJyr^{-1}$ (10%). For a <2°C target, the projections show increased bioenergy deployment across all sectors represented in the model. Bioenergy deployment is prioritised into the power sector, notably for bioelectricity production and the substitution of coal.

The projections suggest a fuel switching from coal to biomass in the power sector. Under such a development, the power sector should aim to capitalise on the projected phase-out of coal via implementing strategies to prolong asset life and minimise associated conversion costs for biomass plants. System-wide identification of plants to convert and retrofit should be in place by 2030 when bioenergy uptake accelerates. However, uncertainty surrounding long-term projections on Europe's access to sustainable biomass may result in lower supply volumes than projected. Acknowledging this, European bioenergy policy should seek to follow a 'merit order of end uses' [157], prioritising bioenergy to sectors where direct electrification and decarbonisation are harder to attain.

Feedstocks

The biomass feedstock composition in Europe alters significantly from the present, which is predominantly sourced from direct woody supply. Projections for the '<2°C' scenario show residues (forestry and agriculture) as the main source of bioenergy (70%) by 2030. By 2050, European access to affordable residues will have reached maximum capacity, shown by uptake of more expensive woody feedstock from forest plantations and energy crops entering the system post-2045. This dynamic is observed elsewhere in a recent study by Hanssen et al. (2020 b), who compared residue demand at a global-level across a suit of 8 IAMs. The share of residues within bioenergy supply decreases around mid-century as supply cannot match increasing bioenergy demand. Thus, the importance of lignocellulosic bioenergy crops and short rotation forestry sources emerge around this time. The projections of the '<2°C' scenario suggest that domestic mobilisation of residues and short rotation forestry in Europe needs to be maximised. This requires effective forest management within these time frames to meet the levels of projected solid bioenergy carrier demand and is in agreement with findings of others [80].

The model projections show post-2030 a rapid transformation for liquid bioenergy demand from 1st generation to 2nd generation advanced lignocellulosic feedstocks due to a favourable emissions profile and production costs. In reality, for Europe, 1st generation feedstocks currently dominate the liquid fuel market. For example, lignocellulosic feedstocks make up only 1% of current bioethanol consumption [158]. A recent survey of European bio-based companies highlights the importance of local access to feedstocks [159]. However, only a small share of Europe's crop/marginal lands are for dedicated lignocellulosic energy crops. Although feedstocks will likely be available on the global market as projected in this study, there remains uncertainty regarding the wide variety of lignocellulosic conversion technologies required. These technologies hold varying levels of readiness ranging from lab to commercial scale [158].

BECCS

The projections from this study indicate BECCS can contribute significantly to European climate targets. The '<2°C' scenario projects carbon capture and storage from bioenergy of 0.73 Gt CO_2eq. yr^{-1} by 2050. Recent studies that utilise partial equilibrium energy system models [160,161] project 1 Gt CO_2eq.yr^{-1} captured through BECCS in the European power sector in 2050, which is similar to the results presented in this study.

At present, there are only two operational commercial-scale CCS facilities in Europe (Sleipner & Snøhvit), capturing 1.5 Mt CO_2eq. yr^{-1}. Many EU member states have placed limitations or complete restrictions on CO_2 storage and have documented unfavourable public opinion [162]. Scaling up to the projected levels of CCS from this study by 2050 requires timely policies with national and EU-level strategies that support the business case of BECCS (incl. infrastructure development) and address implementation barriers and uncertainties.

Compliance with European mitigation targets

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

For sectoral-level targets, the European Green Deal seeks a 90% reduction in GHG emissions from transport by 2050 [7]. Current EU transport emissions are 1.1 Gt CO_2eq. yr^{-1} [140]. Projected transport sector emissions in the '<2°C' scenario are 0.21 Gt CO_2eq. yr^{-1} in 2050. Thus, an 80% reduction for the modelled European region is realised. This is achieved through a combination of electric vehicles and biofuel uptake. In addition, RED II aims for a 14% penetration of renewables in the transport sector by 2030 [27]. However, in our projections, this target is only met in 2043. Power sector GHG emissions in the '<2°C' scenario fall from 1.2 Gt CO_2eq in 2020 to 0.8 in 2030 and -0.3 by 2050. The power sector is projected to attain net neutrality by 2046. This neutrality in the power sector aligns with the European commission's 2050 roadmap targets [163].

Trade

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

3.4.2 Comparison of bioenergy deployment in other studies

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

Other IAMs

As part of the 33rd study of the Stanford Energy Modelling Forum (EMF-33) [129], a multi-model comparison of 11 IAMs was conducted. The comparison was under similar climate mitigation restrictions and BECCS availability constraints as deployed in this study. Their results at a global scale show that most models conclude that when BECCS is prohibited, bioenergy consumption decreases. A detailed assessment was not performed at the European level; however, a subsequent assessment of the projects database was performed by Mandley et al. [142]. At a European level, IMAGE 3.2 projections fall within the ranges of the other participating IAMs for both total bioenergy demand and trade. Annex III.13 provides further detail on this European inter-model comparison. IAMs have acknowledged limitations [164], especially in regards to cost sensitivities; thus, comparison to other approaches is beneficial, as is done in the following.

Recent projections from EU-centred approaches

The REFLEX project [165] combines several detailed EU regional bottom-up energy system models with LCA tools and explores a similar below <2°C emissions trajectory. Their results show that by 2050, 6 EJyr^{-1} of primary bioenergy will enter the EU power system compared to 18 $EJyr^{-1}$ projected in our study. This significant disparity is caused by the REFLEX projections indicating almost no biomass application for electricity generation. Instead, a combination of solar and wind capacity leads to 60% of installed capacity by 2050 compared to 10% in our study. This is not only a result of more favourable assumptions on grid integration and technology costs for solar, but also due to an absence of BECCS as a technology option in the study's power system module ELTRAMOD [166].

Another recent study by Zappa et al. (2021)[167] utilised the power system modelling framework Plexos. The study projects future cost-optimal energy mixes within the electricity sector for the central-western Europe region in line with a <2°C target. Their results project that BECCS deployment initiates post-2037 when economic incentives from net-negative emissions allow the technology to become profitable, in agreement with our results.

3.4.3 Study limitations

Global IAMs such as IMAGE 3.2 aim to capture the complex relationships between human systems such as the energy system explored in this study with natural systems. Due to their global scale and long-run projection horizons, computational power as well as inherent uncertainties on how these systems may develop limit the resolution at which these systems can be represented. Notable uncertainties in global IAMs include interpretation of historical trends, technological change, and estimates on resource and land availability. However, a recent comparative study on IAMs that were used to produce IPCC projections determined that SSP2 scenarios as used in our study tended to closely follow observed CO_2 emission and socio-economic drivers over a 30 year period 1990-2020 [168]. Some of the key uncertainties which may affect the interpretation of our results are discussed below.

Intra-regional specificity

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

Technological representation

The use of annual time-steps implies that IAMs cannot directly represent important aspects which may determine technology selection, such as grid-balancing or regional systems demand flexibility. This weakness extends to the types of conversion technologies and also feedstocks they are able to represent. For instance, some currently significant biomass supply streams, including forest management, pulp wood, and black liquor are not present in IMAGE. See section 1.6.1 for IMAGE 3.2 feedstock representation.

3.4.4 Future research avenues

Deeper mitigation targets

The projections in this study explore bioenergy development in Europe under an emissions trajectory in line with current EU climate legislation. However, given the proposal of the European Green Deal [7] to strengthen commitments to a 1.5°C temperature increase limit, future work should seek to expand the scenario protocol to explore a deeper mitigation pathway and its effects on bioenergy deployment.

Bilateral trade analysis

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

Coupling to regional models

A drawback of global IAMs is that they suffer from interregional specificity and detailed representation, as mentioned in section 3.4.3. An extension of this study could seek to feed globally consistent outputs for demand and import requirements into a more technologically and regionally detailed model that is better suited to evaluate these drawbacks. Coupling with a regional model with intra-regional specificity would also allow for the accounting of detailed system variables at the national level. Examples are, desired demand flexibility, energy storage, penetration of other renewables, bioenergy policy, CCS policy, and intra-regional trade throughout Europe.

3.5 Conclusions

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

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

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

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

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

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

CHAPTER 4

The implications of geopolitical, socio-economic, and regulatory constraints on European bioenergy imports and associated greenhouse gas emissions to 2050

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4. THE IMPLICATIONS OF GEOPOLITICAL, SOCIOECONOMIC AND REGULATORY CONSTRAINTS ON EUROPEAN BIOENERGY IMPORTS AND ASSOCIATED GHG EMISSIONS TO 2050

Abstract

Modern sustainable bioenergy can contribute toward mid-century European energy decarbonisation targets by replacing fossil fuels. Fulfilling this role would require access to increased volumes of bioenergy, with extra-EU imports projected to play an important part. Access to this resource on the international marketplace is not governed by Europe's economic competitiveness alone. This study investigates geopolitical, socioeconomic and regulatory considerations that can influence Europe's bioenergy imports but that are so far underexplored. The effect of these constraints on European import volumes, sourcing regions, mitigation potential and implications on European and global emissions is projected to the year 2050 using a global integrated assessment model. The projections show that Europe can significantly increase imports from 1.5 $EJyr^{-1}$ in 2020 to 8.1 $EJyr^{-1}$ by 2050 whilst remaining compliant with RED II GHG criteria. Under these conditions, bioenergy provides annual GHG mitigation of 0.44 $GtCO_2eq$ in 2050. However, achieving this would require a structural diversification of trading partners from the present. Furthermore, socioeconomic and logistical concerns may limit the feasibility of some of the projected major sourcing regions, including Africa and South America. Failure to overcome these challenges within supplying regions could limit European imports by 60%, reducing annual mitigation to 0.16 $GtCO_2eq$ in 2050. From a global perspective, regions with a comparatively carbon-intense energy system offer an alternative destination for globally traded biomass that could increase the mitigative potential of bioenergy.

4.1 Introduction

Climate change mitigation pathways aimed toward meeting the Paris Agreement project an increased role of bioenergy [129,146]. The use of bioenergy is motivated by the potential to mitigate anthropogenic GHG emissions by substituting fossil fuels. Besides emissions associated with land-use and land-use change, carbon in bioenergy is classified as biogenic. Hence accounting guidelines qualify combustion emissions as zero and, when paired with carbon capture and storage (BECCS), bioenergy can, in principle, deliver net-negative emissions. Furthermore, biomass can be converted into multiple energy carriers (liquid fuels, heat, electricity, and hydrogen) that can supply all end-use sectors, making it a flexible and attractive option for decarbonisation strategies.

Currently bioenergy consumption in Europe stands at 6.7 EJyr^{-1} primary bioenergy and contributes a large share of renewable energy (60%) as part of Europe's effort to mitigate climate change [10]. The majority (96%) of this biomass is EU-sourced, with 89% consumed in the member state (MS) that produces the biomass. Much of this domestic supply is low-grade solid biomass (e.g. wood chips and fuelwood) for residential heating [169]. For large-scale heating and power, wood pellets form the dominant supply. The EU wood pellet market currently consumes 0.45 EJyr^{-1}; extra-EU imports meet 40% of this. For the transport sector, liquid biofuel consumption stands at 0.65 EJyr^{-1} (14% imported).

Over the past decade, the EU has been the largest global importer of modern bioenergy carriers [22]. Total imports are expected to increase in the decades ahead as bioenergy becomes increasingly important within decarbonisation strategies. This is especially true when focusing on higher-quality modern bioenergy carriers deemed necessary for future decarbonisation strategies [26]. Existing bioenergy trade projections show that by 2030 the EU will be primarily sourcing this import from the same regions at present; by 2050, projections point to a possible broadening of sourcing regions to meet increased demand [23–25].

Long term projections of bioenergy demand and trade in the context of mitigation targets rely upon global integrated assessment models (IAMs) that can capture trade between world regions. IAMs are often used to explore the large-scale global effects of climate policy on the energy system and its relationships with natural and human systems. In order to determine production and trade patterns, IAMs consider climate targets, relative production costs and trade costs [23,129,170]. These existing assessments make assumptions on different markets and their connections but typically search for cost-optimal use of the biomass resource base under a global emission constraint. These assessments capture the effects of climate-target induced global competition for bioenergy. However, they preclude the consideration of other factors that may influence this trade, such as regulatory, geopolitical and socio-political constraints.

Regarding regulatory constraints, the EU-wide enforcement of the Renewables Energy Directive recast (RED II) [27] stipulates mandatory GHG reduction criteria for particular end-use applications compared to a fossil fuel comparator. This regulatory measure may constrain the potential of the resource base eligible to be used in Europe, which in turn may influence both European consumption and global bioenergy trade regimes. Geopolitical and logistical aspects are also important to consider. The production and export capacity in regions that currently do not supply the international market requires large scale investment and logistical challenges to mobilise meaningful trade [24]. The challenges associated with expanding production within exporting regions are only being tackled at demonstration scale with large associated capital costs [55]. Furthermore, the formulation of bilateral trade agreements with emerging exporting regions face increased competition from other world regions. Finally, governance and socioeconomic feasibility must also be considered when sourcing bioenergy imports. Concerns have been raised regarding the negative impacts of increased bioenergy demand in regions with poor governance and regulatory accountability, where issues such as deforestation, land tenure insecurity and inequitable supply chains are present [56,58,59].

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

4.2 Materials and Methods

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

4.2.1 Model description IMAGE 3.2

Bioenergy in IMAGE 3.2

This study uses the global integrated assessment model framework IMAGE 3.2 [149], which simulates the environmental consequences of energy and land-use systems worldwide. IAMs are an appropriate tool for exploring mid-term climate change mitigation pathways that meet exogenously defined climate targets while considering systemic and global effects. IMAGE represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change. The human system is represented through energy and agricultural demand, and its impacts in the form of greenhouse gas emissions and land-use change are communicated to earth system models for land, atmosphere, and ocean.

The IMAGE3.2 framework covers all stages of the bioenergy value chain, accounting for feedstock production, associated land-use change, conversion to secondary energy carriers, international trade, and final consumption in end-use sectors [67]. Biomass supply is represented by six aggregated primary feedstock categories: woody crops, grassy crops, maize, sugarcane, oil crops, and residues supplied from agricultural and managed timber operations. The potential bioenergy supply is determined at the grid level by the dynamic global vegetation model LPJml [75]. In order to ensure that bioenergy supply does not interfere with major environmental and social criteria, specific land types are excluded from bioenergy production. These include urban areas, nature reserves, forests and areas projected to be used for food production by assuming a 'food first' principle [73].

Primary biomass can be converted into liquid and solid bioenergy carriers. Liquids include 1st generation and lignocellulosic biofuels. Solid bioenergy carriers (i.e. chips and pellets) can be further converted to hydrogen, electricity or heat. End-use final energy demand sectors include Industry, Transport, Services and Residential. Additionally, biomass can also be used for non-energy purposes, acting as a feedstock for the production of ammonia, methanol, and higher value chemicals [67]. Sectoral bioenergy demand is based on its economic competitiveness for meeting specific energy services of the demand sectors relative to other energy carriers. Bioenergy costs include feedstock, conversion technology, labour, capital, and O&M cost. Bioenergy cost is also influenced by carbon prices implemented within mitigation scenarios that promote low-carbon fuels by adding a price on the potential emission of different bioenergy production routes. For further details on the IMAGE model, see section 1.6.1.

Emissions accounting of bioenergy

For bioenergy emissions accounting, pre-combustion upstream process emissions are determined dynamically at a regional level. They include land-use change, primary biomass production (including fertiliser production/application and energy inputs for cultivation), transport (including intra-regional primary biomass to processing/conversion site and inter-regional trade), process energy for conversion into bioenergy/secondary carriers [76]. Smokestack emissions during final energy conversion from biogenic carbon are considered carbon-neutral as the carbon uptake during the growth phase is accounted for in the land-use component of IMAGE. The production of liquid bioenergy carriers, as well as bio-based electricity, hydrogen, and industrial heat, can be combined with CCS at technology-specific capture rates to produce negative emissions during the conversion process [72]. Additionally, part of the carbon content of biomass used for non-energy purposes in chemical manufacture is assumed to be indefinitely sequestered [77]. See section 1.6.1for a schematic of modelled bioenergy GHG sinks and releases.

Trade representation

The IMAGE model projects bilateral bioenergy trade across 26 macro-regions (See Annex IV.1 for world region representation in IMAGE 3.2). The trade of secondary bioenergy carriers is facilitated based on the regional production cost of bioenergy and associated transport costs. Regional cost supply curves of primary biomass are projected by determining and ordering spatially explicit biomass costs based on yields and land prices. These regional bioenergy supply curves and regional demand are used to determine the optimal bilateral trade. A region imports bioenergy when imported bioenergy cost (export region production plus international transport cost) is lower than domestic production or alternative fuel sources to match the equivalent secondary energy demand.

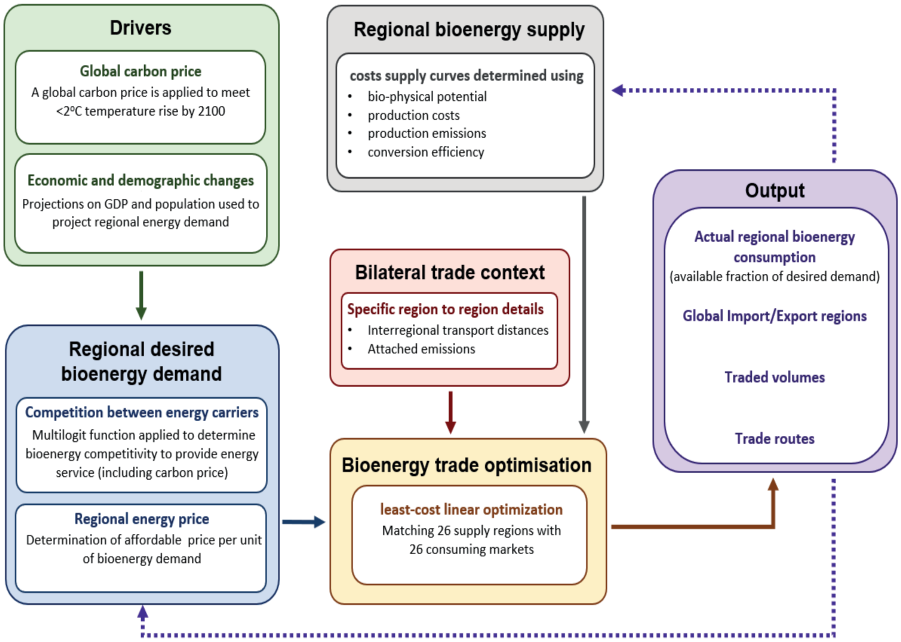

Fig.4.1: Schematic of the drivers, constraints, and formulation of bioenergy trade within IMAGE 3.2. Dashed lines indicate feedbacks from modelled trade and final consumption.

4.2.2 Scenarios

Our scenario analysis builds upon the default SSP2-RCP2.6 scenario of the IMAGE 3.2 model [150]. That is, we present variations of a middle-of-the-road socioeconomic scenario meeting a 2°C climate target. We explore three variations of trade narratives described in Table 4.1, which differ concerning restrictions on regions with which Europe can trade bioenergy. In the default 'Free trade' scenario, trade is allowed with all regions based purely on trade optimisation (see Fig.4.1). In the first variation, 'Current Partners', trade is only allowed with current trading partners. The second variation, 'Feasibility', excludes trade with regions which do not meet a pre-defined socio-political feasibility score. In the final variation, 'RED II', trade is only allowed for bioenergy that meets EU regulations on GHG emission savings.

Within this study, trade is calibrated up to 2020, after which the scenario-specific trade restrictions are applied to Europe. Besides their ability to trade bioenergy with Europe, other world regions are not constrained by the scenario variations [91]. In the 'Free Trade' default scenario, a global carbon budget is enforced by introducing a dynamic carbon price mechanism from 2020 onwards. It is applied to all energy carriers based on their carbon content, effectively promoting lower carbon fuel sources. The projected carbon price is identical across all scenarios, implying that cumulative global and regional emissions may differ across scenarios in order to isolate the effect of trade restrictions.

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

Table 4.1: Overview of key trade constraints applied in the scenario protocol

Scenario	Trade constraints
Free Trade	The 'Free Trade' scenario applies default model settings, where all regions freely trade bioenergy based on the relative cost of delivered bioenergy. Projected trade represents cost-optimal use of the global biomass resource base under a global emission constraint whereby regions with high techno-economic production potentials with low attached costs become global exporters. For this scenario, only techno-economic and biophysical constraints are considered. The scenario settings have been used in previous assessments of international bioenergy developments [23,25,171]. This scenario assumes a middle-of-the-road socioeconomic development as described by the Shared Socioeconomic Pathway (SSP2) [172], meeting a 2°C climate target (RCP2.6). SSP2 follows a path whereby social, economic and technological patterns, including the management of global commons, follow historical patterns. Whilst resource and energy intensities collectively decline, this occurs unevenly between world regions. A 2°C climate target was selected in this study to represent an ambitious global mitigative effort, and the minimal bounds of the Paris agreement considering the observed delay in long-term strategies within recently communicated National determined contributions [173]. As this study reports mid-century developments, a 2°C target provides a pathway more representative of current actions. For carbon price developments under this mitigative pathway, please see Annex IV.7.

Scenario	Trade constraints
Current partners	Global trade patterns do not necessarily develop in line with a least-cost modelling assumption in the' Current partners' scenario. Competition for the global biomass resource base is set to intensify [23], and significant geopolitical uncertainties exist for future trade developments within an immature international market. These developments may be steered by other major importing regions contesting available trade partnerships. Furthermore, regions with large bioenergy resource potentials, such as sub-Saharan Africa and developing Asia, still suffer from relative energy poverty and the 'natural resource curse' [174,175]. The energy strategies of these regions may dictate the market size for extra-EU imports. This scenario assumes that future European extra-EU bioenergy trade is limited to world regions that currently exhibit a meaningful export of modern bioenergy carriers to Europe. An assessment carried out by Proskurina et al. [176] quantifies recent EU trade flows for modern bioenergy carriers and is consistent with other studies [169,177–179]. For pellets, regions include Canada, USA and Russia. For the liquid carriers, bioethanol imports from the USA, Central America (Guatemala), Brazil, Rest of South Asia (Pakistan). Biodiesel and palm oil imports from South East Asia (Malaysia), Indonesia region and Korea region (South Korea).
Feasibility	The 'Feasibility' scenario incorporates techno-economic and socio-political challenges attached to biomass production. This scenario is based on a country-level feasibility assessment for land-based mitigation measures presented in Roe et al. [32]. Their study refines and updates the economic mitigation potential for 20 land-based measures in >200 countries via comparing bottom-up sectoral-level estimates with those from IAMs. The feasibility of implementing the actions required to realise mitigation is highly contextual, considering each country's unique circumstances. Their study aims to quantify a qualitative feasibility framework, conducting a detailed literature review followed by an expert review and only including indicators that provide data from the last five years and hold a demonstratable relationship to the feasibility of implementation. This process resulted in 19 indicators (including bioenergy-specific indicators, for instance, the technical feasibility of BECCS), spanning six dimensions: economic, institutional, geophysical, technological, socio-cultural, and environmental-ecological. The indicators used are listed in Annex IV.1(c). From this, a quantitative index is developed as a proxy for country-level feasibility to implement these measures and realise mitigation potential through assessing barriers and enabling conditions [32]. The country-level feasibility index from Roe et al. [32] is translated into scores for IMAGE3.2 regions via weighting the scores of constituent countries by total agriculture and forested land cover using FAO statistics. Bioenergy trade to Europe is prohibited for regions that score substandard to itself. This limit was selected as a proxy to represent regions with a governance system that can uphold European bioenergy sustainability criteria. The regional restrictions and feasibility scores are shown in Annex IV.1(c). Feasible future trading partners include Canada, the USA, Japan and Oceania.
RED II	The introduction of RED II sets binding GHG emission reduction criteria for bioenergy entering the transport, electricity heating and cooling sectors after 2026. These reductions equate to (at least) 65% in transport, 80% in heating and cooling and 80% in electricity generation [27]. Domestically produced and imported bioenergy must comply with these emission reduction requirements within this scenario. Within this scenario, the GHG emission reduction criteria is assumed to be fixed from 2020 to 2050.

4.2.3 Indicators

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

(i) Net Trade volumes

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

$$\boldsymbol{Net\ Bioenergy\ trade_{r1\ to\ r2} = Bioenergy\ trade_{r2\ to\ r1} - Bioenergy\ trade_{r1\ to\ r2}} \quad \text{(eq.1)}$$

Where:

$_{r1}$ = Importing region
$_{r2}$ = Exporting region

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

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

$$EF\ of\ bioenergy\ imports_{\,r1,t} = \frac{E\_prod_{r2\ to\ r1,bc} + E\_luc_{r2\ to\ r1,bc} + E\_conv_{r2\ to\ r1,bc} + E\_trans_{r2\ to\ r1,bc} - E\_ccs_{r2\ to\ r1,bc,tech}}{\mathrm{FE\_\eta}_{r1,bc,tech}} \quad \text{(eq.2)}$$

Where:

E_prod = emission during cultivation, fertilizer production/application and extraction
E_Luc = emissions arising from land-use change
E_conv = emissions during conversion of primary biomass to secondary bioenergy carriers (including negative emissions captured via CCS during liquid carrier production)
E_trans = emissions from transportation steps (field to Europe's border)
E_ccs = emissions captured via CCS during conversion to final energy carrier (electricity or heat).
FE_η = conversion efficiency of secondary bioenergy carrier into final energy
bc = type of bioenergy carrier, ∈ {solid bioenergy carriers, liquid bioenergy carriers per feedstock(s)
tech = final end use conversion technology

iii) Marginal mitigation from European bioenergy imports

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

$$Mitigation\ from\ bioenergy_{Trade\ scenario} = \ Emissions_{\ Trade\ scenario} - Emissions_{\ Nobio} \quad \text{(eq.3)}$$

4.3 Results

4.3.1 European bioenergy imported volumes & sourcing regions

By 2030 European bioenergy demand is projected to remain static at the 2020 level (3.8 EJ yr^{-1}). The trade constraints applied in the scenarios do not interfere with Europe's bioenergy consumption over the next decade, with similar levels of sourcing largely achieved through a re-routing of supplying regions or increased domestic production. By 2050, however, Europe's bioenergy demand and thus import volumes are projected to increase substantially across all scenarios, driven by a globally enforced <2˚C carbon budget, making low carbon energy carriers increasingly attractive. Fig.4.2 shows that the trade constraints lead to significantly different import volumes and sourcing regions. Results for 2030, cumulative (2020-2050) import volumes, and delivered cost projections are provided in Annex IV.4(a-c).

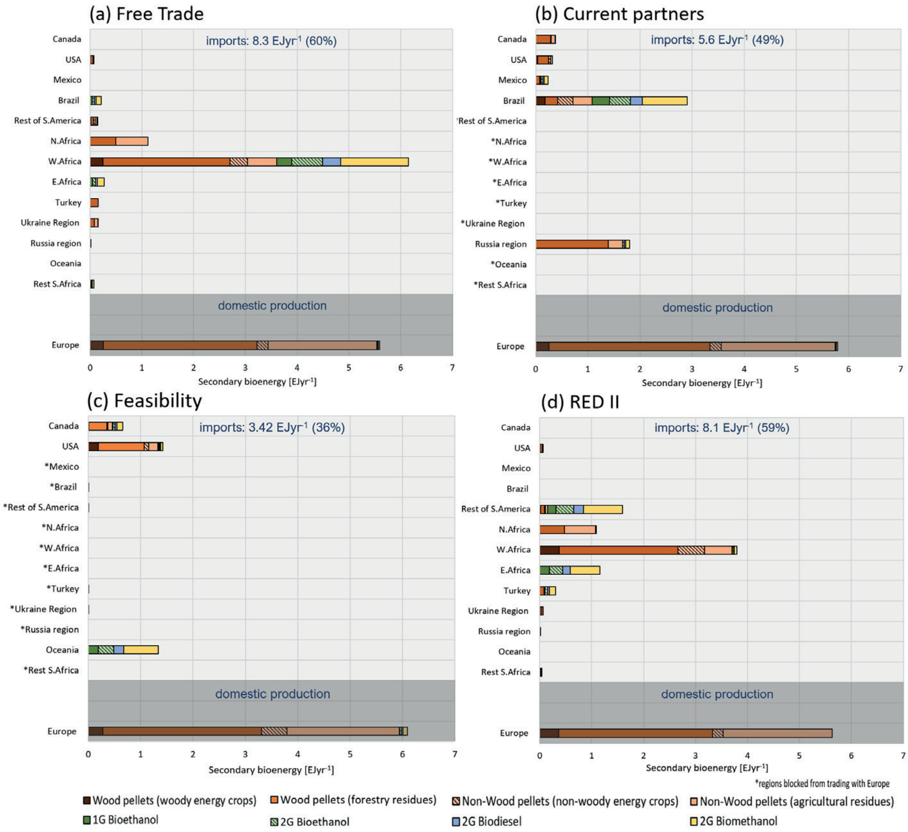

Fig.4.2 European bioenergy import volumes by energy carrier and sourcing regions in 2050.

- only regions that provided bioenergy to Europe in one (or more) of the trade scenarios are presented, with imports expressed as a percentage of annual European consumption.

In the 'Free Trade' scenario in 2050, 60% of European bioenergy demand is met through imports, with the vast majority (74%) arriving from West Africa. According to the default assumptions, the prominent role of this region is due to a large potential for land availability and projected yield improvements, supported by relatively cheap production costs. This global exporting role for the sub-Saharan Africa region is aligned with other major IAMs [23].

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

The 'RED II' scenario can closely match the projected demand seen for 'Free Trade' to 2050. However, to meet this demand whilst remaining RED II compliant requires significant changes to Europe's trading strategy. When comparing trading patterns in 2050 to the 'Free Trade' scenario, a diversification of supplying regions is observed. This occurs because as regions such as West Africa become dominant global exporters, the emissions during the production stage increase due to expansion into lands with higher carbon content and exhaustion of residue supply (Annex IV.2 for a detailed explanation). Europe must diversify supply to regions where production emissions remain within the RED II GHG criteria thresholds but hold higher production costs. This results in a need to spread the import of liquids over several regions (Rest of South America, East Africa and Turkey). Interestingly the 'RED II' scenario holds immediate implications as European liquid bioenergy production is determined to be incompliant, leading to an overall increase in imports to 2035.

The projections show that Europe has limited domestic capacity to cover the import deficit created by trade constraints, as domestic production is similar across all scenarios. This is due to the limited techno-economical potential for bioenergy production at assumed carbon prices. Comparing annual domestic production in the 'Free Trade' scenario to the most constrained 'Feasibility' scenario suggests a possible increase in the domestic production of 0.5 $EJyr^{-1}$ (or +9%) in 2050, mainly from the expansion of pellet production from non-woody crops.

4.3.2 GHG emissions attached to imported European bioenergy

Across scenarios, the emission factors for solid bioenergy carriers consumed in Europe decrease heavily between 2030 and 2050, becoming negative in the long term (Fig.4.3). This dynamic is driven by the increased deployment of BECCS for electricity generation after 2040 (see Annex IV.5), which offers much deeper emission reduction than other end-use streams. For the 'Free Trade' scenario, the emission factor for imported bioenergy ranges from -100 to -200 gCO_2eqMJ^{-1}. Solid carrier supply from the dominant export region West Africa holds one of the highest emission factors observed while still being negative. However, the total volume available affords Europe substantial mitigation (see Annex IV.6 (b-c) for total European annual mitigation potential from bioenergy 2030 & 2050).

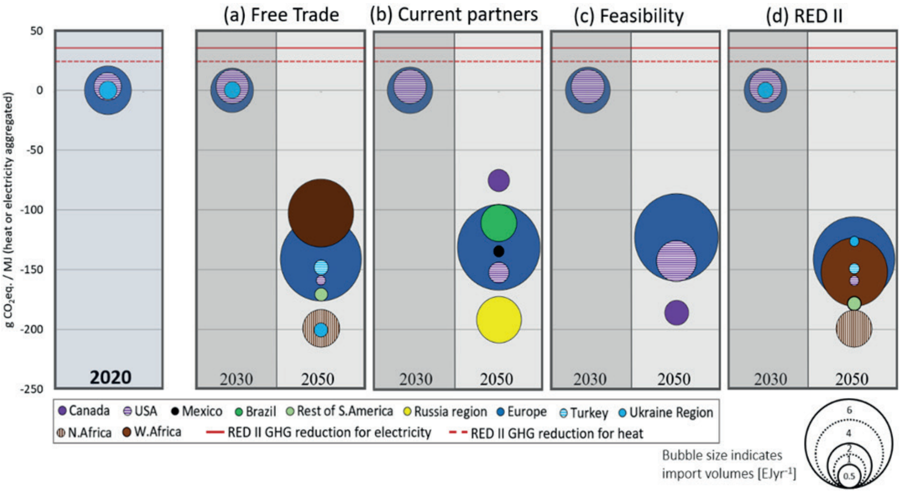

Fig.4.3. Average emission factors attached to European solid bioenergy sourcing in 2030 & 2050
- The centre point of the bubble represents the emission factor associated with sourcing from that region.
- Presented emission factors are aggregated on two levels: i) solid bioenergy supply categories (i.e. residues, energy crops), ii) end-use application(s) in Europe (Annex IV.5) and weighted based on their actual energetic demand

In comparison, the' Current partners' scenario in 2050 effectively replaces residue supply from North Africa with Russian supply that carries slightly larger transportation emissions. The import deficit left by West African supply in the 'Free Trade' scenario is partly compensated by lower emission factor Brazilian supply and higher emission factor Canadian supply. Restricting imports increases the emission factor of domestic

European supply from -140 to -130 gCO_2eqMJ^{-1} due to increased production in less favourable areas.

In the 'Feasibility' scenario, the emission factor of domestic supply further increases to -123 gCO_2eqMJ^{-1} due to the expansion of European sourced non-woody energy crops. A noteworthy observation is the decreased emission factor from Canadian supply compared to the 'Current partners' scenario, even though import volumes are comparable. This is a direct influence of supply switching in other regions from Canada to the now accessible and cheaper Brazilian and Russian sources from which Europe is prohibited in this scenario. The knock-on effect for Europe is access to the same amount of Canadian supply but with a lower emission factor. While this finding has limited implications for Europe, it highlights the complex interactions between regional bioenergy trading strategies and global mitigation (see section 4.3.3).

Although sourcing regions for solid bioenergy imports in the 'RED II' scenario in 2050 are similar to the 'Free Trade' scenario, a significant difference is observed in the emission factors. Imports from the dominant supplier West Africa improve, providing an additional 50 gCO_2eqMJ^{-1} emission reduction. This enhanced mitigation is brought about by prohibiting the production of second-generation (2G) liquid carriers from West Africa in the 'RED II scenario'. In the ' Free trade ' scenario, these energy carriers compete for the same lignocellulosic resource base. This effectively increases production emissions for pellets due to reaching maximum residue supply earlier and expansion of short rotation woody energy crop production into areas with less favourable land-use change emissions, higher fertiliser/energy inputs and transportation distances to conversion sites.

The aggregated emission factors presented for solids bioenergy carriers in Fig.4.3 show complete compliance with RED II GHG regulation across all scenarios due to a sufficient supply of low-emission residues. However, unaggregated assessment of feedstock categories and regulated end-use streams in Annex IV.3(b) rule certain combinations uncompliant. These occur after 2045 for non-residue feedstocks for electricity production without BECCS or heat production within the cement and steel industry, owing to the low energy conversion factors associated with these applications.

Unlike solid bioenergy carriers, which benefit primarily from a sufficient supply of residues and the ability for large-scale pairing with CCS technologies at the point of combustion, the emission factors of liquid carriers are projected to be significantly higher (Fig.4.4). Across scenarios, there is a general trend of decreased emission factors attached to liquid carrier supply from 2030 to 2050 caused by shifting towards less emission-intensive lignocellulosic feedstocks and increased rates of CCS implementation during production. Projections indicate a failure to meet RED II requirements for most sourcing regions, with few sourcing options that satisfy the RED II criteria.

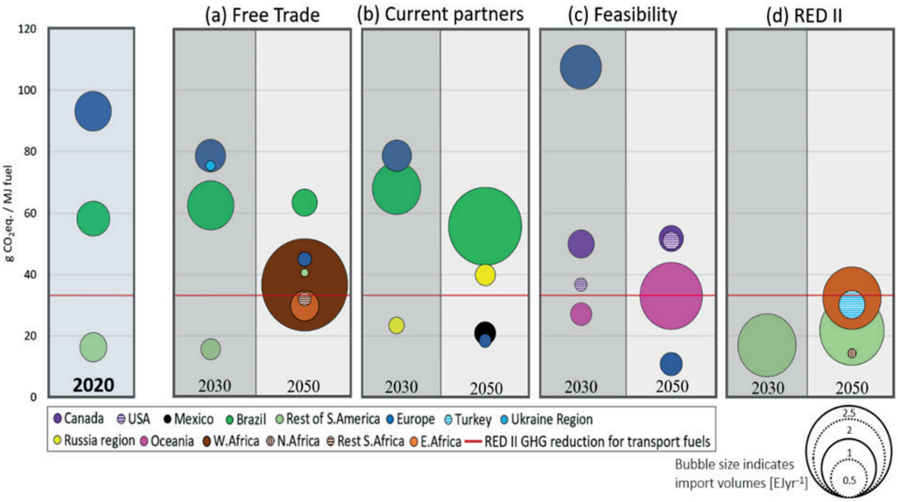

Fig4..4. Average emission factors attached to European liquid bioenergy sourcing in 2030 & 2050.

- The centre point of the bubble represents the emission factor associated with sourcing from that region.
- Presented emission factors are aggregated by supply liquid carrier categories (i.e. biomethanol, bioethanol, biodiesel)

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

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

The 'Feasibility' scenario provides contrasting results. 2030 projections show a substantial increase in the emission factor of domestic supply caused by increased first-generation bioethanol production due to the restrictive trade constraints. By 2050 a large proportion of supply (83%) is RED II compliant, benefiting from low emission factor imports from Oceania. Due to a reliance on North American regions for solid carrier imports, which exhaust the remaining residue supply and move European imports to dedicated woody crops, 2G lignocellulosic fuels from these regions hold emission factors that exceed the RED II threshold.

The projections show large volumes of liquid fuel import with significantly improved emission factors for the' RED II' scenario. Imports are sourced from more expensive sourcing regions of the Rest of South America, East Africa, North Africa and Turkey (16-32 $gCO_2eqMJ_{fuel}^{-1}$ in 2050). As a result, mitigation stemming from biofuels in the transport sector is significantly increased in the 'RED II' scenario compared to all other scenarios (see Fig.4.5) due to maintaining significant imports (via diversification) with diversification RED compliant emission factors.

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

Cumulative net mitigation for Europe

All upstream emissions for bioenergy production are allocated to the consuming region in this study. For the 'Free Trade' scenario, in concurrence with previous studies deploying these model settings [23,171], Europe follows an emission trajectory tightly aligned with its Paris agreement commitments. This amounts to a cumulative net mitigation contribution from bioenergy of 6.2 $GtCO_2eq$ (Fig.4.5a). Limiting bioenergy imports to 'Current partners' does not significantly hamper European mitigation to 2050. This is because Europe largely retains the ability to source solid bioenergy imports, with solid carrier deficit fully covered via increasing domestic production of pellets from agricultural residues. This allows Europe to capitalise on the deep reduction occurring in the power sector with BECCS (Annex IV.5).

However, the 6 EJ shortfall in liquid bioenergy carriers and higher upstream emissions attached to liquid imports cannot be entirely mitigated by other low-carbon fuels in

Europe's energy mix at the carbon price explored. This culminates in 0.35 $GtCO_2eq$ of additional emissions (2020-2050) compared to the 'Free Trade' scenario. The 'Feasibility' scenario provides the lowest GHG mitigation for Europe. Under this trade constraint, liquid and solid bioenergy imports generally hold favourable emission factors. However, import volumes are significantly lower (1.5 $EJyr^{-1}$ for liquids and 3.5 $EJyr^{-1}$ for solids in 2050) compared to the 'Free trade' scenario. Domestic supply cannot cover these deficits, which lead to a cumulative net emissions increase of 1.6 $GtCO_2eq$ compared to the unrestricted 'Free Trade' scenario. Limiting Europe to REDII compliant bioenergy consumption means 9% less liquid bioenergy carrier imports than the 'Free Trade' scenario, whilst solid imports remain unaffected. This lower supply for Europe is due to higher prices of imports and an inability to produce compliant supply before 2035 domestically. However, the benefits of obtaining biofuels with lower emission factors are evident and more than compensate for total volume deficits. Europe increases cumulative mitigation to 7.3 $GtCO_2eq$.

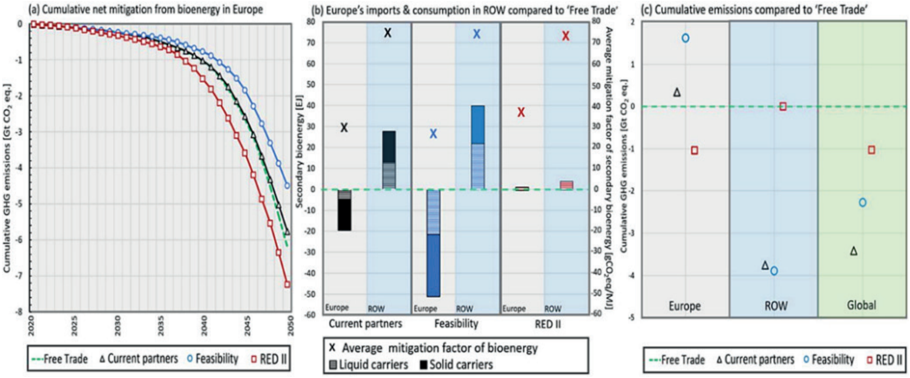

Fig.4.5. The effects of trade constraints on Europe's cumulative GHG mitigation, global bioenergy consumption and global emissions, where:

(a) Cumulative net mitigation from bioenergy in Europe across trade scenarios compared to' No bio' counterfactual.

(b) Difference in cumulative bioenergy imports for Europe and bioenergy consumption in the Rest of the World (ROW) compared to the 'Free Trade' scenario. Including the attached average mitigation per unit bioenergy consumed (averaged over liquid and solid carriers and over time (2020-2050)) compared to the 'Free Trade' scenario.

(c) GHG emissions for Europe, the Rest of the World and globally for trade-constrained scenarios compared to a 'Free Trade' scenario. Numerical data, specifically including the data from the 'Free Trade' scenario used as a benchmark in panels (b) and (c), is provided in Annex IV.6(d).

Effects of European bioenergy trade constraints on global bioenergy consumption

Compared to the unrestricted' Free Trade' scenario, cumulative European imports of secondary bioenergy fall in the trade constrained 'Current partners' and 'Feasibility' scenarios by 20 and 51 EJ, respectively. A fall in European imports of bioenergy creates a situation where the rest of the world can increase consumption (Fig.4.5b). For the 'Current partners' scenario, the rest of the world increases bioenergy consumption by 28 EJ compared to 'Free trade'. There is a disproportionate increase in the rest of the world's liquid bioenergy consumption. Whilst Europe cumulatively imports 5 EJ of liquid biofuels less over the period, the rest of the world increases consumption by 13 EJ. This dynamic is due to Europe moving to more expensive supplying regions, thus, allowing other world regions which are otherwise priced out of the international market to capitalise on cheaper supply from West and East Africa. In the 'Feasibility' scenario, the rest of the world benefits from a large volume of cheaper bioenergy entering the international market. However, the surplus left on the international market does not see complete uptake (11 EJ or 20% less than what Europe does not import compared to the 'Free Trade' scenario). This surplus remains because the carbon price is insufficient to promote further fuel switching within the rest of the world as a cost-minimal <2°C mitigation trajectory is already reached. The 'RED II' scenario witnesses small increases in liquid imports for Europe because all domestic production is determined uncompliant. However, as Europe diversifies its supplying regions, the rest of the world observes small increases in consumption of liquids as some cheaper sources, which are also not compliant with REDII constraints, are opened to other regions.

Effects of European bioenergy trade constraints on global emissions

Bioenergy can be utilised in other world regions with a much stronger mitigative effect. The difference in average mitigation factor from bioenergy between Europe and the rest of the world ranges between 36-46 gCO_2eMJ^{-1}, with the minimum occurring for the 'RED II' scenario because a larger proportion of low emission factor bioenergy is consumed in Europe (Fig.4.5b). All trade constrained scenarios lead to lower cumulative global emissions than the 'Free Trade' scenario (Fig.4.5c). In the case of the 'Current partners' and 'Feasibility' scenarios, this is due to an increased supply of bioenergy to the rest of the world, where bioenergy holds a significantly higher mitigation factor. This increased mitigation in the rest of the world more than compensates for the subsequent emissions increase experienced in Europe, providing net global cumulative mitigation of 3.4 and 2.3 $GtCO_2eq$, respectively. Deeper global emission reductions occur for the 'Current partners' scenario because Europe can maintain a lower emission trajectory due to sustaining solid carrier supply through domestic production. The 'RED II' scenario takes a trading approach that diversifies

European supply across low emission factor regions. Europe effectively moves away from the lowest-cost export regions for marginal supply as their total production for RED II compliant supply is saturated. This allows Europe to retain comparable import volumes to the 'Free Trade' scenario; hence, there is no effect on the GHG mitigation for the rest of the world.

4.4 Discussion

4.4.1 Implications of European trade barriers on bioenergy development

The results suggest that a European energy system transition in line with a <2°C global climate target may require substantially increased bioenergy imports and diversification of trade partners by 2050. The projections for biomass supply and associated costs point to diverse sourcing options that can match RED II compliant European demand. However, whilst technically able to meet EU decarbonisation goals, sourcing of bioenergy may be socioeconomically infeasible from these regions. This is highlighted by a stark contrast in supplying regions between the 'RED II' and 'Feasibility' scenarios (Fig.4.2). European operators must be flexible over time to keep imported bioenergy emission factors compliant as major exporters maximise residue supply and expand dedicated energy feedstock production into lands with higher carbon stocks, lower yield, and increased transportation requirements. Furthermore, Europe's demand for low emission factor bioenergy holds global implications by raising the risk that other regions are restricted to cheaper bioenergy with higher emissions. Thus, Europe may become partially responsible for emissions from additional marginal production in these regions, raising concerns about indirect impacts and questions on where bioenergy on the international market is best deployed.

4.4.2 Priority areas for European bioenergy sourcing policy

Substantial bioenergy contributions of secondary energy to Europe's mitigation targets are technically obtainable under the regulatory confinements of RED II at 3.7 $EJyr^{-1}$ by 2030 and 13.8 $EJyr^{-1}$ in 2050. However, this increased role depends on importing large volumes of bioenergy that should be fostered and steered by timely policy interventions.

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

Meeting the projected European bioenergy demand in 2050 will likely require a substantial diversification of current sourcing regions into areas that hold increased socioeconomic challenges. In order to facilitate the accessibility of sustainable bioenergy from these regions, Europe could pro-actively participate in developing bioenergy policy frameworks and strategic action in key exporting regions within the south Americas and Africa. Bilateral development must be at the core of this process to stimulate and accelerate biomass production and processing and conversion plants to unlock mitigation potential on both sides of the trade agreement. This would ensure increased value retention in producing countries and contribute to economic development. Trade relations could be further strengthened through knowledge sharing and secured investment schemes which include a thorough risk assessment to minimise project failure. Additionally, infrastructure development within exporter regions is an essential component of a successful trade relationship, with poor infrastructure deterring needed foreign investment [180]. Such efforts are needed to safeguard the benefits of trade relations between the EU and the Global South. The wider socioeconomic implications of trade activities must be considered and monitored closely to ensure benefits and avoid conflicts such as human rights, poverty, land grabbing, and biodiversity loss are actively addressed, thereby fostering the bioenergy industry's contribution to alleviating these concerns. Whilst diversification of supply is a challenge for Europe. It provides the opportunity to improve energy security due to a larger array of sourcing options than fossil incumbents that suffer from political and economic shocks.

Improving the transparency of GHG accounting

Projections show that the extra-EU import emission factors can vary dramatically across supplying regions and time scales, leading to possible RED II GHG criteria breaches. Importantly, incompliance may occur even when production expansion is limited to abandoned and marginal lands, as explicitly specified in the IMAGE 3.2 model. Clearly, a rigorous accounting of the whole supply chain from production to combustion is vital to ensure RED II compliance. This study allocates all bioenergy related emissions to the consuming region to illustrate the consequences onto European mitigation efforts. The current accounting framework for GHG emissions derived from imported bioenergy is currently not fit for this purpose due to the complexity of different emissions across the bioenergy supply chain being attributed to different sectors (i.e. LULUCF and energy) and the GHG inventories of different countries (i.e. importer, exporter). Furthermore, international transport emissions are accounted for in neither import nor exporter inventories but instead as 'international bunker fuel emissions'. Whilst the location of emissions is irrelevant from a global climate perspective, it is crucial for determining regional compliance. The latest recast of RED is a minimum safeguard, stipulating that imported biomass is only permitted from exporting nations that report their LULUCF-sector emissions within the UNFCCC [181]. It stops short of insisting that the exporter must account for these emissions. Mandatory emission accounting introduced in the Kyoto Protocol [182] for Annex I countries is now absent in the Paris agreement [3]. In fact, none of the major exporting regions projected in this study account for their LULUCF emissions, meaning upstream production emissions are missing at global level bookkeeping.

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

Bolstering logistical network and operations

Bioenergy logistics present a unique challenge due to seasonality, spatial distribution, and quality variances of feedstocks. Therefore, the associated costs can be considerable and act as a significant barrier to the widespread use of bioenergy [183]. The projections show that bioenergy from domestic production and extra-EU imports may rise to 5.6 and 8.3 $EJyr^{-1}$ by 2050, inferring increased freight transport and distribution networks at both intra- and interregional levels. In addition, projections for a 'RED II' scenario observe immediate growth in extra-EU imports (+50% or 0.75 $EJyr^{-1}$) already by 2030, triggered by increased liquid carrier imports. The volumes and time relevance indicate a need for a flexible inter-modal freight network that maximises integration with the current fossil fuel distribution network and minimises associated transportation costs. Furthermore, this increased import dependency will likely require major European shipping ports to bolster capacity with linked storage and rail distribution facilities to the rest of the continent.

4.4.3 Effects of European bioenergy trade on the global emissions trajectory

The results indicate that the European energy sector may not be the most effective destination for available low emission factor bioenergy on the global marketplace (Fig.4.5b & c). European imports may be better used in other world regions where more emission-intensive energy systems afford greater mitigation per unit of bioenergy. Furthermore, there is a saturation point at which redirected European imports offer no additional global mitigation above 4 GtCO$_2$eq over the period (2020-2050). However, it is too simplistic to conclude that European-bound bioenergy imports should be redirected towards regions with the highest mitigation potential because several aspects are not considered in this analysis. These include i) the ability of regions to afford these imports, ii) the rate of technological development, specifically BECCS within these regions, and (iii) whilst Europe may have a relatively 'cleaner' energy system, it is also tasked with a relatively higher regional mitigation target, aiming for GHG neutrality by mid-century [7].

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

4.4.4 Study limitations and future research avenues

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

The scenario protocol investigated allows for projections of future bioenergy trade implications under long-run RCP 2.6 climate pathways applied to the 'Free Trade' scenario whilst considering a diverse set of constraints for future extra-EU bioenergy trade. However, the scenario analysis can be further extended to unexplored geopolitical considerations may act as key determinants for investment decisions and energy market dynamics. These include territorial conflicts, tariff wars, and financial crises that could further affect Europe's access to imports [184,185]. This study deploys an SSP2 baseline as the basis for important macro socioeconomic parameters, including population growth, technological change and economic growth. These assumptions hold important implications for bioenergy development by influencing crucial factors such as resource, energy, agricultural demand and land availability [67]. Future assessment could explore how other SSP pathways may influence bioenergy shares between world regions through varying assumptions on evenly distributed progress between world regions where SSP2 assumes historical trends continue that route bioenergy deployment into wealthier and more developed economies; as shown in Annex IV.8. Furthermore, at the climate change conference of the Parties (COP 26), a strengthened commitment to a 1.5°C temperature limit was reaffirmed [186], recognising the need for accelerated efforts that need to be initiated this decade. The increased mitigative efforts of 1.5°C scenarios (compared to 2°C) require a more rapid bioenergy deployment, making the feasibility concerns highlighted in this assessment more pressing [129].

Future research should seek to improve understanding of required bioenergy logistics and constraints by linking global modelling to dedicated regional energy and land-use models. This would allow for a detailed representation of intraregional transport requirements, national-level demand distribution, bioenergy technology developments, feedstocks and BECCS storage capacities. The proposed combined modelling framework holds the advantages of a more technologically detailed assessment better equipped to represent importer and exporter market dynamics. Quantitative projections stemming from this framework could allow for a more holistic strategic guidance for where bioenergy related policy prioritisation should be focused towards 2050 to stimulate the projected deployment volumes. Additionally, regional EU-level energy models can be better equipped to place IAM projections into the context of recent EU energy system policies that can hold significant implications for bioenergy developments. For instance, in the recent EU response to energy-security concerns exacerbated by geopolitical conflicts in the Ukraine region, the European Commission called for a 'rapid clean energy transition' within its REPowerEU plan [19]. This address proposes 20 Mt of renewable hydrogen deployment to 2030 and increasing targets for renewable electricity from non-biological sources. Such regional developments can shape the EU's future energy mix.

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

4.5 Conclusion

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

Europe's bioenergy imports are expected to increase and diversify significantly to 2050. The results indicate that Europe can increase domestic bioenergy production from 2.3 $EJyr^{-1}$ to 5.7 $EJyr^{-1}$ by 2050. Nevertheless, European bioenergy imports are projected to increase significantly across all trade scenarios explored, with imports increasing to 8.3 $EJyr^{-1}$ according to the default scenario settings. The highly restrictive 'Feasibility' scenario entails pessimistic assumptions on the availability of extra-EU supply but projects annual European imports to double from 1.5 $EJyr^{-1}$ in 2020 to 3.4 $EJyr^{-1}$ by 2050. Trade volumes would extend much more in a 'RED II' scenario, i.e. 8.1 $EJyr^{-1}$. In order to meet these high import volumes, projections show a major reliance on large low-cost exporters with currently immature bioenergy markets, namely, West Africa, East Africa, North Africa and the Rest of South America.

The biggest risk to the future expansion of European bioenergy imports concerns socio-political, technical, and logistical challenges. The projections presented in this study identified that the largest barrier to EU bioenergy development to 2050 is overcoming potential socioeconomic and technical feasibility issues within major exporting regions. The EU must recognise the impact of this uncertainty on the availability of imports for its mitigation obligations. For example, the 'Feasibility' scenario suggests annual European emissions would increase by 0.26 $GtCO_2eq$ by 2050 compared to a 'Free trade' baseline. In order to avoid this, whilst maintaining a cost-minimal energy transition, the EU can aim at capacity-building within these highlighted regions to improve the viability of realising the projected export potentials. The significance of these findings suggest default bioenergy trade dynamics in global IAM modelling activities would benefit from expanding the representation of feasibility considerations.

RED II sustainability and GHG criteria are not necessarily a long-term barrier to EU bioenergy development. Despite increasing costs of bioenergy imports due to GHG criteria constraints, sufficient extra-EU supply options remain to fulfil the demand for the projected energy transition to 2050. RED II holds minor consequences for pellets due to most of the supply projected coming from low emission factor residue feedstocks. The projections indicate a 10% drop in European supply for biofuels compared to a 'Free trade' situation over the period assessed.

The role of BECCS technologies for mitigation is central to climate effective bioenergy deployment in Europe. BECCS is pivotal for realising the projected demand volumes while remaining RED II compliant due to the beneficially lower emission factor afforded via the technology. Most bioenergy-related mitigation is projected to arrive from pairing solid bioenergy carriers with CCS for electricity and heat generation. This effectively keeps the emission factor of these applications very low and allows dedicated woody energy crop imports with higher production emissions to be utilised post-2040 when residue supply saturates. Solid bioenergy supply remains stable across the trade scenarios explored (>90% of supply in 'Free Trade'). These results indicate that pellet supply for BECCS in power generation in 2050 ranges from 5.3-7.5 $EJyr^{-1}$, with extra-EU imports contributing between 23-50% of pellet supply across the scenarios. In order to unlock the potential of BECCS, installations for the generation of electricity and district heat by power plants and CHP must scale up at unprecedented levels. This would require immediate investments, which are not at present adequately incentivised, owing to a lack of remuneration or support for negative emissions.

Europe may not be the most effective end-user market for interregional traded bioenergy from a global climate perspective. Our projections show that bioenergy deployment in world regions outside of Europe provides greater mitigation (35-45 gCO_2eqMJ^{-1} in 2050) due to these regions' more carbon-intensive energy systems. Under the carbon budget explored, global emissions are lowest when Europe limits extra-EU imports to less than 6 $EJyr^{-1}$ in 2050. Further import restrictions result in no additional global GHG mitigation due to the remaining biomass being too expensive for other regions. However, prioritisation of end-use regions for bioenergy should also consider regional legislative trajectories of climate mitigation targets to 2050 and the ability to ameliorate international technology diffusion of immature technologies such as BECCS.

CHAPTER 5

EU bioenergy supply-chain projections to 2050 using a multi-model framework

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5. EU BIOENERGY SUPPLY-CHAIN PROJECTIONS TO 2050 USING A MULTI-MODEL FRAMEWORK

Abstract

Model-based scenario analysis suggests that bioenergy could play a pivotal role in decarbonising the EU27 & UK energy system to net-zero emission targets by 2050. Assessing this position of bioenergy is complex due to supply requiring global-level considerations such as environmental and socioeconomic criteria, availability of low-emission feedstocks, import availability and sourcing regions, and competition for the international resource base from other world regions. Meanwhile, demand-side dynamics call for a detailed representation of the techno-economic competitiveness of bioenergy and optimal end-use strategies. This study applies a soft-linked multi-model framework that overcomes complexities in capturing biomass supply-chain considerations across spatial and technological resolutions. The framework incorporates the global integrated assessment model IMAGE, the EU energy system model PRIMES and EU-level bioenergy dedicated least-cost energy system model RESolve-Biomass to explore EU27 & UK bioenergy deployment following a <2°C climate scenario. The results indicate that 14.8 $EJyr^{-1}$ of bioenergy could be supplied and fully deployed by 2050 in the EU27 & UK. A cost-optimal strategy pushes 75% of bioenergy deployment into power generation as electricity and heat. Integrated gasification combined cycle and large pellet boiler installations in conjunction with CCS are the major conversion routes projected, limiting bioenergy availability for critical hard-to-abate sectors, including road and aviation transport. At projected deployment levels, the logistical network is placed under significant stress requiring handling capacity increases from current energy carrier operations of +50% in marine ports, +80% in inter-member-state distribution and +150% for domestic distribution. Following the projected strategy, BECCS could provide 1.2 $GtCO_2$ emissions sequestration per year by 2050 but would likely require a dedicated CO_2 network for offshore storage, especially for much of Central and South-East Europe.

5.1 Introduction

EU climate policy aims to steer member state (MS) energy systems away from fossil fuels. Net-zero GHG emissions by mid-century require an accelerated transition into a diverse set of clean energy options. Whilst variable renewable energy technologies will increase to 2050, the residual electricity demand and challenging-to-decarbonise sectors, including steel, cement, chemical industries and heavy-duty transport, are broadly projected to observe increased bioenergy uptake [67,187]. This projected role is due to bioenergy's flexibility for dispatchability, end-use application, cascading principles, affordability, and potential to deliver negative emissions through bioenergy with carbon capture and storage (BECCS) [33,188]. Over the past decade, the EU has been the largest global importer of modern bioenergy carriers [22]. At present sizable proportions of important bioenergy carrier streams, such as wood pellets (35%), biodiesel (>20%) and bioethanol (>20%), rely on extra-EU imports [189,190]. Currently, bioenergy imports account for approximately 2% (33 Mt) of total EU energy imports [140], with this share expected to increase in the decades ahead [23,171]. This increase is driven by an expected saturation of the affordable domestic resource base in tandem with a considerable upsurge of low-cost lignocellulosic residues entering the international marketplace [171]. Therefore, for informed long-term projections of bioenergy deployment at the EU-level, it is essential to consider global-scale supply-side import availability in tandem with the complexities of demand-side energy-system integration at a level that competently represents the EU market.

Integrated assessment models (IAMs) are routinely used to assess long-term scenarios for global energy system developments, with the general purpose of evaluating the impacts of climate change mitigation policies [5,139]. IAMs assess energy systems and their interlinked developments with natural systems, which hold essential functions in determining climate pathways, such as land-use, resource availability, atmosphere and oceans [191]. Global IAMs are well-positioned to explore the role of specific energy options such as bioenergy at a macro-regional scale from a supply and demand perspective. They can account for international import availability and resource competition in the context of limited emissions budgets [23,171]. Furthermore, by considering the complex and dynamic interactions between global biophysical systems, IAMs are well suited to assess the necessity of negative emission technologies, such as bioenergy with carbon capture and storage (BECCS), to meet ambitious climate targets. However, due to their global spatial coverall and long time horizons, global IAMs sacrifice detailed spatial, temporal, power system and technological resolution [70,192]. IAMs often restrict data aggregation to world macro-regions, e.g. Europe. Critically, this coarse aggregation brings significant challenges for understanding the demand-side integration of bioenergy and contribution at a more granular MS-level within the EU.

Alternative long-term EU-centered energy system modelling approaches are available for assessing bioenergy deployment and the effects of bioenergy policy that hold a more detailed, regional-specific representation for demand-side aspects. Hence, they are better equipped to simulate the role of bioenergy in fulfilling energy demand by sector and determine the most cost-effective end-use application. Classification of modelling approaches is notoriously complex [37,38]. However, they can be generically categorised as either; (i) top-down, often general or partial macroeconomic equilibrium models that simulate the correlations between the economy and energy system; examples include POLES [193]. (ii) Bottom-up techno-economical energy system models that perform economic optimisation for dispatch and investment options; examples include TIMES [194]. These models commonly hold rich technological and infrastructure databases and regional spatial disaggregation, which may be used to simulate EU-level trade logistical requirements instead of regionally aggregated data in global IAMs. However, these approaches hold a weaker representation of global supply and demand dynamics and trade aspects – especially in the context of global climate targets. They neglect the interlinked impacts between the energy system and environment nexus and lack global spatial representation. Thus, they do not consider the complex interlinkages between international energy and food markets, which are imperative for a meaningful account of bioenergy import availability.

Conceding that all individual simulation approaches hold limitations for capturing bioenergy complexities over long-time horizons, existing assessment methodologies could benefit from leveraging the strengths of one type of model to inform and advance another via inter-model linkages. An improved assessment would consider global supply and demand dynamics while simultaneously allocating the resource into the EU energy system when considering regional-specific detailed technology portfolios, demand forecasting and full supply-chain trade logistics. Following this criterion and developed in response to identified limitations in existing modelling approaches, this study presents a complementary soft-linked multi-model framework in order to study European bioenergy deployment at greater detail across the full supply-chain. This framework is configured to secure the benefits of both global IAMs and EU-centered energy system models (with Member State granularity) whilst concurrently navigating around aforementioned methodological limitations.

The proposed framework allows for projections to 2050 that consider both (i) supply of bioenergy imports to the EU27 & UK within a global context, accounting for resource competition on the international market from other regions and non-energy purposes; and (ii) dedicated and detailed coverage of MS-level demand-side distribution and allocation of bioenergy carriers covering the complete supply-chain. This synergy of spatial and technological resolutions allows the study to provide an enhanced evaluation of the required developments across the entire supply-chain to facilitate bioenergy's projected role in EU climate mitigation in the year 2050. Concurrently, it increases the policy relevance of IAM-based macro-regional projections and provides an opportunity for feasibility assessment at country-scale disaggregation.

5.2 Methods

5.2.1 Scope & indicator

A multi-model framework is developed to produce projections and pathways of bioenergy development for the EU27 & UK by 2050. 'Middle of the road' assumptions are taken for major socioeconomic drivers (i.e. GDP and population), following the Shared Socioeconomic Pathway (SSP2) [150,152]. Projections follow an energy transition in line with a <2°C climate trajectory. Specific developments explored and presented for the year 2050 include; bioenergy trade flows covering extra-EU and EU-wide flows at MS-level, cost-optimal processing and conversion routes at sectoral level per end-use application, and distribution of macro-regional BECCS projections at an MS-level.

5.2.2 Models

IMAGE

IMAGE 3.2 (Integrated Model to Assess the Global Environment) is a global-scale integrated assessment framework developed to describe the relationships between humans and natural systems and the impacts on the provision of ecosystem services to sustain human development [60]. Technological and socioeconomic representation is aggregated over 26 world regions, and biophysical representation is done on a 5arc-minute grid. The energy system module of IMAGE 3.2, TIMER, is recursive dynamic (i.e. no-foresight) and includes representation of the following end-use sectors; Heavy industry, Transport, Residential and Services, Non-energy and Other. For each demand sector, secondary energy carriers (including solid and liquid biofuels) compete based on relative costs to meet the useful energy demand. Bioenergy costs include feedstock, conversion, labour, capital, and O&M cost. Bioenergy cost is also influenced by carbon prices implemented through mitigation scenarios that promote low-carbon fuels. Bioenergy supply potential is determined at the grid level by the dynamic vegetation model LPJml, which describes crop growth based on local biophysical and climatic conditions [75]. The availability of land to produce bioenergy follows a 'food first' principle, where land available for bioenergy is determined after allocating food production as well as other land-protection measures (no deforestation, limited access to different biomes) [67]. Six primary feedstock categories are represented: maize, sugar crops, oil crops, woody, non-woody, and residues from agriculture and forestry operations. Regional cost supply curves of primary biomass are constructed by determining and ordering spatially explicit biomass costs based on yields and land prices. Primary biomass can be converted into liquid or solid secondary bioenergy carriers, which may be traded between world regions. Trade is facilitated based on regional production and associated transport costs. Thus, regional bioenergy supply curves and regional demand are used to determine optimal bilateral trade, accounting for competition amongst world regions [23,195]. For further details on IMAGE 3.2, please see section1.6.1.

PRIMES

PRIMES (Price-Induced Market Equilibrium System) is a partial equilibrium model that represents all supply and demand sectors of the energy system in separate modules and has been applied for EU energy outlooks to develop and evaluate climate and energy policies. The PRIMES model combines the dynamics of micro-economic foundation and bottom-up engineering modelling at a relatively high level of detail for a long-term time scale. The model simulates an energy market equilibrium for supply and demand, covering cross-border trade in all energy markets simultaneously, resulting from market clearing prices after iterations that involve all the modules. Every module (demand or supply) derives the investment and fuel mix depending on prices and volumes eventually determined in other modules. Among the main model outputs are projections of highly detailed energy balances at MS-level in future years [79]. Energy demand, supply and emission abatement technologies are represented in an explicit and detailed way, calibrated with Eurostat data [196]. Energy Demand is represented by end-use sectors (residential, commercial, transport and ten industrial sectors). Supply is organised by energy production sub-systems (oil products, natural gas, coal, electricity and heat production, biomass supply, hydrogen, e-fuels and other). For bioenergy supply, PRIMES includes a biomass supply module that iterates in a closed-loop formulation with PRIMES to determine the cost-optimal supply and use of biomass to meet demand, including investment into secondary and final transformation. Feedstocks are classified into four broad categories: energy crops, forestry, aquatic biomass and wastes. The PRIMES model includes a wide range of policy instruments of different nature, as. EU-ETS, taxes and subsidies, technology, emission or efficiency performing standards and policy targets among others. For further details on PRIMES, please see section 1.6.2.

RESolve-Biomass

RESolve-Biomass is a dedicated bioenergy, least-cost energy-system model with a spatial resolution at MS-level for the EU27 & UK. The model can determine the least-cost configurations of the bioenergy supply-chain when provided with external projections for energy demand, supply, and technological progress. Exogenous sectoral demand for bioenergy is treated as a potential target, where allocation of bioenergy also considers competition to fulfil energy services from reference fossil fuel commodities. Hence, the model optimises the choice of technology alternatives concerning total system costs to find the least-cost path to meet the demand projections for energy services. It considers the cost-supply curves of various biomass feedstocks and conversion technologies [80]. End-use sectors for biomass represented in the model include bioelectricity, bioheat, biofuels for transport and biochemicals. A prominent feature of the model is the high level of detail regarding bioenergy conversion technologies, related feedstocks and in-between logistics [81]. Within this study, RESolve-Biomass representation coverage extends to 38 primary feedstock categories, 37 intermediate conversion processes, 30 secondary bioenergy carriers (+ 2 chemicals) and 67 final bioenergy conversion technologies. An additional notable feature of the model is the capacity to inter-link MS-level bioenergy production and logistics networks, hence internal trade dynamics can be captured [82]. EU-wide trade of feedstocks and final products is represented by three transport modes, trucks, trains and short sea shipments; extra-EU imports are hauled via ocean tankers [80]. For technological representation, techno-economic assumptions and further details on RESolve-Biomass, please see section 1.6.3.

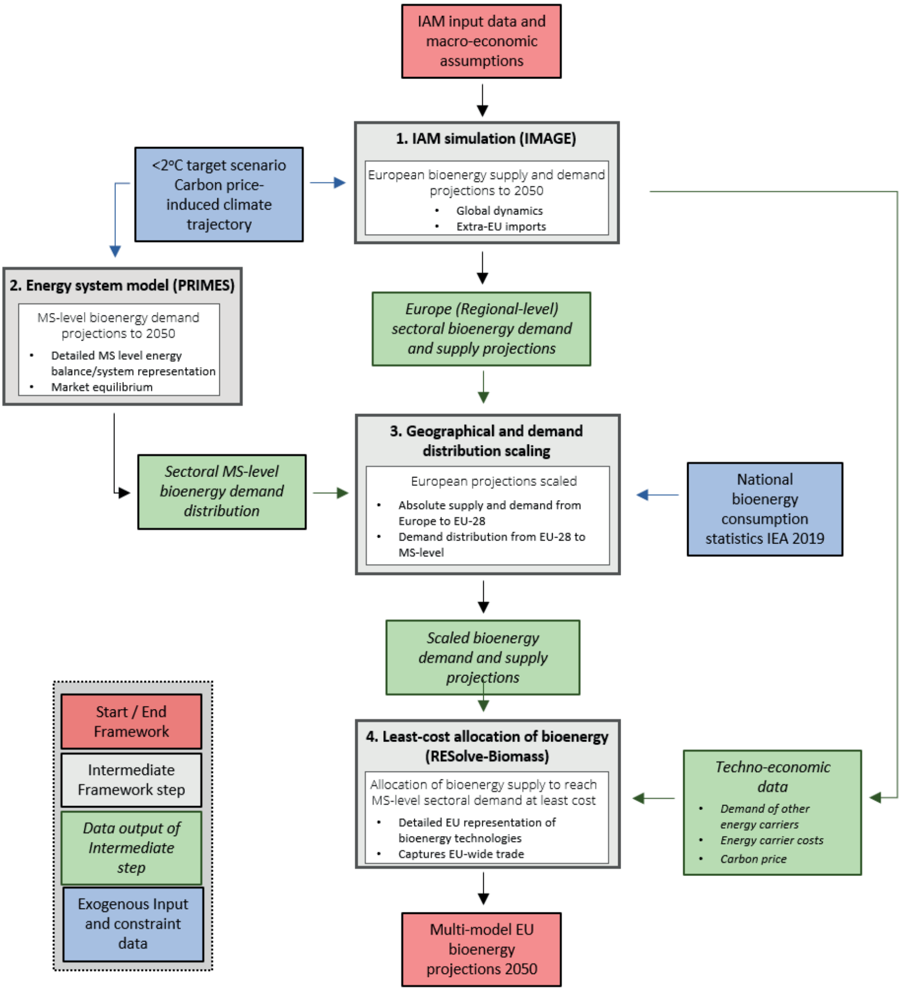


Fig.5.1: Schematic of the modelling framework

5.2.3 Multi-model soft-linked framework

The study uses a multi-model framework that couples IMAGE to RESolve-Biomass, thus downscaling macro-regional projections of bioenergy demand and supply for Europe to detailed bioenergy-technology projections at MS-level. Fig.5.1 provides a schematical overview. First, the global scale IAM IMAGE produces European projections for bioenergy supply and demand dynamics under a <2°C climate target to 2050, see Mandley et al. [195]. Second, intermediate steps are introduced to bridge the spatial and technological resolutions of IMAGE and RESolve-Biomass. This is done by using parallel projections for bioenergy demand at MS-sectoral-level from the partial equilibrium energy system model PRIMES for the year 2050, following a similar <2°C climate trajectory. IMAGE macro-regional absolute demand outputs are scaled and specified to MS-sectoral-level using PRIMES national-level projections as bioenergy demand distribution keys. Additionally, the geographic resolution of IMAGE outputs is down-scaled from Europe to the EU27 & UK using current national bioenergy consumption statistics, which are also used for the non-energy sector MS distribution due to lack of representation in PRIMES. Finally, the downscaled IAM demand and supply projections are fed into the dedicated least-cost allocation EU-level bioenergy model RESolve-Biomass, which allocates the cost-optimal conversion and transportation configurations to meet sectoral demand targets.

In order to facilitate the soft-linking of the modelling framework, methodological assumptions taken for data flows per framework step (see Fig.5.1) are described below.

Data transfer and consistency of the mitigation scenario explored

Data transfers between models occur at 5-year time slices (initiating in 2005) in which allocation within RESolve-biomass occurs dynamically based on concurrent projections of demand, supply potential and techno-economic data (energy carrier cost and carbon price) provided from IMAGE. A <2°C climate trajectory is used in both IMAGE and PRIMES projections. The climate trajectory is enforced slightly differently across demand modelling approaches. IMAGE employs an exogenous remaining global carbon budget to 2100 to realise a Representative Concentration Pathway (RCP2.6) [6,197]. PRIMES projections to 2050 assume a mitigation trajectory in line with the EU roadmap's 80% reduction of GHG emissions from 1990 levels [196]. This target is considered compatible with a <2°C scenario and represents a remaining emissions budget of 86 $GtCO_2eq$ for the EU27 & UK (2015-2050) [198]. The regional

European mitigation trajectory from IMAGE has been shown to tightly follow the EU roadmap emission reduction targets in a previous analysis that used the default RCP2.6 scenario [171]. In this study, EU bioenergy demand (including BECCS targets) and supply determined under IMAGE emission constraints are communicated as an exogenous input to RESolve-Biomass and enforced as demand-side targets (energy carrier mix) at sectoral level prior to minimal-additional-cost-allocation.

Bioenergy representation

Only modern bioenergy is represented. The IMAGE model is used to dictate domestic EU bioenergy supply, providing a 'target' to be used by RESolve-Biomass. The 'target' used in RESolve-Biomass in tandem with the PRIMES MS-sectoral-demand distribution to determine the cost-optimal bioenergy supply-chain configuration (i.e. matching biomass resources to end-use applications when considering transportation, techno-economic competitivity and the carbon price). There is a varied level of bioenergy technological representation between the models (described in full in section 1.6 and Annex V.1). As IMAGE only permits the trade of secondary bioenergy carriers, these have been incorporated into RESolve-Biomass processing chains. This results in a set of six major secondary bioenergy carriers, which may be imported and converted to advanced transportation fuels or final energy. These include wood pellets, pellets from agricultural residues, bio-FT diesel, bioethanol 1G, bioethanol 2G and Biomethanol.

Regional aggregation & Trade logistics

A core component of the framework is the ability to assess global IAM projections with a higher spatial resolution EU27 & UK model, allowing regional characteristics for logistical development not possible at coarser scales. Projections formulated by IMAGE are at a 'European' macro-regional level, including several countries outside this study's geographical scope. Thus, they need to be treated before being communicated to PRIMES (see Annex V.2). To overcome this, IMAGE demand and supply projections are scaled via proportional deduction of non-EU27 & UK nations' bioenergy demand using current national bioenergy consumption statistics from the IEA [199].

Concerning trade costs, in the RESolve-Biomass model, intra-EU trade costs are determined based on bulk density, distance, handling costs, transportation mode and fossil fuel prices to identify optimal logistics. For Extra-EU imports, transportation cost assumptions are communicated from IMAGE at Europe regional scale. Therefore, to ensure these costs are well represented in this framework, imports arrive at EU27 & UK borders considering the shortest distance from supplying regions (as projected from IMAGE) to conversion and end-use facilities. However, it may only be transported to currently large operating harbours in Belgium, the Netherlands, the UK or those judged to be significant future international bioenergy terminals considering projections for key supplying regions. Countries for such international terminals are considered here to be Bulgaria, Greece, Finland, France, Italy, Poland, Romania and Spain (see Annex V.1).

5.3 Results

This section provides the projections of bioenergy developments determined by the modelling framework described above. Section 5.3.1 covers bioenergy MS-level demand distribution and supply from domestic and Extra-EU import flows. Section 5.3.2 elaborates on how this translates into intra-EU trade logistics. Section 5.3.3 presents the major cost-optimised process and conversion pathways per represented end-use sector. Finally, section 5.3.4 provides MS-level BECCS deployment projections. Bioenergy is expressed throughout in terms of secondary energy.

5.3.1 MS-level bioenergy demand, production and import flows

Following a least-cost <2°C energy transition for the EU27 & UK, bioenergy demand is projected to be 14.8 EJyr^{-1} in 2050, with domestic supply providing 6.3 EJyr^{-1}. In Fig.5.1., domestic production is reported as solid carriers, some of which may be processed into liquid carriers. These flows are detailed in section 5.3.3. 95% of domestic supply is projected to be consumed in the producing MS, with production outstripping demand only in the Baltic states (Estonia, Latvia, Lithuania) and Sweden. Extra-EU imports provide a further 8.5 EJyr^{-1} (62% solids, 38% liquids). Central and Eastern European nations hold lower bioenergy demand. Lower demand corresponds with lower macroeconomic driver trends (population and GDP) and shallower decarbonisation trajectories. This is in line with national-level energy action plans, GHG emission reduction targets and the Effort Sharing Regulation [200,201]. Germany significantly leads in national consumption at 2.5 EJyr^{-1}, with five other nations following at 1-1.5 EJyr^{-1} (France, Poland, Italy, Spain, and the UK). Combined, these six nations account for >60% of total bioenergy European demand.

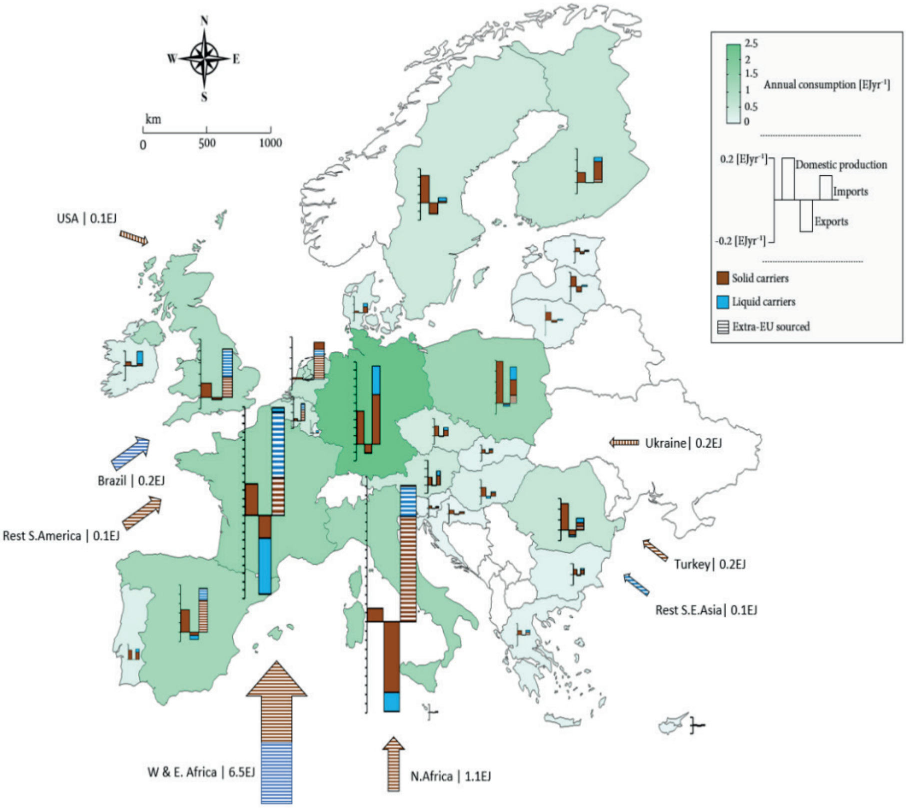


Fig.5.2: Projection of EU27 & UK bioenergy demand distribution and trade dynamics in 2050 [EJyr^{-1}].

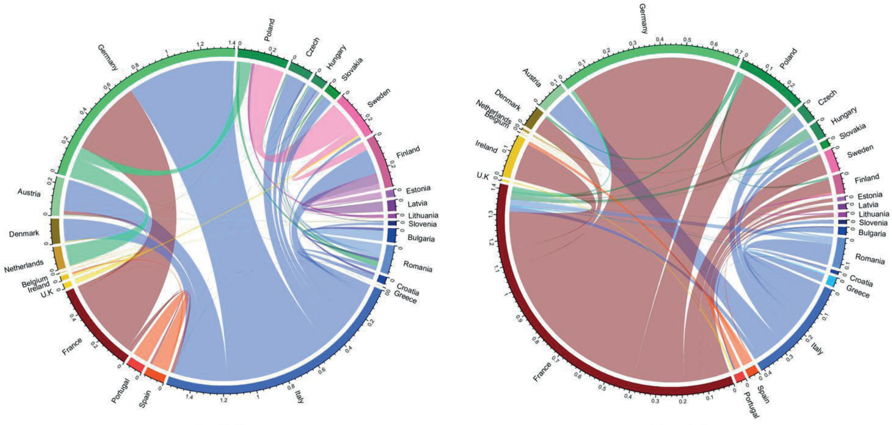
- *Extra-EU flows are only shown to EU27 & UK hub nations (i.e., regional borders). After entering, they may be traded onwards to other MS but are presented as internal trade. These flows are specified in Fig.5.3.*
- *Tabulated projections are provided in Annex V.3.*
- *The influence of import hub selection on the projection is discussed in section 5.4.1.*

Trade optimisation, as executed in this study, generates an import narrative for the region in 2050 as follows. As projected by IMAGE, extra-EU bioenergy supply (8.5 EJyr^{-1}) enters the EU27 & UK primarily through stylised southern European import terminals (see Annex V.1). France (2.5 EJyr^{-1}), Italy (3 EJyr^{-1}) and Spain (0.9 EJyr^{-1}) handle >75% of all bioenergy imports, primarily sourced from the African continent. As projected by IMAGE, this large supply from Africa is a product of favourable production and transportation costs paired with a sizeable techno-economic potential. A detailed assessment of extra-EU supply-side projections used in this study is available in Mandley et al. [195]. Hubs that currently dominate extra-EU imports, the

UK, Belgium and Netherlands, retain a collective 21%. Remaining hubs in Poland, Bulgaria, Romania and Greece collectively handle small volumes (<0.3 EJyr^{-1}) arriving from the East via Ukraine and Turkey.

5.3.2 Intra-EU bioenergy trade flows

In 2050, 3.5 EJyr^{-1} of extra-EU imports (40%) are consumed within the importing hub nation, as the stylised hubs are also major energy-demanding economies [199]. 5 EJyr^{-1} (3 EJ solids & 2 EJ liquids) continue through hubs (including as a further processed fuel) as intra-EU trade flows, represented in the export bars in Fig.5.2. and further depicted in Fig.5.3.



Solids

Liquids

Fig.5.3: Intra-EU bioenergy trade for liquid and solid carriers in 2050 [EJyr^{-1}]

- South East EU is represented by blue shades, South West by red, West by yellow, Central by green and North by pink.
- Where the colour of flows represents the exporter
- Total Intra-EU trade of solids =3 EJyr^{-1}, and for liquids 2 EJyr^{-1}

Italy is the largest intra-EU distributor for solid bioenergy carrier trade, forwarding on 1.5 EJyr^{-1} of the 2.3 EJyr^{-1} it receives from Africa. Italy initiated distribution accounts for (50%) of intra-EU solid bioenergy trade, with half bound for the largest demanding German economy. Germany also receives lower volumes (0.45 EJyr^{-1}) of domestically produced (wood chips) from France. The remaining 0.8 EJyr^{-1} transferring through Italy is spread over Austria, Denmark, Finland and Czech, each receiving 0.1-0.2 EJyr^{-1} and eight further MS, chiefly eastern European nations, each receiving less than 0.05

EJyr^{-1}. Other notable trade flows are short-distance 'neighbour' flows, including 0.1 EJyr^{-1} of African sourced wood pellets from Spain to Portugal, 0.2 EJyr^{-1} domestically harvested roundwood from Sweden to Poland and Finland, and 0.2 EJyr^{-1} domestically harvested cereal straws and stubbles from Germany to the Netherlands and Poland.

For liquid bioenergy carriers, there is a clear-cut difference in intra-EU trade brought about by the marine trade optimisation approach. In this study, France is a gateway to the North and West EU and the Baltic states. Italy serves as the entry point for African imports for the South and East. Large economies dictate to a lesser degree the distribution of bioliquids because bioenergy demand for transport fuels is less biased towards manufacturing economies. France distributes 1.3 EJyr^{-1} of the 1.6 EJyr^{-1} imported liquids without further processing. Italy distributes 0.4 EJyr^{-1} of the 0.7 EJyr^{-1} imported, in which 5% are further converted to advanced fuels or bioethylene. Due to cheaper national processing and refining costs, some large demanding nations such as France receive small volumes of advanced jet fuels processed in Hungary, Romania, Italy and Poland.

5.3.3 Feedstock to end-use (process and conversion flows) per sector

Sectoral-level bioenergy carrier demand for the EU27 & UK is in line with a <2°C global target as determined by IMAGE and distributed by PRIMES at MS-level, considering national-level renewable action plans, specificities, and technological heterogeneity. This amounts to heat [5.8 EJyr^{-1}], electricity [5.2 EJyr^{-1}], transport [2.3 EJyr^{-1}], and chemicals [1.5 EJyr^{-1}]. Within this section, we report the optimised least-cost path to meet final energy sectoral demand targets for bioenergy as projected by RESolve-Biomass.

Heating

Projections of least-cost bioheat supply-chain flows from domestically produced feedstocks, carrier imports and subsequent processing and conversion steps are provided in Fig.5.4, specified per heating sub-sector. Across sub-sectors, 3.8 EJyr^{-1} of bioheat is produced. Large-scale combustion in industrial plants offers the most economical end-use with the potential to integrate with Carbon Capture and Storage (CCS).

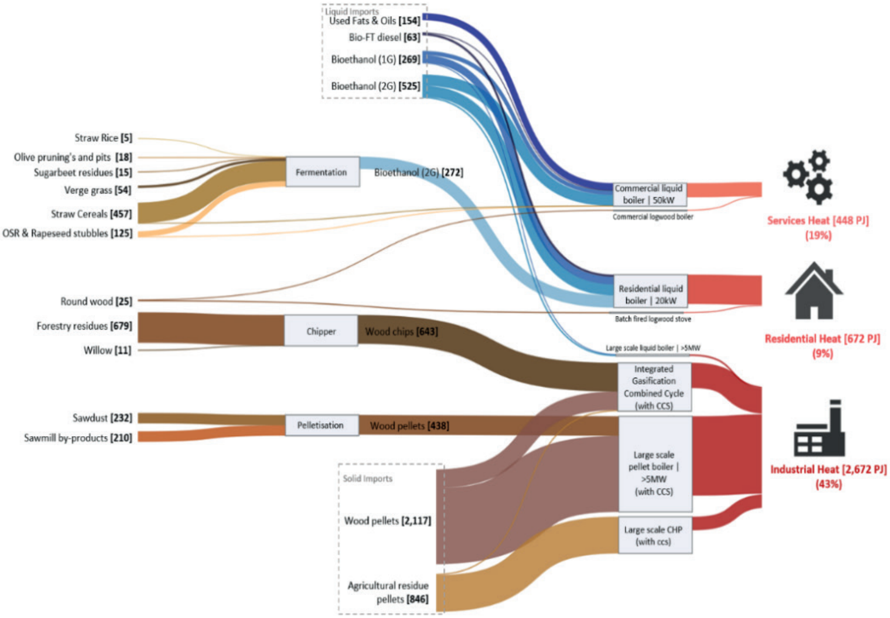


Fig.5.4: Feedstock flows and conversion pathways for bio-heat production for the EU 27 & UK in 2050.
- *Bioenergy streams are presented as [PJyr^{-1}] secondary energy, and end-use applications are presented as [PJyr^{-1}] final energy.*
- *Percentages describe the contribution of bioenergy to total sub-sector heat demand as determined in IMAGE.*

Bioenergy is projected to supply 43% of the total demand for industrial heat in 2050. This is fueled primarily through woody biomass, 65% from extra-EU pellet imports. From domestic feedstocks, waste streams provide a sizable supply of fine particle dust, which is pelletised to increase handling for industrial-scale facilities. Cheap residues and small quantities of short rotation coppice (SRC) are chipped, not pelletised, to produce a homogenous woody fuel. For domestic residues, long-distance haulage is avoided; hence, chipping with comparatively better energy efficiency provides a more economical route rather than prioritising bulk density. These woody carriers are converted to heat within integrated gasification combined cycle installations (BIGCC) and direct combustion in large-scale pellet boilers. Combined with carbon capture and storage, these pathways are determined to be the most cost-effective route for bioenergy to decarbonise heat generation within the industrial sectors. Represented sub-sectors include Cement, Steel, Paper and pulp, and Food. Large pellet boilers produce the high-temperature heat needed for direct industrial activities whilst BIGCC, economically driven by its increased power-train efficiency for electricity production, provides smaller volumes of lower-temperature process heat via steam. Agricultural residue pellets play a much smaller role due to poorer fuel qualities and lower temperature limits. However, highly efficient utilisation in Combined Heat and Power (CHP) installations is projected to be the most cost-effective destination. However, it is limited by useful utilisation, considering a constant lower-grade heat demand.

Bioheat plays a lesser role in the residential and services sectors, where it covers less than 20% of the total heat demand. Small-scale application is projected to be fueled by liquid boilers and minimal contributions from batch-type combustion. These markets are seen as the cost-optimal destination for small amounts of liquid bioenergy carriers due to better storage/transportability at a smaller scale and application in modern boilers without significant alterations. The model framework directs liquid biofuels as a transitionary fuel for the phaseout of oil-fired boilers, which currently demand 1120 PJ (14% of total) in the residential sector alone for space and water heating, especially important in Belgium, Luxembourg, Greece, and island nations [202]. Additionally, 30% of domestic herbaceous biomass from straws and stubbles that hold lower fuel qualities are routed towards bioethanol production.

Electricity

Bioenergy is projected to provide 2.65 $EJyr^{-1}$ final energy or 19% of the EU27 & UK electricity demand in 2050. This is dominantly fueled by woody biomass, of which 40% is extra-EU imported wood pellets, with the remainder supplied domestically. Domestic supply is primarily from assortments of harvested roundwood and landscape conservation activities with a smaller contribution from larger particle industry waste streams still suitable for chipping. Wood chipping provides the major processing step to combine various residual woody feedstocks creating an easier-to-manage homogenous commodity for guarantees on fuel specification.

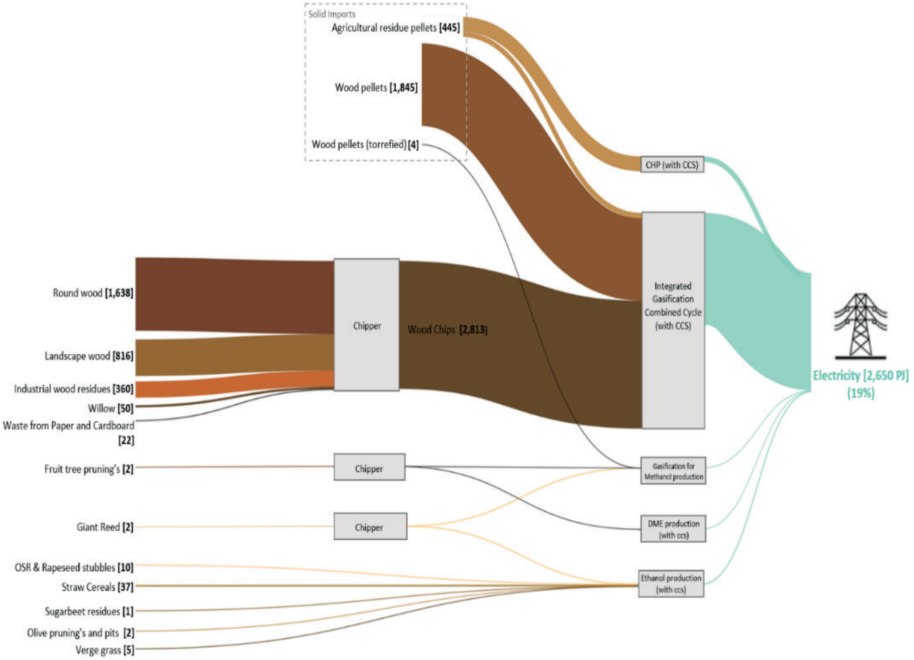


Fig.5.5: Feedstock and conversion pathways for Bio-Electricity production for the EU27 & UK in 2050.

- *Bioenergy streams are presented as [PJyr^{-1}] secondary energy, and end-use is presented as [PJyr^{-1}] final energy*

95% of bio-electricity is produced via BIGCC-CCS, which is projected to be the most cost-efficient route considering the increased efficiency through dual turbines (steam and gas) and avoidance of carbon emissions (and the potential for negative emissions). A benefit of large-scale fluid bed gasification is high fuel flexibility. However, this scale of operation for electricity production makes it unsuitable for district heating but rather for industrial application, as seen in Fig.5.4. Herbaceous feedstocks with poorer fuel qualities play a muted role in electricity generation, with imported agricultural pellets supplying small volumes to CHP plants and marginal electricity generation as a by-product of chemical production for biorefinery processes requirements.

Transportation and Chemicals

Major competition for liquid bioenergy between the chemical and transport sectors is projected by 2050, Transport [2.3 EJyr^{-1}] and Chemicals [1.5 EJyr^{-1}]. For the transport sector, imports are projected to play a significant role within the EU27 & UK maritime sector, fueled mostly by biomethanol imports. Smaller volumes of bioethanol feed the alcohol-to-jet process and use in cars. Bio-FT diesel is projected to be the most economic biofuel for the transport sector. 45% of which arrives from imports, with the remainder produced from maize stover and herbaceous domestic feedstocks pre-processed to grassy chips and converted through the Fischer-Tropsch process in conjunction with CCS. Cost-optimal allocation projects Bio-FT diesel to feed difficult-to-decarbonise sectors, completely satisfying inland navigation and meeting a third of the demand for land-based freight transport. A third of the grassy chips are directed toward jet fuel production for the aviation sector. Similar to light-road transport 'cars', aviation is determined a relatively more expensive sector to decarbonise.

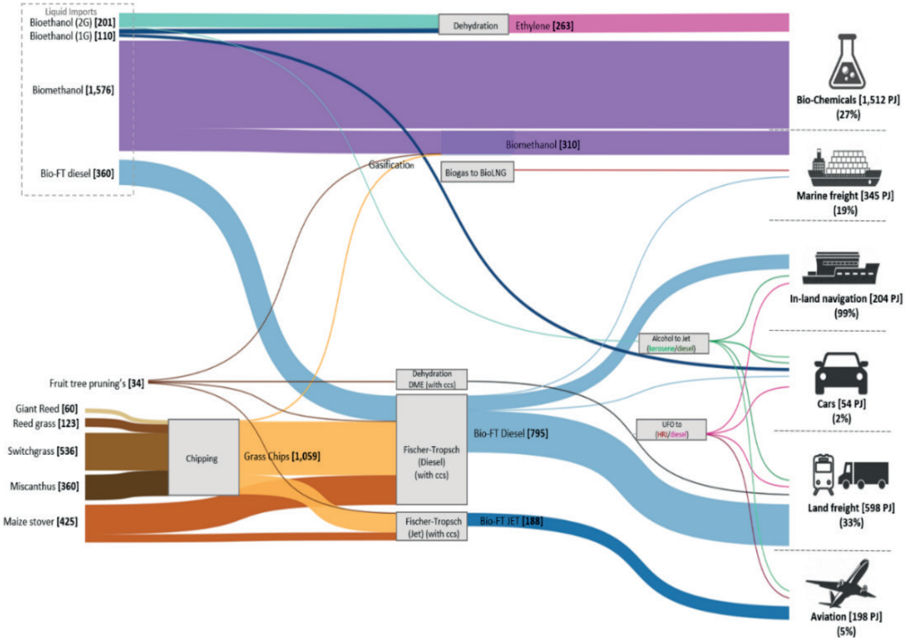


Fig.5..6: Feedstock flows and conversion pathways for bio-chemicals and transport fuel production for the EU27 & UK in 2050.

- Bioenergy streams are presented as [PJyr^{-1}] secondary energy, and end-use applications are presented as [PJyr^{-1}] final energy

The chemical sector is projected as the leading destination for pre-commodified imports of biomethanol and dehydration of bioethanol imports to ethylene. It receives 27% of its feedstock from liquid bioenergy carrier imports in 2050. The chemical sector and non-energetic application of bioenergy within energy system models, including those used within this study's framework, generally hold coarse representation at the intermediates level. Representation is often as building block bulk and platform chemicals, mainly due to fragmented demand between end products and the complexity of conversion routes. This means downstream processing and end-uses such as plastics or surfactants are not covered here.

5.3.4 MS-level BECCS deployment

The framework presented in this study allows macro-regional European IAM projections on BECCS deployment to be assessed at MS-level, considering detailed modelling of MS-sectoral demand distribution and regional technological least-cost allocation. The feasibility of the projections from a techno-economic and policy perspective is discussed in section 5.4.3. Of the 14.8 EJyr^{-1} projected bioenergy consumption, 8.1 EJyr^{-1} (55%) is combusted for power generation (heat and electricity) within CCS facilities, and 1.5 EJyr^{-1} (10%) is processed for transport biofuels with a lower capture rate. As seen in Fig.5.7 below, power generation with BECCS affords 1.16 Gtyr^{-1} CO_2eq. negative emissions or 93% of projected capture.

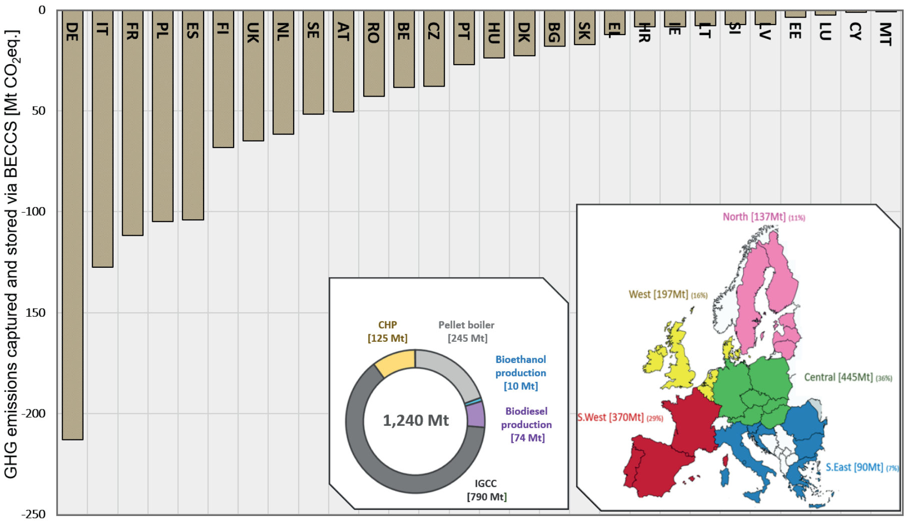


Fig.5.7: Emissions storage from BECCS deployment for the EU27 & UK in 2050 [Mt CO_2eq yr^{-1}] - Bar chart, per MS, pie chart per paired end-use technology, map per sub-region

Compared with Fig.5.1, nations with greater bioenergy demand are generally projected to be the largest deployers of BECCS. However, sectoral-level bioenergy demand is the deciding factor. For instance, Italy, ranked 4th in MS bioenergy consumption, holds 2nd position in BECCS deployment due to a relatively greater share of bioenergy within its electricity generation sector. For the UK and France, the opposite dynamic occurs due to a higher relative bioenergy demand for transport and chemicals sectors (See Annex V.10 for a breakdown of MS sectoral level bioenergy demand). The ten largest BECCS nations represent 80% of the total captured emissions. Grouping these by neighbouring nations to represent regions with a geographical prospect of joint ventures suggests that central and south-west Europe face the most significant challenge in BECCS roll-out due to higher industrial activities within these sub-regions. The feasibility of these projected storage requirements per sub-region is discussed in section 5.4.3.

5.4 Discussion

The soft-linked framework approach lends itself to examining the feasibility of IAM macro-regional supply and demand projections through the lens of regional energy system models that hold improved energy system and trade representation at the MS-level. In the following subs-section for each of the core bioenergy dynamics assessed, we discuss the (i) key development within the presented projections, (ii) implications for the EU27 & UK, and (ii) a reflection on the modelling approach and feasibility screening.

5.4.1 Bioenergy trade and logistics

The projections show a significant upscaling of extra-EU bioenergy imports from current levels of 0.6 EJ yr^{-1} in 2020 [140] to 8.5 $EJyr^{-1}$ by 2050. Additionally, 38% of import is liquid carriers, which increases handling requirements in the present situation, predominantly wood pellets. Proportioning the energy densities of the represented carriers leads to average conversion factors of 17.5 $GJ/td_{ry\ matter}$ and 26.6 $GJ/t_{liquid}s$. This suggests EU27 & UK marine-land import terminals would need to handle 300 Mt of solid bioenergy carriers and 125 Mt of liquid carriers in 2050. Rail, road and inland navigation networks would need to facilitate further MS-MS transportation of 170 Mt of solid bioenergy and 75 Mt of liquid carriers. Mobilisation of domestic feedstocks would require 'short-distance' haulage of 360 Mt of solid carriers.

The implications of these volumes on the European logistics network are significant. It is difficult to assess the feasibility of long-range projections in an explicit way without dedicated transport network modelling that is outside of the scope of this research and lacking in the literature base. To provide context for the projections, we compare to the current situation at three levels; extra-EU, MS-MS distribution, and MS domestic scale collection logistics (Table 5.1).

Within the model framework, EU trade logistics are well represented by RESolve-biomass. However, extra-EU marine import routes are formulated based on least-distance from supplying region to the end-use facility by enforcing minimal shipping distances. Therefore, the representation of marine-land hubs is critical in determining supply chains. The hub selection followed a review of current observations and projected supplying regions. Ultimately, selection tightly corresponds with the current MS-level import capacity of dry and liquid bulk. Eight of the top ten current importers are represented, with the top five importing nations identical (see Annex V.6 for details). Still, it is worthwhile to provide a feasibility check of the major trade routes projected in sections 5.3.1 and 5.3.2. Namely, (i) extra-EU import to Italy and France and (ii) the subsequent MS-MS distribution northbound to mainly Germany, Poland and C&E EU MS.

Italian and French port terminals would require at least a doubling in current handling capacity to facilitate the projected supply from Africa via conventional transport modalities. However, liquid bioenergy carrier by pipeline is not represented as a modality within the modelling framework. A large proportion of liquid imports are from Africa (2.9 EJyr^{-1}) to the Mediterranean coast of the EU by 2050. At these levels, economies of scale may support the development of a trans-Mediterranean dedicated biofuel pipeline. Such infrastructure is already in place for fossil fuel supply at a comparable scale (2 EJyr^{-1}); see Annex V.7 for details. Hence, at the scales projected, it could be worth representing pipelines at an interregional level in future modelling activities.

Table 5.1: Trade and logistical network implications for distributive levels

Extra-EU	For extra-EU imports (marine-land), a comparison of projections with current import volumes of dry and liquid bulk cargo as reported by Eurostat [203] at major ports within stylised hub nations of this study is provided in Annex V.4. Solid bioenergy imports (300 Mt) in 2050 are equivalent to 50% of the current EU27 & UK annual dry bulk import (65% of included hubs). Individual modelled hubs would need to bolster current capacity in major port terminals by 14-213% over the next 30 years to accommodate this. The most challenging (>50% increase) include Belgium, Spain, France and Italy. EU ports are better equipped to handle bulk liquids at double the quantity of solids. Because of this, the required expansion of handling capacity for liquids at marine terminals is less substantive at <20% of current capacity except for France (50%).
MS-MS	For MS-MS trade, we consider large consignment transportation via rail or inland shipping networks, which are important in some nations (Netherlands, Belgium and Germany). In Annex V.5, the current capacity of MS-MS trade is specified for haulage of energy commodities from the exporter perspective (Coal and lignite; crude petroleum and natural gas) whilst accounting for the modal split between rail and inland shipping at MS-level. The difference between the current capacity MS-MS trade (137 Mt) and the requirements in 2050 for bioenergy alone (245 Mt) are striking. EU MS-MS fleet and infrastructure capacity would require an increase of 80% over the next 30 years to satisfy projections. This bottleneck is due to several logistical factors within the current energy transport network; major coal-consuming nations, Poland and the Czech Republic are largely self-supplying or via a marine port. Natural gas and oil have established pipelines that bypass the need for conventional MS-MS transport. In contrast, liquid biofuels are still reliant on them due partly to the relatively small-scale operation. 75 Mt liquid bioenergy in 2050 is not small-scale and equates to 22% of current oil demand in the EU. At the projected 2050 scale, imported liquid bioenergy carriers justify integration into the current oil pipeline network, pointing to a more centralised end-use role. This adoption would limit conventional transport requirements to solid imports (170 Mt), much closer to the current MS-MS capacity, with the possibility of converting parts of the incumbent fossil fuel transportation network during phaseout.
Domestic	Road transport is added to the modalities for national-level mobilisation of domestically produced biomass and again compared to current energy commodities transportation at MS-level (see Annex V.5). Domestic bioenergy transport in 2050 (360 Mt) is equivalent to 150% of the current capacity across the EU27 & UK. For perspective, the freight of all goods in Greece in 2019 was 345 Mt [204]. Current capacity at the EU-level is split 50/50 between rail and road. However, due to decentralised sourcing from field to conversion facility, a proportionally larger increase for road transport may be expected for bioenergy. This projection would likely entail a significant increase in large tonnage lorries on European roads, specifically in Germany, Spain, France, Poland, Sweden and Romania (each >20 Mtyr^{-1}). Unlike MS-MS level distribution, collection of primary biomass cannot be solved by pipeline. Thus, vehicle fleets would need to be expanded.

For MS-MS distribution Annex V.8 shows the current and planned core and comprehensive Trans-European rail networks [205]. There are existing core rail networks linking large-capacity maritime port terminals between Italy and France to Germany already in place, albeit less developed than NW Europe. High-speed core freight lines planned for construction before 2030 could facilitate bridging the Brenner axis (from Verona, IT towards Munich, DE), with notable expansion and capacity-building operations underway [206]. Annex V.8 for a map of the Trans-European freight network of shipping ports and railroad, with construction status.

4.2 Processing and conversion routes

Considering supply constraints, systematic-level projection from IMAGE, when downscaled to MS-sectoral level via PRIMES, suggests a major role for bioenergy across all represented end-use sectors by 2050. Contributing; 5.8 EJyr^{-1} (25%) of total heat demand, 5.2 EJyr^{-1} (19%) of electricity, 2.3 EJyr^{-1} (14%) of transport and 1.5 EJyr^{-1} (27%) for chemicals. Bio-based heat remains the largest demand sector, but relative growth is stronger in bio-based electricity and biofuels. Dependency on bioenergy imports varies across major end-use sectors; heating (68%), electricity (44%), transport (33%) and chemicals (100%). Under the premise of a low-cost energy transition to meet <2°C, bioenergy is broadly directed into high emission intensity end-uses, where BECCS can be applied, including power production and biofuels for marine and land-based freight.

Considering the rich level of bioenergy technologies represented within RESolve-Biomass, cost-optimal allocation suggests a handful of conversion pathways dominate the configuration of the EU27 & UK bioenergy deployment in 2050. For the power sector, large-scale facilities that benefit from economies of scale and improved efficiency are prevalent. The projections show that key conversion technologies are those that can be integrated with BECCS with flexible handling capacities for cheap woody carriers. These include BIGCC, large-scale pellet boilers and CHP plants. For solid carriers, chipping proves the best processing option for homogenisation of the domestic resource base. Intra-EU transport distances do not support the business case for pelletisation on the internal market. The transportation sector observes limited uptake of bioenergy where cheap imports of biomethanol and FT-Diesel provide most biofuel demand. Chipped herbaceous feedstocks are routed towards common liquid fuels via Fischer–Tropsch synthesis to FT-diesel and Jet fuel with CCS. Chemical sector biomass demand is modelled at a coarser level of platform building blocks. Hence, conversion routes are not specified, with cheap biomethanol imports forming the predominant supply.

Projected scale-up (5-15 $EJyr^{-1}$) of bioenergy supply chains to 2050 is significant. To assess the implications, we compare to the current situation at the sectoral level (Table 5.2).

The soft-linking approach means that projections for future processing and conversion routes assume that cheap international imports promote technologies that this supply can facilitate. Assuming that supply (determined in this study by IMAGE with coarser feedstock representation) drives demand at a technological level is disputable. The emergence of technological advancements over this time frame could shape future feedstock preferences in import streams [131]. Due to one-directional data flows, this demand-led market dynamic is not captured for the higher technological representation of RESolve-Biomass within the presented framework.

RESolve-Biomass holds a wide variety of bioenergy processing and conversion steps within its technological representation, as seen in Annex V.1. However, conversion streams are narrowed to large-scale facilities that can integrate CCS to meet the sectoral bioenergy demand targets at least cost by 2050. The major consuming technology BIGCC shows promising efficiency and environmental improvements over the conventional steam cycle and is widely considered a key future technology. However, it is only proven at a demonstration level [213] but is now considered on the verge of commercial scaling [214,215].

Narrowing of technologies into CCS-compatible technologies over the long-term is driven by the projected carbon price, which reaches approximately 100 $€_{2018/tonne}$ by 2050, and also directs domestically produced liquids to routes that incorporate CCS during processing. This carbon price signal is crucial for BECCS projections to meet the enforced climate pathway at least system cost. Currently, the EU-ETS carbon future prices are approximately €90/tonne, mainly in response to recent gas prices [216]. However, the early-stage development of BECCS and its political and technical feasibility across the EU27 & UK leave its future deployment uncertain.

Table 5.2: Process and conversion route implications for end-use sectors

Heat	The current capacity for useful modern bio-heat production from solid and liquid bioenergy carriers is 3 EJyr^{-1} or 17% of total EU27 & UK heat demand [207]. By 2050 the projections suggest a conservative increase to 3.8 EJyr^{-1} (25% of total heat demand). However, 60% of current demand is met by small-scale applications in the residential and service sector. By 2050 this proportion inverts to 70% produced for industry, creating a situation where residential and services sectors must compensate for 0.8 EJyr^{-1} via other renewable sources. Industrial heat production is projected to triple from 0.9 to 2.7 EJyr^{-1}. Thus, a dedicated supply of solid carriers and integration or retrofit of pellet boiler systems will be substantial within non-auto-producing industries i.e. paper, pulp and wood products, which currently represent 80% of industrial bioheat demand [208,209]. Expansion into other industrial sub-sectors requires strategic planning of industrial location to ensure efficient high-temperature process steam distribution from electricity generation in BIGCC-CCS facilities, which produce 20% of projected bioheat. These locations must also be appropriate for CCS implementation. Major demanding nations face significant challenges in scale-up of industrial bio-heat except for Finland and Sweden, which already have substantial bioheat production within wood-based industries, see Annex V.11 for a MS-level comparison of current and projected industrial bioheat demand.
Electricity	Bioenergy currently provides 0.7 EJyr^{-1} (6%) of EU27 & UK electricity generation, of which 55% is from woody biomass carriers [207]. Some nations, such as Italy and Germany, prioritise generation from biogas through fermentation in small-medium scale plants, whereas others, notably the UK, deploy large-scale wood-fuelled installations. 2050 projections suggest a significant increase in bioelectricity to 2.7 EJyr^{-1} or 19% of total electricity demand. Least cost-allocation follows a UK-like strategy prioritising generation in large-scale wood-fuelled BIGCC installations. A comparison of projected bioelectricity at MS-level to current solid bioelectricity generation is provided in Annex V.12. All nations require a significant scale-up of solid bioenergy fuelled BIGCC-CCS, ranging from a tripling of current capacity in the UK to nations with negligible solid-fuelled bioelectricity facilities, such as Germany and Italy that each require >0.7 EJyr^{-1}. The same need for strategical planning of facilities as observed for heat production is required. Whilst BIGCC-CCS plants at a commercial scale are not present in Europe; there is potential scope to retrofit natural gas combined cycle plants to BIGCC-CCS if a connection to a CCS network is viable [210]. BIGCC-CCS projections by 2050 would entail significant indoor storage requirements for year-round utilisation, adding further pressure to the logistical issues already raised. Meeting 2050 projections requires significant investment into both specialised handling and conversion technologies.
Transport	Current bioenergy for transport in the EU27 & UK is similar in scale to bioelectricity at 0.7 EJyr$^{-1,}$ contributing 5% to the total sectoral demand [211]. This is 90% domestically produced and almost exclusively used as fuel for cars as biodiesel. The 2050 projections suggest a doubling of final biofuel provision to 1.4 EJyr^{-1}, which is modest when considering EU biofuels in the transport sector have doubled over the last decade [212]. From a production perspective, current EU27 & UK capacity is already sufficient to meet projected domestic production in 2050. The only significant changes from today's landscape are re-directing biodiesel into inland freight transport and significant uptake of imported BioLNG into marine transport, where import terminals appear well equipped to transfer these volumes. Under the projected developments, decarbonisation of air and car transportation would need to seek other low-carbon options to meet regulatory RES targets.

It is inherently difficult to model capital depreciation assumptions that keep pace with technology-specific regulatory measures. The framework's structural assumption for a steady phaseout of residential and commercial oil boilers is debatable. For instance, Belgium, a nation with considerable reliance on oil boilers, plans to introduce a phaseout in 2025 and will already have a complete ban on use by 2035 [217]. A more rapid than modelled phaseout within the built environment could potentially re-route 1.1 $EJyr^{-1}$ into advanced biofuels for the transportation sector.

Whilst the projections presented here could be labelled feasible; they are not in line with recent EU targets. For instance, there is no biogas entering the power sectors. The European Commission targets 35 billion cubic meters of biomethane production (1.2 EJ) in 2030 within the REPowerEU plan. If we consider the supply of municipal sewage feed to have plateaued and crop-based feedstocks banned because of RED II regulations [27], a conservative estimate (50% agricultural residues) [218] would require 75 $Mtyr^{-1}$ of feedstock. This is half of the domestic non-woody feedstock production projected in 2050. This would directly impact the transport sector's access to feedstock supply and is concerning given the equally ambitious target for 63% of aviation fuels from sustainable fuels by 2050, with advanced biofuels seen as a significant contributor [219]. Outside of energy, the EU's bioeconomy action plan seeks the rapid promotion of biomass resources for chemical and material manufacture [220]. Ultimately, the projections shown here seek to present the lowest cost configuration for an energy transition to meet a <2°C target which appears to be divergent from EU biomass policy targets indicating the absence of future policy support for the presented projections.

5.4.3 BECCS deployment

By 2050, 10.8 $EJyr^{-1}$ or 82% of bioenergy used (excluding biochemicals) is with BECCS, either through processing into fuel or combustion. For heating and electricity, power generation in large-scale facilities with BECCS is projected to account for 18% of the total energy demand. Annual emission storage could reach 1.2 Gt CO_2yr^{-1}, with Southwest and Central Europe facing the most significant storage challenges. Large national economies with higher industrial production, e.g., Germany, Italy, France, Spain, the UK and Netherlands, are projected to have the largest BECCS deployment, followed by nations with relatively large domestic woody biomass production and currently high levels of renewables in their energy system Sweden and Finland.

Considering the projected role of BECCS, it is worthwhile checking the technical and socio-political implications of the projected results compared to the current development for CCS across the three major technological steps at the EU27 & UK level (Table 5.3).

Table 5.3: BECCS implications for major operational phases

Capture	Emission capture from BECCS technologies has seen slow progress with current global capture at 1.5 Mtyr^{-1} [221], far below the EU27 & UK projections of 1.2 Gt CO_2yr^{-1} in 2050. However, the technology surrounding the capture phase is demonstratable at a commercial scale for all the major conversion pathways assessed. Please see Annex V.13 for an overview of BECCS technological readiness levels. Both pre and post-capture technologies are projected at large scale. BIGCC-CCS relies on pre-combustion capture, which currently reduces the net electric efficiency of an IGCC power plant from 47% to 36%. Pre-combustion capture costs within IGCCS facilities are sizable but, given adequate carbon penalty costs, are comparable to other renewables, with cost reductions expected through advanced solvents, sorbents, and membranes [222,223]. Direct-firing in large-scale pellet boilers requires post-combustion capture of the flue gases. Both of these technologies need significant advancements for our projected scale-up. For the cost-effective deployment of BECCS, our projections suggest scale-up strategy should focus on large-scale power and industrial installations. Currently, 89% of emissions from the power and heat sector come from large-scale installations (those emitting > 100 Kt CO_2yr^{-1}), which may be retrofitted and tend to be located in clusters with existing pipelines in place (IOGCP). Hence the projections lend themselves to EU27 & UK incumbent centralised energy system configuration for shared capture facilities.
Transport	As part of the Trans-European Network-Energy (TEN-E) regulation, the latest list of projects of common interest (PCIs) for a cross-border carbon dioxide network are all focused on Northwest Europe, with Germany and France as other large countries with the intention to join a North sea network [224]. Recent directions in CCS deployment in Europe favour offshore storage, with the Connecting Europe Facility funding the northern lights project in the North Sea [225]. If offshore storage is the leading solution for BECCS in 2050, it would require a substantial carbon network across the continent. The Re-Stream project estimates that >50% of onshore pipeline is suitable for CO_2 transport in the gaseous phase and a minimum of 70% offshore for dense phase transportation [226]. This sounds promising, but we must reflect on the volumes of negative emissions projected here. To clarify, at 556m^3 per tonne of $CO_{2,}$ we are projecting 667 billion m3 a year. The total natural gas consumption in the EU27 and UK currently sits at 500 billion m^3 [227]. Thus, even with a highly reusable pipeline network, its likely network expansion will be a considerable undertaking and potential bottleneck.

Storage	Overall estimates for CO_2 storage in the EU27 & UK vary widely. Conservative estimates place economically feasible storage at approximately 150 Gt [228,229]. The distribution of storage capacities at the MS-level is provided in Annex V.15. Compared to the projected storage from BECCS at the sub-regional level as seen in Fig.5.7, notable areas of concern are the Central European region (Germany, Poland, Austria, Czech, Slovakia and Hungary) which holds a limited storage capacity (24 Gt) but large BECCS deployment (0.45 Gt CO_2yr^{-1} in 2050). At these ratios, a maximum of 50yrs operational is possible. Considering that BECCS deployment in a 2100 modelling horizon for IMAGE peaks in 2080 at about +40% of 2050 levels and other CCS techs play an equal part, this could reduce to <20 yrs. The same narrative holds at MS-level for large BECCS deployers Finland, Sweden and Italy, which have unfavourable BECCS to storage capacity ratios. These regions must realistically seek connectivity to large storage reservoir capacities in the North Sea between the UK and Norway and offshore of Baltic states. Effectually this agrees with current observations. This strategy of offshore storage falls in line with social acceptance and political support, which strongly favour offshore storage due to decreased risk perception [230].

The significant role of BECCS deployment seen in this study's projections is a product of favourable techno-economic attributes driven by an assumed carbon price that drives the decarbonisation of the energy system [72]. By creating negative emissions, BECCS relieves pressure from the emissions cap, effectively lowering the price of future emissions permits [231]. Whilst the economic incentivisation from carbon price assumptions can be considered reasonable as they are very close to current market prices on the EU-ETS [216], technical performance is unproven, with no BECCS facility currently capturing more than 1 $MtCO_2yr^{-1}$.

Long-term modelling projections with a large deployment of BECCS have been criticised due to challenges in capturing adequate value-based assumptions for these socio-technical constraints, which may prevent overly optimistic or too pessimistic assumptions on switching to BECCS as the cheapest carbon dioxide removal technology [232–234]. However, it is pertinent to acknowledge that NET technologies are broadly projected critical to meeting EU27 and UK climate targets of 2°C and essential for net-zero by 2050 following a 1.5°C scenario. The IPCC concluded that without CCS technology, the cost of mitigation relative to cost-effective scenarios such as the pathway presented in this study would be 138% more expensive on average [91]. At an EU-level compliant <2°C scenarios within central strategic policy communications suggest CCS deployments of 3-13 Gt of CO_2 storage to 2050 in the EU energy roadmap [235] and 600 $MtCO_2yr^{-1}$ CCS (50% from BECCS) in the long-term strategic vision laid out in a 'clean planet for all' [236]. However, unlike this study, these communicated strategic visions hold constraints on sectoral deployment of bioenergy, i.e., 40% for power generation and 60% for transport or do not consider extra-EU imports. Beyond the mixed messages from supranational strategic guidance, there are socio-political barriers, especially concerning storage locations that can stop CCS projects in their wake [237]

It is useful for contextualisation of the presented projections to be compared to CCS projections of other global IAM and EU-centered models for the EU. Butner et al. (2020) [238] reviewed CCS and BECCS deployment across model types with highly varying scenario narratives but a common 2°C target. They provide a projected range for 2050 for CCS stored emissions of 0-3,850 Mt CO_2 yr^{-1}, and BECCS 0-1,336 Mt CO_2 yr^{-1}. This study's projections of 1,240 Mt $CO_2 yr^{-1}$ fall in the higher end of this range for BECCS due to most models not capturing extra-EU import potential, thus indirectly implementing a resource constraint. From an infrastructure perspective, a significant scale-up of CCS technology is broadly projected within the EU27 & UK by 2050, in line with the projections presented here. Bauer et al. [129] explore the results of several IAMs, indicating that although considerable bioenergy is used in combination with CCS, BECCS is not necessarily the driver of bioenergy use. Restricting BECCS leads to the reallocation of bioenergy to non-CCS technologies. Some studies indicate that restriction of BECCS would increase overall bioenergy deployment due to a greater need for low-carbon fuels due to the absence of additional abatement from CCS [239].

Assessing any one link of the BECCS chain individually (suitable biomass supply, technological readiness, adequate carbon network, political support) seems feasible, but projecting the scale-up by 2050 may be more of a question of timing. The complexities of the deployment at the projected scale mean a cognisant effort is required across the whole chain simultaneously and promptly. This requires unlocking bottlenecks for investor confidence by proving large-scale implementation in the coming years within key projects that focus on mutualising economies of scale via clustering and reusing existing infrastructure.

5.4.4 Future research avenues

The proposed framework provides an intuitive computationally non-intensive soft-linking methodology, offering an improved assessment over existing approaches. This method may be reproduced for macro-regional outputs from global IAMs and their corresponding regional energy system models, which is especially useful for regions with high energy imports. Downscaling bioenergy macro-regional demand projections and incorporating dedicated technological conversion representation increases the relevance of global IAM projections for supranational and MS-level climate targets, scenario development and policy. The projections from this study are more tangible to direct salient formulation of quantitative bioenergy integration within nationally determined contributions and highlight the needed coordination across national governance scales.

The inclusion of MS-level trade optimisation allows for a description of future bio-commodity flows at an interregional, national and sectoral level. This allows projections for the multi-level attribution of emissions per traded unit of bioenergy consumption. This may be further applied as future representative coefficients within I-O modelling activities. Such research can be beneficial for forward-thinking industries when planning future fuel or resource mix and seeking assurances on future environmental compliance risks during product design and investment decision-making.

While improving on the current literature base, the long-term trade route optimisation approach performed in this framework remains too coarse for system planning. At a minimum, a sensitivity analysis of critical developments should be performed. These include;

- (i) Inclusion of other notable marine hub nations such as Germany. The weighting of modality transportation costs across the entire supply-chain should be performed to offer alternative logistic development pathways (the effects of this are highlighted in Annex V.9)
- (ii) Restriction of BECCS to assess the bioenergy developments in the absence of this divisive technology which also steers trade flows to a large extent.

Future research would benefit from further soft-linking to (i) a dedicated EU power system model with higher spatial granularity than MS-level and end-use facility representation to enhance demand distribution projections such as Plexos [192] and (ii) a geographically explicit grid-level bioenergy-plant localisation optimisation model such as BeWhere [240]. Ideally, such projections would be paired with a dedicated transportation network analysis at the grid level that includes detailed bioenergy-specific logistical components and complexities. These include costs for capacity upgrading, infrastructure integration and storage requirements [241], the potential for telematic applications, and other sensitivities to aspects such as tariffs and taxes.

Chemicals and materials are coarsely represented within global modelling activities with a limited or absent representation of circular economy strategies, cascading principles or detailed final product demand. Recent model development by Stegmann et al. [78] provides a method for capturing these interactions with the energy system. The inclusion of this work into future macro-regional demand projections could improve understanding of optimal biomass deployment approaches and may increase the mitigation benefits of biomass.

5.5. Conclusions

When considering supply from a global perspective and demand from a regional perspective, bioenergy can play a significant role across all represented end-use sectors within an EU energy transition to 2050. Biomass could contribute 5.8 EJyr^{-1} (25%) of total heat demand, 5.2 EJyr^{-1} (19%) of electricity, 2.3 EJyr^{-1} (14%) of transport and 1.5 EJyr^{-1} (27%) for chemicals. Downscaled macro-regional bioenergy supply and demand dynamics from a global IAM provide more tangible and policy-relevant insight into implications at MS-level when considering regional least-cost modelling. MS-level demand distribution focuses >50% of total demand towards the industry-heavy economies of Germany, France, Poland, Italy and Spain, which are projected to require a ten-fold increase in power generation from bioenergy by 2050. These nations hold particularly challenging bottlenecks to realise projections because of a lack of capacity in the transportation network for energy commodity trade, unfavourable onshore negative emissions storage potential or both.

Projected volumes of EU27 & UK bioenergy by mid-century of 14.8 EJyr^{-1} may place increased strain at all distributive levels of the European energy commodity transportation network. These challenges are due largely to replacing incumbent fossil carriers like oil and gas with dedicated pipeline networks. Potential bottlenecks concern MS-MS bioenergy distribution of imports and short-haulage of decentralised seasonal collection of domestically produced biomass. This is most challenging in larger producing nations, such as Germany, Spain, France, Poland, Sweden and Romania. Higher density, low-cost bulk transport requires strategically planned electricity and industrial installations to minimise the logistical challenges for large-scale bioenergy trade. Phaseout of coal will partially alleviate network expansion. However, an ex-ante cost-benefit analysis of an EU biofuel pipeline network would be beneficial to realise the projected integration of bioenergy. The projections suggest that, although ambitious and requiring significant upgrading of the incumbent energy carrier transportation network, the scale of bioenergy integration into the EU27 & UK's energy system as projected at a macro-regional scale under the global IAM can be feasibly deployed.

Cost-optimal allocation prioritises biomass use for power generation, combined with carbon capture and storage, rather than hard-to-abate sectors. 2050 projections suggest bioenergy resources could be predominantly directed towards centralised large-scale power generation (electricity and heat) facilities with the potential for BECCS. When considering global supply constraints, this restricts available biomass resources for end-uses deemed sub-optimal by this assessment, including aviation and cars. Such allocation does not correlate well with current regulatory trends, opinions and targets, such as the renewable energy and fuel quality directives. This indicates a misalignment between supranational policy and cost-optimal transition pathways regarding sectoral bioenergy deployment.

Large-scale BECCS deployment provides a possible carbon dioxide removal option for the EU27 & UK in 2050. Biomass supply is sufficient to fuel 1.2 Gt CO_2eq. yr^{-1} removals, with 50% delivered from extra-EU imports. Considering the projected distribution of BECCS, this is likely dependent on cross-border collective storage projects significant for Southwest and Central Europe, where there is unfavourable storage available. Realising the projected negative emissions requires sizable infrastructure scale-up and concerted support to kickstart deployment in the near future, including a credible accounting system for negative emissions. Ultimately implementation of the presented BECCS projections requires specific sustainability protocols, measurement, reporting and verification (MRV) standards, and policies across the complete supply-chain from promoting mobilisation of low emission feedstocks in supplying regions through to CCS deployment strategies that support shared infrastructure across countries. Ultimately, due to efficiency decreases for power generation and finite CO_2 storage potential, transition policies must consider the role of BECCS as a complement to deep emission reductions through the large-scale increase of renewable energy technologies, clean fuels, and energy efficiency saving measures.

CHAPTER 6

Summary, Discussion & Conclusions

6. THESIS SYNTHESIS: SUMMARY, CONCLUSIONS AND DISCUSSION

6.1 Research Context

The Paris agreement aspires to limit global-level temperature rise to well below 2°C, striving for 1.5°C. This global goal requires governments around the world to impart climate policy to steer the reduction of anthropogenic greenhouse gas emissions. Most human-induced emissions are derived from fossil fuels deployed for energy purposes. Decarbonising energy systems worldwide relies on societal changes surrounding consumption, energy and resource efficiency measures, and substituting fossil sources with lower-emission alternatives. Biomass provides an attractive option for such substitution and is currently the largest renewable energy source utilised worldwide. This position is primarily due to its versatility as fuel across major sectors and biogenic carbon being considered climate neutral at the point of consumption. However, realising such emissions reductions requires careful management. Bioenergy can be utilised in all major end-use sectors and act as a flexible source for balancing the electricity grid when paired with other intermittent renewables and an approach following deep electrification. Furthermore, in conjunction with carbon capture and storage, it may provide the potential to achieve net-negative emissions, which are widely considered crucial in achieving overarching climate targets.

At an EU level, current bioenergy consumption stands at 5.6 $EJyr^{-1}$, accounting for 64% of total renewable energy consumption. Of this, 96% of biomass used for energy is EU-sourced, with 89% derived from the member state it is consumed in, with EU biomass production exceeding that of domestic gas or coal. Bioenergy is recognised as a fundamental contributor in future efforts to decarbonise the EU's energy system. Many of the National Renewable Energy Action Plans (NREAPS) indicate immediate milestones that place urgency on the contribution from biomass. However, global and regional level modelling efforts widely project an increased role in the EU transition will intensify the need for imports from other world regions.

However, bioenergy faces opposition in the EU climate debate as a mitigation option. Critique is built around several core arguments, including: access to sustainable feedstocks; carbon pay-back periods; attached emissions considering land-use change; uncertainty surrounding bioenergy with carbon capture and storage (BECCS) deployment; dependency on subsidies; and competition between different biomass end uses, including non-energy applications. Assessing the role of bioenergy in decarbonising the EU's energy system towards 2050 requires a better understanding of these critiques and uncertainties

There are complex interactions between the EU bioenergy sector and natural and human systems. These interactions advocate an integrated approach for analysing the mitigation potential of bioenergy. Assessments should consider demand when striving for a least-cost transition and capture the dynamic interlinkages with global biophysical and socio-economic systems. Previous assessments fall short of detailed analysis of these dynamics at an EU level and fail to capture the interregional trade requirements and challenges therein from a global perspective. Given the expected increasing demand for biomass in the EU, capturing these aspects is essential to represent better the complexity of bioenergy development at larger scale deployment and provide insights into the required infrastructure and market facilitation.

The formulation of climate mitigation strategies, energy-mix portfolios and steering policies is conducted at the national or supra-national level for the EU. Therefore, evaluating bioenergy's climate mitigative 'role' in energy-system transitions is most useful for decision-support at a system level, i.e. the entire EU energy system. For bioenergy, a system-level assessment presents more challenging considerations than other renewable energy sources where diffusion rates are the primary determinant, such as wind and solar. This is because bioenergy requires constant sourcing, much like conventional fuels, with the addition of vigilant management practices to ensure environmental benefits are realised. The techno-economic performance and mitigation potential of bioenergy depend on considerations that span a complex delivery-chain that covers both supply and demand dynamics and the aforementioned geographical scales. Such a broad scope of considerations is beyond previous modelling efforts. Within this thesis, this collective of considerations is termed 'Root-Chute' and builds upon the current knowledge base to better understand bioenergy development within the EU to 2050.

6.2 Aims and Research questions

This thesis aims to advance the assessment of the future role of bioenergy as a climate mitigation option for the EU to mid-century. This is achieved by improving EU-level projections at a systems level via accounting for the critical considerations within supply and demand dynamics across global and regional scales, traversing the full delivery-chain and attached emissions. The following research questions were addressed to achieve this aim:

1. What do quantitative assessment approaches project for the role of Bioenergy within EU decarbonisation strategies?
2. How consistent are modelling assessments for representing EU-level bioenergy and climate policy targets and capturing Root-Chute considerations?
3. To what extent can global bioenergy competition for the resource base and trade constraints shape EU mitigation potential from bioenergy and vice-versa?
4. How feasible are long-term projections for EU bioenergy deployment and mitigative potential from the perspective of logistical supply, scale-up, management practices and technological advancements?

Table 6.1: Thesis chapter overview and contribution toward the outlined research questions

Title		**RQ1**	**RQ2**	**RQ3**	**RQ4**
2	EU bioenergy development to 2050	+++		++	
3	Integrated assessment of the role of bioenergy within the EU energy transition targets to 2050	+	+	++	
4	The implications of geopolitical, socioeconomic and regulatory constraints on European bioenergy imports and associated GHG emissions to 2050		+++	++	+++
5	EU bioenergy supply-chain projections to 2050 using a multi model framework	+		++	+++
6	Thesis synthesis	**X**	**X**	**X**	X

6.3 Summary of the results

Chapter 2 provides a review-based analysis of recent supply and demand dynamics projections for EU bioenergy to 2050. The review consolidates projections stemming from resource-focused, demand-driven and integrated assessment approaches. Projections are synthesised to identify absolute ranges, determine cohesion with policy and draw insights on the implications for the scale of development, trade and energy security. The inter-approach comparison indicates that bioenergy has an important role in the future EU energy mix regardless of technology development and trade constraints.

Supply-side studies have undergone methodological harmonisation efforts in recent years. Despite this, due to remaining differences in the assumptions for key uncertainties such as feedstock yields, technical potential estimates still range from 9–25 EJ yr^{-1} for EU domestically available biomass for energy in 2050. The extent to which this resource base can be utilised in the long term lies within its economic accessibility, which is governed by four factors: (1) price developments and availability of imports (demand projections do not envisage this as a barrier by 2050), (2) developments of other low-carbon technologies, (3) profitability of non-energy bio-based products and (4), enforced sustainability criteria for GHG reductions.

Demand-side projections (from demand-driven and IAM approaches) range between 5-19 EJ yr^{-1} by 2050. This range is primarily due to variations in study assumptions on key influential developments such as economic competitivity of bioenergy, energy efficiency gains within the power sector, flexibility for meeting mitigation targets and technological portfolios. Upper-bound technical supply estimates can thus meet future demand wholly based on the domestic resource base. This would allow to reduce the total EU primary energy import dependency by 22 percentage points from the current EU roadmap trajectory. However, due to part of this domestic resource base being deemed economically inaccessible or of insufficient quality, studies indicate that EU imports are projected to increase, ranging from 4% to 13-76%. Limitations in the accessibility of feedstock from other world regions due to increasing global demand could produce a case in which imported EU biomass is sourced from less sustainable, more complex supply chains, leading to lower GHG emissions savings. Furthermore, the emergence of non-energy applications is projected to compete for at least 10% of the biomass needed to fulfil bioenergy demand in 2050.

Chapter 3 provides the first step of the thesis towards incorporating ‘Root-Chute’ considerations within 2050 bioenergy projections for an EU energy transition to meet mid-century climate targets. The study utilises the global IAM IMAGE to produce a detailed regional EU-level assessment within a global context when considering technological limitations, including the prohibition of all bioenergy or biomass paired with carbon capture and storage. This approach serves as an important intermediate step to explore optimal end-use strategies when considering global dynamics and as a point of comparison for i) validation of IAM EU-level climate trajectory representation and ii) credence that finer resolution data leads to improved assessment. The chapter projects bioenergy demand, sectoral deployment, feedstock, and inter-regional import for the EU to 2050. Employing a global model allows for projections of EU decarbonisation strategies consistent with global climate targets and captures the effects of biomass production and consumption in other world regions.

EU bioenergy demand is projected to increase significantly and play a substantial role within a low-cost EU energy system transitioning to meet mid-century climate targets. The projections suggest a '< 2°C' emission trajectory for the EU that closely follows current legislated climate targets is possible to 2050. Achieving would require a tripling of bioenergy deployment according to least-cost projections. This equates to a 27% (14 EJ yr^{-1}) contribution to the EU's total primary energy demand by 2050. As a result, there is a substantial restructuring of bioenergy deployment, with power generation becoming the dominant end-use sector, representing 60% of bioenergy consumption in 2050. Preference for power generation is motivated by the availability of net-negative emissions when paired with BECCS within large-scale facilities. Bioenergy could contribute up to 27% (8.5 Gt CO_2eq.) of the cumulative GHG mitigation required, with BECCS providing 0.7 Gt CO_2eq. yr^{-1} net-negative emissions by mid-century. The model projects a substantial shift from 1st generation feedstocks for liquid bioenergy carriers to advanced and lignocellulosic sources, whose shares are projected to increase from 20% (0.3 EJ yr^{-1}) in 2030 to 90% (3 EJ yr^{-1}) by 2050.

To match this demand, the model projects biomass imports to increase from 4% of its current supply to 60%. Bioenergy could provide up to 1 Gt CO_2eq. or 40% of the overall mitigation needed by the EU in 2050. This is based on large-scale use for power production (8.4 EJ yr^{-1}), with industry (1.7 EJ yr^{-1}), transport (1.4 EJ yr^{-1}), buildings (1.4 EJ yr^{-1}), and non-energy energy sectors (1 EJ yr^{-1}), getting smaller shares. By 2050, 55% of total EU bioenergy use is projected to be coupled with BECCS. Bioenergy supply comes primarily from agricultural and forestry residues, as these sources have low upstream GHG emissions. However, as demand increases, energy crops are increasingly used (constituting 10% of the EU bioenergy supply in 2050), especially in providing advanced liquid fuels. The results show that one route for achieving an EU energy transition is based on the rapid deployment of BECCS and the mobilisation of sustainable imports of second-generation feedstocks.

Chapter 4 expands on default regional-focused assessment using an IAM by developing a scenario protocol that explores the consequences of plausible future developments for EU bioenergy carrier imports from the international marketplace. The scenarios cover supply-side concerns for geopolitics and feasibility barriers and potential impacts of EU demand-side sustainability regulations, namely, RED II GHG criteria. Additions are made to the IMAGE model that allows for the enhanced allocation of supply-chain emissions per unit of imported EU bioenergy to identify RED II incompliant biomass. The effect of trade constraints on EU import volumes, sourcing regions, mitigation potential and implications on EU and global emissions is projected to the year 2050.

The projections show that the EU can increase imports from 1.5 EJ yr^{-1} in 2020 to 8.1 EJ yr^{-1} by 2050 whilst remaining compliant with RED II GHG criteria. Under these conditions, bioenergy can provide annual GHG mitigation of 0.44 Gt CO_2eq in 2050. However, achieving this would require a structural diversification of trading partners from the present into areas that hold increased socio-economic challenges. Furthermore, import-sourcing regions change over time, requiring EU operators to be flexible. This diversity in sourcing regions to 2050 is needed for RED II compliance because major exporters with the lowest production costs maximise residue supply towards 2050. This leads to expansion into dedicated energy feedstock production on lands with higher carbon stocks, lower yield, and increased transportation requirements.

Regulatory measures such as RED II hold challenging yet surmountable barriers to EU bioenergy deployment. The most significant risks to the future expansion of EU bioenergy imports concern socio-political, technical, and logistical challenges. Projections suggest that failure to overcome these challenges could result in an annual EU marginal emissions increase of 0.26 Gt CO_2eq by 2050. These findings suggest global IAM modelling activities would benefit from expanding the representation of feasibility considerations within their default bioenergy trade dynamics rather than as applied here as add-on scenario constraints. Furthermore, the results highlight that the EU may not be the most effective end-user market for interregional traded bioenergy from a global climate perspective. Our projections show that bioenergy deployment in world regions outside the EU provides deeper mitigation (35-45g CO_2eq MJ^{-1} in 2050) due to these regions' more carbon-intensive energy systems. Under the carbon budget explored, global emissions are lowest when the EU limits extra-EU imports by 25% to 6 EJ yr^{-1} in 2050. However, the prioritisation of end-use regions for bioenergy should also consider regional legislative trajectories of climate mitigation targets to 2050 and the ability to progress immature technologies such as BECCS.

Chapter 5 develops and applies a soft-linked multi-model framework that allocates EU bioenergy supply as projected under a global context to individual member states' demand and over an increased set of intermediate conversion (37) and end-use (67) technologies. This approach overcomes complexities in capturing biomass supply-chain considerations across spatial and technological resolutions. The framework incorporates the global integrated assessment model IMAGE, the EU energy system model PRIMES and the European Bioenergy dedicated least-cost energy system model RESolve-Biomass to explore EU27 & UK bioenergy deployment following a '<2^{o}C' climate scenario. Bridging this divide for technological and geographical resolutions permits a deeper assessment of the implications and feasibility of bioenergy projections from a logistical, techno-economic and policy perspective.

The results indicate that 14.8 EJ yr^{-1} (8.5 EJ of which is imported) of bioenergy could be supplied and fully deployed by 2050 in the EU27 & UK. Bioenergy can play a significant role across all represented end-use sectors within an EU energy transition to 2050. Biomass could contribute 5.8 EJ yr^{-1} (25%) of total heat demand, 5.2 EJ yr^{-1} (19%) of electricity, 2.3 EJ yr^{-1} (14%) of transport and 1.5 EJ yr^{-1} (27%) for chemicals. A cost-optimal strategy pushes 75% of bioenergy deployment into power generation as electricity and heat. Preference for power generation is motivated by large-scale BECCS deployment provides a possible carbon dioxide removal option for the EU27 & UK in 2050. Biomass supply is sufficient to fuel 1.2 Gt $CO_2eq.yr^{-1}$ removals, with 50% delivered from extra-EU imports. Considering the projected distribution of BECCS, this is likely dependent on cross-border collective storage projects significant for Southwest and Central Europe, where unfavourable storage is available. Realising the projected negative emissions requires a sizable infrastructure scale-up.

Integrated gasification combined cycle and large pellet boiler installations in conjunction with CCS are the major conversion routes projected, limiting bioenergy availability for critical hard-to-abate sectors, including road and aviation transport. MS-level demand distribution focuses >50% of total demand towards the industry-heavy economies of Germany, France, Poland, Italy and Spain, which are projected to require a ten-fold increase in power generation from bioenergy by 2050. These nations hold particularly challenging bottlenecks to realise projections because of a lack of capacity in the transportation network for energy commodity trade, unfavourable onshore carbon storage potential or both.

At projected deployment levels, all distributive levels of the EU energy commodity transportation network are placed under significant stress. Comparing to the incumbent handling capacity of current energy carrier operations for fossil fuels, i.e. coal, oil, and natural gas, highlights the logistical challenges faced. Marine port terminals receiving projected imports need to increase their handling of liquid and dry bulk fuel capacity by +50%, with particular concerns for dry bulk (pellets) where the fossil alternative coal tends to rely on rail haulage. Once inside of EU borders, the inter-member-state distribution would require a significant increase of +80% over the next 30 years if bioenergy supply chains are restricted to their current transportation regiments, i.e. no dedicated pipeline. Domestic distribution of internally MS-sourced feedstocks suggests a +150% increase in short haulage via road and rail by mid-century to mobilise national-level resources. Higher density, low-cost bulk transport of bioenergy carriers requires strategically planned electricity and industrial installations to minimise the logistical challenges for large-scale bioenergy trade. Phaseout of coal will partially alleviate network expansion. However, an ex-ante cost-benefit analysis of an EU biofuel pipeline network would be beneficial to realise the projected integration of bioenergy.

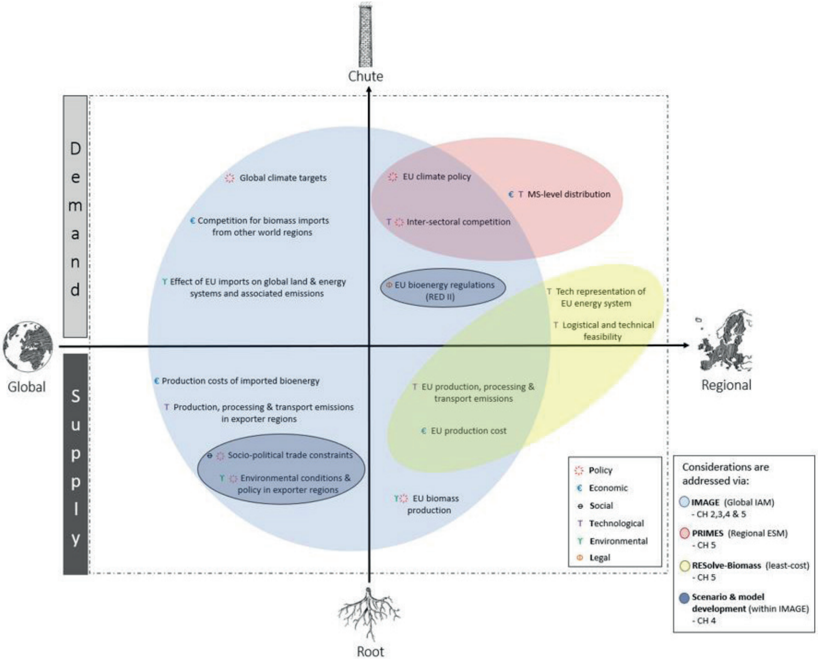


Fig.6.1: Thesis chapter and model coverage of consideration within systematic-level 'Root-Chute' assessment of Global-European bioenergy delivery-chains.

- Considerations at global and regional levels that are further dichotomised along the supply vs demand axis may pertain to market dynamics. This is especially true of economic considerations, which can be steered by both supply and demand forces. Hence, positioning within the schematic above is motivated by subjective weighting but is, in part, arbitrary.

6.4 Thesis findings and conclusions

RQ.1: What do quantitative assessment approaches project for the role of Bioenergy within EU decarbonisation strategies?

The comparison of bioenergy projections (based on different approaches) points to a consensus that EU bioenergy demand will increase significantly to 2050. While this is fueled by a sufficient supply, studies show different sourcing strategies. At the EU level, current bioenergy consumption stands at 5.6 EJ yr^{-1}. In the literature, different bioenergy deployment projections for 2050 can be found based on resource-focused, demand-driven, and integrated assessment approaches (Chapter 2). A review of them shows that EU demand, as projected by purely demand-driven approaches, will increase to 8.5-12 EJ yr^{-1} by 2050. Demand-driven assessments account for the economic accessibility of feedstocks via exogenous input of stand-alone feasibility studies, which tend to ignore or hold a simplified representation of import availability. Global IAMs afford a better representation of global delivery-chain considerations, including import potential (including representation of costs and attached emissions). This leads to increased bioenergy demand projected for the EU in the IAM IMAGE used throughout this thesis to 14 EJ yr^{-1} (60% from imports) by 2050. This scale of deployment sits within a clustering of demand projections from demand-driven and IAM approaches between 10-15 EJ yr^{-1} by 2050. This level of demand is well within the limits of upper bound estimates for domestic supply stemming from EU resource-focused assessments, which show a surplus of 13-24 EJ yr^{-1} in 2030 and 1-23 EJ yr^{-1} by 2050. However, the extent to which this domestic resource base is utilised in the long term lies within its techno-economic accessibility and attached emission factors, which are not considered within resource-focussed assessments.

Bioenergy is projected to play a substantial role across all end-use sectors within a low-cost EU energy system transition that meets mid-century climate targets. IMAGE 3.2 projections in Chapter 3 suggest a '< 2°C' emission trajectory at the least system cost requires a tripling in bioenergy deployment. This equates to a 27% (14 EJ yr^{-1}) contribution from bioenergy to the EU's total primary energy demand by 2050. Bioenergy deployment at minimum doubles in each sector by 2050, affording the EU versatility within its decarbonisation strategy. However, projections suggest an effective emissions reduction strategy requires a substantial restructuring, with power generation becoming the dominant end-use sector, representing 60% of bioenergy consumption in 2050. Under a '<2°C' scenario, biomass and bioenergy deployment across the sectors is distributed as follows: 62% Power, 12% Industry, 10% Non-Energy, 8% Transport, and 8% Buildings. Under these conditions, bioenergy could contribute up to 27% (8.5 Gt CO_2eq.) of the cumulative GHG mitigation required, with BECCS providing 0.7 Gt CO_2eq. yr^{-1} net-negative emissions by mid-century.

Limiting bioenergy applications, particularly BECCS within the EU, will likely lead to a more costly mitigation pathway. Chapter 3 considers an EU energy-system-wide constraint applied to domestic and imported bioenergy via prohibiting bioenergy-related investment post-2020 to formulate a 'No bio' scenario that aims to meet a '<2°C' target. Over the period assessed (2020-2050), prohibiting bioenergy leads to a cumulative emissions increase of 8.5 Gt CO_2eq (or 27% of the cumulative GHG mitigation required, with BECCS providing 0.7 Gt CO_2eq. yr^{-1} net-negative emissions by mid-century. BECCS is a key technology for mitigation projections contributing 20% (7 Gt CO_2eq) of EU-aligned climate commitments by 2050. Chapter 4 highlights the importance of BECCS when considering RED II GHG constraints. Pairing solid bioenergy carriers with CCS for electricity and heat generation effectively keeps the emission factor of these applications very low (RED II compliant). It allows for the consumption of dedicated woody crop imports with higher production emissions to be utilised post-2040 when residue supply saturates.

Cost-optimal allocation prioritises bioenergy use for power generation, combined with carbon capture and storage, rather than hard-to-abate sectors that are incentivised within EU policy. From the soft-linked multi-model framework developed in chapter 5, 2050 projections suggest that bioenergy resources could be predominantly directed towards centralised large-scale power generation (electricity and heat) facilities with the potential for BECCS. When considering global supply constraints, this restricts available biomass resources for end-uses deemed economically sub-optimal by this assessment, including aviation and cars. Such allocation does not correlate well with current regulatory trends, opinions and targets, such as the renewable energy and fuel quality directives which pursue ambitious integration of biofuels for short-term (2030) sectoral targets. This indicates a misalignment between supranational policy and cost-optimal transition pathways regarding sectoral bioenergy deployment.

RQ.2: How consistent are modelling assessments for representing EU-level bioenergy and climate policy targets and capturing Root-Chute considerations?

Global IAMs can offer plausible regional representation to readily assess bioenergy deployment, which is well aligned with EU bioenergy integration and climate policy targets. Global IAMs fulfil a primary role of assessing decarbonisation strategies over long-term global climate trajectories holding a unique benefit in accounting for interactions between the energy system, natural systems and global regions. While IAM model runs can also be used for regional-level assessment under global carbon budgets (Chapter 3), such studies lack regional-specific climate and bioenergy integration targets that more detailed models can provide. Representation of EU climate targets and sectoral deployment policy is quintessential to the usefulness and feasibility of the model outputs at the regional level. For *EU Climate targets*, Chapter 3 highlights that IMAGE the EU emissions trajectory following a '< 2^{o}C' global climate target holds a very tight fit to the equivalent legislative EU targets of 40% by 2030 and 80% by 2050 compared to 1990 baseline values. The pace of decarbonisation efforts at the EU level is representative of the urgency of climate policy. For *EU bioenergy integration targets*, comparing IMAGE projections to the quantitative policy strategy provided in the European Commission's Energy Roadmap 2050 'High RES' scenario (13.5 EJ yr^{-1}) shows almost identical bioenergy deployment at 13.6 EJ yr^{-1} by 2050. There is tight alignment for deployment within industry and buildings for sectoral deployment projections, with both policy and projections indicating 3 EJ of Bioenergy. However, IMAGE projects significantly stronger bioelectricity generation at 8.4 EJ yr^{-1} than the 5 EJ proposed in the roadmap, with the differences felt in the transport sector where IMAGE projections are lower by a similar margin. This disagreement is due to IMAGE holding favourable economic advantages of net negative emissions within electricity generation with BECCS, where capture rates are greater than in producing liquid biofuels with CCS. Besides this rerouting of higher production to electricity production, deployment visions between the two sources hold a close resemblance, showing a strong agreement between deployment as envisaged by policy and IAMs.

IAMs can further improve how they capture Root-Chute bioenergy considerations at regional levels. Global IAMs such as IMAGE are well-positioned to explore the role of specific energy options such as bioenergy at a macro-regional scale from a supply and demand perspective. They can account for international import availability under market competition from other regional actors when accounting for production and transportation costs, and attached emissions. They can perform this in the context of limited emissions budgets and consider the complex and dynamic interactions between global biophysical systems. However, they hold several critical limitations. (i) under default runs, they do not assess important wider socio-economic and political considerations that can act as additional constraining factors for imports. (ii) RED II GHG constraints require the summation of emission point sources across the entire delivery-chain. They are, by default, attributed across regions and sectors, so they may not be applied as a regulatory criterion. (iii) They hold relatively low regional geographic and technological resolution. No individual modelling approach can encompass all the relevant nuances required for a precise assessment of the bioenergy delivery-chain. However, there is significant scope to refine current IAM modelling efforts.

It would be useful to extended global IAM to assess broader socio-economic considerations and bioenergy-specific regulations that span global delivery-chains. Chapter 4 extended default IMAGE runs by incorporating socio-economic and geopolitical feasibility assessments through dedicated scenario development. Furthermore, reformulation of GHG allocation was performed to provide dynamic emissions factors used to enforce RED II GHG emissions constraints into the IMAGE-TIMER framework. RED II is a crucial regulatory tool within the EU used to quell the risks of unsustainable feedstock sourcing that lead to poor emissions performances in bioenergy delivery chains. Within chapter 4, IMAGE is adapted to take advantage of pre-existing dynamic regionally aggregated data such as LUC emissions, end-use technology efficiency, transport fleets' fuel mixes and production emissions that span a global delivery network, and their evolution over time. Furthermore, adjustable GHG emission constraints are applied to restrict incompliant bioenergy supplies on a regional basis. The approach provides a macro-level assessment of the implications of introducing single supply chain legislation, which has shown to have large-scale knock-on effects on EU biomass sourcing. This observation is made possible via the use of a global IAM, which considers absolute demand and international trade at a global scale.

Bioenergy assessment approaches can be further integrated to increase techno-economic and geographical specificity whilst retaining supply and demand dynamics under a global context. Within Chapter 5, a framework is developed that leverages the benefits of multiple approaches to increase the robustness of assessments regarding geographical and technological regional specificity. This is achieved via a soft-linked model framework that joins three modelling approaches. These include the global integrated assessment model IMAGE, the EU energy system model PRIMES and the European Bioenergy dedicated least-cost energy system model RESolve-Biomass. Increasing geographical representation to scale bioenergy demand at a national and sectoral-level using existing model runs from the main EU energy-system model PRIMES allows for improved feasibility assessment. This approach also holds the advantages of incorporating national-level policies and targets such as sector-wide efficiency targets and emissions caps. The representation of competition of end-uses for bioenergy when considering a detailed EU-specific technology set and transportation costs was achieved through the addition of RESolve-Biomass. The joint framework improves the depth of insights into (i) bioenergy flows and the logistical requirements for imports to end-use nations. (ii) Conversion and end-use technology portfolios and their variation at MS-level. (iii) The implications of increased use of BECCS concerning the required CO_2 transport networks and storage sites across the EU.

RQ.3: To what extent can global bioenergy competition for the resource base and trade constraints shape EU mitigation potential from bioenergy and vice-versa?

IMAGE projects that, under a free trade paradigm and <2ºC mitigative pathway, the EU could import 8.3 EJ yr^{-1} or 60% of total EU bioenergy demand by 2050. This takes place under a global context considering economic competitivity with other world regions that are increasing bioenergy demand within their own decarbonisation strategies. The projected EU imports represent 25% of the total projected interregional traded bioenergy carriers (33 EJ yr^{-1}), suggesting the EU remains a key destination for bioenergy on the international market. By 2050, the majority (74%) of EU bioenergy imports are projected to be supplied from West Africa, where a sizeable techno-economic production potential, residue availability and favourable supply-chain costs prevail. These conditions promote bioenergy's economic attractiveness, especially when paired with carbon capture and storage, to avoid emission costs. However, projections formulated based on techno-economic potential alone overlook potential barriers to mobilising the biomass potentials in major export regions.

Geopolitical and socio-economic feasibility considerations for biomass production and trade could significantly reduce EU bioenergy imports. Chapter 4 applied further trade constraints to the EU's access to the international bioenergy market beyond the 'Free trade" default projections, which include only interregional resource competition. A geopolitical scenario is developed to explore uncertainties for trade agreements within an immature international market that restricted EU imports to current trading partners. Under these constraints, EU imports fall to 5.6 EJ yr^{-1} (-32%), with Brazil and Russia emerging as major supplying regions. This situation results in an annual emissions increase of 0.15 $GtCO_2eq$ by 2050 compared to a 'Free trade' case. This fall in mitigation is due to the resultant EU energy deficit being replaced partly by imported bioenergy that holds higher emission factors (from remaining allowed world regions) and alternative energy carriers that are more GHG intensive. A further feasibility scenario that represents the techno-economic and socio-economic challenges of production and mobilisation of biomass at a regional level is introduced. When blocking trade with regions scored below the EU for the feasibility of sustainable exports, EU imports are restricted to 3.4 EJ yr^{-1} (-59%). This is sourced solely from the North Americas and Oceania regions. This situation leads to an annual emissions increase of 0.26 $GtCO_2eq$ by 2050 compared to a 'Free trade' run.

The Renewables Energy Directive recast (RED II) GHG reduction criteria does not constrain the contribution of Bioenergy to EU climate mitigation targets. Within chapter 4, the IMAGE model was adapted to capture the complete chain of emissions from production to use for regulated end-use technologies. This allowed for the prohibition of EU bioenergy streams that do not comply with RED II, i.e. resultant emission reductions must equate to (at least) 65% in transport, 80% in heating and cooling and 80% in electricity generation compared to a prefixed fossil comparator. The projections show similar levels of bioenergy deployment and imports as projected for a 'free trade' scenario are achievable. However, RED II compliance increases challenges for imports because the EU is compelled to diversify supplying regions over time in order to keep the biomass supply within the RED II emission constraints. This broadening of supplying regions is observed because absolute global demand for imports towards 2050 can push production in certain regions beyond their potential at low emission factors. Thus, for some exporters, marginal production is forced into lands with less favourable land-use change emissions, higher fertiliser/energy inputs and increased transportation distances to conversion sites.

EU bioenergy imports can directly affect other world regions' mitigative ambitions, but this knock-on effect is limited at the projected scales. Chapter 4 shows that bioenergy deployment in world regions outside the EU provides more significant relative mitigation (35-45 g CO_2eq MJ^{-1} in 2050) due to these regions having more carbon-intensive energy systems. Under the carbon price explored, global emissions are lowest when the EU limits imports to less than 6 EJ yr^{-1} in 2050. Limiting EU imports to this level reduces global emissions by a maximum of 3.5 Gt CO_2 eq cumulative over the period assessed (2020-2050) compared to the default 'free trade' scenario. Further import restrictions (<6 EJ yr^{-1}) for the EU result in no additional global GHG mitigation due to the remaining biomass being projected as too expensive for other regions to access.

RQ.4: How feasible are long-term projections for EU bioenergy deployment and mitigative potential from the perspective of logistical supply, scale-up, management practices and technological advancements?

Residues and lignocellulosic crops are projected to become the dominant bioenergy sources for the EU to 2050. However, this development is subject to EU regulatory reform. The IMAGE projections of bioenergy development following a '<2°C' scenario used in chapters 2-5 are within the feedstock boundaries set by the EU and take a food-first principle (meaning that they do not have to impact food supply). Under a '<2°C' scenario, IMAGE projects a substantial shift away from 1st generation feedstocks for liquid bioenergy carriers to advanced and lignocellulosic sources, whose shares increase from 20% (0.3 EJ yr^{-1}) in 2030 to 90% (3 EJ yr^{-1}) by 2050. For solid bioenergy carriers, residues are the exclusive feedstock utilised until 2045. Afterwards, the EU reaches maximum residue supply and extends to wood-based energy crops. For mid-century climate targets, the projections from this study indicate that residues can provide 11 EJ yr^{-1} of the total 14 EJ demand in compliance with RED II GHG criteria. However, the European Parliament recently (September 2022) voted on the formulation of updating to RED III requirements that could dramatically hinder the feasibility of projections presented here. In RED III, primary woody biomass, which under the European Commission's definition includes sources categorised as residues in the projections presented in this thesis (i.e. wood recovered from natural mortality and felling; and thinning activities) are to be capped at current levels (3.5 EJ yr^{-1}). Chapters 3 and 4 project this doubling to 6.5-7 EJ yr^{-1} by 2050. This deficit of 3.5 EJ yr^{-1} would need to be substituted with other low-carbon fuels.

Bioenergy with CCS is projected to contribute significantly as a net-negative technology for meeting the EU's mitigation targets to 2050. Still, there are significant deployment challenges for the EU over this time frame. By 2050 following a '<2°C' scenario, bioenergy contributes 27% of the required GHG mitigation (Chapter 3). Chapter 5 highlights these challenges when considering specified MS-level demand distribution. Scale-up of capture requires rapid rollout from the current global capture rates of 1.5 $MtCO_2eq\ yr^{-1}$ to an unprecedented 1.2 $GtCO_2eq\ yr^{-1}$ from BECCS alone in the EU by 2050. To realise the projected potential of BECCS, installations at large-scale electricity and heat plants must scale up to unprecedented levels by 2050 (1.14 $GtCO_2eq\ yr^{-1}$), and to a lesser extent, within liquid fuel production sites (0.8 $GtCO_2eq\ yr^{-1}$). Scale-up of this magnitude likely depends on significant cross-border collective storage projects for Southwest and Central Europe, where storage is unavailable or unfavourable. This aligns with recent directions in CCS deployment in the EU that favour offshore storage in the North Sea. If offshore storage is the leading solution for BECCS in 2050, it would require a substantial carbon network across the continent that can handle larger volumes of storage-bound CO_2 than the current capacity of the EU natural gas network. Estimates of 50-70% of existing pipeline infrastructure could be re-purposed to serve a CO_2 network across the EU. However, this pipeline may compete with a hydrogen network, and capture sites would require significant retrofit at existing power and industrial sites to minimise stranded assets. Realising BECCS projections requires specific sustainability protocols, measurement, reporting and verification (MRV) standards, and policies across the complete supply chain, from promoting the mobilisation of low-emission feedstocks in supplying regions to CCS deployment strategies that support shared infrastructure across countries

Capitalising on a mitigation strategy that promotes large-scale bioenergy imports requires concerted EU efforts to safeguard environmental benefits across the global south. IMAGE projections indicate that Europe can increase domestic bioenergy production from 2.3 EJ yr^{-1} to 5.7 EJ yr^{-1} by 2050 (chapter 3). This disagrees somewhat with resource-focussed assessments (Chapter 2) that do not represent the economic competition, socio-economic feasibility or RED II GHG constraints. Nevertheless, European bioenergy imports are projected to increase significantly across all trade scenarios explored in Chapter 4. Compared to other explored trade scenarios, the sourcing of RED II compliant bioenergy is achieved through diversification of sourcing with a significant reliance on large low-cost exporters with currently immature bioenergy markets, namely, West Africa, East Africa, North Africa and the Rest of South America. These economies hold (a) lower socio-economic feasibility ratings and (b) do not hold significant trade with the EU at present. The largest barrier to EU bioenergy development to 2050 is overcoming potential socio-economic and technical feasibility issues within major exporting regions and mobilising low-emission factor feedstocks onto the international marketplace. This strategy would then require the EU to both formulate bioenergy trade relations with the multiple regions across the global south and safeguard the benefits for both parties. This requires a more significant effort than a 'Free Trade' scenario which would hypothetically allow the EU to concentrate these efforts into West & North Africa alone and require a less intensive monitoring protocol.

The projected volumes of EU bioenergy deployment by mid-century of 15 EJ yr^{-1} will likely place increased strain at all distributive levels of the EU energy commodity transportation network. Chapter 5 considers supply from a global perspective and demand from a regional perspective. When bridging geographical and technological constraints through an improved framework, projections show that imports (8.5 EJyr^{-1}, of which 62% is solids and 38% liquids) would require a 300 Mt increase in capacity solid energy carrier import handling at EU marine-land terminals by 2050. This is equivalent to 50% of the current EU annual dry bulk import of energy carriers. This is less problematic for liquid carriers due to a high capacity in conventional liquid energy import capacity. Internal EU-wide distribution between marine terminals and end-use facilities presents further challenges. Compared to the current MS-MS trade of energy carriers (137 Mt) by rail and inland shipping, the requirements in 2050 for bioenergy alone (245 Mt) require an increase of 80% capacity over the next 30 years to satisfy projections. This bottleneck is primarily due to natural gas and oil having established pipelines that bypass the need for conventional MS-MS transport. In contrast, liquid biofuels are still reliant on road and rail modalities due partly to the relatively small-scale operation. The projected 75 Mt MS-MS trade of liquid bioenergy in 2050 equates to 22% of the current oil demand in the EU. There is also bioenergy sourced internally at the MS level which by 2050 stands at 360 Mt, which equals 150% of the current capacity when summated across the EU27 & UK. Due to decentralised sourcing from field to conversion facility, a proportionally larger increase is expected for road transport. This projection would likely entail a significant increase in large tonnage lorries on European roads, specifically in Germany, Spain, France, Poland, Sweden and Romania (each >20 Mt yr^{-1}). Unlike MS-MS level distribution, the collection of primary biomass cannot be solved by pipeline. Thus, vehicle fleets would need to be expanded. Higher density, low-cost bulk transport requires strategically planned electricity and industrial installations to minimise the logistical challenges for large-scale bioenergy trade. Phaseout of coal will partially alleviate network expansion.

6.5 Key limitations & recommendations for future research

Regional technological and geographical specificity of IAM projections needs to be improved to increase their relevance for guiding regional decarbonisation policy. This thesis has used a global IAM to produce EU-level results for bioenergy developments. Global IAMs hold the distinct capacity to capture the broader context, i.e. interactions between the energy system and natural systems and between global regions. However, due to the use of aggregated data for large macro-regions, global IAMs lack technological and geographical specificity. Policy support is best suited at the same geographical level that it is constituted (i.e. (supra) national). There are two possible solutions to bridge the divide of global modelling for regional and national strategy guidance.

(i) *Coupling or integrating with regional-specific (or national) models.* Chapter 5 presented a method for coupling IAMs with regional scale models that hold more detailed techno-economic and geographical representation. This offers improved insight into policy support while accounting for global dynamics. Future EU bioenergy assessments could benefit from further soft-linking to (a) a dedicated EU power system model with higher spatial granularity than MS-level and end-use facility representation to enhance demand distribution projections [192]; (b) a geographically explicit grid-level bioenergy-plant localisation optimisation model such as [240], and (c) a dedicated transportation network analysis at the grid level that includes detailed bioenergy-specific logistical components and complexities. These include costs for capacity upgrading, infrastructure integration and storage requirements [241], the potential for telematic applications, and other sensitivities to aspects such as tariffs and taxes. This is particularly relevant for biofuels and BECCS, which will rely heavily on infrastructure networks. The inclusion of this work into future macro-regional demand projections could improve understanding of optimal biomass deployment approaches, logistical practicalities, and capacity-expansion needs and may steer policy to increase the realised mitigation benefits of biomass.

(ii) Statistical *downscaling of IAM projections.* IMAGE projects energy and environmental outputs for 26 world regions. These outputs can be downscaled where relevant through statistical methods. Such methods can transform IAM outputs based on relationships calculated with current high-resolution observations (e.g. energy demand for the IMAGE region 'Europe' may be downscaled to an MS level by use of national-sectoral level consumption figures reported annually within Eurostat databases). This can inform national-level policy formulation better while simultaneously exploring global development's implications. This approach was employed prior to the data transfer from IMAGE to PRIMES in chapter 5 to downscale IMAGE 'Europe region' bioenergy demand projections to the EU. Downscaling was performed via extrapolation of recent national bioenergy consumption statistics. This simplified (less modelling-intensive) approach lends itself to providing output to regional scale models that do not align well geographically with the 26 world regions of IMAGE.

Regional policy representation in IAMs needs to be advanced to increase their relevance for guiding regional decarbonisation policy. Alongside improved regional technological and geographical specificity mentioned above, regional assessments (e.g. EU-level) stemming from Global IAMs would also benefit from increased regional policy representation. For bioenergy assessments, two major focal points should be addressed:

(i) Specific bioenergy-relevant policy representation could refine assessments to better align with observable policy directions at EU level. This thesis takes steps towards enhancing the representation of EU bioenergy policy in global context IAMs. However, it is essential to acknowledge that the rapidly changing prescription of EU climate and bioenergy targets swiftly depreciates the merit of the outputs presented. EU-level changes within the policy landscape can include wide-reaching structural change and niche bioenergy-specific amendments that can reshape the energy carrier's outlook and are more complex to capture with models. Since the initiation of the modelling activities presented in this thesis, fundamental changes include: (i) A cap on primary woody biomass (including forestry residues). However, this remains to be quantitatively defined. (ii) Targeted promotion of biomethane production to 35 bcm (or 1.3 EJ yr^{-1} by 2030) within the REPowerEU plans. (iii) A growing focus on applying biomass for substituting fossil fuels in a wider bioeconomy for material and chemical manufacture. It should be noted that the EU is not unique in bioenergy-

related policy prescriptions, and the actions of other regions may have notable effects at an EU level. For instance, if another major importing region prioritises BECCS, this could influence EU access to imports.

(ii) Climate-relevant policy representation in IAMs could be improved at the regional level. For broader climate policy beyond bioenergy alone, IAMs frequently make projections according to a common set of shared socio-economic pathways (SSPs), providing a harmonised context for assessing different climate scenarios. Whilst this offers a solution space, it lacks the precision of regional political, technical, and societal capacity. Scenarios are also routinely developed to account for national-level climate-relevant policies such as Nationally determined contributions (NDCs). Nevertheless, such scenarios act only as entry points within modelling activities whereby long-term horizons transition back to global goals such as a <2°C target. This is a trade-off for global-level modelling to the horizons of 2050 and beyond, where most regional climate policy targets do not exceed 2030. However, climate urgency is spurring increasingly frequent policy releases, from regional GHG targets such as the EU adopting a steeper decarbonisation target to net-zero emissions by 2050 and sector/technology-specific strategies. Regional climate policy can significantly affect the decarbonisation strategies determined within IAM runs. Therefore, a more frequent reformulation and representation of EU supranational and sectoral level climate targets that capture current policy would benefit the relevancy of policy guidance stemming from IAMs at the regional level.

Feasibility assessments hold significant implications for bioenergy deployment and should be further incorporated into modelling projections. Whilst the ability to capture policy developments mentioned above can steer bioenergy dynamics, IAMs disagree regarding their energy mix choices. These differences are driven by differing assumptions and representation of the feedbacks between human systems to energy and natural systems (chapter 2). For instance, macroeconomic components of IAMs that act as energy demand and supply drivers are rule-based, following optimised rational expectations. There are conditions outside of these modelling assumptions that can also steer bioenergy developments. This thesis shows that the viability of supplying and deploying bioenergy within the EU also depends on boundary conditions that are not as explicit as policy communications. For instance, Chapter 4 highlights that broadening feasibility considerations into supply potential projections could hold significant implications for energy trade. The selection of parameters to determine feasibility, such as existing trade and socio-economic feasibility indexes for land-based mitigation measures, offer an initial starting point. Feasibility assessments may be further broadened to include other potential barriers, such as financial and legal aspects. However, scenarios capturing speculative geopolitical considerations, which may affect scenario narratives and have major implications on the model projections, remain unviable to capture according to current scenario studies. Such developments have high uncertainty and can only be accounted for post-facto. A recent example concerns the conflicts observed for energy trade between the EU and Russia.

The synergy of global IAM approaches and bottom-up environmental assessment methods can increase the scope of environmental impact assessment and mitigation potential of bioenergy delivery-chains. Bottom-up approaches such as Life Cycle Assessment (LCA) provide a standardised methodology that accounts for multiple environmental indicators throughout a product or service life cycle. However, they are data-demanding, applied at a case-study level, and do not account for changes in the supply and delivery system of a product (i.e. 'background' changes in land-use, electricity production, etc.). Assessing a product group en masse from diverse sources and end-uses is needed to provide insight into future supply potentials and their environmental impact. Ex-ante (or prospective) LCAs simply do not have broad enough system boundaries or temporal scope to account for future uncertainties. At the same time, **g**lobal-level IAMs are limited concerning their representation of broader environmental impacts beyond GHG emissions, and also tend to aggregate technologies and geographic scopes, which reduces their capacity for environmental impact accounting at finer resolutions. Interlinkages between IAMs and LCAs are starting to emerge via IAMs, providing macro system-wide changes across scenarios to improve prospective LCA studies, that aim to alleviate the limitations of both methodologies [242–244]. However, there is a requirement to implement back into IAMs the multiple environmental impacts of different technology routes provided by LCA to allow for future IAM projections to account for the broader implications of projected pathways. This is especially important for a bioenergy strategy that safeguards low-emission resources from diverse sourcing regions with region-specific environmental characteristics. Such efforts will aid in bioenergy assessments by providing a more robust assessment of their mitigative performance and broader implications on environmental and sustainability goals, particularly for emerging technologies.

6.6 Recommendations for policy makers and stakeholders within the bioenergy delivery-chain

Safeguard low-emission bioenergy delivery-chains at a global level. Critical safeguards are needed to guarantee emission reductions are achieved across bioenergy delivery-chains but are complex to implement ,monitor and verify, with standardised accounting methods still under development. Progress can be seen within the EU-wide enforcement of the Renewables Energy Directive recast (RED II) [27]. RED II stipulates mandatory sustainability and GHG reduction criteria and accounting guidance for major end-use applications compared to a fossil fuel comparator. This also extends to imports. Such safeguards need to be extended on a global basis within other world regions. Chapter 4 shows there can be a wide variance in the emission factors of bioenergy delivery chains which can lead to leakage of GHG emissions to other world regions if they do not have similar regulatory control. Specific sustainability protocols, measurement, reporting and verification (MRV) standards, and policies are needed across the complete supply chain, from promoting mobilisation of low-emission feedstocks in supplying regions through to end-use and cascading. Although this issue is global in nature, major importers such as the EU hold the responsibility and market power to influence and implement trade certification across the bioenergy sector, irrespective of regional policy.

Incentivise large importers of bioenergy to diffuse bioenergy technology knowledge globally. Chapter 4 shows that regions with less developed energy systems could provide a greater global mitigative effect from biomass imports than Europe, but this relies on the availability of emerging technologies and advanced biofuels. In reality, wealthier regions are likely to claim disproportional shares of bioenergy on the international market. Deeper mitigative trajectories to 2050 and the ability to progress technology diffusion of immature technologies such as BECCS and production of advanced biofuels somewhat defend the take-up of available exports by more developed world regions. However, biomass is a limited resource which means major importers have a duty to justify reduced mitigation costs associated with low-cost bioenergy imports. Large importers should focus on fostering a global knowledge-sharing platform to improve the international diffusion of emerging bioenergy technologies from lower (concept and demonstration scales) to feasible commercial applications. This should be developed within a time frame that aligns with the global climate urgency. Suppose biomass is to fulfil a bridging function to meet EU climate targets, once the EU has crossed the bridge, biomass should be used as efficiently as possible elsewhere, with global emissions reductions and a just transition as the ultimate target.

Incentivise Carbon dioxide removal (CDR) technologies. CDR technologies such as BECCS are projected to be essential in most climate pathways limiting climate change <2°C. Global GHG reduction commitments are well behind this target, making CDR technologies increasingly important in response to late system-wide mitigation action. However, the incentivisation of CDR technologies is far from operational within international policy to scale up at the volumes projected in this thesis and other mitigation pathways as presented in the AR6 [6]. International institutions could increase supportive efforts to advance policy frameworks to ensure rapid scale-up of CDR technologies and representative carbon credit accounting within fiscal instruments such as carbon markets. Concerted efforts on this front are required globally. They must anticipate short- and long-term action with realistic but firm global sequestration targets set along intermediate milestones to net zero. For BECCS, as with other CDR's, this will also likely entail setting clear accounting rules for transboundary CDR value chains to ensure that double counting is avoided.

Initiate EU investment for up-scaling domestic sustainable production and for its sourcing activities with trade partners. If the EU pursues a decarbonisation strategy that maximises low-cost biomass, imports and domestic collection of agricultural and forestry residues will need to increase significantly. Substantial bioenergy contributions to Europe's mitigation targets are technically obtainable under the regulatory confinements of RED II at 3.7 EJ yr^{-1} by 2030 and 13.8 EJ yr^{-1} by 2050. However, this increased role depends on importing large volumes of bioenergy from diversified sourcing regions. The EU must recognise the uncertainty surrounding the availability of imports for its mitigation obligations. For example, the 'Feasibility' scenario (Chapter 4) suggests annual EU emissions would increase by 0.26 $GtCO_2eq$ by 2050 compared to a 'Free trade' default. In order to avoid this whilst maintaining a cost-minimal energy transition, trade agreements should be fostered through timely policy intervention.

The EU can aim at capacity building within highlighted exporter regions to increase sustainable production potentials. Europe could proactively support developing bioenergy policy frameworks and strategic action in key exporting regions in South

America and Africa. Bilateral development must be at the core of this process to stimulate and accelerate biomass production, infrastructure, processing, and conversion plants to unlock mitigation potential on both sides of the trade agreement. This would ensure increased value retention in producing countries and contribute to economic development. Trade relations could be further strengthened through knowledge sharing and secured investment schemes, including a thorough risk assessment to minimise project failure. The broader socioeconomic implications of trade activities must be considered and monitored closely to ensure benefits and avoid conflicts. These include human rights, poverty, land grabbing, and biodiversity loss, which must be actively addressed, fostering the bioenergy industry's contribution to alleviating these concerns. Whilst diversification of supply is a challenge for Europe, it provides the opportunity to improve energy security due to a larger array of sourcing options than fossil incumbents.

Develop a strategic action plan for the EU energy infrastructure network. The existing pipeline network across the EU is inadequate to support a decarbonisation strategy that deploys CCS, liquid biofuels, and/or hydrogen. Pipelines are a concern that needs to be addressed today, considering four main aspects. First, imported liquid bioenergy carriers are projected to increase to 75Mt by 2050. Second, projected carbon captured by BECCS in 2050 would require a substantial transport network across the continent that can handle volumes of storage-bound CO_2 larger than the current capacity of the EU natural gas network. Third, promotion of biomethane production is targeted to 35 bcm (or 1.3 EJ yr^{-1} by 2030) within the REPowerEU plans. Fourth, the European Commission's Fit for 55 package set a target of 10 Mt domestic renewable hydrogen production and 10 Mt renewable hydrogen imports by 2030. Considering the urgency of the EU climate commitments, infrastructure planning needs clear guidance for major import terminals and distributive networks that match the demand for hydrogen and liquid bioenergy. In addition, a CCS timeline with intermediate milestones for pipeline capacity upgrading and storage locations is needed. Such strategies must integrate MS-level 5yr NDC cycle communications with transmission system operator's implementation plans to set concrete roadmaps that ensure the infrastructure is ready ahead of time.

Annexes

A

ANNEX II

Annex of Chapter (2)

Annex II.1: Characteristics of the resource assessment studies included

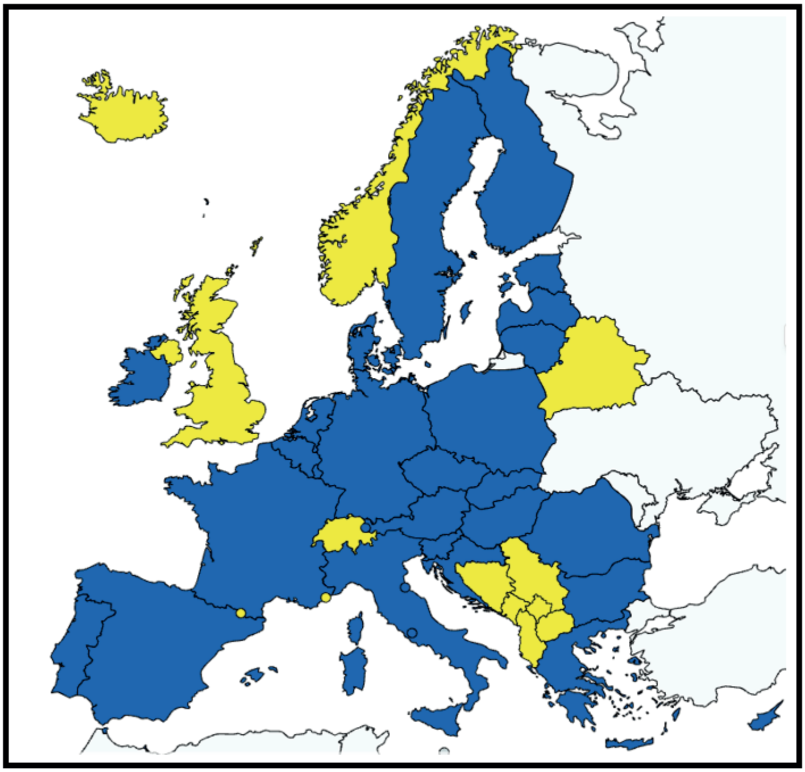
Study	Method	Objective	Constraints	Key factors in Scenario(s) explored
EEA* * *(2006)	Statistical analysis & Spatially explicit	*‘Assess how much biomass is technically available for energy production without increasing environmental pressures’*	Sustainability	***(i)*** High yield for bioenergy crops (increased supply is driven by dedicated bioenergy crops) ***(ii)*** High fossil fuel prices, ***(iii)*** Liberisation of agricultural markets ***(iv)*** 40% GHG reduction by 2030 ***(v)*** Strict environmental constraints ***(vi)*** self-labeled ‘conservative estimate’
Ericsson and Nilsson* * *(2006)	Statistical analysis	*‘Produce a more detailed biomass resource assessment for Europe than previously undertaken’*	Implementation	**(S1) Low biomass harvests:** ***(i)*** forestry residues & energy crops wields >40% from 2002 levels ***(ii)*** 25% of arable land for energy crops
				(S2) High biomass harvests: ***(i)*** forestry residues & Energy crops yields increase further >30% ***(ii)*** land availability for EC increases further
De Wit & Faaij* * *(2010)	Statistical Analysis & Cost supply analysis	*‘Assess EU cost & supply potentials for biomass resources’*	Economic, Sustainability	**(S1) Baseline:** ***(i)*** yields rise in line with historic trend for W. Europe with ‘upward deviation for C&E Europe
				(S2) Low yield Energy crops: ***(i)*** Strict sustainability criteria increases organic farming use of arable land and yields fall overall
				(S3) High yield Energy crops: ***(i)*** yields in C & E EU increase quicker to match W Europe by 2030)
Biomass Futures (2012)	Statistical analysis & Spatially explicit	*‘Provide a comprehensive strategic analysis of biomass supply options and their availability in response to different demands’*	Sustainability	**(S1) Reference:** ***(i)*** GHG mitigation criteria – biofuels & Liquids <50% compared to fossil fuel. Excludes compensation for ILUC
				(S2) Sustainability: ***(i)*** All bioenergy used in EU must meet <80% reductions compared to fossil and ILUC compensation is included

Study	Method	Objective	Constraints	Key factors in Scenario(s) explored
Biomass Policies (2014)	Statistical analysis & Spatially explicit & Cost supply analysis	*'Develop integrated policies for the mobilisation of resource efficient indigenous bioenergy'*	Implementation, Sustainability	**(S1) Conservative**: ***(i)*** current forestry harvest rates but residue collection does increase under sustainable practices
				(S2) Additional mobilization: increased forestry biomass mobilisation through implemented policy (based on EFOS medium mobilization estimates)
JRC – EU – TIMES (2015)	Statistical analysis & Spatially explicit & Cost supply analysis	*'Present the biomass potentials input currently used in the JRC-EU TIMES model'*	Sustainability, Market	**(S1) Low availability: *(i)*** Bioenergy not a priority ***(ii)*** non-energy use prioritised ***(iii)*** weak stimulation for biomass supply ***(iv)*** strict sustainability criteria ***(v)*** low mobilization
				(S2) Med availability: *(i)* current trends ***(ii)*** sustainability and resource efficient constraints
				(S3) High availability: *(i)* demand increases ***(ii)*** willingness to pay higher price ***(iii)*** greater mobilization ***(iv)*** economically outcompete other technologies
Bio Sustain (2017)	Statistical analysis & Spatially explicit & Cost supply analysis	*'Assess plausible policy options to ensure the sustainable production and use of bioenergy in the EU beyond 2020'*	Sustainability, Market	**(S1) Restricted: (i)** low mobilisation ***stimulants (i)*** land restrictions for wood ***(iii)*** high extra EU competition ***(iv)*** low investment
				(S2) Reference: *(i)* current trends in forestry production ***(ii)*** Extra-EU biomass demand follows BAU – medium export capacity
				(S3) Resource: *(i)* maximum utilisation of wood (ii) strong investment ***(iii)*** high export of biofuels

ANNEX III

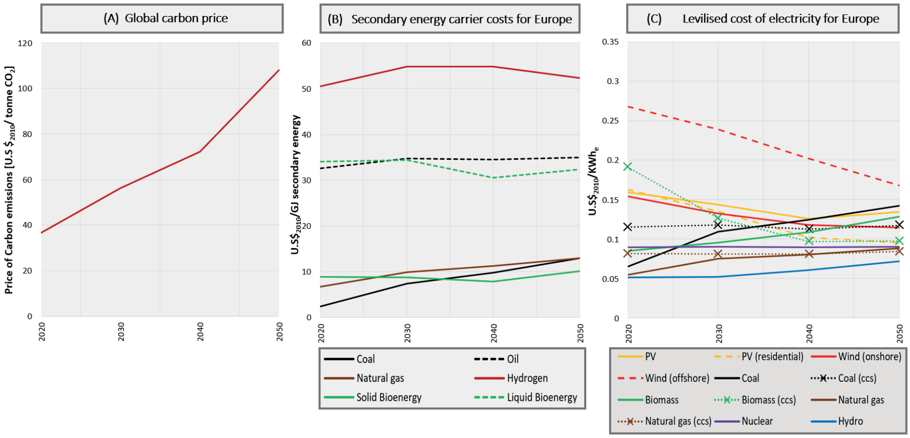
Annex of Chapter (3)

Annex III.1: The European region as represented in IMAGE 3.2



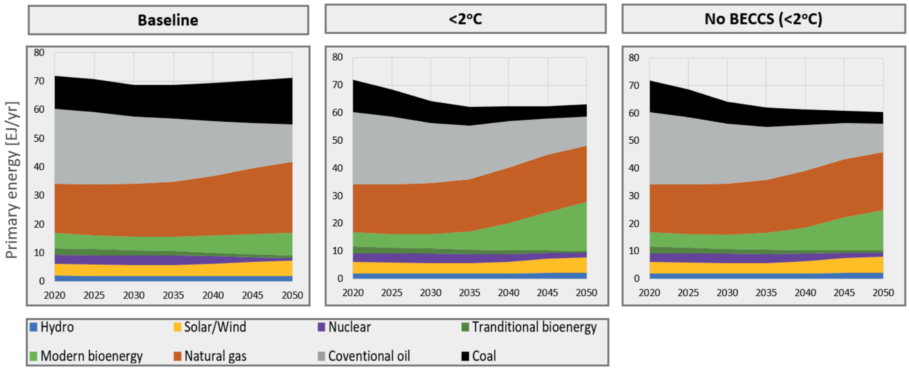
The member states of the European Union are represented in blue. In yellow additional nations included in the IMAGE 3.2 region represented as 'Europe' within this study: Albania, Andorra, Belarus, Bosnia & Herzegovina, Iceland, Kosovo, Monaco, Montenegro, Norway, N. Macedonia, Serbia, Switzerland and the UK.

Annex III.2: Development of the applied carbon price, energy carrier price and levilised cost of electricity production in Europe for the mitigation scenarios



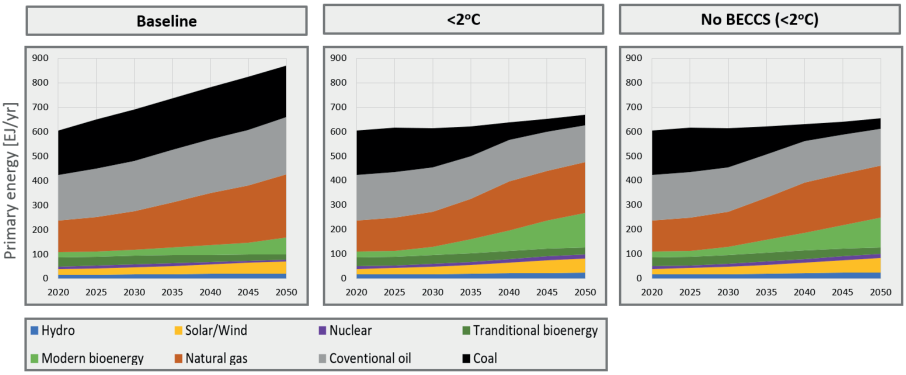
- The price of global CO_2 emissions applied in projections that adhere to a <2°C global target. This price is applied equally to all energy carriers represented by the model based on their carbon content.
- Secondary energy carrier costs for Europe per GJ. The full cost of secondary energy carriers including: carbon price, production costs, O&M wages, transport & distribution, refining and end-use tax.
–The Levilised cost of electricity production in Europe per KWh electricity. Including: carbon price, production capital (including early retirement), O&M wages, transport & distribution, refining, end-use tax.

Annex III.3: Total primary energy demand development by energy carrier in Europe 2020-2050



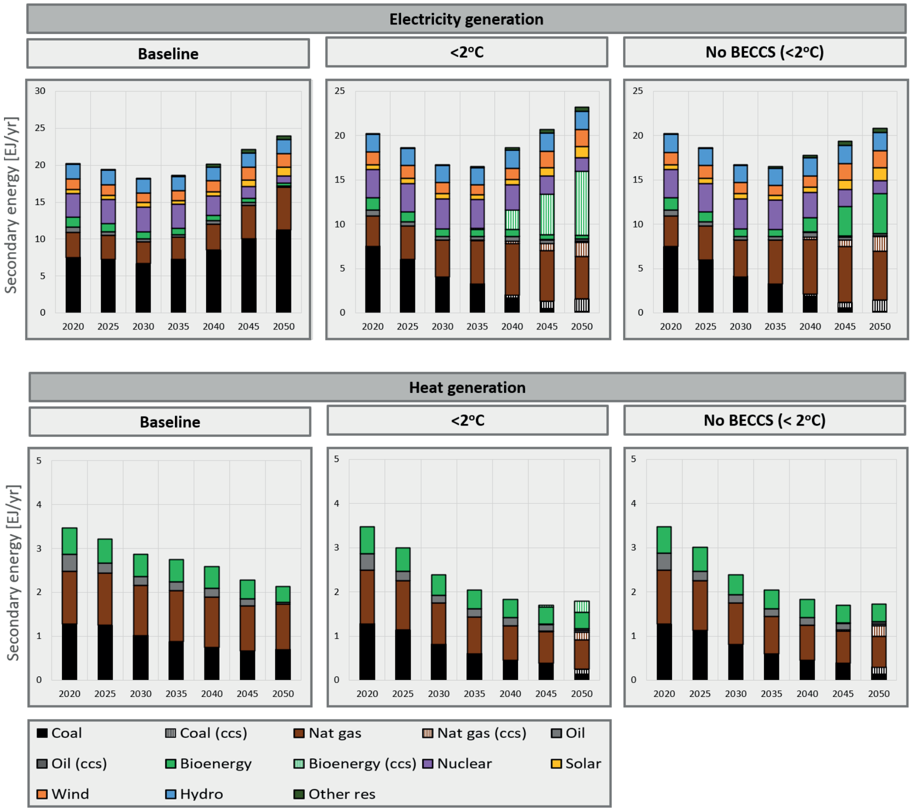
The total primary energy demand for Europe 2020-2050 is projected and aggregated per major energy carrier represented within IMAGE 3.2. Most notable observations include the drop in demand in climate mitigation scenarios '2˚C' & 'No BECCS', this is primarily due to an increased uptake of energy efficiency measures and most notably resources demand reduction strategies. Within the mitigation scenarios, the increased use of modern bioenergy displaces significant proportions of both coal and oil over the period to 2050. Other RES in the form of solar and wind play a smaller role in offsetting the electricity demand from nuclear phase-out.

Annex III.4: Total Global primary energy development by energy carrier 2020-2050



The total primary energy demand for the world 2020-2050 is projected and aggregated per major energy carrier represented within IMAGE 3.2. The global trends follow similar to those of Europe(Annex III.3). However, there are some pronounced differences. i) phase-out of oil is not observed, but a very strong displacement of coal by modern bioenergy is prioritised. ii) solar and wind have increased importance at a global scale.

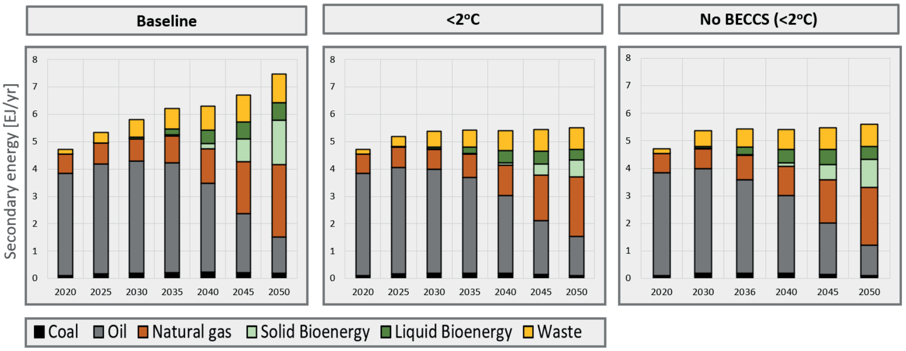
Annex III.5: Power sector energy demand per energy carrier (2020-2050) electricity and heat breakdown in Europe



The power sector (electricity and heat generation) consumption of all energy carriers represented within IMAGE 3.2 is projected for Europe 2020-2050. Here this is disaggregated between heat and electricity production.

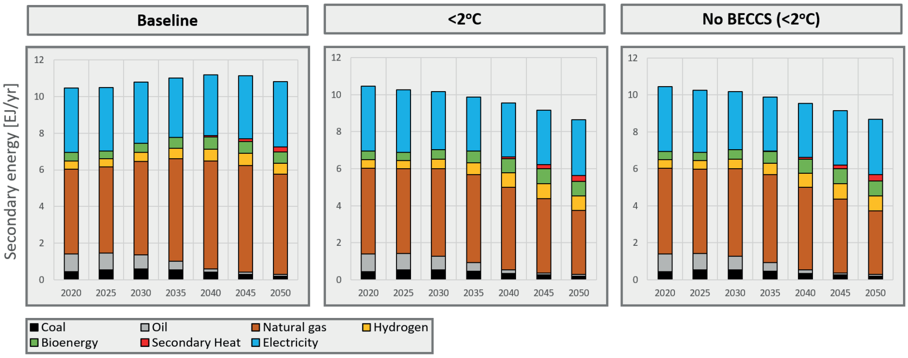
Annex III.6: Secondary energy used in the Non-energy sector by energy carrier 2020-2050 for Europe

(A) Material & Chemicals sectors



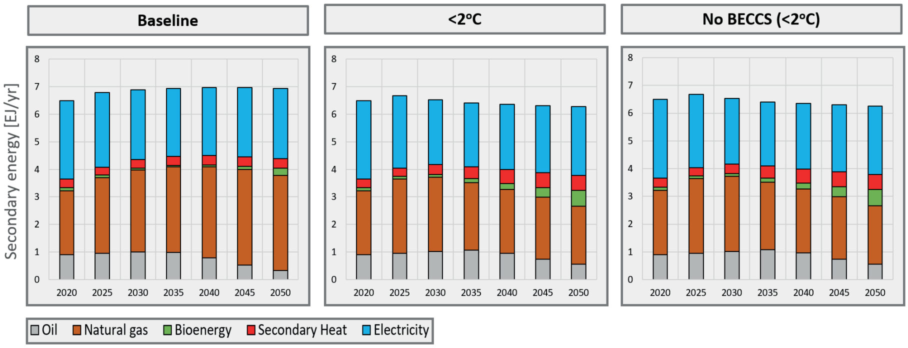
The secondary energy demand of the European non-energy sector is projected per energy carrier. Here inter-scenario trends follow closely to those seen in Annex III.3 highlighting the influence of the narrative resource efficiency assumptions.

(**B**)*Residential sector by energy carrier 2020-2050 for Europe*



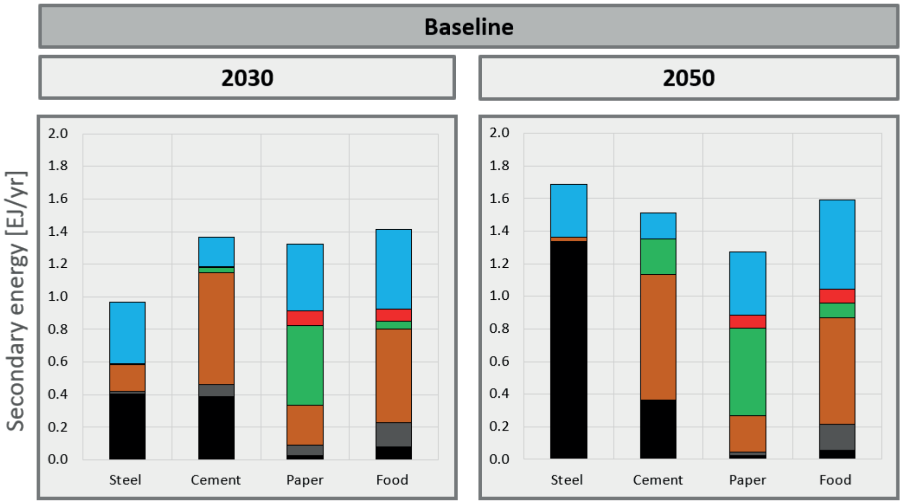
The secondary energy demand of the European residential sector is projected per energy carrier. Here underlying price induced energy efficiency effects in the mitigation scenarios show a falling energy demand for the sector.

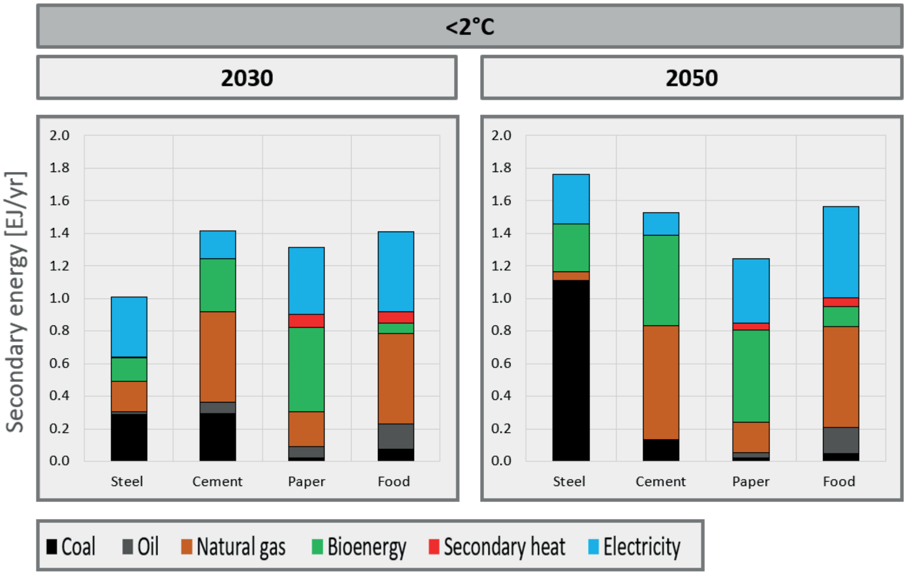
(C) Services sector by energy carrier 2020-2050 for Europe



The secondary energy demand of the European residential sector is projected per energy carrier.

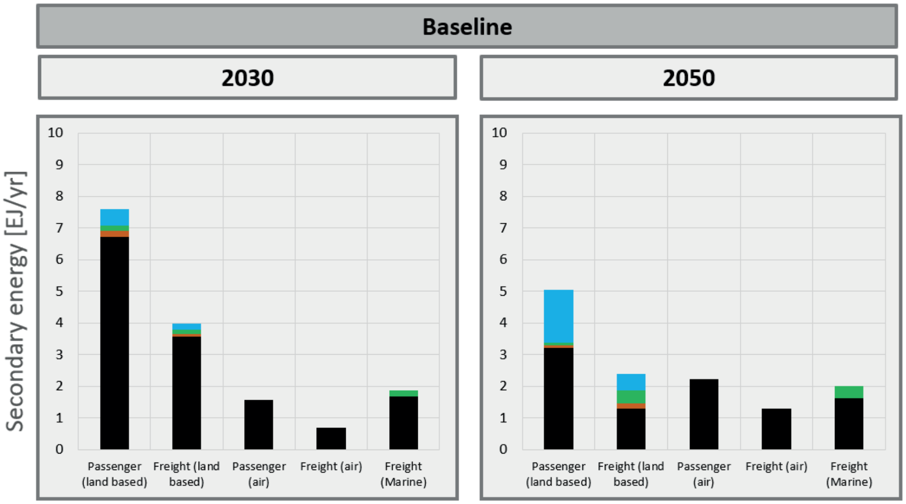
Annex III.7: Secondary energy used in the Industry sub-sectors by energy carrier 2020-2050 for Europe

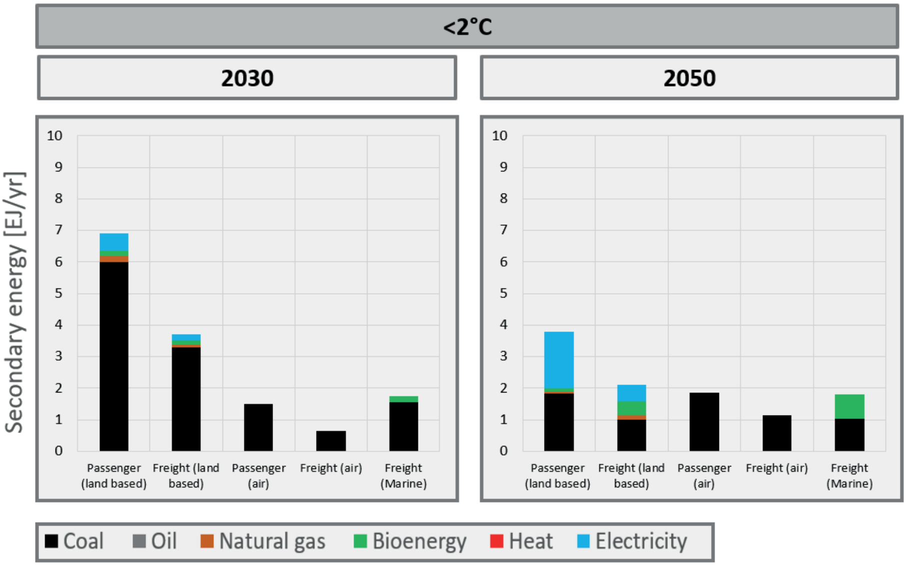




Secondary energy demand for the industry sector is presented for Europe 2020-2050. Sub sectors include Steel, Cement, Paper & food. Secondary heat here refers to recycled waste heat from industrial processes.

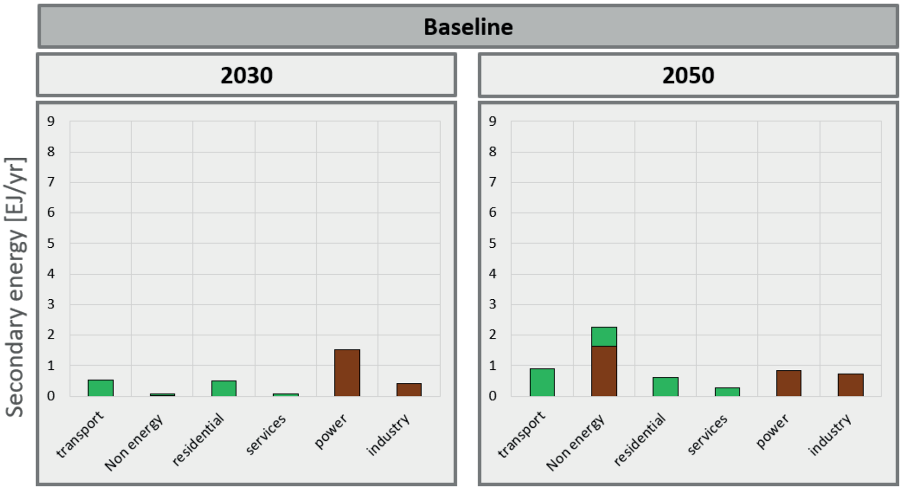
Annex III.8: Secondary energy demand in the Transport sector by energy carrier 2030 & 2050 for Europe

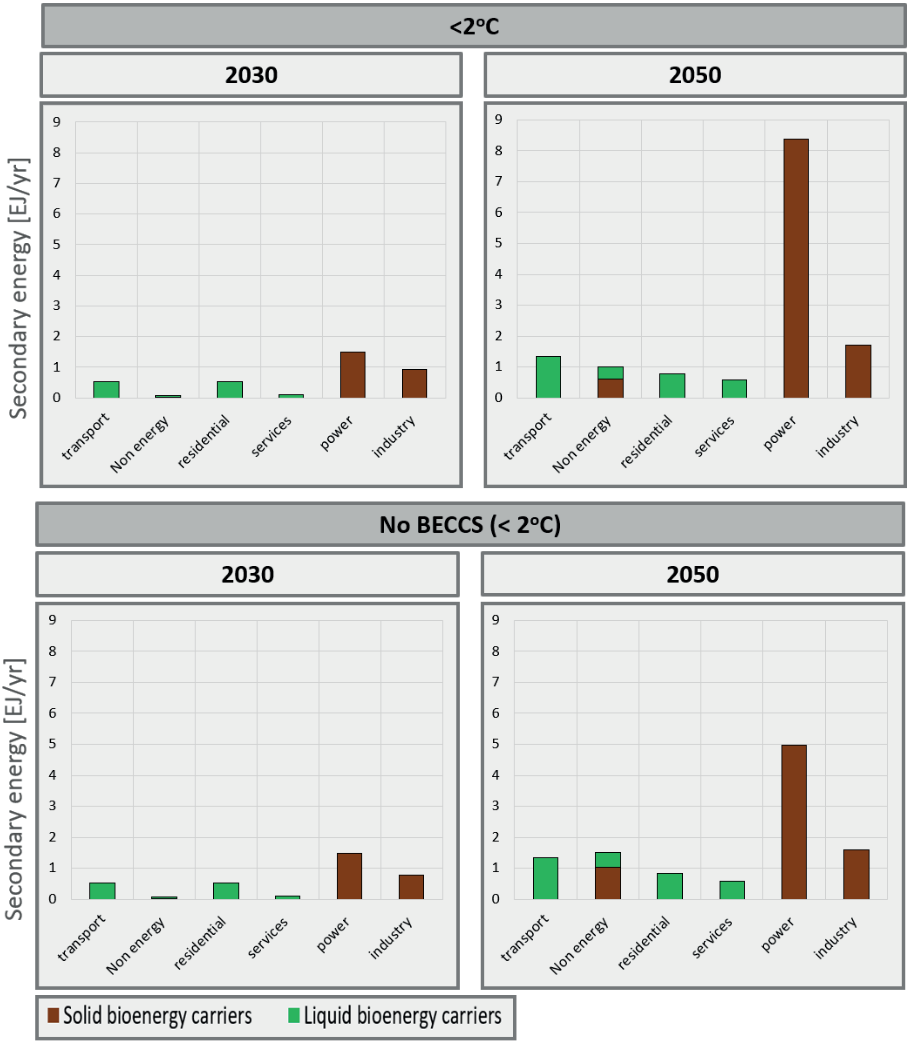




Above the secondary energy carrier demand for the European transport sector is shown for the baseline and '<2˚C' scenario for snapshot years 2030 & 2050. Transport is disaggregated to show the modes of transport represented within IMAGE 3.2.

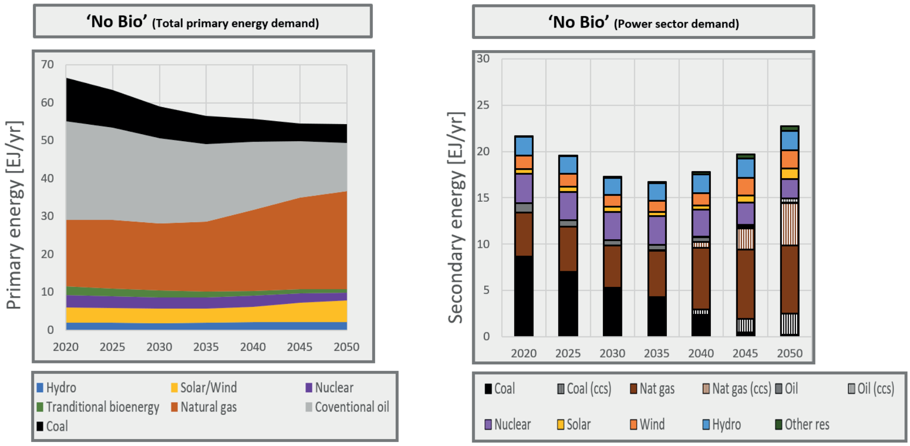
Annex III.9: Liquid and Solid bioenergy carrier demand in end use sectors for Europe 2030 & 2050





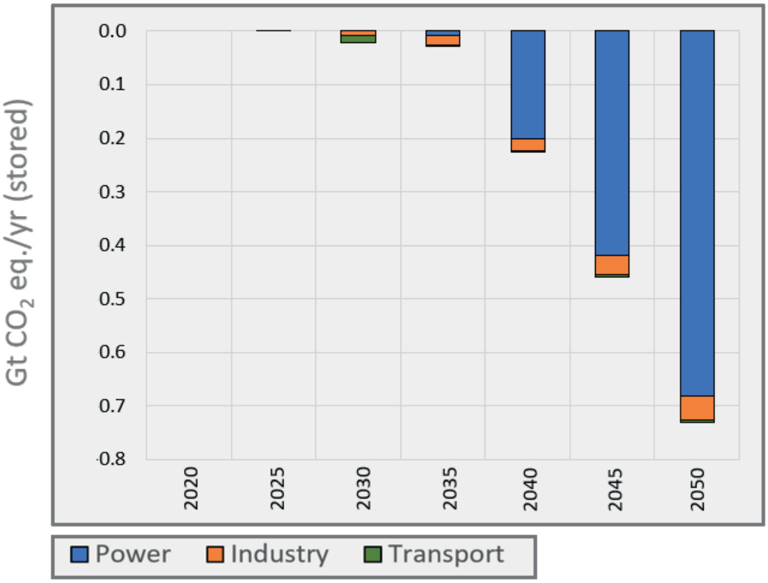
The bioenergy demand when desegregated into liquid vs solid bioenergy carriers is presented for end-use sectors across the scenarios for Europe in the snap shot years 2030 & 2050.

Annex III.10: The developments of Europe's energy demand under a <2˚C global target in the absence of bioenergy



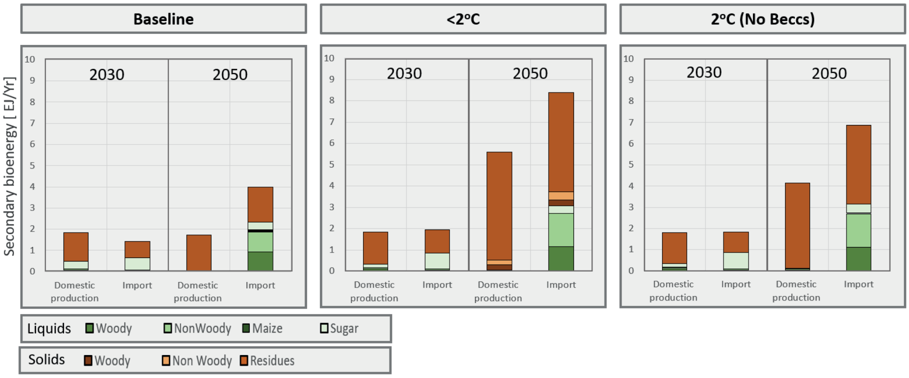
The projections for the European energy system energy carrier demands for a <2˚C global target in the absence of bioenergy. In the left-hand panel when compared to Annex III.3 '<2˚C' we observe that under the conditions of no bioenergy the EU deploys an increased amount of natural gas into the energy system. In the panel on the right it is apparent that in the power sector this results in a doubling of natural gas combined with CCS for power generation when compared to the climate mitigation scenarios with bioenergy above in Annex III.5. Furthermore, at these system costs the trends observed for other renewables remain largely unchanged over the period to 2050.

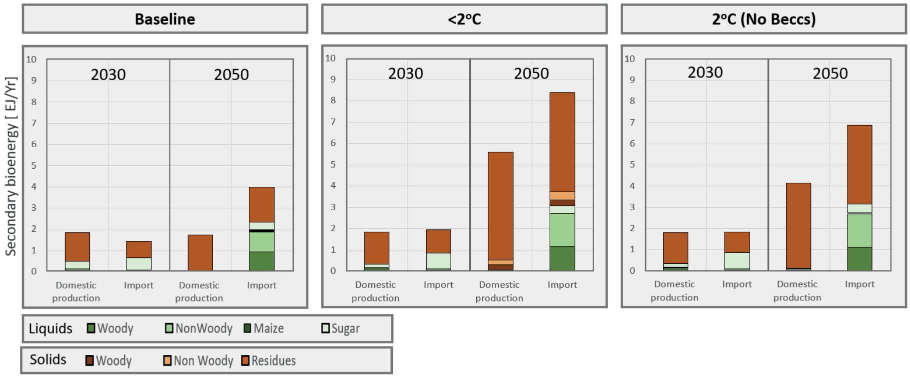
Annex III.11: BECCS stored emissions per sector in Europe 2020-2050 for a <2°C scenario



The breakdown of GHG emissions captured and stored using BECCS in Europe between the period 2020-2050 per end-use sector within IMAGE 3.2. Power generation, more specifically the generation of electricity using residues is the dominant source of BECCS emissions stored. The transport sector uses here explicitly refer to BECCS during the production of liquid biofuels consumed in the transport sector.

Annex III.12: Domestic and imported supply of EU feedstock consumption in 2030 & 2050





The projected bioenergy demand for the EU in 2030 & 2050 from domestic produced bioenergy carriers vs imported sources, when disaggregated into bioenergy carriers.

Annex III.13: Comparison to other IAM projections at European level

To gague the robustness of the estimates produced here and put the numbers into context a brief comparison is made to other bioenergy IAM studys at an EU level.

As a precursor to this study a review of projections from 11 other IAMs bioenergy demand from 2020-2050 in the EU was performed from outputs achieved as part of the 33rd study of the Stanford Energy Modelling Forum (EMF-33)[142]. Which aimed to quantitatively consider the developments bioenergy under boundary climate policy conditions similar to the Paris agreement. The set of IAM's include in this comparison study are comprised of, general equilibrium, intertemporal optimization and dynamic recursive models akin to the IMAGE 3.2 model here [72]. A more detailed model specification description is available and published elsewhere [129].

The comparative study utilised a similar scenario protocol in which an additional No BECCS scenario was enforced. The EMF-33 did not aim for a detailed regional assessment. However, the exercise was able to yield total EU demand and interregional trade requirements at a significantly cruder level. Of the partaking IAM's (11) yielded total EU bioenergy demand estimates and (5) produced reliable runs able to hit the 2°C without BECCS.

Comparison of study results to the EMF-33 estimates for EU Primary bioenergy demand (reported in [EJyr^{-1}] for the year 2050

	(N)	Range	IMAGE 3.2
2°C	11	4.5 – 19.8	17.7
2°C No BECCS	5	4.4 – 13.2	14.5

From table 2 we can deduce that the IMAGE3.2 is placed in the higher ranges of these estimates for both with/with-out BECCS.

For interregional import requirements (6) models had the ability toreport imports for the 2°C scenario and only (3) under conditions of prohibited BECCS. Table 3 below indicated once more the IMAGE 3.2 estimates for interregional import demand is on the upper side of estimates in-line with those of overall bioenergy demand seen above.

Comparison of study results to the EMF-33 estimates for EU Primary bioenergy trade (reported in [EJyr^{-1}] for the year 2050

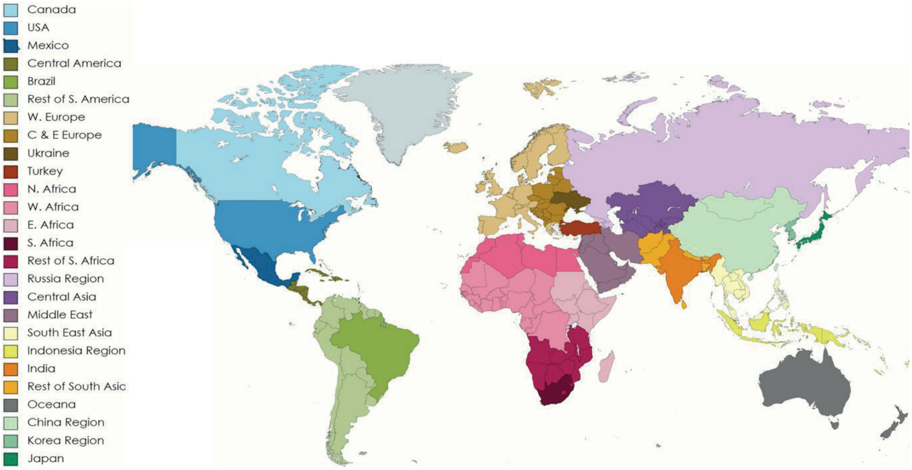
	(N)	Range	IMAGE 3.2
2°C	8	-8 - 9.5	9.5
2°C No BECCS	6	-3 - 7.9	7.9

These differences in the prevalence of bioenergy within the EU energy system are due to a combination of key assumption differences pertaining to total energy demand in the EU, food demand, biomass feedstock prices, price per unit energy for non-fossil energy sources (competitivity), and natural system parameters including biomass supply which are endogenously derived within each model. These underlying causes for model discrepancies in bioenergy deployment are discussed at length in a recent publication as part of the EMF-33 project [72].

ANNEX IV

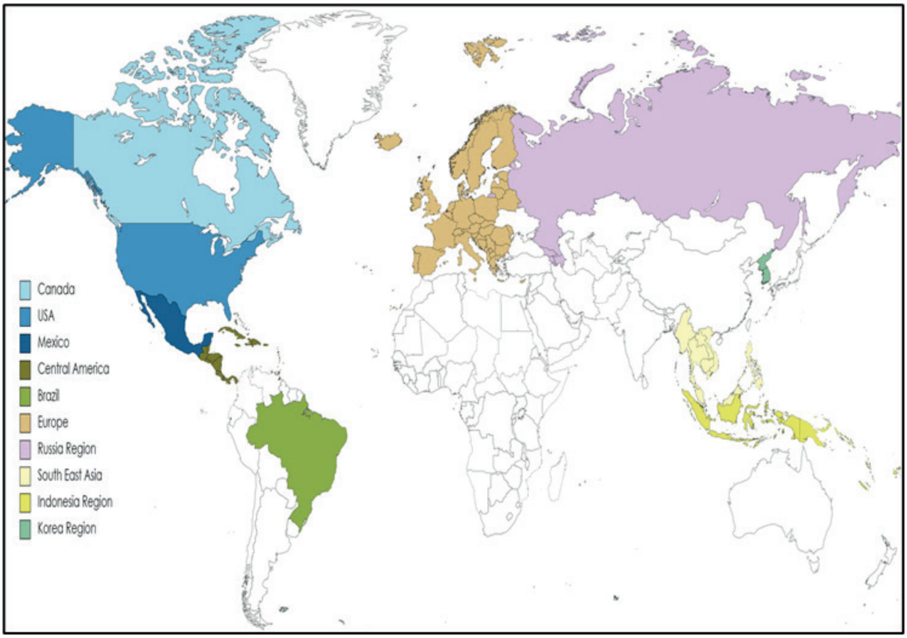
Annex of Chapter (4)

Annex IV.1 Regional variation in Trade scenarios



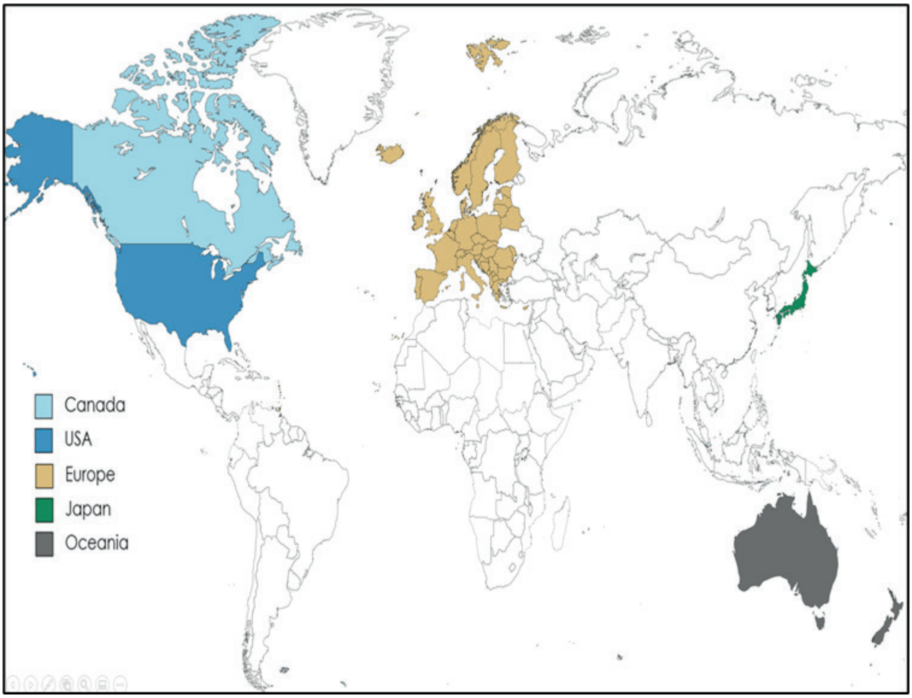
(B) World Regions represented in the IMAGE 3.2 Model.

Within this study, the regions’ W.Europe’ and ‘C & E. Europe’ are combined to represent Europe. All other world regions (24) represented by the IMAGE3.2 model are displayed. These are the regions allowed to trade bioenergy with Europe in both the ‘Free Trade’ & ‘RED II’ scenarios.



(A) World Regions allowed to trade with Europe in the 'Current partners' scenario.

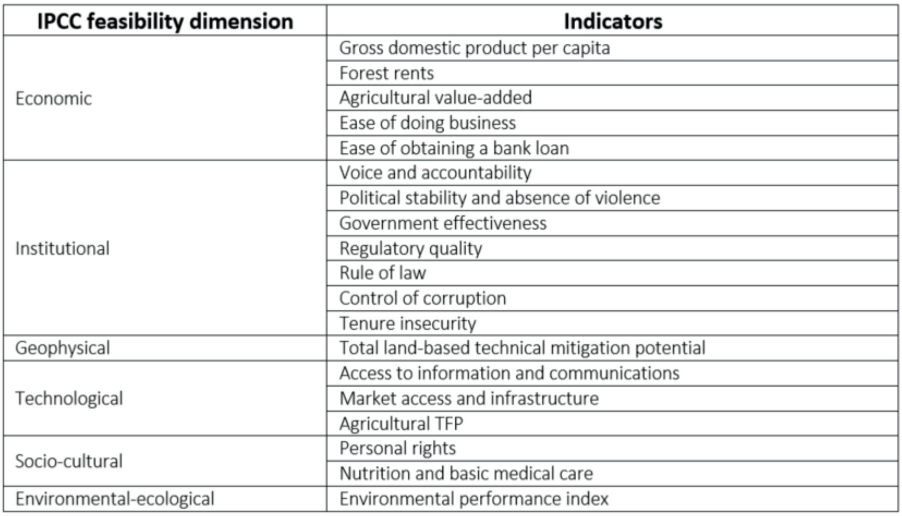
This figure represents world regions that are allowed to trade bioenergy with Europe in the 'Current partners' scenario. They represent regions that hold significant trade in bioenergy with Europe at present. Greyed out regions are prohibited from trading with Europe, but they may continue to trade with other world regions.



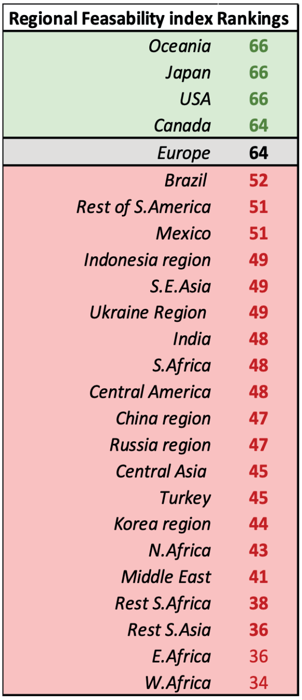
(C) World Regions allowed to trade with Europe in the 'Feasibility' scenario.

World regions that are allowed to trade bioenergy with Europe in the 'Current partners' scenario. They represent regions deemed feasible to comply with European sustainability criteria when taking into account techno-economic and socio-political challenges. Blanked out regions are prohibited from trading with Europe, but they may continue to trade with other world regions. The regional feasibility scores as determined by the approach described in Table 4.1 are presented below.

Feasibility indicators assessed in Roe et al., 2021 [32]

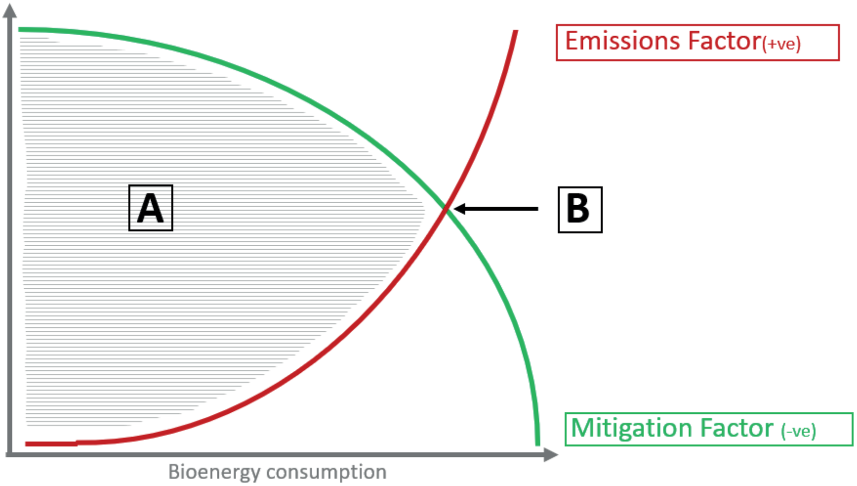


IPCC feasibility dimension	Indicators
Economic	Gross domestic product per capita
	Forest rents
	Agricultural value-added
	Ease of doing business
	Ease of obtaining a bank loan
Institutional	Voice and accountability
	Political stability and absence of violence
	Government effectiveness
	Regulatory quality
	Rule of law
	Control of corruption
	Tenure insecurity
Geophysical	Total land-based technical mitigation potential
Technological	Access to information and communications
	Market access and infrastructure
	Agricultural TFP
Socio-cultural	Personal rights
	Nutrition and basic medical care
Environmental-ecological	Environmental performance index



Regional Feasability index	Rankings
Oceania	66
Japan	66
USA	66
Canada	64
Europe	64
Brazil	52
Rest of S.America	51
Mexico	51
Indonesia region	49
S.E.Asia	49
Ukraine Region	49
India	48
S.Africa	48
Central America	48
China region	47
Russia region	47
Central Asia	45
Turkey	45
Korea region	44
N.Africa	43
Middle East	41
Rest S.Africa	38
Rest S.Asia	36
E.Africa	36
W.Africa	34

Annex IV.2: Marginal emission mitigation of bioenergy



Conceptual diagram for the role of demand onto bioenergy mitigation potential.

In the diagram above, the emissions curve represents emissions released during the production of bioenergy via: Land use change, indirect land-use change, cultivation, transportation, conversion to bioenergy/final energy carrier. The mitigation potential curve represents the reductions in emissions from substituting the current aggregate emissions factor for end uses with bioenergy.

There are a multitude of dynamics at play that influence the total mitigation capacity of bioenergy available (A) and the point at which emissions from bioenergy become net positive (B) compared to the incumbent energy mix at any given time step.

> (A) The emission mitigation from bioenergy is dependent on the difference between the emissions for bioenergy production, and the mitigation bioenergy achieves from the substitution of fossil fuels. As seen above, as consumption increases, so does the associated emissions factor of bioenergy used in the system. This dynamic is driven by the explicit assumption that feedstocks with lower overall emissions (especially from LUC) are utilised first. Furthermore, it explicitly assumes that bioenergy displaces the most emitting fossil fuel sources first. This is in line with the use of a carbon price in the projections.
> (B) The point at which bioenergy is no longer providing mitigation and thus the position of which dictates (A) is driven left or right along the x-axis (so, dictates the total volume of bioenergy that can be consumed) by drivers and barriers.

Drivers: (shifts the EF line downwards and (B) to the right)

- Technical improvements. E.g. efficiency gains in conversion processes and improved land management and yields.
- Net-negative emissions from the deployment of BECCS or sequestration of embodied carbon into biobased materials.

Barriers: (shifts the EF line upwards and (B) to the left)

- Global climate targets influence other world regions to increase bioenergy demand. This creates a situation in which exporting regions utilise a greater proportion of their own resource base, and importing regions face stiffer competition on the international market. This effectively pushes the EU's bioenergy supply further up the emissions factor curve, limiting supply as sourcing options are pushed further towards lands with higher degradation, larger transport distances and regions with lower yield and conversion efficiencies.
- Regional specific EU regulatory control such as the RED II GHG reduction criteria stipulate that bioenergy must perform to strict default reduction values (calculated based on current energy mix). This effectively means that a likely significant proportion of area A is rendered unavailable.
- Much of the EU's bioenergy demand is projected to be met via imports where access to bioenergy with lower emission factors becomes further limited due to geopolitical factors, including the difficulty of mobilising biomass in regions with an underdeveloped export infrastructure and perceived corruption to uphold EU standards. These factors accelerate the speed at which point B is reached via lowering import availability.

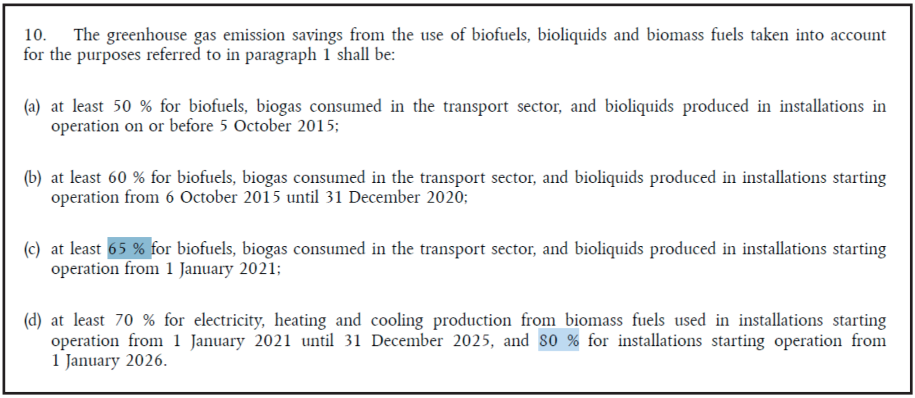
Annex IV.3: Allocation of bioenergy related emissions in this study

(A) Setting the GHG reduction criteria as defined in RED II

The following excerpts are taken directly from the Renewable Energy Directive recast [27].

In relation to the GHG saving criteria:

Article 29: Sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids and biomass fuels L 328/132



10. The greenhouse gas emission savings from the use of biofuels, bioliquids and biomass fuels taken into account for the purposes referred to in paragraph 1 shall be:

(a) at least 50 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations in operation on or before 5 October 2015;

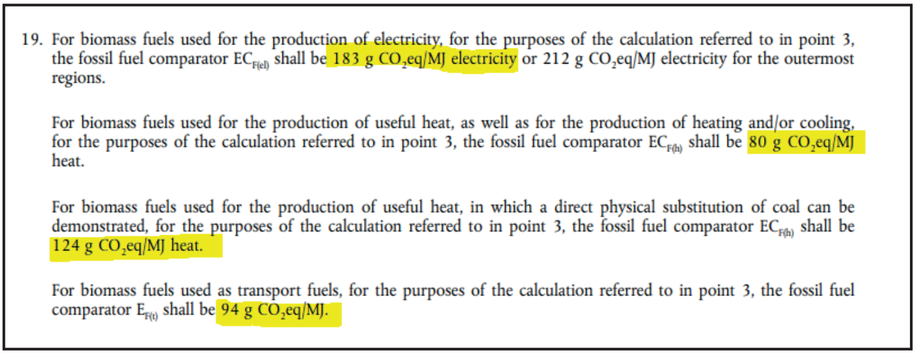
(b) at least 60 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 6 October 2015 until 31 December 2020;

(c) at least 65 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 1 January 2021;

(d) at least 70 % for electricity, heating and cooling production from biomass fuels used in installations starting operation from 1 January 2021 until 31 December 2025, and 80 % for installations starting operation from 1 January 2026.

In relation to the fossil fuel comparators that savings shall be assessed on:

Annex VI: Rules for calculating the Greenhouse gas impact of Biofuels, bioliquids and their fossil fuel comparators. Part B .19 pg. (L 328/186)



19. For biomass fuels used for the production of electricity, for the purposes of the calculation referred to in point 3, the fossil fuel comparator $EC_{F(el)}$ shall be 183 g CO_2eq/MJ electricity or 212 g CO_2eq/MJ electricity for the outermost regions.

For biomass fuels used for the production of useful heat, as well as for the production of heating and/or cooling, for the purposes of the calculation referred to in point 3, the fossil fuel comparator $EC_{F(h)}$ shall be 80 g CO_2eq/MJ heat.

For biomass fuels used for the production of useful heat, in which a direct physical substitution of coal can be demonstrated, for the purposes of the calculation referred to in point 3, the fossil fuel comparator $EC_{F(h)}$ shall be 124 g CO_2eq/MJ heat.

For biomass fuels used as transport fuels, for the purposes of the calculation referred to in point 3, the fossil fuel comparator $E_{F(t)}$ shall be 94 g CO_2eq/MJ.

Due to an increasing Carbon tax implemented within this study, the vast majority of fuel substitution within the projected European energy transition in IMAGE is from coal for heating purposes; thus, the value of 124g CO_2eqMJ^{-1} heat is the selected fossil comparator is selected.

The RED II GHG reduction criteria thresholds applied within this study are assumed fixed and applied as follows:

Bioelectricity = **36.6 gCO_2eqMJ^{-1}**
Bioheat = **24.8 gCO_2eqMJ^{-1}**
Bio transport fuels = **32.9 gCO_2eqMJ^{-1}**

(B) IMAGE end-use streams regulated by RED II

From the sectoral and technological representation within IMAGE 3.2 the following end-use streams are identified to be regulated by RED II GHG reduction criteria and are therefore subject to the cut-off limits within the RED II scenario.

Solid bioenergy carriers

1. ***Electricity generation without CCS***
    1. steam turbine
    2. combined cycle
    3. CHP
2. ***Electricity generation with CCS***
    1. steam turbine
    2. combined cycle
    3. CHP
3. ***District heating for buildings***
    1. CHP
    2. District heating plant (water boiler)
4. ***Heat in Industry***
    1. Food sector (water boiler)
    2. Paper sector (water boiler
    3. Cement sector (dry feed rotary kiln w/wo CCS))
    4. Steel sector (BF-BOF route w/wo CCS)

Liquid bioenergy carriers

5. ***Transportation fuels***
    1. Passenger (road, rail, marine, aviation)
    2. Freight (road, rail, marine, aviation)

Note: some applications of modern bioenergy carriers included within the IMAGE model are not subject to the RED II constraints due to installation capacity being below the regulated threshold. These include pellets used within the building sector for small scale heating (i.e. outside of district heating installations), biomass used for hydrogen production and small amounts of liquid fuels used as process fuels within the non-energy sector.

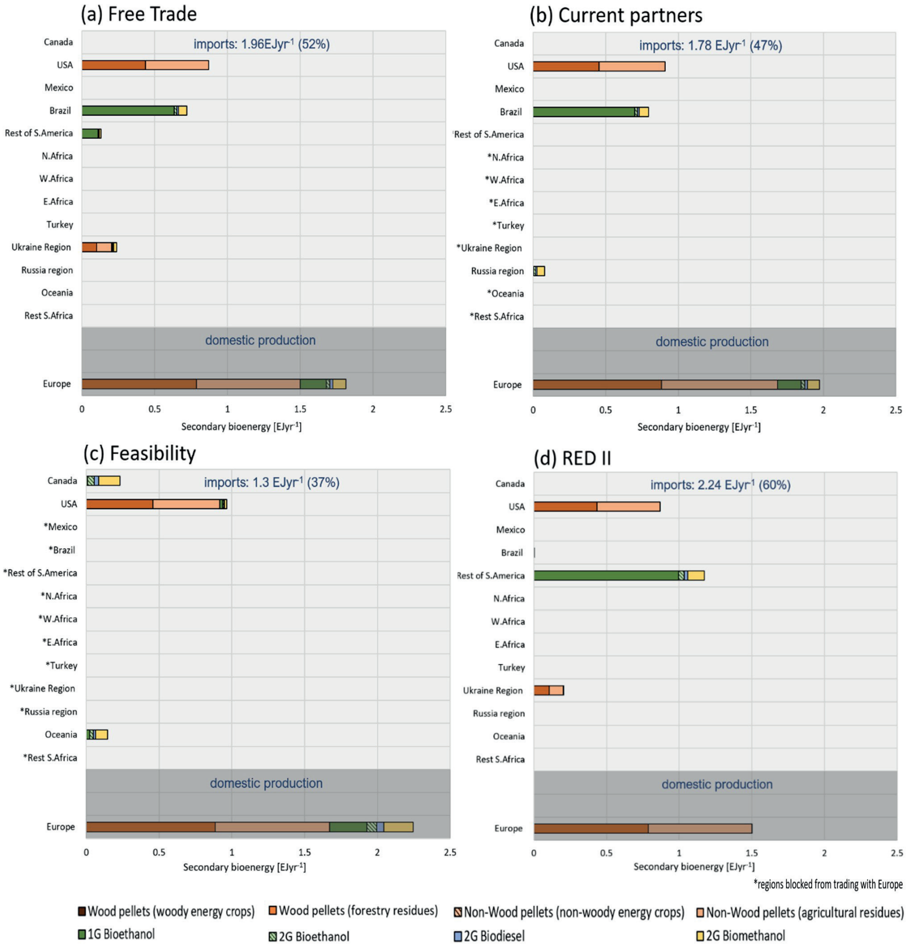
(C) Calculation of bioenergy emission factors used to apply the RED II GHG saving criteria

Within this study, the emissions accounting procedure for bioenergy in IMAGE 3.2 is tightly aligned to that of RED II, considering that the RED II methodology lends itself to process-based LCA assessment. Below, the formula used to determine bioenergy emissions as laid out in RED II [27] is presented alongside the accounting as calculated in IMAGE 3.2.

$$E = e_{ec} + e_{l} + e_{p} + e_{td} + e_{u} - e_{sca} + e_{ccs} - e_{ccr}$$

		RED II Methodology	**IMAGE 3.2**
E	=	Total emissions from the use of the fuel.	
e_{ec}	=	Emissions from the extraction or cultivation of raw materials.	- Emissions from energy used for cultivation and extraction of biomass and for fertiliser application. - The efficiency of conversion to electricity or heat is included as in RED II methodology for each separate end-use stream identified in above. - Energy requirements for storage & drying are assumed to be zero, with wastes and leakages captured within $e_{p\ \text{below.}}$
e_{l}	=	Annualised emissions from carbon stock changes caused by land-use change.	- Forestry carbon stock changes resulting from harvested residues are determined as zero. Bioenergy dedicated crops are only allowed to grow on natural grasslands or abandoned agricultural lands. - The coupled dynamic global vegetation model LPJmL [245] [246] is used to provide LUC factors to IMAGE whilst considering IMAGE projections for dynamic factors such as the land-use scenarios and the impact of climate change. This study assumes a median land-use scenario (SSP2) in combination with a 2.6 Wm^{-2} radiative forcing climate scenario [76]. - A 20 yr. annualisation for changes to carbon stock is applied as stipulated in RED II methodology. -Excludes the bonus of 29 g CO_2eqMJ^{-1} biofuel or bioliquid if biomass is obtained from restored degraded land as stipulated in RED accounting
e_{p}	=	Emissions from processing;	- Emissions from process energy inputs during conversion (using regional average emissions intensities), and includes efficiency (wastes losses) of conversion from primary biomass to secondary bioenergy carriers where applicable. - Negative emissions resulting from BECCS application during liquid bioenergy production is accounted for at this stage.
e_{td}	=	Emissions from transport and distribution;	All transport emissions from field to end-use (excluding internal European transport)
e_{u}	=	Emissions from the fuel in use.	Biogenic emissions are ruled net-neutral identical to RED II
e_{sca}	=	Emission savings from soil carbon accumulation via improved agricultural management.	Emissions reductions from positive soc accumulation are determined in the calculation of e_l factor above.
e_{ccs}	=	Emission savings from CO_2 capture and geological storage.	BECCs emissions are subtracted (accounting for assumed technologically specific capture rates in Europe)
e_{ccr}	=	Emission savings from CO_2 capture and replacement.	CO_2 capture and replacement is not technologically represented within IMAGE3.2

Annex IV.4: Supplementary bioenergy import projections



(A) European bioenergy import volumes from sourcing regions and domestic production in 2030

In the ‘Free trade’ scenario, total European bioenergy demand in 2030 holds static at 2020 levels (3.8 EJyr^{-1}), with imports gradually increasing to account for 52% of demand. In 2030 this level of demand can be met across the other trade scenarios for solid bioenergy carriers (2.6 EJyr^{-1}), and only the ‘Feasibility’ scenario fails to meet liquid demand (1.2 EJyr^{-1}). Meeting this demand under the applied trade constraints is achieved through alternating sourcing regions and increased domestic production.

Prohibiting trading regions to already established bioenergy trading partners (‘Current partners’), considered a likely development by 2030 [23] [24], results in minor changes to Europe’s trading patterns with small amounts of solid bioenergy supply from the Ukraine region replaced by domestic production. For liquids, a short-fall from the Rest of South America is substituted with further reliance on Brazil and small amounts of 2G biomethanol from Russia. The ‘Feasibility’ scenario shows an identical pattern for solid carriers promoting domestic production. A different pattern unfolds for liquids whereby regions with larger production of maize and sugar crops are blocked, meaning Europe is forced to rely on more expensive 2G fuels sourced from both Canada and Oceania. This results in an overall liquid carrier deficit of 0.2 $EJyr^{-1}$. The ‘RED II’ scenario mirrors solid bioenergy carrier sourcing. Conversely to the other scenarios, domestic production of liquids is abandoned due to non-compliance with the RED II GHG constraints. The same narrative applies to Brazilian sourced bioethanol. This leads to Europe shifting liquid supply to Rest of S. America, which can mostly be met through 1G bioethanol.

(B) European bioenergy import volumes from sourcing regions

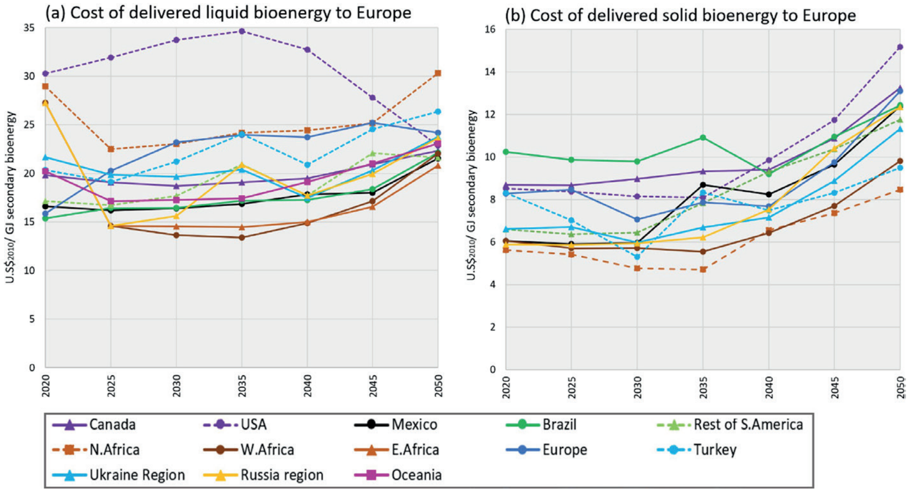
Below, the numerical data is presented for European bioenergy imports in 5yr intervals and cumulatively over the period 2020-2050. The imports are aggregated into solid and liquid energy carriers for comparative simplification.

Europe's bioenergy imports in 5yr interval and cumulatively (2020-2050), reported in EJ of secondary bioenergy.

	2020	2025	2030	2035	2040	2045	2050	(2020-2050)
Free Trade								
Solids	0.87	0.92	1.07	1.06	2.07	3.54	5.25	60.73
Liquids	0.62	0.58	0.89	1.53	2.11	2.73	3.10	49.96
Total	1.49	1.50	1.96	2.59	4.18	6.26	8.35	**110.68**
Current partners								
Solids	0.63	0.66	0.91	0.95	1.62	2.57	3.53	46.02
Liquids	0.67	0.67	0.87	1.51	2.03	2.24	2.11	45.18
Total	1.30	1.34	1.78	2.46	3.66	4.81	5.65	**91.20**
Feasibility								
Solids	0.89	0.75	0.95	0.67	0.88	1.39	1.79	31.14
Liquids	0.68	0.42	0.49	0.81	1.23	1.39	1.63	28.34
Total	1.57	1.18	1.43	1.48	2.11	2.78	3.42	**59.48**
RED II								
Solids	0.87	0.92	1.07	1.06	2.06	3.48	5.18	60.14
Liquids	0.59	1.02	1.17	1.54	1.90	2.41	2.96	51.01
Total	1.46	1.93	2.24	2.59	3.96	5.88	8.14	**111.15**

An interesting observation appears when comparing the cumulative trade flows. There is an increase in overall European bioenergy imports within the 'RED II' scenario, i.e. a restrictive regulation actually bolsters bioenergy imports to Europe. This unexpected dynamic is caused by Europe in the 'Free Trade' scenario <2035 being placed into a situation in which it can no longer domestically produce liquid bioenergy carriers because the EF attached to them is in exceedance of the RED II GHG criteria. Therefore, an early increase in imports from the Rest of S.America is relied upon to fulfil this short-fall. Even though >2035 liquids imports become lower in the 'RED II' scenario, cumulatively, this trade restriction actually increases bioenergy imports to Europe.

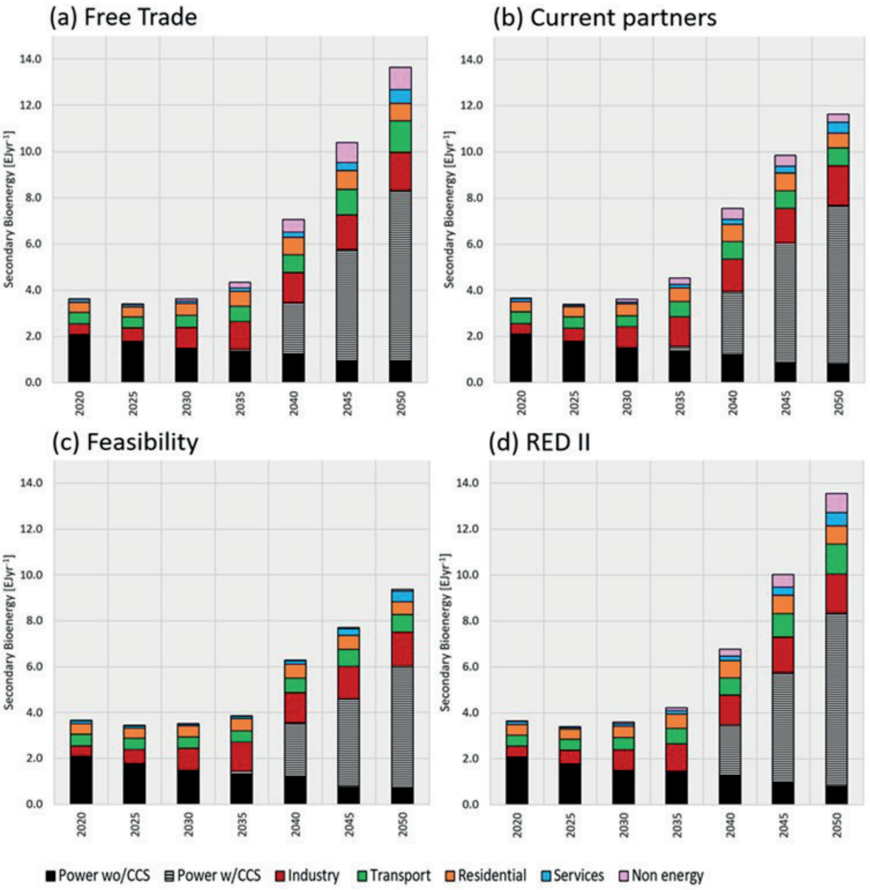
In terms of cumulative bioenergy imports (2020-2050), prohibiting trade with non-established regions in the 'Current partners' scenario creates an import short-fall of 19.5 EJ (15 EJ solids and 4.5 EJ liquids), approximately five times current annual European consumption. The 'Feasibility' scenario projects a substantially larger deficit of 51 EJ (30 EJ solids and 21 liquids.



(C) Development of cost of delivered bioenergy carriers to Europe (2020-2050).

Above the delivered cost of solid and liquid bioenergy carriers to Europe is presented for a marginal unit (GJ) of energy under default model condition, i.e. the ‘Free Trade’ scenario. These delivered costs strongly influence the trading strategy of Europe. The pricing data shown above is intended to be interpreted as a reference point for comparing exporting region’s competitiveness for supplying Europe. However, during the optimisation process, these biomass cost supply curves are dynamic within time-step(s), i.e. prices increase as total production rises.

Annex IV.5: Sectoral deployment of European bioenergy across trade scenarios (2020-2050)



Above the sectoral bioenergy deployment within end-use sectors represented by IMAGE is displayed across the trade scenarios (2020-2050). Important observations include:

A significant short-fall in the power sector for the 'Feasibility' scenario as it stands alone in incurring large unavailability of solids bioenergy supply >2040, which leads to a marked reduction of 2 EJ of electricity production with BECCS. This has large implications for European mitigation due to the substantial negative emissions provided by this technology. However, the sector does hold the scope to deploy other low-carbon technologies to bridge this mitigation gap partly. The effect on mitigation is discussed in sections 4.3.2 and 4.3.3.

A shortage in liquids bioenergy access observed across trade constraint scenarios inadvertently and disproportionally dampens bioenergy uptake in the non-energy sector. Any liquid bioenergy supply is primarily routed to the transport sector where deeper emissions reductions than the average energy mix can be achieved, hence the most cost-effective uptake due to the overarching carbon tax. In the strictest 'Feasibility' scenario, the non-energy sector moves to completely fossil-based.

Annex IV.6: Supplementary bioenergy emission projections

Below the total annual emissions from production to consumption attached to European bioenergy imports is displayed per sourcing region in 2030 & 2050. A 'true' mitigation potential attached to this bioenergy is identified, which is not possible to deduce from the EF projections alone. This mitigation potential is determined by comparison to the emissions occurring to provide the same energy service for Europe in the absence of bioenergy, the 'No bio' scenario. This approach is used to reflect the true mitigation potential of bioenergy compared to a system that is able to re-direct the cost of bioenergy into other available low-carbon technologies.

(A) Snap-shot overview of the average mitigation factor (solids and liquids) of European bioenergy imports:

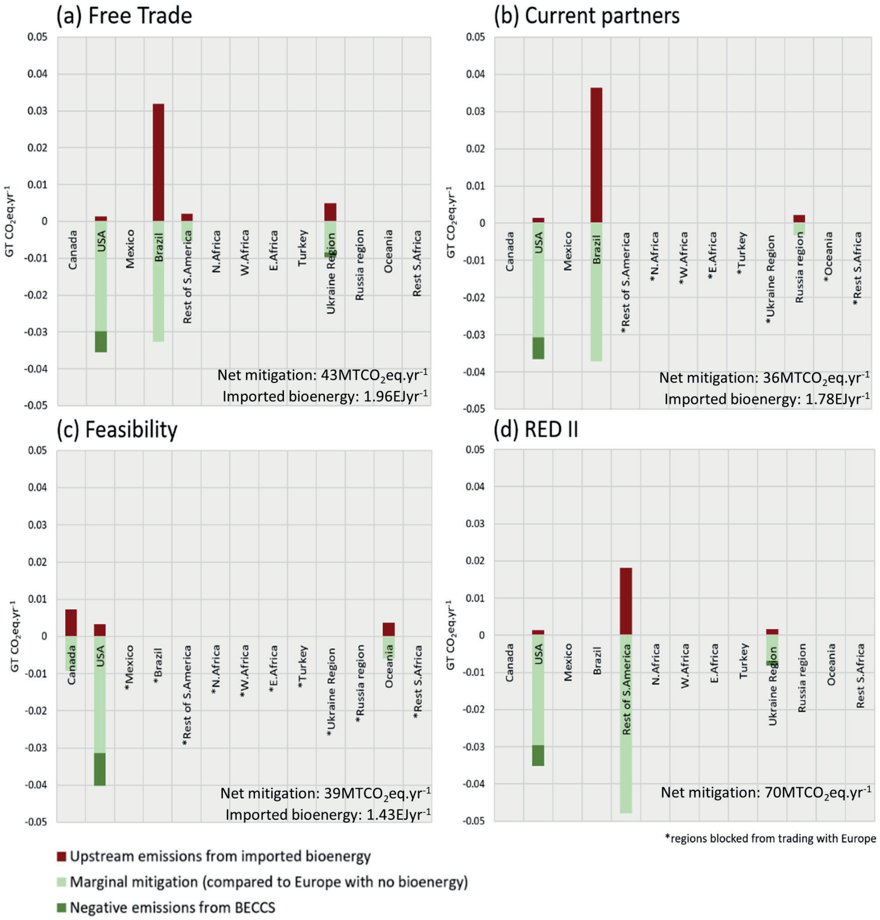
Average MF gCO_2Mj^{-1} imported secondary bioenergy

Scenario	**2030**	**2050**
Free Trade	22	50
Current partners	20	48
Feasibility	27	48
RED II	31	54

By 2030 in an unrestricted 'Free Trade' scenario, bioenergy imports provide Europe with 43 $MTCO_2yr^{-1}$ GHG mitigation. A suppressed access to bioenergy imports in the 'Current partners' and 'Feasibility' scenarios reduces mitigation to 36 and 39 $MTyr^{-1,}$ respectively. The 'Current partners' scenario constraints allow Europe access to more bioenergy imports than the heavily constrained 'Feasibility' scenario yet realises lower mitigation. This highlights the importance of importing 'sustainable' bioenergy with lower production emissions. Within the 'Feasibility' and 'Free trade' scenarios, a significant proportion (0.7 $EJyr^{-1}$) of Europe's imports arrives from Brazilian 1G bioethanol in 2030. This Brazilian supply carries relatively high land-use emissions, which push the EF > 62$gCO_2eqMJ_{fuel}^{-1}$, which effectively means net-zero mitigation. Within the 'Feasibility' scenario, Europe replaces 1G bioethanol imports with 2G liquids (mainly in the form of 2G biomethanol) from Oceania & Canada regions with lower attached EF of 27 and 50 $gCO_2eqMJ_{fuel}^{-1}$.

This is evident in table Annex IV.4(b), whereby the average MF from imported bioenergy in 2030 for the 'Feasibility' scenario outperforms both 'Free Trade' and 'Current partners' scenarios. Whilst the 'Feasibility' scenario sources liquids from regions that can provide lower attached upstream emissions, the additional costs reduce overall liquids import by 0.4 $EJyr^{-1}$. To curtail this short-fall, Europe increases domestic liquid production by 0.3 $EJyr^{-1}$ (Annex IV.4(a)); this increased production raises the average EF of European produced liquid bioenergy from 78 to 107 $gCO_2eqMJ_{fuel}^{-1}$ (Fig4..4) effectively eliminating the additional mitigation from liquid imports. Hence both 'Current partners' and 'Feasibility' trading patterns lead to the same outcome from an emissions perspective for Europe by 2030 (Fig 4.5, panel a).

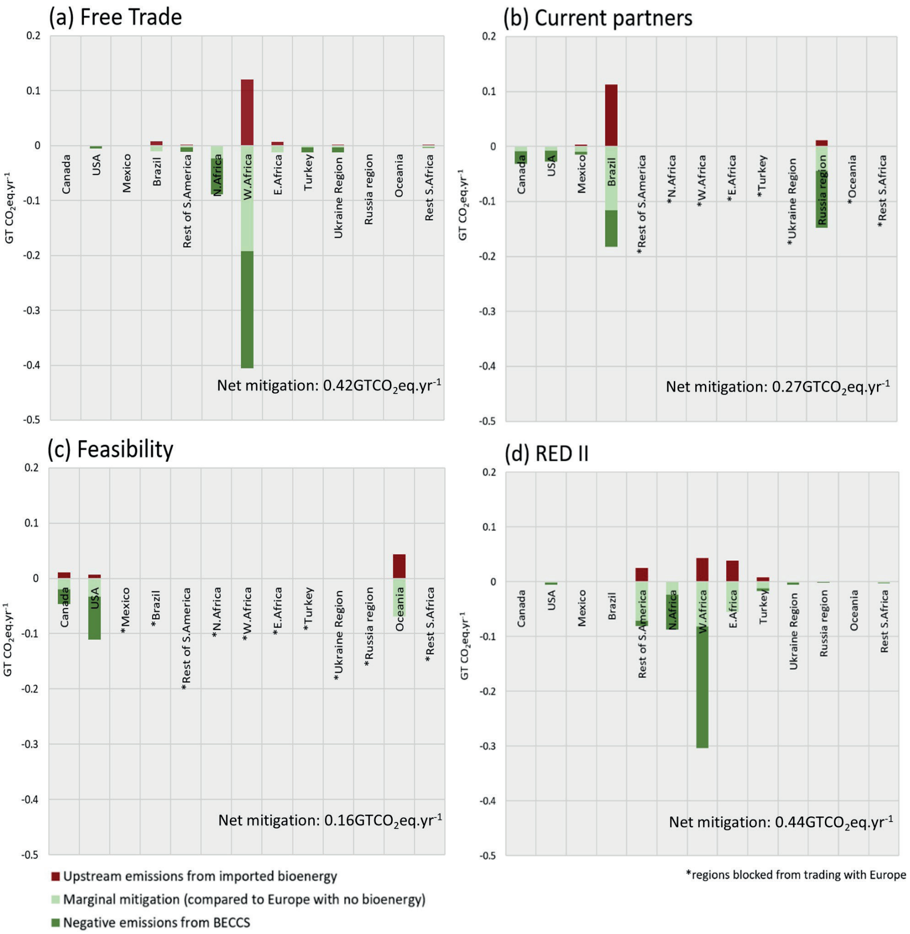
In the 'RED II' scenario, Europe observes the highest import volumes due to European self-supply of liquid bioenergy being substituted by imports due to its incompliance (Annex IV.49(a)) This scenario shifts all liquid demand (>97% of the liquid demand in the 'Free trade' scenario) to imports from the Rest of S.America region, which holds an average EF of 17$gCO_2eqMJ_{fuel}^{-1}$. (fig.4.4). Shifting sourcing away from Brazil and Europe in 2030 to the slightly more expensive supply affords Europe an additional 27 $MTCO_2eqyr^{-1}$ compared to the 'Free Trade' scenario in 2030.



(B) Total emissions and mitigation attached to bioenergy imports to Europe per sourcing region 2030

Annual mitigation from imported bioenergy increases ten-fold compared to 2030. In the ‘Free trade scenario’ to 0.42 GTCO$_2$eqyr^{-1} in 2050. The majority of this mitigation stems from the import of solid bioenergy carriers that hold low EF’s from W & N Africa. Competition for lignocellulosic primary biomass resources from liquid bioenergy production in the West Africa region results in production expansion into areas that hold higher associated land-use emissions; hence the EF of both solid and liquid carriers are increased, leading to a situation in which European liquid imports from these regions are not RED II compliant at 37 CO$_2$eqMJ$_{fuel}^{-1}$ but still affords Europe mitigation compared to the RED II fossil comparator. The ‘Current partners’ scenario projects Europe's absolute annual mitigation from imports fall decisively due to a lack of solid bioenergy that can be used with CCS. A reliance on Brazil means that Europe imports 1EJyr^{-1} less bioenergy overall and with a higher EF 58 $CO_2eqMJ_{fuel}^{-1}$. This is reflected in similar upstream emissions as projected for the 'Free Trade' scenario. Annual mitigation potential from bioenergy imports is reduced by 0.15 $GTCO_2eqyr^{-1}$. The 'Feasibility' scenario shows this potential fall further projecting a 0.26 $GTCO_2eqyr^{-1}$ reduction. This is heavily constrained due to only small net-exporting regions being available for solid carrier trade in Canada and the USA which are also the most expensive sourcing regions. Whilst the Oceania region offers liquid carriers with a better performing (and even compliant) EF 32.9 $CO_2eqMJ_{fuel}^{-1}$ the export potential of the region is limited.

The 'RED II' scenario is unable to match import volumes achieved in the 'Free Trade' scenario in 2050. The effect of global demand by 2050 completely alters Europe's sourcing strategy. Unlike 2030 where single regional switching was sufficient, Europe must now diversify the supply of liquid imports to multiple regions. This is due to two dynamics (i) Europe's substantial import demand in 2050 can if allowed push upstream emissions of a supplying region above the RED II GHG criteria level (32.9 $gCO_2eqMJ_{fuel}^{-1}$), (ii) increased demand from the ROW within the cheapest and most important global exporters (namely West .Africa) either pushes the average EF attached to liquid carriers above 32.9 $gCO_2eqMJ_{fuel}^{-1}$, ruling out European import, or significantly decreases the import potential of European imports until the supplying region reaches this limit. This is demonstrated in the 'Free trade' scenario where liquid imports from West .Africa are uncompliant with European RED II standards. To ensure compliance, liquid imports are shifted to regions with lower upstream emissions that are able to provide bio transport fuels below the RED II limit; East Africa 32, Rest of S.America 21, and Turkey 30 $gCO_2eqMJ_{fuel}^{-1}$. By shifting liquid supply from West .Africa, competition between solids and liquids for lignocellulosic primary biomass resources in the region is alleviated, which means the EF of imported solids bioenergy carriers from West .Africa are lower in the 'RED II scenario' -152 g compared to -103 $gCO_2eqMJ_{heat/electricity}^{-1}$ in the 'Free trade' scenario. From a climate perspective, the RED II scenario performs best for Europe, offering an additional 0.2 $GTCO_2eqyr^{-1}$ mitigation with the trade offering the best average MF.



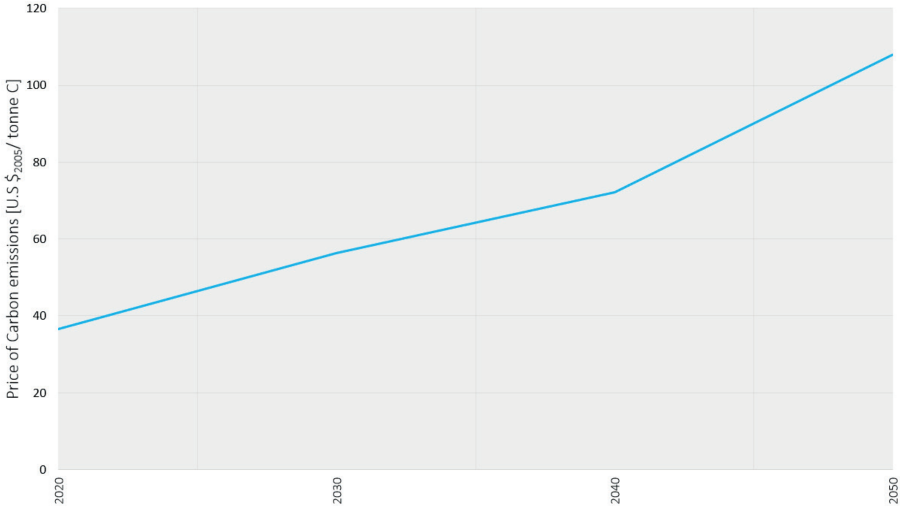
*regions blocked from trading with Europe

(C) Total emissions and mitigation attached to bioenergy imports to Europe per sourcing region 2050

(A) Cumulative bioenergy consumption and emissions data for explored trade scenarios and a 'No-bio' counterfactual

	No bio	Free Trade		Current partners		Feasibility		RED II	
	Secondary bioenergy consumption [EJyr^{-1}]								
		Liquids	*Soilds*	*Liquids*	*Soilds*	*Liquids*	*Soilds*	*Liquids*	*Soilds*
Europe	N/A	57	142	51	142	40	127	52	143
ROW		297	1099	310	1114	319	1117	301	1099
Total		354	1241	361	1256	359	1244	353	1242
	Europe cumulative GHG emissions [GtCO$_2$eq.]								
Europe	90.6	84.5		84.9		86.2		83.5	
ROW	907	806		802		802		806	
Total	998	890		887		888		890	
	Average mitigation factor of bioenergy (2020-2050) [gCO$_2$eqMJ^{-1}]								
Europe	N/A	31		30		28		37	
ROW		72		74		73		72	

Annex IV.7: Development of Carbon price to 2050



The price of Carbon emissions applied within RCP2.6 mitigative pathway (<2°C)

The price is applied equally to all energy carriers represented by the model based on their carbon content.

Annex IV.8: Development in regional shares of bioenergy consumption and production


Consumption 2020 [15.5 EJyr^{-1}]

Production 2020 [15.5 EJyr^{-1}]

Consumption 2050 [113 EJyr^{-1}]

Production 2050 [113 EJyr^{-1}]

Development of world regional shares for global bioenergy demand and production in 2020 & 2050

For 2020 we observe that regions with large production are largely the dominant consumer. However, by 2050 the largest economies begin to import which leaves relatively less developed economies with large production such as West & East Africa and the Rest of South America as net exporting regions. Whilst large economies with large domestic production still import. Bioenergy distribution is generally flowing from the direction of less developed world regions to more developed regions.

ANNEX V

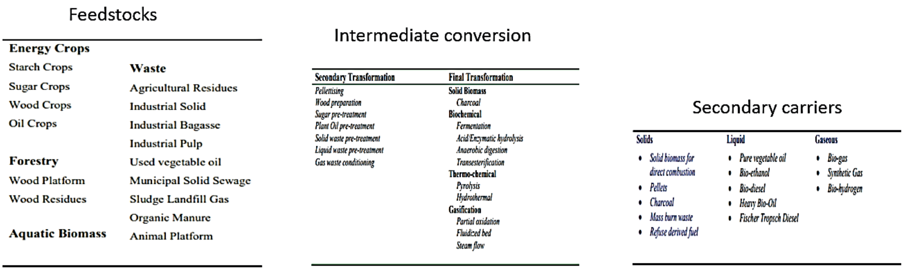
Annex of Chapter (5)

Annex V.1: Detailed description of PRIMES and Resolve Biomass trade and technological representation

PRIMES

Bioenergy representation in PRIMES

The PRIMES Biomass-supply sub-module covers a broad range of feedstock types, conversion processes and secondary bioenergy carriers, an overview is provided below. It is an economic supply model that computes the optimal use of biomass/waste resources and investment in secondary and final transformation, so as to meet a given demand of final biomass, projected to the future by the rest of the PRIMES model. The biomass supply model determines the consumer prices of the final biomass/waste products used for energy purposes and also the consumption of other energy products in the production, transportation and processing of the biomass [247].



Feedstocks

Energy Crops	
Starch Crops	**Waste**
Sugar Crops	Agricultural Residues
Wood Crops	Industrial Solid
Oil Crops	Industrial Bagasse
	Industrial Pulp
Forestry	Used vegetable oil
Wood Platform	Municipal Solid Sewage
Wood Residues	Sludge Landfill Gas
	Organic Manure
Aquatic Biomass	Animal Platform

Intermediate conversion

Secondary Transformation	Final Transformation
Pellettising	**Solid Biomass**
Wood preparation	*Charcoal*
Sugar pre-treatment	**Biochemical**
Plant Oil pre-treatment	*Fermentation*
Solid waste pre-treatment	*Acid/Enzymatic hydrolysis*
Liquid waste pre-treatment	*Anaerobic digestion*
Gas waste conditioning	*Transesterification*
	Thermo-chemical
	Pyrolysis
	Hydrothermal
	Gasification
	Partial oxidation
	Fluidized bed
	Steam flow

Secondary carriers

Solids	Liquid	Gaseous
• *Solid biomass for direct combustion*	• *Pure vegetable oil*	• *Bio-gas*
• *Pellets*	• *Bio-ethanol*	• *Synthetic Gas*
• *Charcoal*	• *Bio-diesel*	• *Bio-hydrogen*
• *Mass burn waste*	• *Heavy Bio-Oil*	
• *Refuse derived fuel*	• *Fischer Tropsch Diesel*	

(A) Bioenergy categories represented in PRIMES [247]

The PRIMES biomass model solves for cost minimisation from the perspective of a biomass supply planner, with perfect foresight for demand, fuel prices, biomass costs and technology improvement potentials. The model determines: a) the optimal use of biomass/waste resources, b) the investments in technologies for biomass conversion to bio-energy commodities, c) the use of land, d) the imports from outside the EU and the intra-EU trade of feedstock and bio-energy commodities, e) the costs and the consumer prices of the final bio-energy products as well as f) the GHG emissions resulting from the bio-energy commodities for EU production. The decision on investment for the secondary and final transformation processes is endogenous. Improvements in each technology are described by one learning-by-doing curve for each technology, uniform for all Member States of the EU; therefore learning-by-doing effects spill over to the whole EU [79].

1.3. RESolve-Biomass

Bioenergy trade representation in RESolve-Biomass

The model includes raw feedstock production, processing, transport and distribution. One of the most important features of the RESolve-Biomass model is the ability to link the national production chains allowing for international trade. By allowing trade, the future cost of bioenergy and biochemicals can be approached in a much more realistic way than when each country is evaluated separately. RESolve-Biomass allows for trade of feedstocks and final products by means of trucks, trains and short sea shipments within Europe. Extra-EU import is hauled via ocean tankers [80]. Transportation costs associated with internal EU-wide trade are determined within the model based on bulk density, distance, transportation mode, fossil fuel prices handling costs to identify optimal logistics. For international trade cost assumptions are communicated from IMAGE as part of the energy carrier cost for bioenergy (this is comprised of world region production and transportation costs). In the model this imported biomass can arrive from any of the IMAGE world regions however may only be transported to currently large operating harbours in Belgium, the Netherlands, the UK; and those judged to be important future international bioenergy terminals, Bulgaria, Greece, Finland, France, Italy, Poland, Romania and Spain. Whilst the location of future biomass import terminals are selected based on projections of supplying regions and absent of dedicated logistic capacity transport optimization projections they remain of course arbitrary.

In general the import narrative for the region in 2050 follows a storyline in which Southern European import terminals in France, Spain and Italy handle >75% of all imports primarily from the African continent. The current hubs that show meaning import UK, Belgium and Netherlands retain a collective 21% of imports whilst remaining hubs in Poland, Bulgaria, Romania and Greece collectively handle small volumes (<300 $PJyr^{-1}$) arriving from the Ukraine and Turkey. Small amounts may additionally arrive from Russia to Finland.

(A) EU27 & UK Bioenergy import terminals in 2050 within this study. Bioenergy representation in RESolve-Biomass

Within this study RESolve-Biomass representation coverage extends to 38 primary feedstock categories, 37 intermediate conversion (and pre) processes, 30 secondary bioenergy carriers (+ 2 chemicals) and 67 final bioenergy conversion technologies. Lignocellulosic feedstock production costs and potentials are provided as input for the model from [248] and non-lignocellulosic [249]. It is assumed that every country in the model has one possible production location for each raw material and one location for a possible processing plant for each conversion (sub) process. This means that each country has the possibility to have a full chain of conversion facilities. The model decides if a certain feedstock and technology will actually be utilized. Bioenergy imports allowed in this study are matched to those that may be traded in IMAGE and consist of a set of six secondary bioenergy carriers; wood pellets, agricultural pellets, bio-FT diesel, bioethanol 1G, bioethanol 2G and Biomethanol (with the addition of small amount 150 PJ held static of UFO assumed previous study's [250,251]). Bioenergy technologies that can be utilised in tandem with carbon capture and storage (both intermediate and final energy conversion processes) are noted in the figure below.

To avoid an unrealistic rapid uptake of feedstock and conversion technologies, growth restrictions are applied separately for feedstock and conversion [80]. For biofuels and large scale advanced technologies, the investment costs reduce in time depending on the past cumulative output volumes of the technology or via the development of the scale of installations. As such, the model includes endogenous learning [252].

Primary Feedstocks

Forestry-based
- Additional Harvestable Roundwood
- Current Roundwood production
- SRC Willow

Forestry-based residues
- Landscape care wood
- Primary forestry residues

Agricultural
- Cereals
- Forage maize
- Giant reed (Perennial grass)
- Maize
- Miscanthus
- Reed Canary Grass
- Soya
- Sugarbeet
- Sunflower seed
- Switchgrass
- Rapeseed

Agricultural residues
- Stover from grain maize
- Straw from cereals
- Straw from rice
- Stubbles from OSR and Rapeseed
- Prunings and pits from olives
- Prunings from fruit trees
- Leave and beet top from sugarbeet
- Verge grass

Secondary residues
- Black liquor
- Saw dust
- Sawmill by-products
- Other industrial wood residues
- Organic waste from Industry

Tertiary residues
- Collected VFG
- Common sludges
- Dry manure
- Landfill
- MSW
- Paper cardboard
- Post consumer wood
- Used fats/oils
- Wet manure

Conversion to SE carriers

Conversion to solid carriers
- Chipping of prunings
- Chipping of wood
- Pelletisation of wood
- Pelletisation of agricultural residues
- Torrefaction

Conversion to liquid carriers
- wood pre treatment
- Straw & grass pre treatment
- Staw & grass > EtOH **WITH CCS**
- Starch > EtOH
- Biomethane from gas
- gasification > biomethanol **WITH CCS**
- Cellulose to EtOH **WITH CCS**
- FT-liquid production
- Bio-FT > diesel **WITH CCS**
- Bio-FT > kerosene **WITH CCS**
- DME production **WITH CCS**
- Biomethane > BioLNG
- Gassification for SNG
- Alchol-to-Jet
- Hyrdothermal Liquefaction (HTL)
- Hydrotreated Esters and fatty acids (HEFA)
- HEFA > diesel
- Hefa > Jet
- Pyrolysis oil production
- Pyrolysis oil co-processing
- Pyrolysis > diesel production
- Pyrolysis > jet production
- Transesterif-oil seed
- Transesterif-palm oil
- Transesterif-used fats
- All- feedstock digestion
- Mono digestion of manure
- Co-digestion of manure
- Manure co-substrate mixing
- Digestion of VFG
- oil extraction from seed and soya
- Ethylene from ethanol

SE bioenergy carriers

Solid bioenergy carriers
- Wood pellets
- Agricultural residues pellets
- Chipped grassy crops
- Chipped prunings
- Wood chips
- Torrefied wood pellets
- wood chips

Liquid bioenergy carriers

Advanced biofuels
- Bio-FT-diesel
- Bioethanol 1st
- Bioethanol 2nd
- Biomethanol
- Alchol to Jet (diesel)
- Alchol to Jet (gasoline)
- Bio-Dimethyl ether
- Bio-FT-jet
- Bio-Heavy fuel oil
- Biodiesel
- Bio- Liquified Natural gas
- Biomethane for Transport
- bio- hydro-treated diesel 1G
- bio- hydro-treated diesel 2G
- bio- hydro-treated jet 2G
- bio- Hydrothermal liqufaction diesel
- bio- Hydrothermal liqufaction gasoline
- bio- Hydrothermal liqufaction jet
- Pure vegetable oil
- Pyrolysis diesel
- Pyrolysis gasoline
- Pyrolysis HFO
- Pyrolysis jet

other
- bioethylene
- biohydrogen

Conversion to Final energy

Heating

Residential
- batch fired logwood stove for heat (15 kW)
- wood chips boilers - small scale (10 kW)
- wood pellet boiler - (20 kW)
- grassy perennials boiler - small scale (10 kW)
- liquid biomass boiler - (20 kW)

Industry
- Biomass IGCC
- CHP using solid biomass > (10 MW)
- CHP using solid biomass - (0.5 - 10 MW)
- CHP-liquid
- Gas engine for biogas from all-feedstock digestion - CHP
- Landfill & sewage gas engine - CHP
- Large scale pellet boiler > (5 MW)
- Local heating plant for straw large scale (5 MW)
- Local heating plant for wood chips - large scale (5 MW)
- Local heating plants for proccessed grassy crops-large scale (5MW)
- Large scale CHP using agri residue pellets **WITH CCS**
- Medium scale CHP using straw
- Medium scale wood gasification CHP > 0.5MW
- MSW-CHP
- Pyrolysis oil in CHP combustion engine
- Pyrolysis oil to steam
- Waste combustion - heat only
- Large scale pellet boiler (>= 5 MW) **WITH CCS**
- Biomass IGCC **WITH CCS**
- Large scale liquid biomass boiler (>= 5 MW)

Services
- Boiler for liquid biomass
- Gas engine for biogas from manure co-digestion - CHP
- Local heating plant for straw small scale (0.15 MW)
- Logwood boiler - commercial
- wood pellet boilers -large scale (50kW)
- Wood chip boilers-large size (50 kW)
- Gas engine for biogas from VFG
- grassy perennials boiler (50 kW)
- liquid biomass boiler - 50 kW

Electricity
- Biomass IGCC
- CHP using solid biomass > (10 MW)
- CHP using solid biomass (0.5 - 10 MW)
- CHP-liquid
- Direct co-firing coal process
- Dry manure combustion for Power
- Bio-FT towards diesel
- Gas engine for biogas from all-feedstock digestion - CHP
- Gas engine for biogas from manure co-digestion - CHP
- Gas engine for biogas from manure mono digestion - CHP
- Landfill & sewage gas engine - CHP
- Liquid combustion
- Large scale CHP using agri residue pellets **WITH CCS**
- Medium scale CHP using straw
- Medium scale wood gasification CHP > 0.5MW
- MSW electricity only
- MSW-CHP
- Pyrolysis oil in CHP combustion engine
- Thermal conv solid biomass - Electricity only
- Gas engine for biogas from VFG
- Biomass IGCC **WITH CCS**

Transport
- Bus: ICE CNG
- Bus: ICE Diesel
- Cars: ICE CNG
- Cars: ICE Diesel
- Cars: ICE Gasoline
- HDV: ICE CNG
- HDV: ICE Diesel
- HDV:ICE DME
- Train
- Aviation
- Marine shipping
- inland shipping

Chemicals
- Biomethanol as platform chemical
- Bioethylene as platform chemical

(C) Technological representation of bioenergy in RESolve-Biomass as used within this study.

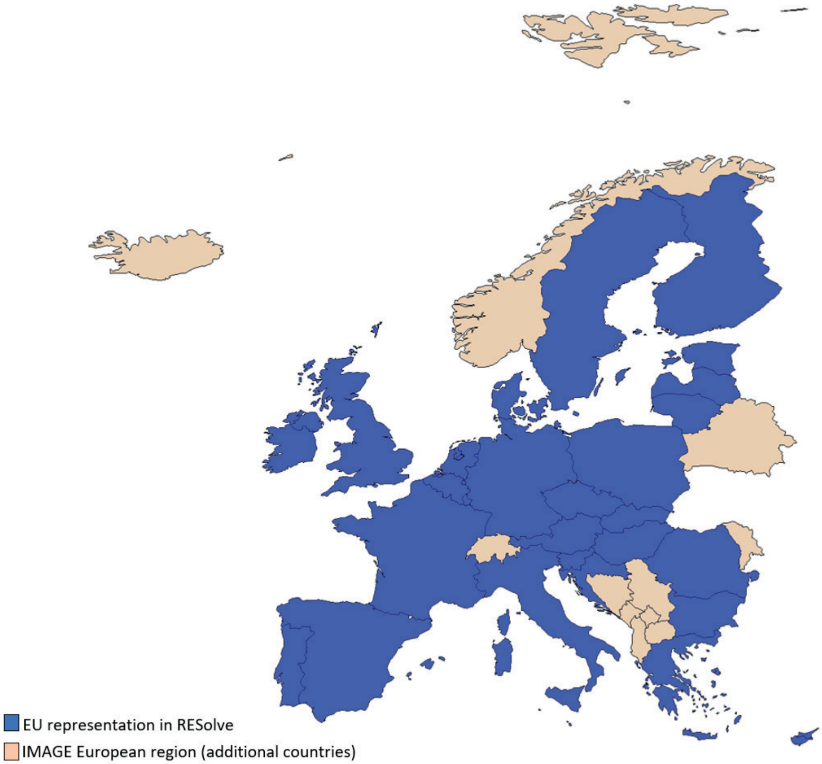
Techno-economic assumptions of Resolve-Biomass within the study for major conversion routes in 2050

Process	OPEX [€_2018/GJ]	CAPEX [€_2018/GJ]	Efficiency	Wood pellets	Agricultural residues	2G ethanol	Used fats and oils	Input cost [€_2018/GJ]	CO2 stored [ton/GJ_output]	CO2 benefit from CCS [€_2018/GJ]	Total cost [€_2018/GJ]
ATJ	6.5	1.4	76%			X		119		0.00	**127**
Bio-FT towards diesel	4.6	5.8	53%	X				26		0.00	**36**
Bio-FT towards diesel wCCS	4.6	6.3	56%	X				25	0.09	9.05	**27**
Bio-FT towards kerosene	3.5	4.7	64%	X				21		0.00	**30**
Bio-FT towards kerosene wCCS	3.5	5.2	67%	X				21	0.07	7.03	**22**
Biomass gasification for methanol production	3.5	4.4	62%	X				22		0.00	**30**
Biomass gasification for methanol production wCCS	3.4	4.9	65%	X				21	0.07	7.30	**22**
HEFA-HRD/HRJ	3.1	2.0	89%				X	16		0.00	**21**
HTL-D	4.4	8.3	54%	X				26		0.00	**39**
HTL-DJ	4.4	8.3	54%	X				26		0.00	**39**
Straw and grass based EtOH	5.7	5.3	51%		X			27		0.00	**38**
Straw and grass based EtOH wCCS	5.7	5.3	41%		X			33	0.03	3.32	**41**
Wood based EtOH	15.0	7.1	51%	X				27		0.00	**49**
Wood based EtOH wCCS	15.0	7.1	41%	X				33	0.03	3.32	**52**
Biomass IGCC wCCS	2.1	4.2	52%	X				27	0.26	26.04	**7**
CHP using solid biomass 0.5 - 10 MW	3.6	9.2	92%	X				15		0.00	**28**
DME production	10.6	5.9	60%	X				23		0.00	**40**
DME production wCCS	11.3	6.4	62%	X				22	0.07	7.32	**33**
Large scale CHP using agri residue pellets wCCS	4.2	8.0	70%	X				20	0.30	30.28	**2**
Medium scale CHP using straw	4.4	7.6	70%		X			20		0.00	**32**
Large scale liquid biomass boiler (>= 5 MW)	1.9	1.4	89%			X		101		0.00	**105**
Large scale pellet boiler (>= 5 MW)	1.4	2.1	90%	X				15		0.00	**19**
Large scale pellet boiler (>= 5 MW) wCCS	1.4	2.1	75%	X				18	0.14	13.89	**8**
Local heating plant for straw large scale (5 MW)	10.3	4.5	78%		X			18		0.00	**33**
Local heating plant for straw small scale (0.15 MW)	7.0	8.1	89%		X			16		0.00	**31**

Wood pellets	€_2018/GJ	13.9
Agricultural residues	€_2018/GJ	13.9
2G ethanol	€_2018/GJ	90.1
Used fats and oils	€_2018/GJ	13.9
CO2	€_2018/ton	101.3

Annex V.2: Geographical scaling between model representations

The geographical boundaries of the Integrated Assessment model IMAGE overlaid with the representation of EU27 & UK as represented by PRIMES and RESolve-Biomass are presented below.



Geographical representation between IMAGE and Resolve-Biomass.

Annex V.3: Detailed projections for MS-level supply and demand developments

Below is provided the tabulated format of figure 1 within the manuscript for closer review. Member states are ordered by total consumption of bioenergy in the year 2050.

MS-level Supply and demand projections for the EU in 2050 [EJyr-1 secondary energy]

	Consumption	Production	Imports	Exports
Luxembourg	0.05	0.01	0.04	0.00
Estonia	0.05	0.06	0.02	0.04
Slovenia	0.08	0.05	0.04	0.01
Latvia	0.09	0.14	0.02	0.07
Croatia	0.09	0.07	0.04	0.02
Lithuania	0.09	0.11	0.02	0.03
Greece	0.15	0.08	0.08	0.01
Slovakia	0.18	0.09	0.11	0.01
Bulgaria	0.18	0.09	0.11	0.02
Ireland	0.23	0.05	0.19	0.00
Portugal	0.26	0.12	0.14	0.00
Denmark	0.27	0.04	0.23	0.00
Hungary	0.27	0.22	0.11	0.05
Czech Rep	0.40	0.23	0.19	0.02
Belgium	0.46	0.05	0.41	0.01
Sweden	0.51	0.64	0.12	0.25
Austria	0.52	0.19	0.34	0.01
Romania	0.61	0.51	0.23	0.13
Finland	0.62	0.17	0.44	0.00
Netherlands	0.72	0.03	0.70	0.01
United Kingdom	1.04	0.25	0.82	0.04
Spain	1.25	0.47	0.94	0.16
Italy	1.35	0.30	3.02	1.97
Poland	1.40	0.78	0.68	0.06
France	1.45	0.76	2.59	1.90
Germany	2.48	0.80	1.90	0.22
EU Total	**14.83**	**6.31**	**13.55**	**5.03**

Annex V.4: Comparison of Current EU 27 & UK marine hub import capacity to projected 2050 bioenergy imports

In the table below the current import capacity for the EU 27 & UK major marine ports import in 2019 and for modelled induvial hub nations are displayed for the year 2019 for both solid and liquid bulk as reported by Eurostat [203]. Alongside this is presented the import projections for solid and liquid bioenergy carriers and the percentage of capacity expansion required. *expressed as a % of observed 2019 trade. Dry and Liquid bulk categories were selected as suitable proxies to represent the handling requirement facilities in current port operations needed to facilitate bioenergy trade flows. Dry and Liquid bulk categories were selected as suitable proxies to represent the handling requirement facilities in current port operations needed to facilitate bioenergy trade flows.

Comparing current solid and liquid bulk capacity in EU 27 & UK major marine ports with projected bioenergy imports [Mtdm and Mtliquid]

	'Dry bulk' (2019)	solids bioenergy import (2050)	expansion*	('liquid bulk' in 2019)	liquid bioenergy import (2050)	expansion*
EU 27 & UK	586	300	51%	1033	125	12%
Italy	62	133	213%	140	25	18%
France	48	51	107%	115	59	51%
Spain	65	39	59%	137	9	7%
United Kingdom	71	20	28%	119	18	15%
Netherlands	117	25	21%	197	5	2%
Belgium	28	15	54%	56	6	10%
Poland	22	8	37%	22	0.2	1%
Romania	10	4	35%	11	0	0%
Greece	13	3	20%	41	0	0%
Finland	18	2	14%	23	0	0%
Bulgaria	3	1	25%	8	0	0%

***expressed as a % of observed 2019 trade**

Nomenclature:

Dry bulk – ores, coal, agricultural products, construction materials, other and non-specified

Liquid bulk – liquified gas, crude oil, refined oil products, chemicals, other and non-specified

Custom database links to Eurostat 203

Annex V.5: Comparison of current EU 27 & UK MS-MS and domestic energy commodity transportation with study projections in 2050 at MS level

In the table below the current EU-wide international and MS internal transportation volumes of fossil fuel commodities by transport modality are presented alongside the MS-MS export and domestic mobilisation requirements from the 2050 projections of this study. Within the left side-of the table data taken for MS-MS transport is attributed to the exporting country from Eurostat statistics to correlate with the study projections.

Current EU 27 & UK MS-MS and domestic energy commodity transportation with study projections in 2050 at MS level. Reported in [Mt]

	International MS-MS distribution					National level distribution					
	current fossil fuel transport			bioenergy transport 2050		National level distribution				bioenergy transport 2050	
	Rail export	Inland shipping export	Total export	export	expansion*	Rail	Inland Shipping	Road	Total	mobilisation	expansion*
Belgium		1.6	1.6	0.3	17%		0.2	0.7	0.9	2.9	317%
Bulgaria	0.7	0.1	0.8	1.2	156%	1.8		0.9	2.7	5.4	202%
Czech	13.3		13.3	0.9	7%	9.6		4.8	14.4	13.1	91%
Denmark								0.2	0.2	2.2	1369%
Germany	8.3	19.7	28.0	12.3	44%	18.5	3.2	7.3	29.1	45.8	158%
Estonia	4.0		4.0	2.1	53%	3.7		0.3	4.0	3.6	90%
Ireland								0.9	0.9	2.7	287%
Greece								26.0	26.0	4.3	17%
Spain	0.3		0.3	8.0	2629%	1.3		4.1	5.4	26.8	495%
France	0.2	0.5	0.7	80.9	11414%	0.4	0.8	5.6	6.9	43.5	631%
Croatia	1.3	0.1	1.5	1.1	75%	0.5	0.1	0.6	1.2	4.3	371%
Italy	0.3		0.3	102.7	38035%	0.1		13.7	13.8	17.2	124%
Latvia	16.7		16.7	3.9	23%	0.8			0.8	7.9	982%
Lithuania	3.1		3.1	1.5	47%	1.8		0.3	2.0	6.1	304%
Luxembourg								0.3	0.3	0.4	117%
Hungary	4.0	0.5	4.5	2.1	46%	2.2		1.6	3.7	12.4	334%
Netherlands	7.6	22.5	30.1	0.4	1%	0.7	1.3	0.4	2.4	1.8	77%
Austria	2.0	0.1	2.1	0.6	30%	1.3		1.0	2.3	11.0	471%
Poland	21.5	0.1	21.5	2.6	12%	69.1	0.4	34.3	103.8	44.5	43%
Portugal								0.2	0.2	7.1	4390%
Romania	1.7	1.1	2.7	6.6	242%	8.8	0.1	1.1	10.1	29.0	288%
Slovenia	1.3		1.3	0.3	24%	0.3			0.3	2.6	747%
Slovakia	3.6	0.2	3.8	0.6	15%	0.9		0.3	1.1	5.0	439%
Finland	0.5		0.5	0.1	19%	0.8		1.5	2.3	9.9	428%
Sweden	0.1		0.1	14.5	13187%	0.1		2.0	2.1	36.4	1701%
United Kingdom				2.0		3.5		3.1	6.5	14.2	218%
EU27 & UK	91	46	**137**	245	179%	126	6	111	**243**	360.3	148%

**expressed as a % of observed 2019 trade. Fossil energy commodities were selected to present the current scale of fuels for energy service demand transported throughout the EU 27 & UK.*
Nomenclature: Traded energy commodities refer to Eurostat standard good classification [GT02] Coal and Lignite; crude petroleum and natural gas.
Custom database links to Eurostat: Rail data: [253]: Inland shipping data: [254]: Road data: [204]: Transport modality per country: [255]

Annex V.6: Marine-land import hub nations included in this study and the current handling capacity

Included marine-port hub nations and 2019 handling capacity of dry and liquid bulk goods combined [Mtyr^{-1}][203]

Country	Mtyr^{-1} Dry & Liquid Bulk import (2019)
Netherlands	314
Italy	202
Spain	201
UK	191
France	163
Germany	94
Belgium	84
Greece	54
Sweden	54
Poland	44
Finland	41
Portugal	38
Denmark	31
Romania	22
Ireland	20
Lithuania	15
Croatia	12
Bulgaria	12
Slovenia	10
Estonia	7
Latvia	6
Malta	3
Cyprus	3

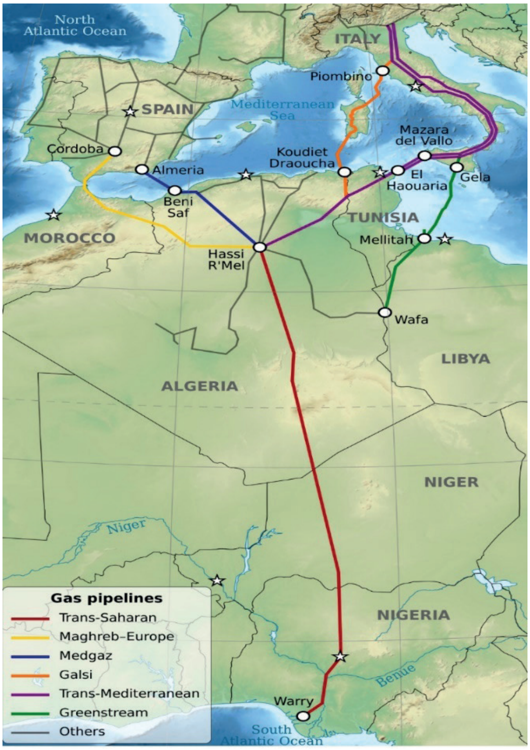
As seen above the top five current import handling nations for liquid and dry bulk goods (largely fossil fuel commodities) are included within the study's set of stylised marine-land hubs represented by the green text. These nations also represent the largest 5 importing hubs within the study's 2050 projections.

Annex V.7: Current Africa to Europe natural gas network

The current Africa to Europe gas network is comprised of three major tributary lines that have transport capacities of:

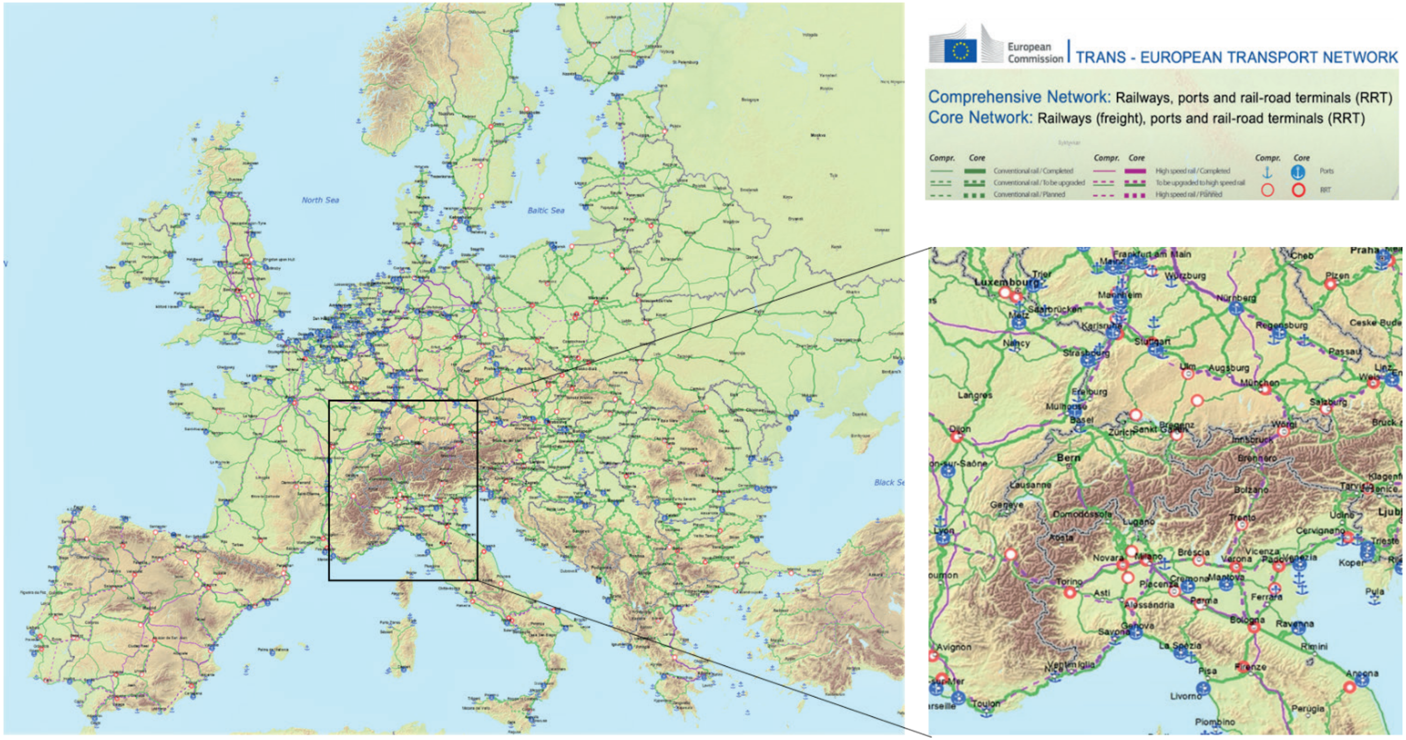
Maghreb-Europe: 12 billion m^3
Medgaz: 10 billion m^3
Trans-Mediterranean: 30 billion m^3
Energy density of natural gas = 38.3 MJm^{-3}

Total capacity of the three lines = 2EJ



Africa-Europe natural gas network.

Annex V.8: Overview of EU logistical Freight network



TENtec TRANS European freight network of shipping ports, rail-road and rail terminals
High resolution original images available through: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/site/en/maps.html

Annex V.9: Simplified example of maritime trade optimisation approach on to projected trading routes

Although planned EU transportation network upgrades for hinterland connectivity with multi-modal ports over the coming decade suggest the major projected trade routes are feasible. Due to a lack of maritime Extra-EU transportation optimisation it is debatable whether the highest MS-level demanding nation Germany is (i) supplied by France and Italy terminals as projected (ii) those with shorter in-land haulage requirements (Netherlands and Belgium), or (iii) direct maritime freight not represented within this study. A simplified case of the major projected trade routes of bioenergy in 2050 accounting for possible maritime trade routes is presented below.

A recent assessment of freight transport costs estimate current freight prices between key modalities that may influence future trade routes for both bulk solids and liquid haulage.

Freight transportation costs [256]

Transport modality	**Dry bulk (€$_{2018}$ per tonneKM)**	**Liquid bulk (€$_{2018}$ per tonneKM)**
Maritime shipping	0.0032	0.0049
Rail	0.012	0.015
Inland navigation	0.033	N/A
HDV (large road i.e. trucks)	0.09	0.09

The simplified example to the right shows the implications of including detailed port-port distances within trade optimisation rather than the shortest distance between world regions approach taken within this study (selected due to the spatial representation of world regions in the IAM IMAGE).

In the example we look at the largest trade route of West Africa to Germany (Berlin) as a static end-use point. 3 routes are explored with two modalities considered (i) maritime shipping, (ii) inland rail from port to Berlin.

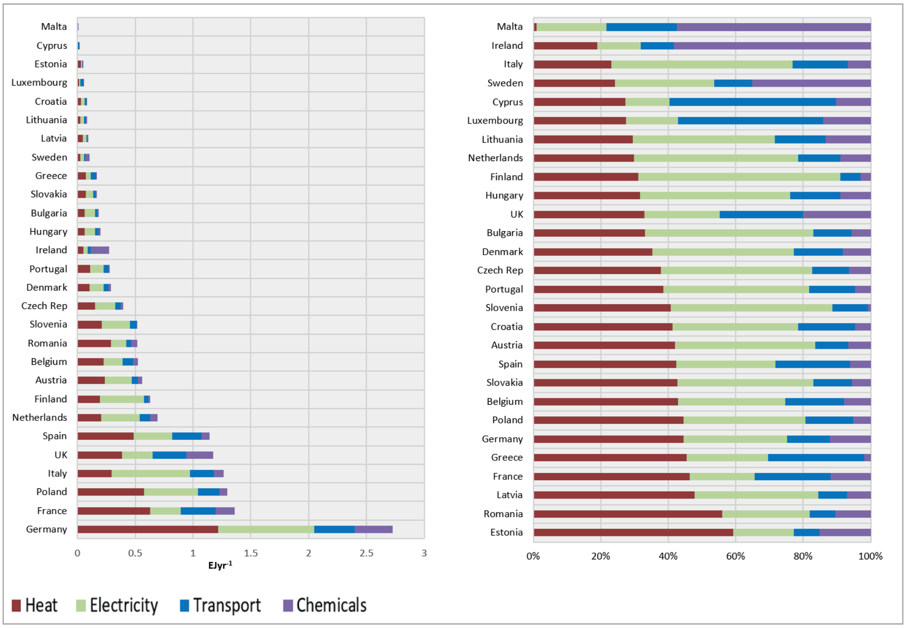
The largest bulk port terminals are selected for each route.

Where: present current German bioenergy import trade ctions of this stud Hamburg – direct shipping and not included as a hub in this study which are collectively much larger. This suggests the similar route costings (+/- 18%) somewhat downplay the importance of the modelling approach from a cost-perspective. But it does have a sizable impact on MS-MS level transport capacity requirements seen a the difference in rail Km which is raised as an area of concern within future EU bioenergy logistics due to a large required expansion of the current energy commodity transportation capacity as shown in Annex V.5.

Route	Maritime [Km]	Rail [Km]	Total cost per tonne [€ 2018] dry bulk	liquid bulk
Abidjan-Rotterdam-Berlin	7950	604	32.7	48.0
Abidjan-Hamburg-Berlin	8465	250	30.1	45.2
Abidjan-Genoa-Berlin	7370	1004	35.6	51.2

Annex V.10: Sectoral bioenergy demand at MS-level

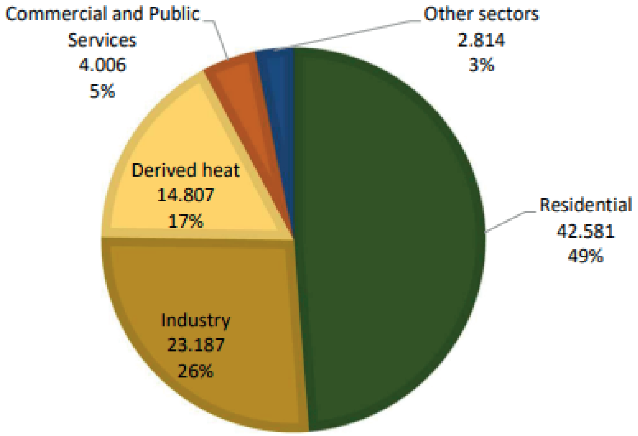
Below the bioenergy demand as projected by IMAGE and distributed by PRIMES is displayed at sectoral-level per MS in terms of absolute demand and percentage per sector at MS-level.



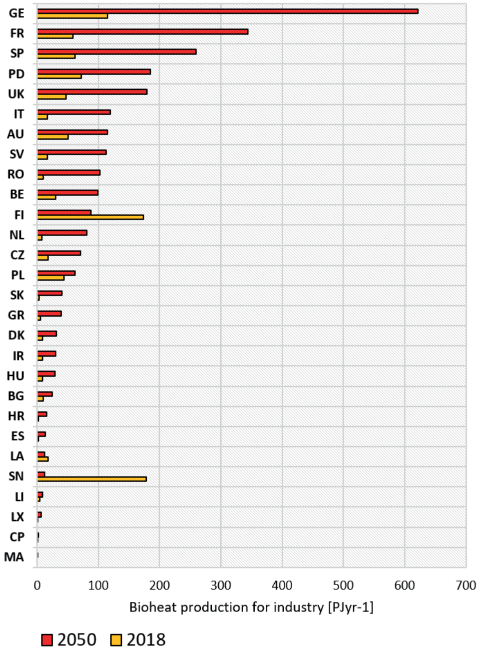
MS-level sectoral bioenergy demand in 2050 alongside the sectoral demand % per sector at MS-level.

Annex V.11: Industrial Bio-Heat demand MS-level

The industrial demand for bioheat in 2018 is compared to 2050 projections at MS-level.

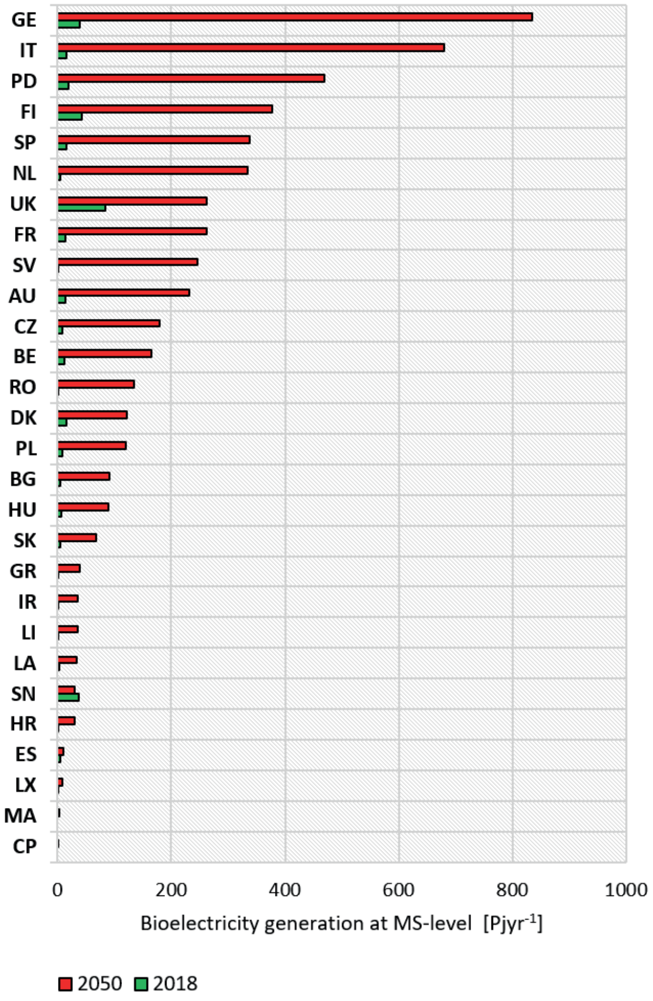


(a) Current bioheat distribution per subsector sub-sector in 2018



(b) Current (2018) industrial bioheat demand compared to 2050 projections at MS-level [207]

Annex V.12: Bioelectricity demand MS-level

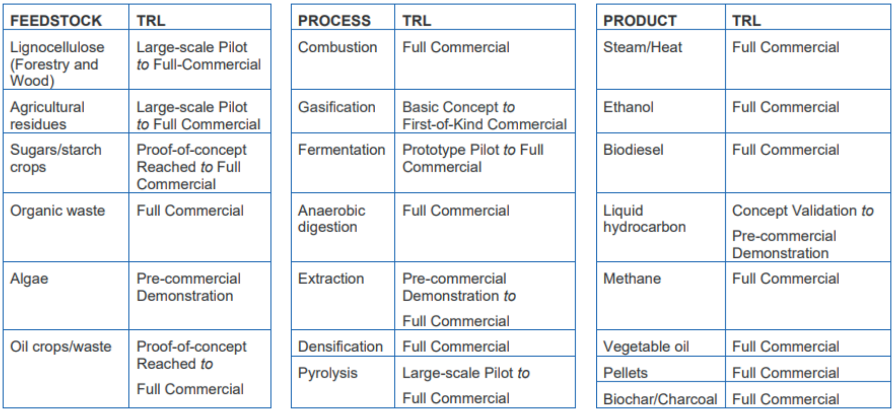


2050 projections of bioelectricity generation compared to current generation from solid bioenergy carriers at MS-level
2018 data sourced from [207]

Annex V.13:. Current development of CCS technologies

In the table below the technological readiness level (TRL) ranges for fundamental parts of the bioenergy to BECCS chain is presented. Technologies assumed central to these projections i.e. residues feedstocks passing through either combustion, gasification, fermentation or anaerobic digestion; for steam/heat (also subsequently used for electricity generation), Ethanol and Biodiesel. These technologies range from pilot commercial to full commercial operations.

TRL range for fundamental BECCS operation chains as presented in [221]



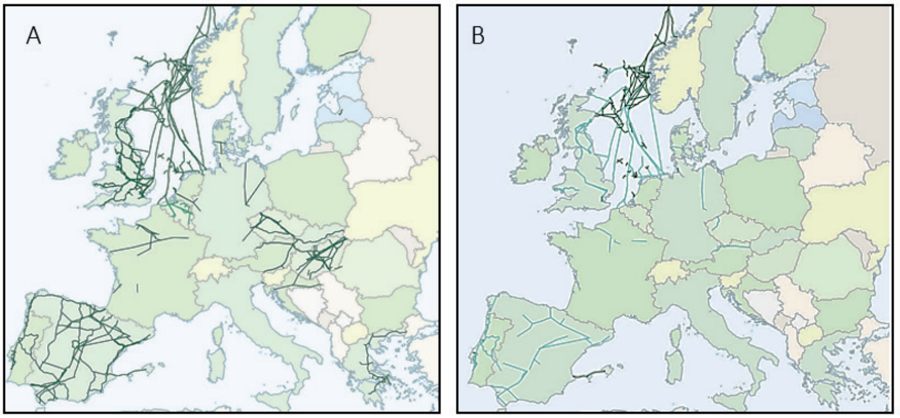
FEEDSTOCK	TRL
Lignocellulose (Forestry and Wood)	Large-scale Pilot *to* Full-Commercial
Agricultural residues	Large-scale Pilot *to* Full Commercial
Sugars/starch crops	Proof-of-concept Reached *to* Full Commercial
Organic waste	Full Commercial
Algae	Pre-commercial Demonstration
Oil crops/waste	Proof-of-concept Reached *to* Full Commercial

PROCESS	TRL
Combustion	Full Commercial
Gasification	Basic Concept *to* First-of-Kind Commercial
Fermentation	Prototype Pilot *to* Full Commercial
Anaerobic digestion	Full Commercial
Extraction	Pre-commercial Demonstration *to* Full Commercial
Densification	Full Commercial
Pyrolysis	Large-scale Pilot *to* Full Commercial

PRODUCT	TRL
Steam/Heat	Full Commercial
Ethanol	Full Commercial
Biodiesel	Full Commercial
Liquid hydrocarbon	Concept Validation *to* Pre-commercial Demonstration
Methane	Full Commercial
Vegetable oil	Full Commercial
Pellets	Full Commercial
Biochar/Charcoal	Full Commercial

Annex V.14: Current pipeline network that may be reused for the purpose of a CO_2 network

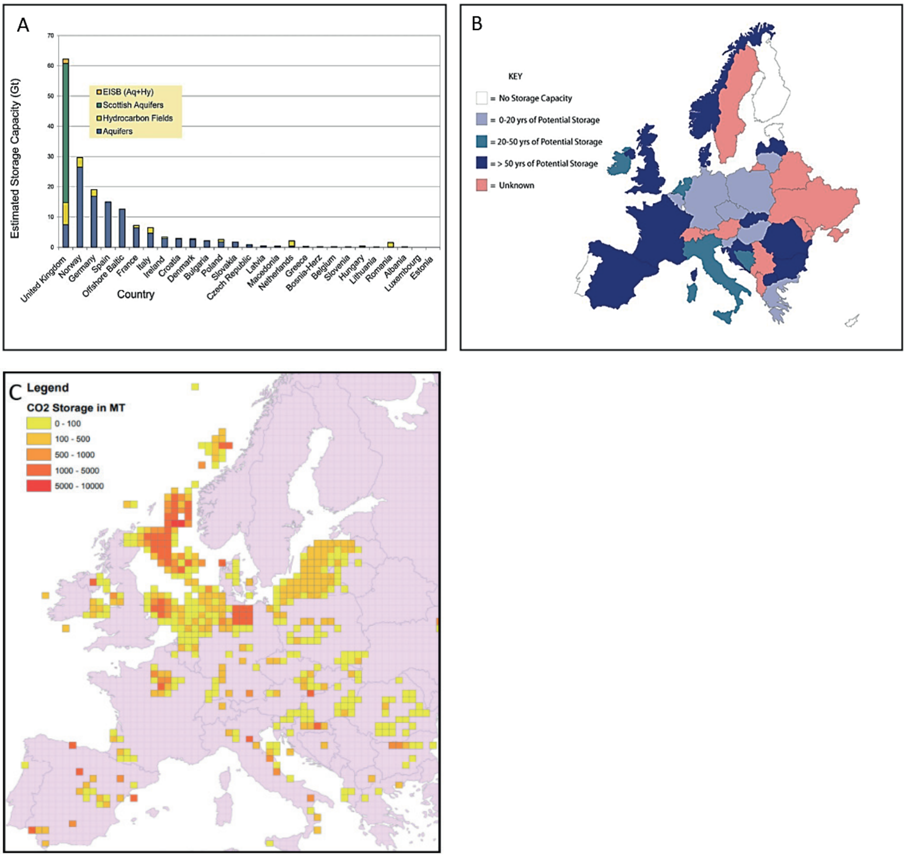
Below are the results from the assessment of reusable oil and gas pipelines for CO_2 transport in gaseous and dense phases. The screening assessments identify large portions of the network are reusable with a pronounce trend to the denser network grid of North West Europe.



Re-usable EU27&UK pipelines for a CO2 transportation network as presented in [226]
A- Suitable for gaseous state CO_2 transport
B- Suitable for dense phase CO_2 transport

Annex V.15: Estimates of CO2 storage potential for EU27 & UK

Below national level storage potential for the EU 27 & UK are presented as determined within the Geocapacity [229] project with supplemented additional studies focusing on offshore storage in the North sea and Baltic regions [228].



The CO_2 storage of the EU27 & UK

-Panel A: Potential per MS and offshore regions as presented in [228]

-Panel B: Displays the potential storage time-frames per MS when considering GHG emissions from power generation at large facilities as determined in [229].

-Panel C: Displays the storage capacity location by basin as displayed in [257]

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NEDERLANDSE SAMENVATTING

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Onderzoekcontext

Het Akkoord van Parijs beoogt het begrenzen van de globale temperatuurstijging tot maximaal 2°C, en streeft naar een maximale temperatuurstijging van 1.5°C. Regeringen over de hele wereld moeten bijdragen aan klimaatbeleid om de toename in de uitstoot van antropogene broeikasgassen te beperken. De meeste antropogene emissies worden veroorzaakt door het gebruik van fossiele brandstoffen voor het opwekken van energie. Het decarboniseren van energiesystemen over de hele wereld hangt af van maatschappelijke veranderingen in consumptie, efficiënt gebruik van energie en grondstoffen, en het vervangen van fossiele brandstoffen met alternatieve met lagere uitstoot. Biomassa is een aantrekkelijke optie voor een dergelijke vervanging, en is wereldwijd momenteel de meest gebruikte hernieuwbare bron van energie. Biomassa is veelzijdig als brandstof in belangrijke sectoren, bovendien wordt biogene koolstof beschouwd als klimaat-neutraal op het punt van consumptie. Echter, het realiseren van de beoogde emissie reducties vereist zorgvuldig management. Bio-energie kan gebruikt worden in alle belangrijke sectoren voor eind-gebruik, en is een flexibele bron om het energienetwerk in evenwicht te brengen, in combinatie met andere intermitterende bronnen van hernieuwbare energie. Bovendien biedt bio-energie in combinatie met koolstof afvang en opslag een mogelijkheid om negatieve emissies te bereiken, iets dat algemeen beschouwd wordt als cruciaal in het bereiken van klimaatdoelstellingen.

Het huidige gebruik van bio-energie in de EU is 5.6 EJ/jaar, 64% van de consumptie van hernieuwbare energie. Van deze biomassa is 96% afkomstig uit de EU, en 89% van de biomassa wordt geconsumeerd in het land van herkomst. De productie van biomassa overtreft de productie van gas en steenkool. Bio-energie wordt gezien als een fundamentele component van het decarboniseren van het energiesysteem van de EU. Veel landen voorzien een belangrijke en urgente rol voor biomassa in hun National Renewable Energy Action Plans (NREAPs). Globale en regionale modellen projecteren veelal dat door een toenemende rol voor biomassa in de energie transitie, de vraag naar biomassa import uit andere regio's zal toenemen.

In het EU klimaat debat is er echter weerstand tegen bio-energie als mitigatie optie. De kritiek op biomassa is vooral gebaseerd op argumenten gerelateerd aan; de beschikbaarheid van duurzame grondstoffen, koolstof 'pay-back periods', emissies gerelateerd aan landgebruik veranderingen, onzekerheden rondom de implementatie van bio-energie met koolstof afvang en opslag (BECCS), afhankelijkheid van subsidies, concurrentie tussen verschillende biomassa eind-gebruik types, inclusief non-energie toepassingen. Een beter begrip van de rol van bio-energie in het decarboniseren van het energiesysteem van de EU tot 2050 vereist een beter begrip van deze onzekerheden.

Er zijn complexe interacties tussen de bio-energie sector van de EU en natuurlijke en antropogene systemen. Deze interacties pleiten voor een integrale aanpak voor de analyse van het mitigatie potentieel van bio-energie. Analyses moeten de vraag naar biomassa en de dynamische verbindingen tussen wereldwijde biofysische en socio-economische systemen in aanmerking nemen in een streven naar een kosteneffectieve transitie. Voorgaande analyses schieten tekort in een gedetailleerde analyse van deze dynamieken op EU niveau, en vangen de interregionale handelsvereisten en uitdagingen niet van een globaal perspectief. Gegeven de verwachte toename in de vraag naar biomassa in de EU is het meenemen van deze aspecten in analyses een essentiële stap om de complexe ontwikkelingen in de grootschalige toepassing van bio-energie beter te vertegenwoordigen en om inzichten te verschaffen in de vereiste infrastructuur en marktfacilitering.

Het formuleren van klimaatmitigatie strategieën, energie-mix portfolio's en sturend beleid voor de EU gebeurd op nationaal en supra-nationaal niveau. De evaluatie van de rol van bio-energie in klimaatmitigatie en transformatie van het energiesysteem is vooral nuttig voor de ondersteuning van beleidsvorming op een systeem niveau, oftewel voor het complete energiesysteem van de EU. Een analyse op systeemniveau is een grotere uitdaging voor bio-energie dan voor andere hernieuwbare energiebronnen, waarvoor de diffusiesnelheid de belangrijkste beperkende factor zijn, zoals het geval is voor wind- en zonne-energie. Bio-energie vereist, net als conventionele brandstoffen, een constante aanvoer van grondstoffen. Daarnaast is constante waakzaamheid ten opzichte van beheer praktijken noodzakelijk met het oog op het realiseren van een positieve impact op het milieu. De techno-economische prestatie en het mitigatie potentieel van bio-energie zijn afhankelijk van aspecten en omstandigheden in de gehele complexe waardeketen, inclusief dynamieken van zowel vraag als aanbod en het geografische schaalniveau. Dit brede scala aan aspecten en omstandigheden is voorheen buiten beschouwing gelaten in modeleringsstudies. In deze thesis worden deze aspecten samengevoegd onder de term 'Root-Chute', oftewel van de wortel tot de fabriekspijp, en bouwt voort op huidige kennis om de ontwikkelingen van bio-energie in de EU tot 2050 beter te begrijpen.

Doelen en onderzoeksvragen

Deze thesis heeft als doel het bevorderen van de analyse van de toekomstige rol van bioenergie als een mitigatie optie voor de EU tot 2050. Dit is bereikt door het verbeteren van EU-niveau projecties op systeemniveau, door essentiële aspecten gerelateerd aan dynamieken in vraag en aanbod op globale en regionale schaal, inclusief de emissies over de gehele leveringsketen. Om dit te bereiken zijn de volgende onderzoeksvragen behandeld:

1. Hoe groot is de rol van bio-energie in de decarbonisatie strategieën van de EU volgens projecties van kwantitatieve analysemethodes?
2. Hoe consistent zijn verschillende modelering studies over de representatie van bio-energie en klimaatbeleid, en het in acht nemen van de Root-Chute aspecten?
3. In hoeverre kan het EU mitigatiepotentieel beïnvloed worden door handelsbeperkingen en globale concurrentie voor bio-energie grondstoffen, en vice-versa?
4. Hoe realistisch zijn lange termijn projecties voor de toepassing van bio-energie en het mitigatie potentieel in de EU, rekening houdend met logistieke aanvoer, opschalen, beheerpraktijken en technologische ontwikkelingen?

Tabel 1: *Overzicht van de hoofdstukken in deze thesis, en bijdrage per hoofdstuk aan de onderzoeksvragen. OV = onderzoeksvraag.*

Title		OV1	OV2	OV3	OV4
2	Bio-energie ontwikkelingen in de EU tot 2050	+++	++		
3	Integrale analyse van de rol van bio-energie in de energietransitie doelstellingen van de EU tot 2050	+	++	+	
4	De implicaties van geopolitieke, socio-economische en regelgeving- beperkingen voor de import van bio-energie in de EU, en bijbehorende broeikasgas emissies tot 2050		++	+++	+++
5	Projecties van de EU bio-energie waardeketen tot 2050 aan de hand van een multi-model raamwerk	+	++		+++
6	Thesis synthese	**X**	**X**	**X**	**X**

Samenvatting vanz de resultaten

Hoofdstuk 2 biedt een analyse van de recente projecties van vraag en aanbod dynamieken voor de bio-energie voor de EU tot 2050 op basis van een review. De review combineert projecties vanuit grondstof-gerichte, vraag-gedreven en integrale analyse methodes. Projecties hebben als doel het stellen van absolute ranges, het bepalen van samenhang met beleid en het geven van inzichten in de implicaties van de schaal waarop ontwikkelingen, handel en energiezekerheid worden geïmplementeerd. Vergelijkingen tussen verschillende methodes geven aan dat bio-energie een belangrijke rol zal spelen in de toekomstige energie-mix in de EU, onafhankelijk van de technologische ontwikkelingen en handelsbeperkingen.

De methode van studies gericht op het aanbod van bio-energie zijn recentelijk geharmoniseerd. Desalniettemin spant de range van technisch potentieel van biomassa voor energie beschikbaar in eigen regio van 9–25 EJ/jaar, dit komt onder andere door onzekerheden in de aannames over de opbrengst van grondstoffen. De mate waarin de beschikbare grondstoffen op de lange termijn daadwerkelijk benut kunnen worden hangt af van de economische toegankelijkheid, wat bepaald wordt door de volgende vier factoren; (1) ontwikkelingen in de prijs en beschikbaarheid van import (projecties van vraag voorzien dit niet als een barrière tot 2050), (2) ontwikkelen in andere technologieën met lage koolstofimpact, (3) de winstgevendheid van non-energetische 'bio-based' producten, en (4) naleving van duurzaamheidscriteria voor het verminderen van broeikasgas emissies.

Projecties van de vraag naar bio-energie (vanuit vraag gestuurde en Integrated Assessment Model - IAM -methodes) variëren van 5-19 EJ/jaar tot 2050. Deze range is vooral het gevolg van variatie in de aannames in de studie op het gebied van invloedrijke ontwikkelingen, zoals de economische concurrerende vermogen van bio-energie, verbeteringen van de energie-efficiëntie in de energiesector van de EU, de flexibiliteit in het behalen van mitigatie doelstellingen en technologische portfolio's. De bovengrens van de schattingen van het technische aanbod kunnen de toekomstige vraag compleet dekken met grondstoffen vanuit de eigen regio, daarmee vermindert mogelijk de totale primaire energie in de EU die afhankelijk is van import met 22%. De import in de EU worden verwacht toe te nemen van 4% tot 13-76%, veroorzaakt doordat een deel van de grondstoffen in eigen regio economisch ontoegankelijk is, of van onvoldoende kwaliteit. Beperkingen in de beschikbaarheid van grondstoffen vanuit andere wereldregio's door de toename in wereldwijde vraag zou kunnen leiden tot een situatie waarin geïmporteerde biomassa in de EU vanuit complexere en minder duurzame waardeketens afkomstig is, wat leidt tot een vermindering van de emissie-besparingen. De verwachting is dat de opkomst van non-energetische toepassingen zal concurreren voor te minste 10% van de biomassa die nodig is om aan de vraag te voldoen in 2050.

Hoofdstuk 3 zet de eerste stap in de thesis om het 'Root-Chute' principe, oftewel van de wortel tot de fabriekspijp, te integreren in de analyse voor bio-energie projecties als onderdeel van de energie transitie in de EU, voor het behalen van klimaatdoelstellingen, tot 2050. Deze studie maakt gebruik van het globale IAM IMAGE om gedetailleerde regionale analyses te genereren op EU-niveau, binnen de globale context, en neemt technologische beperkingen zoals het verbod op het gebruik van alle bio-energie of biomassa in combinatie met koolstof afvang en opslag. Deze aanpak dient als een belangrijke tussenstap om optimale eind-gebruik strategieën te bepalen met in acht neming van wereldwijde dynamieken en als punt van vergelijking voor i) validatie van de representatie van EU klimaatkoersen in IAMs, en ii) verbeterde analyse door verhoogde resolutie van de aanpak. Dit hoofdstuk geeft een prognose van bio-energie vraag, sector-specifieke inzet van bio-energie, grondstoffen en inter-regionale import voor de EU tot 2050. Door gebruik te maken van een wereldwijd model kunnen de prognoses voor decarbonisatie van de EU afgestemd worden met globale klimaatdoelstellingen, en worden de effecten van biomassa productie en consumptie in andere wereldregio's meegenomen.

De EU vraag naar bio-energie zal naar verwachting significant toenemen en zal een substantiële rol spelen in een betaalbare energie transitie om klimaatdoelstellingen voor 2050 te behalen. Prognoses geven aan dat een klimaatkoers tot 2050 voor de EU van '2°C', dat huidige wettelijk vastgelegde klimaatdoelstellingen volgt, mogelijk is. Het bereiken van deze doelstellingen tegen de laagste kosten resulteert in een verwachte verdriedubbelde toepassing van bio-energie, overeenkomstig met een bijdrage van 27% (14 EJ/jaar) aan de totale primaire energie vraag van de EU in 2050. Dit resulteert in een substantiële herstructurering van de toepassing van bio-energie, waarbij energieopwekking, het belangrijkste eind-gebruik wordt, en daarmee verantwoordelijk voor 60% van de consumptie van bio-energie in 2050. De voorkeur voor elektriciteitsopwekking is gemotiveerd door de beschikbaarheid van net-negatieve emissies via Bio-energie met koolstof afvang en opslag (afgekort in het Engels als BECCS) binnen grootschalige installaties. Bio-energie kan tot 27% (8.5 Gt CO_2eq.) bijdragen aan de benodigde cumulatieve emissiereducties, met een bijdrage van BECCS van 0.7 Gt CO_2eq./jaar in negatieve emissies in 2050. Het model voorspelt een substantiële verschuiving van 1^e generatie grondstoffen voor vloeibare bio-energie naar meer geavanceerde en lignocellulose bronnen, de bijdrage van deze geavanceerde bronnen zal naar verwachting toenemen van 20% (0.3 EJ/jaar) in 2030 naar 90%(3 EJ/jaar) in 2050.

Om aan deze vraag te voldoen voorspelt het model een toename in biomassa import van 4% naar 60%. Bio-energie kan tot 1 Gt CO_2eq. of 40% van de benodigde mitigatie in de EU leveren in 2050. Dit is gebaseerd op grootschalig gebruik voor elektriciteitsopwekking (8.4 EJ/jaar), wat resulteert in een kleiner aandeel voor de industriële sector (1.7 EJ/jaar), transport sector (1.4 EJ/jaar), bouw(1.4 EJ/jaar), en andere non-energetische sectoren (1 EJ/jaar). Modeluitkomsten geven aan dat in 2050, 55% van het bio-energie gebruik gekoppeld is aan BECCS. Het aanbod van bio-energie komt met name vanuit landbouw en bosbouw residuen, omdat deze bronnen lage broeikasgas emissies veroorzaken in de keten. Met toenemende vraag neemt ook het gebruik van energie gewassen toe (tot 10% van het aanbod van bio-energie in de EU in 2050), met name als grondstof voor vloeibare brandstoffen. De resultaten geven aan dat een koers voor het bereiken van de energie transitie in de EU gebaseerd is op het snel uitrollen van BECCS en de mobilisatie van duurzame import van 2^e generatie grondstoffen.

Hoofdstuk 4 bouwt voort op standaard regionale-gerichte analyses door gebruik te maken van een IAM voor het ontwikkelen van een scenario protocol dat de gevolgen van aannemelijke toekomstige ontwikkelingen in de EU import van bio-energie (grondstoffen) op de internationale markt onderzoekt. De scenario’s dekken de zorgen over de geopolitieke risico’s en haalbaarheid barrières, en de potentiële impacts van EU vraag-gerichte duurzaamheid criteria, met name de RED II emissiereductie criteria. De allocatie van emissies in de handelsketen per eenheid van geïmporteerde bio-energie is verbeterd in het IMAGE model, zodat biomassa dat voldoet aan de RED II criteria geïdentificeerd kan worden. Het effect van handelsbeperkingen op de import volumes van de EU, regio van oorsprong, mitigatie potentieel en de implicaties voor EU en wereldwijde emissies zijn bepaald tot het jaar 2050.

De model-voorspellingen geven aan dat de EU de import kan verhogen van 1.5 EJ/jaar in 2020 tot 8.1 EJ/jaar in 2050 in overeenstemming met de RED II broeikasgas criteria. Onder deze omstandigheden kan bio-energie een jaarlijkse broeikasgas mitigatie realiseren van 0.44 Gt CO_2eq in 2050. Om dit te bereiken is een structurele diversifiëring van handelspartners echter noodzakelijk, richting regio’s die een hoger risico op socio-economische risico’s met zich meebrengen. De regio’s van oorsprong voor import veranderen over tijd, dit vereist EU operateurs om flexibel te zijn. Deze diversiteit in bevoorrading regio’s in 2050 is noodzakelijk om aan RED II criteria te voldoen, omdat belangrijke exporteurs met lage productie kosten het gebruik van residuen maximaliseren in 2050. Dit resulteert in de uitbreiding van de productie van energie gewassen en grondstoffen op land met hogere koolstofopslag, lagere opbrengsten en hogere transport kosten.

Beleidsmaatregelen zoals RED II creëren overkomelijke barrières voor de inzet van bio-energie in de EU. De meest significante risico's voor de toekomstige uitbreiding van EU bio-energie import hebben betrekking op socio-politieke, technische en logistieke aspecten. Prognoses geven aan dat indien deze barrières niet overwonnen worden, de jaarlijkse marginale broeikasgas emissies kunnen toenemen met of 0.26 Gt CO_2eq in 2050. Deze resultaten suggereren dat wereldwijde IAM modeleringsstudies meer gebaat zijn bij een uitbreiding van de standaard bio-energie handel dynamieken met de vertegenwoordiging van haalbaarheid aspecten dan als add-on grenswaarden, zoals toegepast in deze studie. De resultaten benadrukken bovendien dat de EU mogelijk niet de meest effectieve eindgebruik markt is voor interregionaal verhandelde bio-energie, vanuit een globaal klimaat perspectief. Onze resultaten geven aan dat het inzetten van bio-energie in wereldregio's buiten de EU een diepere (35-45g CO_2eq MJ^{-1} in 2050) mitigatie mogelijk biedt, gezien de koolstof intensievere energie systemen in deze regio's. Binnen het onderzochte koolstofbudget zouden wereldwijde emissies het laagst zijn als de EU de extra-EU import beperkt tot 25% tot 6 EJ/jaar in 2050. Het prioriteren van eindgebruik regio's voor bio-energie zou echter ook rekening moeten houden met regionale beleidskoers voor klimaat mitigatie doelstellingen tot 2050, en de mogelijkheid voor ontwikkeling in nieuwe technologieën zoals BECCS.

Hoofdstuk 5 ontwikkelt een 'soft-link' multi-model raamwerk, en past dit toe, wat het EU bio-energie aanbod in globale context alloceert aan de hand van de vraag van individuele deelstaten, en onder een toenemende reeks aan conversie en eindgebruik technologieën. Deze aanpak neemt complexiteiten in de bio-energie waardeketen in beschouwing, over verschillende ruimtelijke en technologische resoluties. Het raamwerk omvat het globale Integrated Assessment model IMAGE, het EU energie-systeem model PRIMES en het 'least-cost' model voor het Europese bio-energie systeem RESolve-Biomass, om de inzet van bio-energie inde EU27 en het VK te onderzoeken onder een '<2°C' klimaatscenario. Het overbruggen van deze technologische en geografische resoluties maakt een diepere analyse van de gevolgen en haalbaarheid van bio-energie prognoses vanuit logistiek, techno-economisch en beleidsperspectief mogelijk.

De resultaten geven aan dat 14.8 EJ bio-energie per jaar (waarvan 8.5 EJ geïmporteerd is) geleverd en ingezet kan worden in 2050 in de EU27 en het VK. Bio-energie kan een significante rol spelen in alle behandelde eindgebruik sectoren als onderdeel van de energie transitie in 2050. Biomassa kan 5.8 EJ/jaar (25%) bijdragen aan de totale vraag naar verwarming, 5.2 EJ/jaar (19%) van elektriciteit, 2.3 EJ/jaar (14%) van transport en 1.5 EJ/jaar (27%) vanuit de chemische sector. Een kosten-optimale strategie resulteert in een inzet van 75% van bioenergie als elektriciteit en warmte. Een voorkeur voor het genereren van warmte en elektriciteit is gemotiveerd door de grootschalige inzet van BECCS, dat afvang van broeikasgassen mogelijk aamkt voor de EU27 en dhet VK in 2050. De aanvoer van biomassa is voldoende om 1.2 Gt CO_2eq afvang per jaar te realiseren, waarvan 50% afkomstig is van extra-EU import. Gezien de verwachte verspreiding van BECCS is dit naar waarschijnlijkheid afhankelijk van grensoverschrijdende projecten voor collectieve opslag in het Zuidwest en Centraal Europa, waar ongunstige opslag beschikbaar is. Het realiseren van de voorspelde negatieve emissies vereist een sterke opschaling.

De belangrijkste voorspelde conversie routes zijn geïntegreerde vergassing en pellet verbrandende gecombineerde cyclus installaties, samen met koolstof afvang en opslag, wat de beschikbaarheid van bio-energie beperkt voor sectoren waarin emissiereducties lastig te realiseren zijn – zoals weg- en luchtverkeer. De verspreiding van vraag over de deelstaten focust >50% van de totale vraag richting de geïndustrialiseerde economieën in Duitsland, Frankrijk, Polen, Italië en Spanje, waarvan verwacht wordt dat ze een vertienvoudiging in elektriciteit zullen doormaken tot 2050. Deze landen hebben lastige knelpunten om de prognoses te realiseren door een gebrek aan capaciteit in het transport netwerk voor de handel in energie, of ongunstig koolstof opslag potentieel op land, of beiden.

Als bio-energie ingezet wordt op het voorspelde niveau zullen alle distributie netwerken in jet EU energie transport netwerk onder significante stress komen te staan. In vergelijking met de huidige verwerkingscapaciteit van bestaande systemen voor fossiele brandstoffen zoals kolen, aardolie en aardgas brengt dit belangrijke logistieke uitdagingen aan het licht. Haventerminals zullen hun capaciteit voor het verwerken van grondstoffen in vaste en vloeibare vorm moeten vergroten met 50%, met name de capaciteit het verwerken van bulk (pellets), waarvan fossiele alternatieven zoals kool met name afhankelijk zijn van treinvervoer. Eenmaal aangekomen binnen de grenzen van de EU vereist de distributie tussen deelstaten een significante toename van 80% over de komende 30 jaar als de bio-energie leveringsketens beperkt zijn tot de huidige systemen, dat wil zeggen, zonder aanvullende pijplijn. De distributie van internationaal geworven grondstoffen binnen de regio geeft een toename in 150% aan in weg- en treintransport over korte afstand om nationale grondstoffen te mobiliseren in 2050. Bulk transport van hogere dichtheid bio-energie (grondstoffen) vereist een strategies gepland elektriciteitsinstallaties en industrie, om de logistieke uitdagingen van grootschalige bio-energie handel te verminderen. Het uitfaseren van kolen zal deels de uitbreiding van het netwerk verzachten. Een ex-ante kosten-baten analyse van een EU pijplijn netwerk voor biobrandstoffen zou echter gunstig zijn om de voorspelde integratie van bio-energie te realiseren.

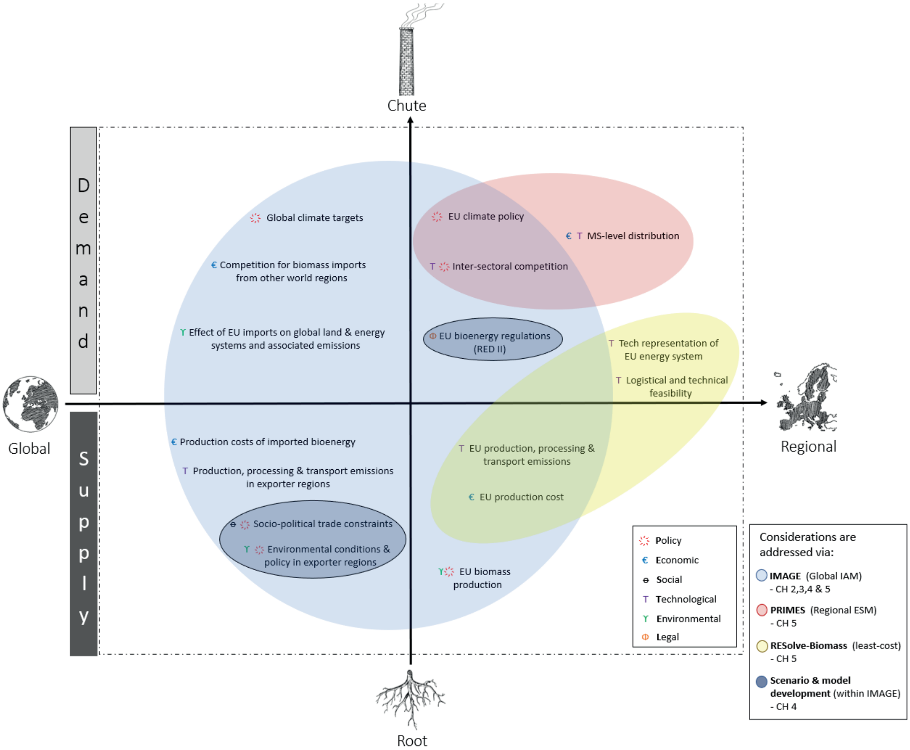

Fig.1: *De behandeling van 'Root-Chute' systeem-niveau aspecten van globale en Europese leveringsketens van bio-energie in de hoofdstukken van deze thesis.*

- Aspecten op wereldwijde en regionale schaal betreffende de marktdynamieken zijn gesplitst in vraag versus aanbod. Dit is met name het geval voor de economische aspecten, die zowel door vraag als aanbod dynamieken gedreven worden. Zodoende is de positionering in het bovenstaande schema gemotiveerd door subjectieve weging en deels arbitrair.

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AK

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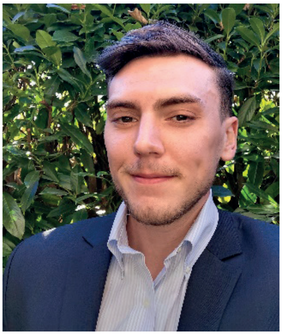

Steven James Mandley was born on August 5th 1986 in the United Kingdom. His studies include Environmental management (BSc, 2005-2008) in Nottingham University, the UK; and Sustainable Development (MSc, 2012-2014) at Utrecht University, the Netherlands. His master's thesis focused on the identifying energy and material efficiency measures within large-scale construction projects for the built environment.

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Steven is presently conducting and advancing environmental assessment methodologies to quantify the impacts of products and services within global-scale supply chains. The role is within a large global food corporation and agricultural commodities.