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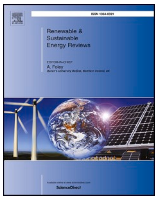

EU bioenergy development to 2050

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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 to 25 EJyr-1 of EU domestically available biomass for energy in 2050. Demand side projections range between 5 and 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% 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.

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 [1]. 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 [2]. Of this, 96% of biomass used for energy is EU-sourced and 89% is derived from the member state (MS) it is consumed in Ref. [3], with EU biomass production exceeding that of domestic gas or coal [4]. 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) [5].

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 [6]. 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 [7]. 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 [8]. 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 [9]. However, the supply and demand dynamics for EU bioenergy in the

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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 supranational 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 [10–12].

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 [13].

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 [14,15], Forestry [16,17], Agricultural Residues [18,19] and waste streams [20]). 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 [21,22] or the demand side [23,24] 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, CO2 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 [12].

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. Methodology

2.1. Characteristics of the reviewed assessment approaches & study inclusion parameters

2.1.1. 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 [25]. 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.

2.1.2. 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 [26]. 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 [26] with climate and energy policy inclusion crucial [10].

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 [25], 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.

2.1.3. 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 [27]. 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 [10,28].

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. 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 [29–31]. 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 [31], 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 [10] 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. 1 provides a schematic of the review framework.

3. EU bioenergy projections to 2050

3.1. Policy overview

3.1.1. 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 [32]. 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 [6], 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

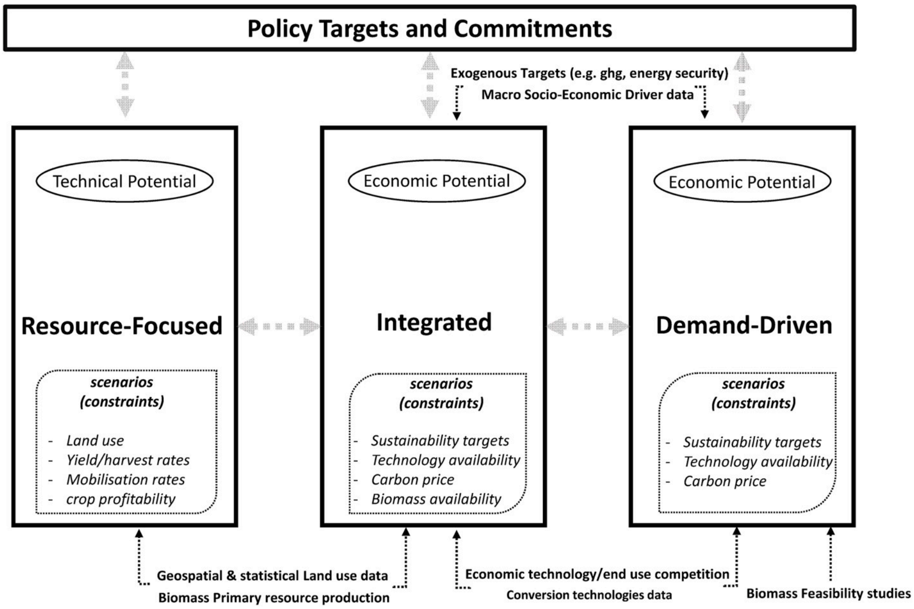

Fig. 1. Framework of the review, highlighting key characteristics of bioenergy assessment approaches.

short-term (2018–2023) market analysis for the IEA [1], 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 [33] and the IEA's Sustainable development scenario which projects a needed RES mix of 28% by 2040 [24]. The renewable energy directive II recast [34] 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 to 80% post 2026 with a stringent list of sustainability constraints [34].

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 $EJyr^{-1}$] [35].

3.1.2. *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 [8]. 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 [7]. 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) 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 [36]. 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 [37]. Facilitation policies for bioenergy include agricultural policies stimulating the production of energy crops, increased residue collection, and/or increased yield of crops.

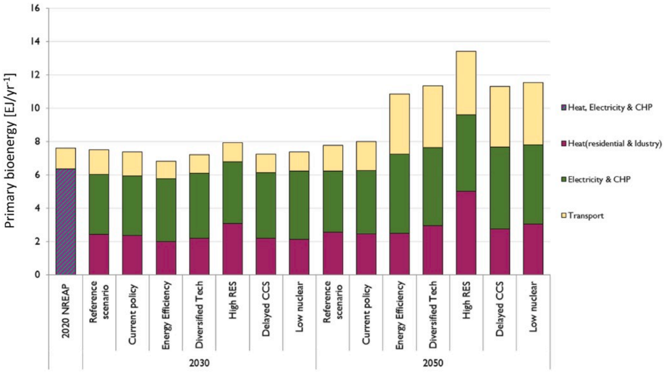

Fig. 2. *Evolution of Absolute Domestic EU Primary bioenergy within major end-use sectors: Own calculations using data from the EU Energy Roadmap 2050* [37].

Fig. 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.

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 (BBE) project [10]. 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 [30]. 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' [38], 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 [39], Biomass policies and S2biom [40] 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. 3. In the short-term to 2020 large differences appear in the amount of primary bioenergy available, ranging between 4.8 and 21.6 $EJyr^{-1}$, the mid-term 2030 show a range of between 8.6 and 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.

Variation in the estimates arise from one or more of three key

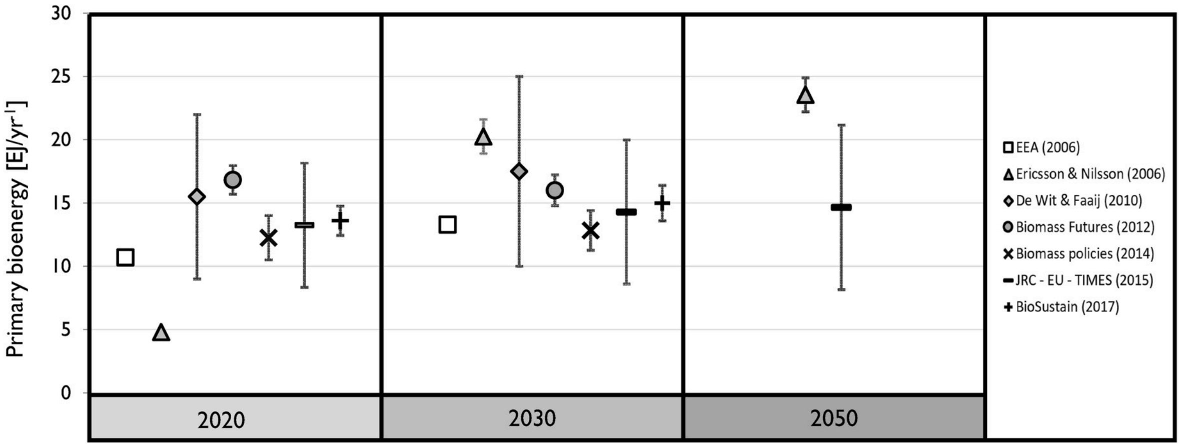

Fig. 3. *–Total EU Domestic bioenergy production Technical Potentials 2020–2050: As projected by the Resource assessment approach * pre 2011 assessments are calibrated to EU level as part of the EC project BEE.*

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 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 and 20 EJyr^{-1}. This reflects the conclusions reached by Panoutsou [41] that between 2008 and 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 [42]. Pre 2010, future land use and yield developments are more crudely estimated. A recent review on EU scale land and bioenergy potential studies [29] 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 [43] (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’ [44] 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.

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, optimization, partial or general equilibrium models [45] and are based on cost-supply of aggregated resources [25].

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. 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}.

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) [46]. 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 [47]. 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 and 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 [48]. RES

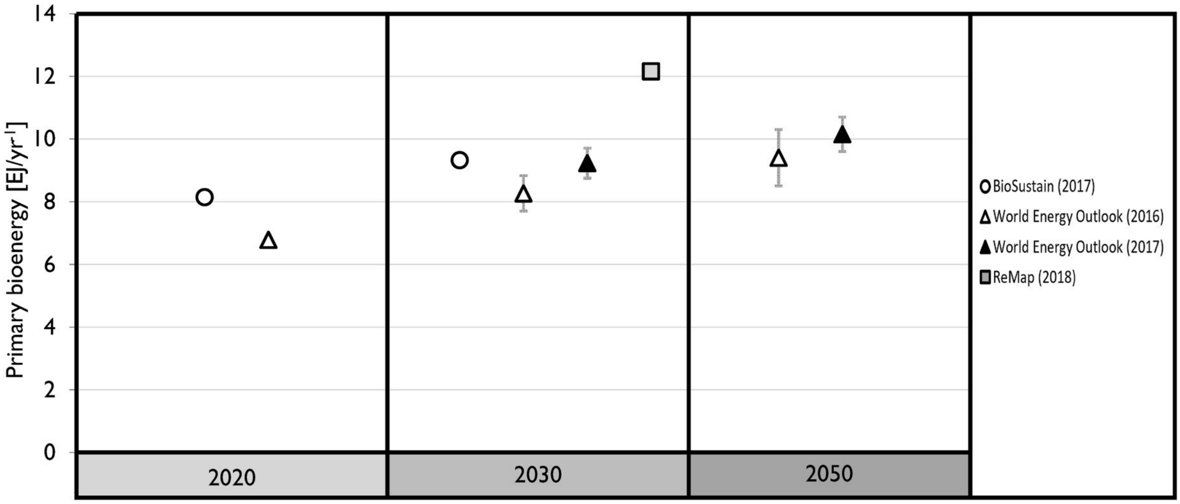

Fig. 4. *–Total EU Primary bioenergy demand 2020–2050: As projected through the Demand-driven approach.*

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 [49]. 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. 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 [50]. 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 1080 Gt CO_2 [50]. 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 [51]. 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 [51].

The close grouping of the projected developments over a span of 30 years is observed in Fig. 4. This is partly due to their formulation under conditions that conform tightly to intermediate policy targets most notably a GHG reduction of 40% [6], RES shares of >27% [34] and an energy efficiency target of 30% accordance to the EC's energy efficiency directive and its proposed revision [52] 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.

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 Modelling Forum (EMF-33) which aimed to quantitatively consider the development of bioenergy development towards climate targets consistent with the Paris Agreement [53]. The EMF 33 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 [54] 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. [54], 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

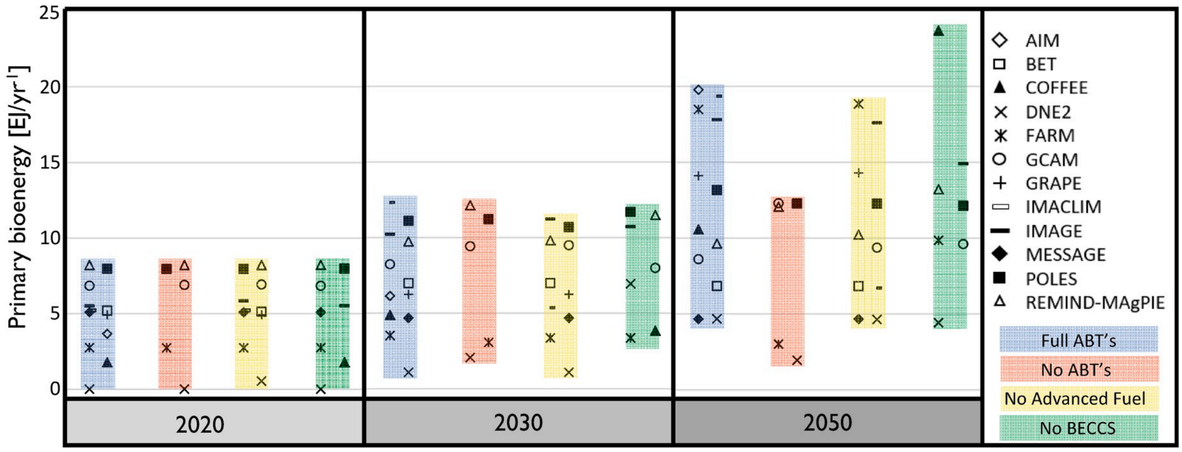

Fig. 5. *–Total EU Primary bioenergy demand 2020–2050: As projected by EMF33 participating IAM's: Under a harmonised global emissions constraints for varying bioenergy technology availability scenarios.*

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. 5 presents the projections of EU primary bioenergy demand for varying technology availability scenarios from the IAM's that participated within the EMF-33 study.

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 and 2030 with a model average increase of +60% (6%/yr) absolute primary energy demand. Between 2030 and 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 [55]. The model comparison shows under full ABT availability, bioenergy deployment will contribute between 7 and 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 and 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. 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 [54]. 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.

4. Synthesis

Drawing from the quantitative insights derived in the previous sections, Fig. 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

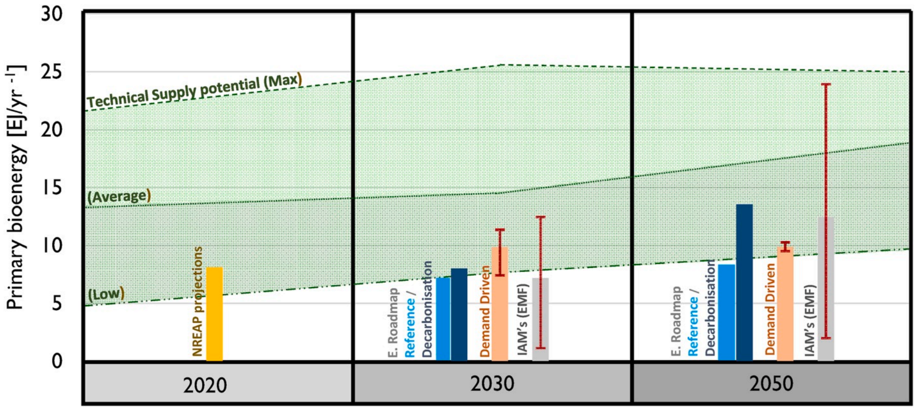

Fig. 6. *–Comparative synthesis of assessment approaches and policy ambitions 2020-2050.*

envisaged in policy.

From Fig. 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. 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. 4, 2040 projection held static for 2050 within Fig. 6 synthesis) and taking a more aggressive energy efficiency strategy, which closely aligns to the 'energy efficiency' decarbonisation scenario in Fig .2 at 11 EJyr^{-1} in 2050.

As shown in Fig. 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 favorable. 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.

4.1. *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 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. 6) exceeds almost all demand projections investigated, a substantial share depends upon the active implementation of supply-side developments discussed in section 3.2, most notably the realisation of yield improvements and land availability for bioenergy dedicated crops and mobilisation of forestry biomass.

4.2. *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).

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. 7 when compared with the possible supply developments (A-C, as defined in box 1).

When comparing trade as reported by the studies focusing on future demand included within this review to the ranges of EU technical

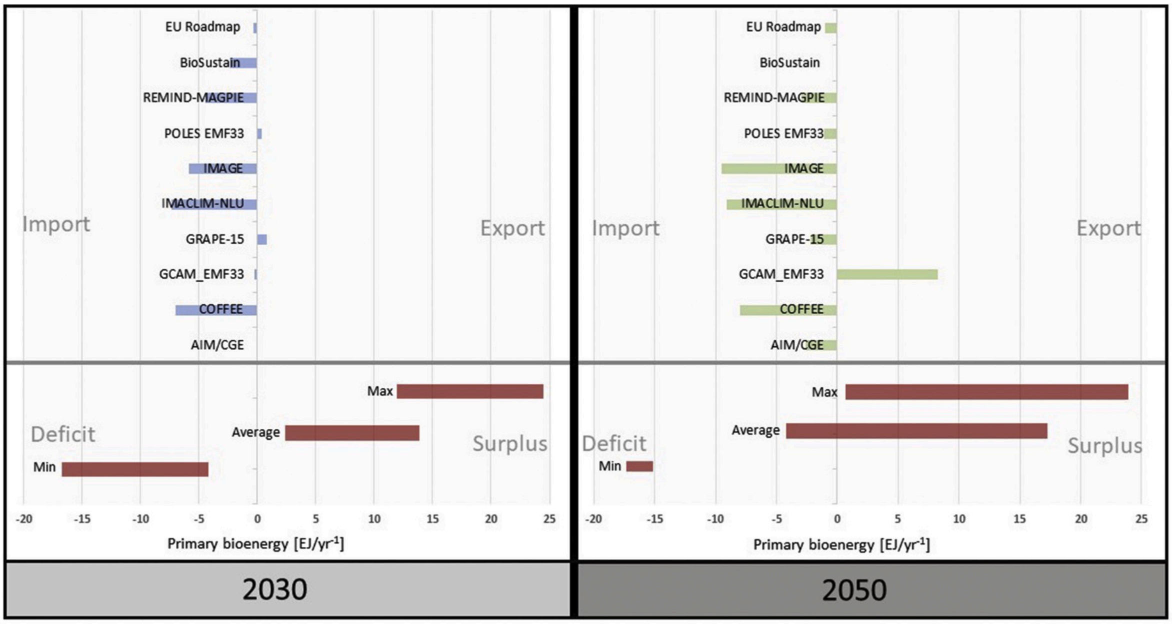

Fig. 7. –Comparison of annual net trade as projected by individual studies (upper panel) and possible trade developments (A–C) from box.1 (lower panel).

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 [55]. 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 vol 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. 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. [56] 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.

4.3. Implications for energy security

The current utilisation of bioenergy in the EU stands at 5.63 $EJyr^{-1}$ [2] of which 4% is imported. Upper range future demand projections (Fig. 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 [57,58]. 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. [59] employs the same EMF 33 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 [36]. 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. 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% [60] and fossil-fired average 49.7%).

(b) At exploitation levels equivalent to the largest bioenergy deployment seen in Fig. 6 as the upper IAM's projections for 2050, where advanced bioenergy technologies are available, EU import dependency could fall from 58% to 36%.

4.4. 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 [22]. 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 [61]. 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.

4.5. 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 [62]. 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 [63] Schipfer et al. [64], 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 and 2.3 $EJyr^{-1}$ of primary biomass to facilitate the transitional switch [64]. 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. 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 [65]. Daioglou et al. [62], 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).

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 [66] The projections for future EU bioenergy demand range between 5 and 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 bioproducts 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 favorably 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. 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 * (201 0)	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
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 mobilisation**: increased forestry biomass mobilisation through implemented policy (based on EFOS medium mobilisation 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 mobilisation **(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 mobilisation ***(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

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