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We didn’t start the fire

The role of bioenergy in decarbonisation scenarios

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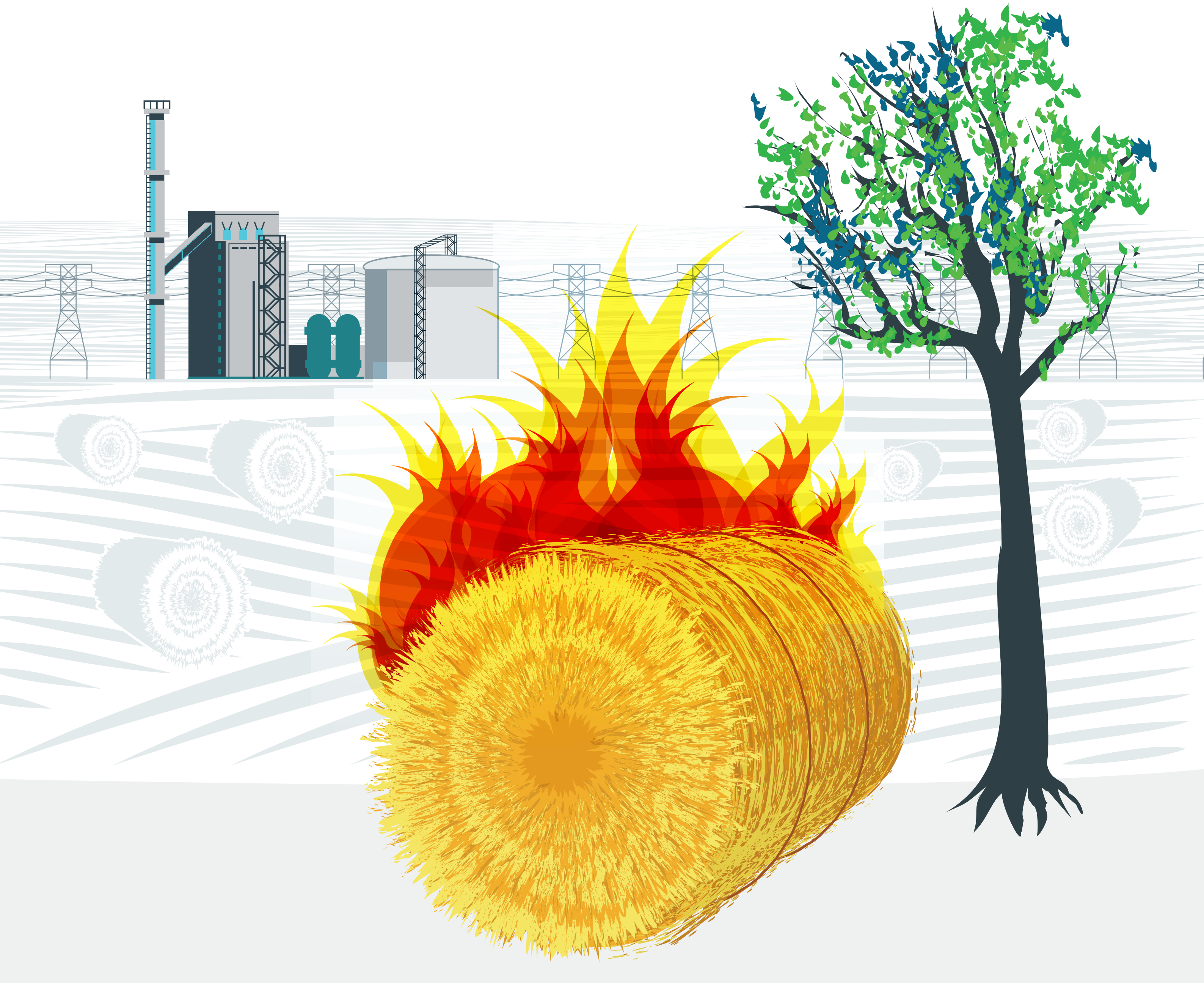

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1. Introduction

As the world moves into the energy transition required to deliver 2050 climate mitigation targets, the number of pathways and scenarios modelled to illustrate ways to deliver GHG reduction goals is growing faster than global CO_2 emissions. In this report, we have been asked to review a number of these scenario studies, some focused on the European Union and some globally, with a view to identify the main assumptions made about the role of bioenergy in the transition. All studies reviewed that make an assessment at the EU level analyse the full EU-28, i.e. the UK is included in the EU in these studies. After discussing each of these specified studies in turn, the report contains a briefer review of results published in several other reports, then a chapter comparing some of the results and finally a brief discussion.

1.1. Units

The reports reviewed herein use a wide and potentially bewildering range of energy units, often choosing those most relevant to the sector being discussed – one report may use terawatt hours for power but barrels of oil equivalent for liquid fuels. For the sake of comparability, all energy values quoted here are converted from the original quoted units into million tonnes of oil equivalent (Mtoe), unless otherwise stated. Readers should be aware of the distinction between energy values quoted in terms of primary energy (chemical energy contained within biomass) and final energy (energy consumed after allowing for conversion efficiency and distribution losses). Delivering 1 Mtoe of final energy could require 2 or 3 Mtoe of primary energy, depending on the form the energy is delivered in. Losses tend to be highest for delivery of biomass energy as electricity, lowest for delivery as heat.

2. European Commission: A Clean Planet for all (European Commission, 2018b)

2.1. Introduction

“A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy” was published in November 2018 by the European Commission. The aim of the strategy is described as being to, “present a vision that can lead to achieving net-zero greenhouse gas emissions by 2050 through a socially-fair transition in a cost-efficient manner”. The strategy does not directly set policy, but provides context for the next phase of development of EU climate policy.

The strategy is built around eight modelled decarbonisation scenarios, and a baseline scenario for comparison. Five scenarios are tuned to deliver about 80% GHG emissions reductions by 2050 compared to 1990 levels. A sixth scenario combines elements of the first five to reach a 90% GHG reduction. The final two scenarios assess pathways to zero emissions in 2050. The scenarios are:

1. Electrification – rapid electrification, and a focus on heat pumps for building heat
2. Hydrogen – creation of a hydrogen economy for heating, transport and some industrial applications
3. Power-to-X – electrogas and electrofuels for heating, industry and transport
4. Energy efficiency – efficiency improvements and modal shift for transport
5. Circular economy – more recycling and materials substitution, ‘mobility as a service’
6. Combination – smorgasbord of the most cost-effective measures identified in the other scenarios
7. 1.5 degree technical – additional carbon capture (including BECCS) added to the combination scenario
8. 1.5 degree sustainable lifestyles – the combination scenario with additional lifestyle adjustments (less air travel, less meat eating, enhancement of the natural carbon sink)
    a. This scenario is accompanied by a sensitivity case investigating options to minimise biomass demand.

2.2. Overview of modelling approach

The modelling approach is described in European Commission (2018b) and online. The modelling of the scenarios is undertaken using the PRIMES-GAINS-GLOBIOM model suite, where PRIMES is an energy system model, GAINS models non-CO_2 GHG impacts, and GLOBIOM-G4M-CAPRI is

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a (suite of) agriculture and land use model(s). There are various interlinkages within this system, and the three 'top-level' models are broken down into sub-models and modules.

The scenarios are differentiated by setting different 'coordinating policies', which "develop infrastructure and pursue R&D&I on enabling technologies, as well as setting producer expectations, consumer preferences and public acceptance."

All scenarios include a 'stylised carbon price' which increases to 250 €/tCO_2e in the 80% reduction scenarios and 350 €/tCO_2e in the zero emissions scenario.

2.2.i) Geographical coverage

The modelling systems covers all EU Member States and candidate countries, plus (where 'relevant') Switzerland, Norway, and Bosnia and Herzegovina.

2.2.ii) Sectoral coverage

The modelling system covers the whole European economy (electricity, transport, industry, heating, forestry, land use, agriculture) with modelling of social welfare, employment, pollution and health. International and domestic aviation are included in the modelling, and quoted results include emissions from international aviation. Overall aviation activity in terms of 'passenger transport activity' grows by around 2% per year, doubling aviation activity by 2050. We note that this is below aviation industry predictions for aviation growth rates (generally at least 3.5% per year). Aviation is predicted to become 42% more efficient by 2050 compared to 2015 in the most aggressive scenarios – International maritime emissions are treated separately.

2.2.iii) Role of bioenergy

The strategy states that:

> *"Sustainable biomass has an important role to play in a net-zero greenhouse gas emissions economy. Biomass can directly supply heat. It can be transformed into biofuels and biogas and when cleaned can be transported through the gas grid substituting natural gas. When used in power generation, CO_2 emitted can be captured creating negative emissions when stored. And it can substitute for carbon intensive materials, particularly in the building sector but also through new and sustainable bio-based products such as biochemicals (e.g. textiles, bioplastic and composites).*
>
> *A net-zero emissions economy will require increasing amounts of biomass compared to today's consumption."*

The modelling includes bioenergy for heat and power, including BECCS, biogas production, and transport biofuels including first- and second-generation technologies. Biofuel pathways assessed in the PRIMES-Biomass are listed in Table 1.

Table 1. Bioenergy technology options in the modelling

	Fuel	Process
First generation	Biodiesel	Transesterification
	HVO	Hydrotreatment and deoxygenation
	Ethanol	Fermentation
	Biogas	Anaerobic Digestion
		Waste methane collection from landfill, sewage sludge
	RDF	Waste sorting
Second generation cellulosic	Ethanol	Enzymatic Hydrolysis and Fermentation
		Enzymatic Hydrolysis and deoxygenation Hydrotreatment and deoxygenation
	Drop-in fuels	Gasification and FT
		Pyrolysis, Gasification and FT
		Pyrolysis, deoxygenation and upgrading
		Pyrolysis, Gasification, FT and upgrading
		HTU process, deoxygenation and upgrading
	Bio-heavy fuel oil	Hydrothermal Upgrading (HTU process)
		Pyrolysis
		Black liquor upgrading
	Methanol	Gasification and methanol Synthesis
	DME	Gasification and DME Synthesis
	Biogas	Gasification
		Catalytic Hydrothermal Gasification
Algal	Biodiesel	Transesterification
	HVO	Hydrotreatment and deoxygen-ation

Processes are characterised by cost modelling including capital and operational costs, feedstock costs and variable input costs. Costs are assumed to reduce over time, and it is likely that the details of the model outputs are quite sensitive to assumptions about cost hierarhies.

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2.2.iv) Consideration of biomaterials and cascading use

The Circular Economy Action Plan is considered as part of the baseline for all scenarios. Cascading use of materials is further emphasised in the circular economy scenario. In this scenario, it is assumed that waste management is improved providing streams of standardised recyclable materials for industry that can displace virgin resource production. Reduced primary consumption of biomass resources for materials makes some of those resources available for bioenergy feedstock. The use of industrial biomass wastes for bioenergy is explicitly identified, and is relatively stable across scenarios at a little under 100 Mtoe. Assumed availability of these biomass wastes is not strongly affected by circular economy assumptions.

2.2.v) How is use of bioenergy determined?

Bioenergy demand is determined through the PRIMES model (for transport, the PRIMES-TREMOVE transport submodel). Demand and supply for each energy source are calculated based on supply-demand balancing and detailed characterisation of process costs for each scenario.

2.2.vi) Characterisation of 'negative emissions' technologies

The main negative emissions technologies considered in the modelling are BECCS, and improvement of the land carbon sink. Negative emissions compensate for ongoing emissions in 'hard to decarbonise' sectors identified as agriculture and transport.

2.2.vii) LULUCF and farming

Biomass supply requirements calculated for each scenario with PRIMES are output to the GLOBIOM-G4M-CAPRI models to assess potential LULUCF and agricultural impacts.

2.3. Assumptions on biomass availability

2.3.i) Feedstocks considered

PRIMES Biomass includes a range of potential bioenergy feedstocks:

- Food crops (starch crops, sugar crops, oil crops)
- Energy crops (herbaceous crops and wood crops)
- Stem wood
- Forestry residues
- Other residues and wastes (agricultural residues, wood waste, black liquor, solid industrial waste, used oils and fats, municipal waste, sewage sludge, landfill gas, manure, animal waste)
- Algae

A range of final bioenergy production pathways are considered for liquid biofuels, biogas, electricity and heat. Material availability in the EU is assessed for each feedstock and cost supply curves are set. A biomass pricing model is used to determine utilisation rates for each feedstock in response to bioenergy demand. Documentation from 2014[1] identifies vegetable oil (largely palm oil) and solid biomass as the two importable resources (E3MLab/ICCS, 2014). Cost supply curves are set on these imports, and supply is informed by consideration of international demand for bioenergy.

2.3.ii) Sustainability considerations

The strategy assumes that the RED II will enhance the sustainability of bioenergy in the EU, and refers to the Commission paper "Sustainability of Bioenergy" from the RED II impact assessment (European Commission, 2016b). In relation to energy crops the strategy notes that, "care will need to be taken with consequences in terms of biodiversity or other environmental sustainability." The GLOBIOM model assesses the associated forest carbon sink change from increased forest biomass removals. Increasing removals above levels that would be considered sustainable would therefore result in net CO_2 emissions undermining delivery of the GHG goal, which militates against assuming excessive removals in the modelling. The PRIMES biomass documentation (E3MLab/ICCS, 2014) states that the basic sustainability criteria from the RED are applied, but these would not limit harvesting of agricultural or forestry residues. It was not clear from the documentation analysed whether or how additional sustainability criteria from RED II are included in the modelling. There does not appear to be any explicit limitation of biomass harvesting rates on biodiversity grounds, and there are no specific recommendations for additional policy action to improve biomass sustainability. Nevertheless, the coupling of the PRIMES biomass consumption results to GLOBIOM land use modelling ensures that potential carbon stock impacts of biomass use are considered even in the absence of explicit sustainability criteria.

2.4. Role of bioenergy in scenario outcomes

The scenarios modelled require between 50 and 140 Mtoe of final energy from biomass Figure 1. In 2050, this is 10% to 19% of EU final energy demand. Biomass contributes to the energy supply across the board, but expansion of renewable electricity in the scenarios is still dominated by wind and solar.

1 This was the most recent version of the PRIMES biomass documentation we were able to identify – the online PRIMES manual page links to an older 2010 version.

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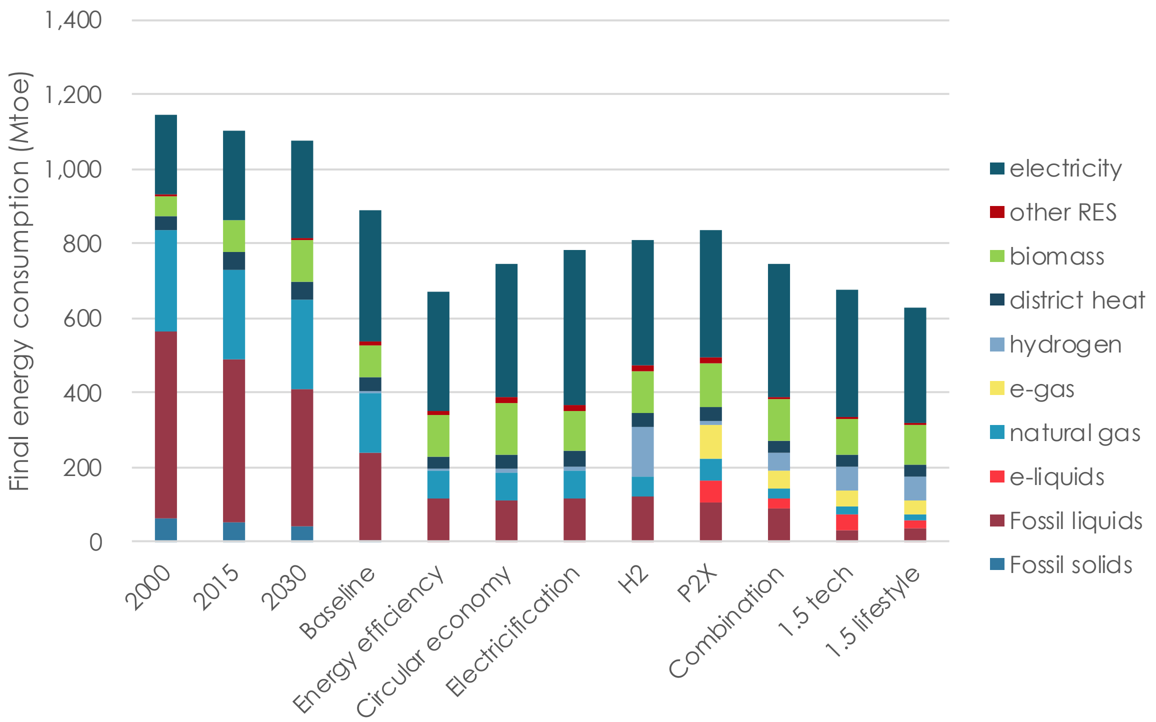

Figure 1. Total final energy consumption by scenario

Source: European Commission (2018b) Figure 20

Producing this final energy requires from 150 to 320 Mtoe of biomass primary energy resources. As seen in Figure 2, wastes and energy crops are the largest feedstock sources in most scenarios, with a significant additional contribution from agricultural and forestry residues. In all scenarios, it is assumed that the collection and use for bioenergy of the biomass component of waste increases by 50% or so. Stemwood use for bioenergy remains relatively constant but collection of forest residues increases significantly. The use of food crops for transport biofuels is almost eliminated, but agricultural residue collection increases. The largest change to biomass supply is the expansion of energy cropping, mostly grassy energy crops, but also some short rotation coppicing.

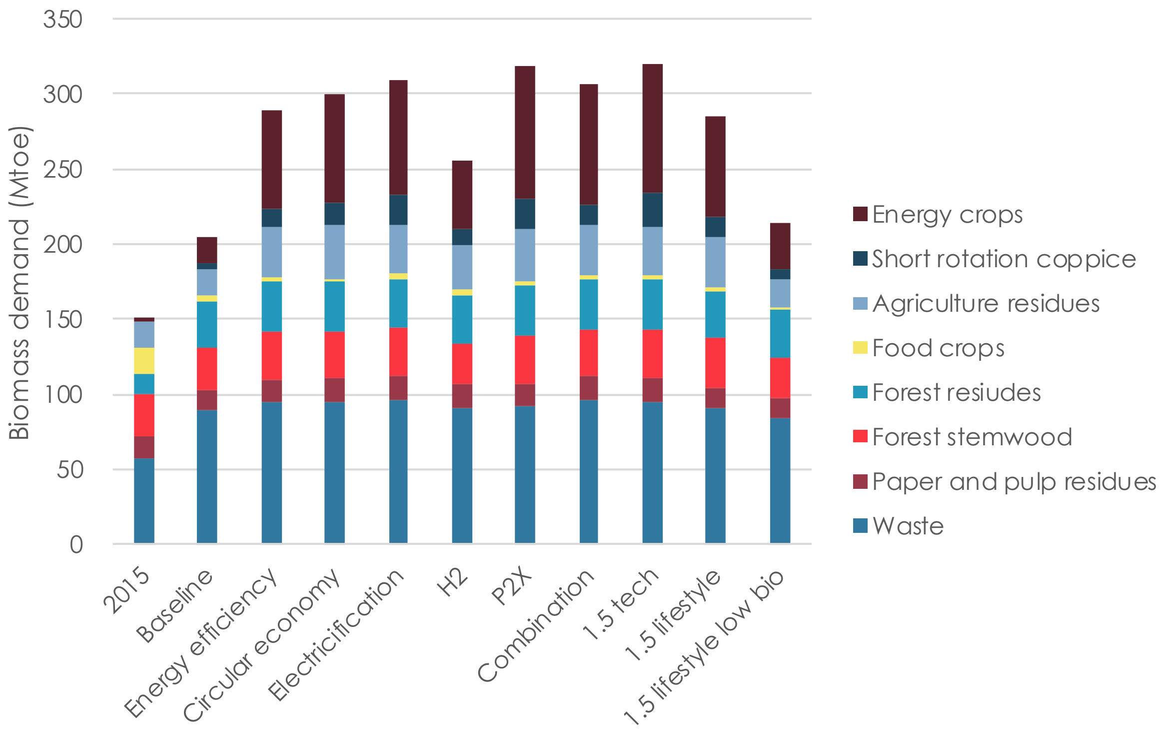

Figure 2. Biomass feedstock requirements by scenario

Source: European Commission (2018b) Figure 84

The low biomass sensitivity case for the 1.5 degree lifestyle scenario reduces primary energy feedstock demand from 290 to 220 Mtoe.

2.4.i) Bioenergy utilisation by sector and mode

The largest source of biomass demand in all scenarios is power generation. Biomass utilisation for power also supplies heat - the use of district heating and combined heat and power increases, meeting 50% of heat demand in most scenarios. In all but the 1.5 °C scenarios industry is the second largest demand source – in those scenarios, however, industry is overtaken by transport. Demand for biofuels in road transport remains as large as or larger than demand for biofuels in aviation in all scenarios in 2050.

One interesting feature of the EU modelling is that biomass demand for electricity increases (compared to the baseline) in scenarios with significant e-fuel consumption. The report states that, “The use of e-fuels in transport would reduce the biofuel requirements of the transport sector, leaving biomass available for other uses, such as for heat, electricity and as a feedstock.” Given that e-fuels are sometimes seen as a biomass-free alternative to advanced biofuels, this suggests that a more complex relationship between e-fuel consumption and biomass demand needs to be considered. Indeed, the P2X scenario has one of the highest levels of overall

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biomass demand. Using electricity to produce gaseous and liquid fuels and then using biomass to produce electricity is counter-intuitive, as significant energy is lost in electricity generation from biomass which could be directly gasified and then itself synthesised into gaseous and liquid fuels. This would only appear rational if there was significant excess renewable electricity capacity in specific locations that could not readily be transmitted through the grid to areas of higher demand, but could be used for hydrogen production. Based on the documentation available, it seems that the P2X scenario may need further development to avoid irrational outcomes.

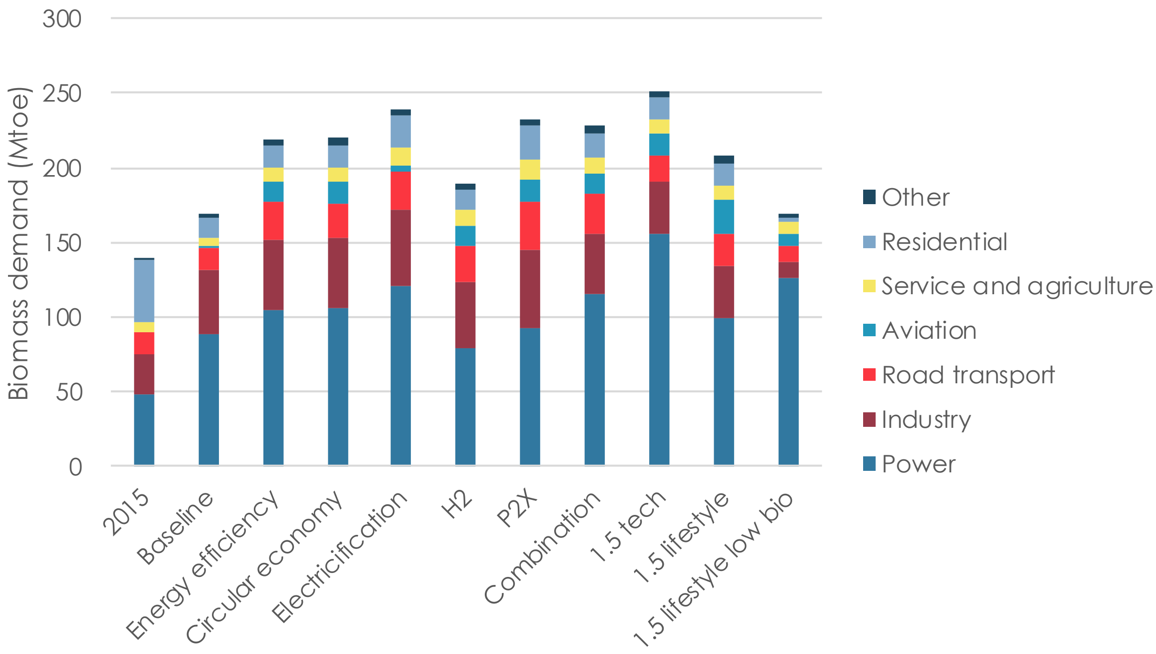

Figure 3. Modelled biomass demand by sector/mode

Source: European Commission (2018b) Figure 83

2.4.ii) Role of imports

In all scenarios considered, biomass is mostly domestically produced, with only 4-6% of solid biomass being imported. The assessment did not consider the sustainability implications of an export driven biomass supply industry in other regions, and despite labelling biomass imports as 'sustainable' potential induced GHG emissions due to biomass imports are not included. First generation biofuel use is almost eliminated in all scenarios, so there are no significant feedstock imports for first generation biofuels.

2.4.iii) Implications for LULUCF?

The biomass demand assumptions for each scenario from PRIMEs are input into GLOBIOM to model associated land use impacts. The main change predicted to land use in most scenarios is the conversion of 'non-productive grassland and shrub' to energy crop production. Energy cropping expands by up to 29 Mha.

Agricultural land use for non-energy crops shrinks slightly in all scenarios, but shows the largest reduction in the 1.5 degree lifestyle scenario, reflecting reduced meat consumption. Yields for agricultural crops are assumed to increase over time, and this presumably allows small reductions in agricultural area without reducing food production. In the case of strong climate change-related impacts on yields, it may be more difficult to expand energy crop production without impacting agriculture or forestry. There is a small amount of afforestation in all cases, and greater afforestation in the 1.5 degree lifestyle scenarios. This afforestation is treated as an alternative to BECCS in the modelling, and afforested land appears to be treated as non-commercial (not a source of biomass for energy or timber). The use of stemwood for bioenergy is more or less constant at the 2015 level across the scenarios. The low 1.5 degree lifestyle low-biomass sensitivity case shows no significant additional afforestation, but a larger area of non-productive grassland and shrub.

The study notes that the use of short rotation coppice instead of increasing stemwood harvest prevents reductions in the forest sink, and emissions from changes to the forest sink and any lost biomass sequestration are considered by the modelling. The 1.5 degree scenarios include modest incentives for increases in the forest carbon sink (30 to 80 €/tCO_2e). In the 1.5 degree tech scenario changes to agricultural practices allow cropland to become a net carbon sink by 2050.

2.4.iv) Regulatory recommendations

The 2050 scenarios show cellulosic biofuels replacing food-crop based biofuels almost entirely, although with some conversion of agricultural land to energy cropping. This would require successful commercialisation of biomass to liquids technologies and development of biomass supply chains.

All scenarios show some transfer of activity from aviation to rail, driven by a presumed gradual 'internalisation of external costs', which would need to be policy led.

The average price of electricity to final consumers is expected to increase by 30% to 70%, with the largest increase in the P2X scenario where electricity demand grows most. It is unclear how the development of the P2X industry would be achieved in the context of such high consumer electricity prices. As noted by (Malins, 2017), without very significant reductions in electricity prices P2X technologies will remain much more costly than biomass-based alternatives. This high cost is reflected in the cost modelling, with the P2X scenario resulting in higher transport energy expenditures than the baseline (in all other scenarios electrification allows energy expenditures to fall). One answer might be to import P2X fuels from regions with lower cost renewable electricity, but this does not appear to be represented in the modelling as the P2X scenario sees primary energy consumption in Europe increase.

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3. IEA World Energy Outlook 2019 (International Energy Agency, 2019)

3.1. Introduction

The International Energy Agency (IEA) publishes annual World Energy Outlooks, providing the IEA's view of the state of and medium-term (to 2040) prospects for the global energy supply. The WEO modelling is informed by climate change commitments but not driven by any assumption about meeting climate targets, and the IEA notes that, "the world is still a long way from meeting its environmental objectives, both in terms of climate and air quality." There is less discussion of biomass in the 2019 World Energy outlook than the 2018 edition (International Energy Agency, 2018), and thus some of the characterisation below draws on the older report on the assumption that underlying assumptions remain comparable.

3.2. Overview of modelling approach

The WEO is built on modelling work by the IEA's internal team, based on results from a range of modelling tools and informed by expert opinion. The modelling focuses on the implications of national policies on energy use, presenting results for 'current policies' (policies already adopted), 'stated policies' (assuming additional policy is introduced consistent with stated intentions of policy makers) and 'sustainable development' (which assumes that stronger policies are implemented to deliver goals on climate change, energy access and pollution). Modelling results are presented for 2030 and 2040.

3.2.i) Geographical coverage

The WEO is global in scope, with results presented at a mix of resolutions (some global, some regional, and some focusing on specific groups of countries).

3.2.ii) Sectoral coverage

The modelling is explicitly energy focused, and considers other sectors only to the extent that is necessary to assess energy demand.

3.2.iii) Role of bioenergy

Both 'traditional' and modern bioenergy are included in the assessment, and bioenergy is treated as a low carbon renewable technology. Traditional bioenergy includes use of wood in open fires and in cookstoves, and is less efficient than modern centralised used, with larger negative health impacts due to air pollution.

3.2.iv) Consideration of biomaterials and cascading use

The sustainable development scenario includes ‘material efficiency strategies’. This includes “reduce concrete-steel composite construction” but it is unclear whether this implies biomaterial alternatives.

3.2.v) How is use of bioenergy determined?

Bioenergy consumption is assessed based on IEA’s policy assumptions in each scenario, and in-house analysis of the expected split between renewable technologies in meeting renewables targets. In the sustainable development scenario, IEA assume that aviation biofuel use expands in a way consistent with aviation meeting the stated target of 50% GHG emission reduction compared to 2005 by 2050.

3.2.vi) Characterisation of ‘negative emissions’ technologies

Bioenergy with CCU is identified as a negative emissions technology. The report notes with regard to negative emissions technologies that, “Many of the technologies or methods involved are unproven at scale, and could have negative consequences outside the energy system related to land use, biodiversity and food security.”

3.3. Assumptions on biomass availability

3.3.i) Feedstocks considered

IEA believes that there are about 10 billion tonnes of cellulosic (and lignocellulosic) material available ‘sustainably’ worldwide (International Energy Agency, 2018), and considers this resource available for advanced biofuel production or other biomass energy use. There does not appear to be any direct assessment of potential competing demands for biomass from biomaterials. This represents about 4,000 Mtoe of primary biomass energy. The IEA scenarios assume the utilisation of no more than 14% of this material for bioenergy. Wood availability is set by IEA to be below annual regrowth rates to allow overall forest wood stocks to increase, but the CO_2 implications of foregone sequestration do not appear to be directly assessed.

The IEA includes first generation food-based biofuels in its assessment. While the assessment is not explicit about the assumed feedstocks for biofuels in 2040 the largest sources of growth are regions with little current focus on advanced technologies, suggesting that 2040 biofuel production could still be dominated by food-based fuels. The 2018 report acknowledges that, “Concerns have been raised about [the] sustainability [of conventional biofuels] in some countries.”

3.3.ii) Sustainability considerations

IEA’s characterisation of sustainably available cellulosic material is material whose harvesting or collection does not compete with food production or reduce biodiversity. Advanced biofuels are those that, “do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.” IEA does not suggest specific sustainability criteria

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that could or should be applied to cellulosic biomass harvesting. IEA assumes that advanced biofuel production will be able to achieve carbon neutrality, and on that basis calculates that the cost of delivering CO_2 abatement through advanced biofuels would be around 150 $/$tCO_2e$. ILUC is not discussed except to claim that it is not a concern for advanced biofuels. The possibility that first generation biofuel consumption may not support climate goals is not acknowledged.

The WEO includes water use modelling, showing large increases in water withdrawals and consumption associated with expanded use of biofuels. Annual withdrawals increase (2016 to 2030) from 30 billion cubic metres to 110 billion cubic metres, while consumption increases from 14 to 46 billion cubic metres. Biofuel production accounts for about two thirds of energy-related water consumption by 2030. Biomass for electricity is, in contrast, associated with much more modest water consumption.

3.4. Role of bioenergy in scenario outcomes

The IEA forecast increases in modern bioenergy use in all scenarios, offset somewhat in the sustainable development scenario by large reductions in inefficient traditional bioenergy use. Total global primary bioenergy demand reaches 1,600 Mtoe in 2040 in the sustainable development scenario, 1,700 Mtoe in the current policies scenario and 1,800 Mtoe in the stated policies scenario. In the EU, primary biomass demand for energy is 240 Mtoe in the sustainable development scenario, 210 Mtoe in the current policies scenario and 220 Mtoe in the stated policies scenario.

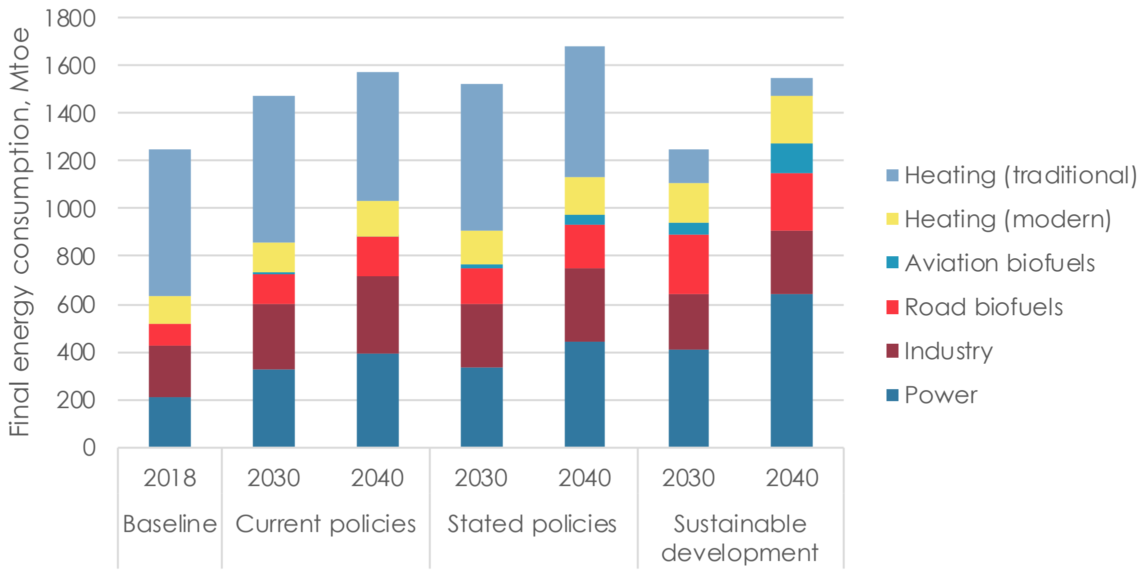

Figure 4. Primary biomass demand for energy in IEA WEO 2019

3.4.i) Bioenergy utilisation by sector and mode

Consumption of biomass for energy is shown divided into industry, biofuels and buildings in Figure 5. Biofuel use grows in all scenarios, with strong growth in aviation biofuel use by 2040 in the sustainable development scenario although even so road transport remains the main consumer of liquid biofuels. Total global 2040 biofuel consumption in the sustainable development scenario is four times higher than in 2018.

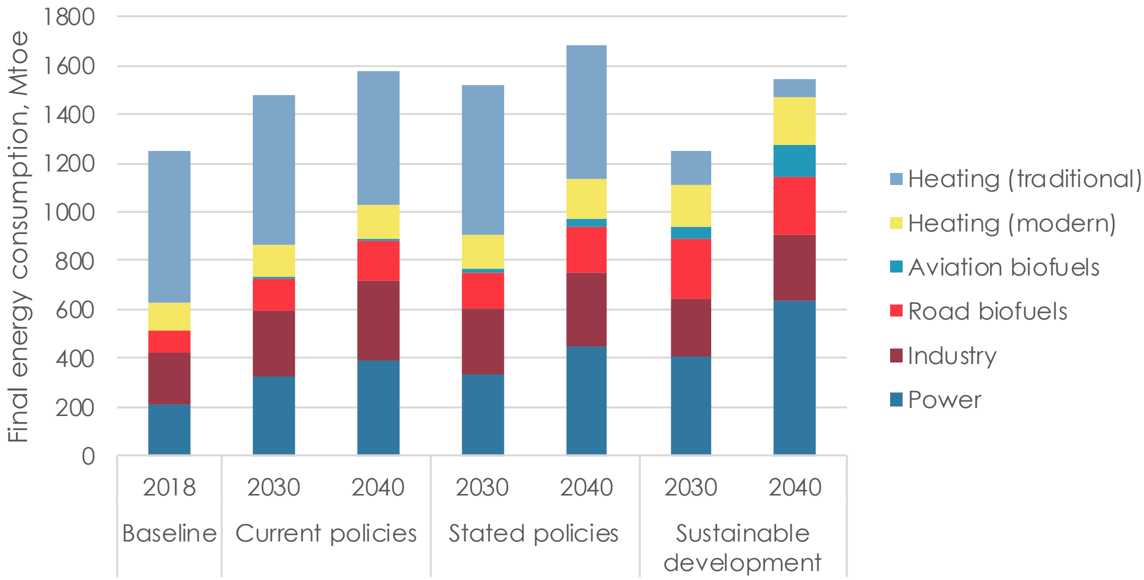

Figure 5. Final consumption of biomass energy in IEA WEO 2019 (global)

In the EU the IEA list no significant traditional biomass use. Biomass use is expected to grow in all sectors, although in the sustainable development sector biofuel use peaks in 2030 (at three times 2018 levels) and is falling in 2040 as vehicle electrification expands. This scale of expansion of total biofuel consumption would require a significant increase in transport renewables ambition in the Renewable Energy Directive. Biomass power generation increases by 50% in the sustainable development scenario.

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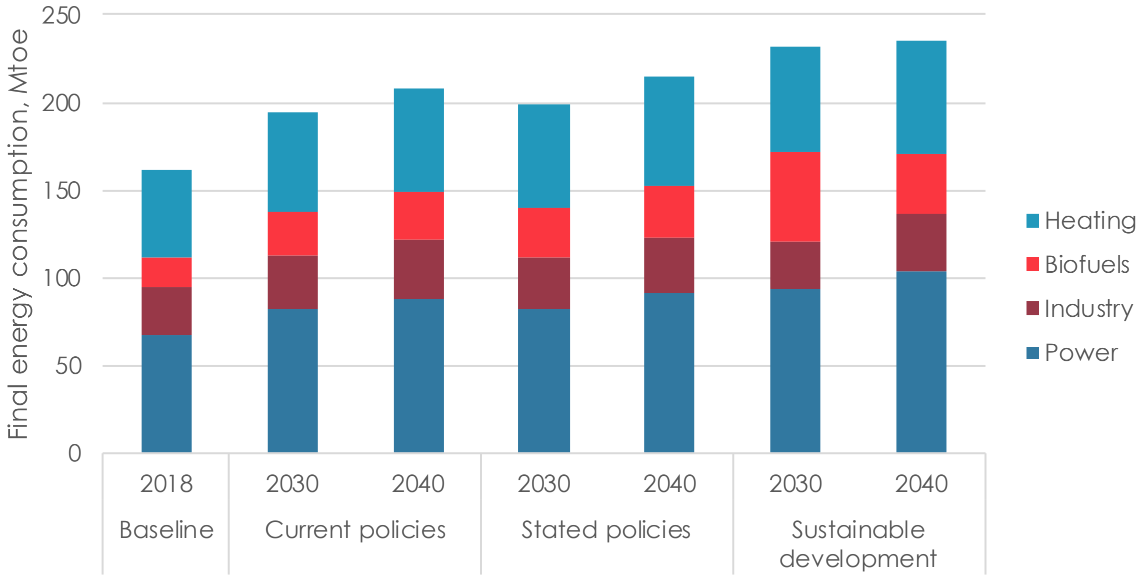

Figure 6. Final consumption of biomass energy in IEA WEO 2019 (EU)

Note: aviation and road biofuel use data are not presented at the regional level

3.4.ii) Implications for LULUCF?

The IEA assume that advanced biofuels can be produced without land use impacts. The impacts of first-generation biofuel expansion are not discussed.

3.4.iii) Regulatory recommendations

The WEO is a policy centred report, and the IEA are clear that policy is a vital lever to deliver global goals (International Energy Agency, 2018):

> *"the WEO underlines once again that policies matter. We should not underestimate the effort required to get to the outcomes described in our main scenario, the New Policies Scenario, which holds up a mirror to the ambitions of policy makers around the world, as they exist today. But nor should we underestimate the need and the potential to improve on these outcomes and to deliver a more secure, affordable, and sustainable energy future."*

IEA acknowledge the specific need to support advanced biofuels with policy (International Energy Agency, 2018),

> *"The future of advanced biofuels therefore will depend critically on continued technological innovation to reduce production costs as well as stable and long-term policy support."*

No specific recommendations are made regarding ensuring the sustainability of biomass use, or how policy should shift demand from conventional to advanced biofuels.

4. IRENA Global Energy Transformation, a Roadmap to 2050 (IRENA, 2019)

4.1. Introduction

The International Renewable Energy Agency (IRENA) publishes annual reports presenting a view of the renewable energy transition. This report (IRENA, 2019) presents two scenarios for the development of the energy economy, a 'reference case' based on current and planned policy actions, and a 'REmap case' that is intended to be consistent with a 2 degree Celsius global warming scenario.

4.2. Overview of modelling approach

The IRENA roadmap runs from 2016 to 2050, and is based on in-house analysis, drawing on other IRENA reports, cost assessment and modelling. The modelling includes a macroeconomic assessment identifying GDP increases from investment in an energy transition.

4.2.i) Geographical coverage

The IRENA roadmap is global in coverage, and in general presents results only at the global level.

4.2.ii) Sectoral coverage

The modelling is explicitly energy focused, and considers other sectors only to the extent that is necessary to assess energy demand.

4.2.iii) Role of bioenergy

IRENA explicitly notes that its role is to promote 'all forms of renewable energy' including bioenergy.

4.2.iv) Consideration of biomaterials and cascading use

Biomaterials are not included directly in the IRENA analysis, but the report does state that, "additional efforts are needed to reduce emissions in non-energy use (such as using bioenergy and hydrogen feedstocks)".

4.2.v) How is use of bioenergy determined?

The details of the modelling approach taken for the 2050 scenarios are not laid out in detail.

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The 2050 results appear to draw on a combination of cost of technology assessment, expert judgment and identified policies, rather than on a single underlying modelling framework.

4.2.vi) Characterisation of 'negative emissions' technologies

BECSS is not discussed in the Roadmap. LULUCF is assumed to deliver a net sink by 2050, but no detail is given regarding the measures needed to deliver this change.

4.3. Assumptions on biomass availability

4.3.i) Feedstocks considered

There does not appear to be any restriction on feedstocks considered. IRENA do not indicate the assumed breakdown of feedstocks in 2050 bioenergy or biofuel consumption.

4.3.ii) Sustainability considerations

IRENA states that biofuel consumption "must be scaled up sustainably" to meet demand from hard to electrify sectors. They also note that, "Bioenergy must be produced in ways that are environmentally, socially and economically sustainable. There is a very large potential to produce bioenergy cost-effectively on existing farmland and grassland, without encroaching upon rainforests, and in addition to growing food requirements."

4.4. Role of bioenergy in scenario outcomes

Bioenergy use increases significantly in the IRENA modelling, doubling to 3,000 Mtoe of primary energy consumption.

4.4.i) Bioenergy utilisation by sector and mode

Biomass energy delivery by sector is shown in Figure 7. Heat for industry and buildings is the largest user of biomass energy in the REmap scenario, followed by transport where biofuel consumption quadruples and then electricity generation.

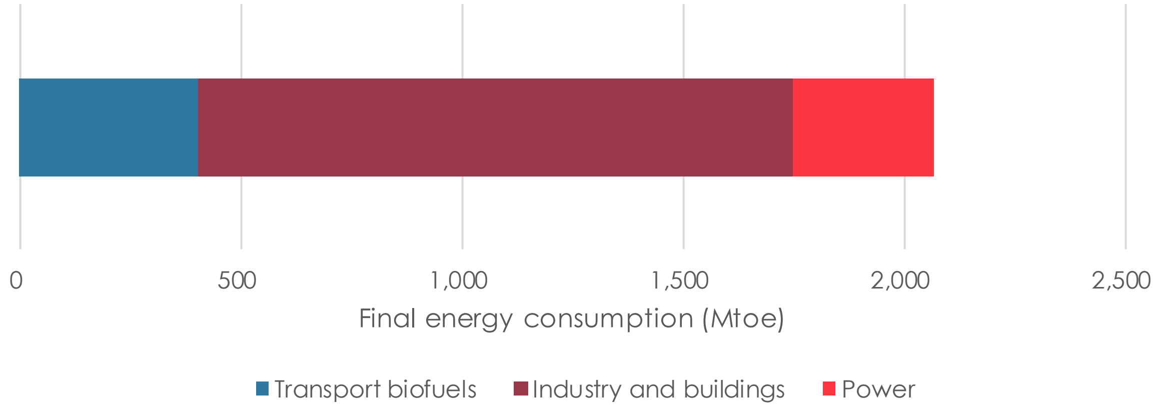

Figure 7. Final biomass energy consumption by sector in the REmap scenario (IRENA, 2019)

IRENA identify bioenergy having a particular role in, “sectors that are hard to electrify, such as shipping, aviation and certain industrial processes”.

IRENA, assume that traditional use of bioenergy will be more or less eliminated by 2050 in both the reference and REmap scenarios.

4.4.ii) Implications for LULUCF?

IRENA assume exogenously that LULUCF emissions are eliminated by 2050, with LULUCF becoming a net sink for the rest of the century. The Roadmap does not explicitly consider the implications of increased bioenergy use for LULUCF, beyond the assertion that there is a large potential to produce bioenergy without encroaching upon rainforests. Conversion of grassland appears to be treated as acceptable, and there is no discussion of potential changes in carbon storage due to grassland conversion.

4.4.iii) Regulatory recommendations

IRENA make several direct recommendations for policy to support renewables, including biomass. The Roadmap notes that regulatory frameworks for transport biofuels have been uncertain for the past decade, and identified this uncertainty as having prevented investment. Progress on expanding the use of biofuels is characterised as ‘off track’ with relation to the REmap target of 650 billion litres per year by 2050. In particular, several recommendations are made relating to transport biofuels.

These include:

1. Removal of subsidies for fossil fuels.
2. Adopting policies to increase production of both first- and second-generation biofuels.

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3. Introducing specific mandates for advanced biofuels alongside 'financial de-risking' measures.
4. A proposal to "implement carbon pricing to increase the competitiveness of renewable fuels in the shipping and aviation.
5. An explicit focus and dedicated policy for hard-to-electrify sectors, "such as aviation, shipping and long-haul road transport."

There are no recommendations relating to sustainability, and the only recommendation relevant to feedstock choice is the call for specific advanced biofuel mandates. The modelling assumes that LULUCF emissions fall to zero by mid-century, but does not discuss any tension between this assumption and expanded bioenergy use.

5. Öko-Institut for the Greens/EFA, the Vision Scenario for the European Union 2017 Update for the EU-28 (Matthes, Hermann, & Zimmer, 2017)

5.1. Introduction

The Vision Scenario is the result of modelling by the Öko-Institut for the Green and European Free Alliance political groupings in the European Parliament. The report sets out two scenarios – a reference scenario, and the 'Vision Scenario'. The reference case is based on existing policy and a target of 42% emissions reduction (compared to 1990) by 2050. The Vision Scenario is intended to be consistent with limiting global heating to 2 degrees Celsius, delivering a 93% emissions reduction by 2050. It is described as, "the first comprehensive scenario analysis for the European Union that addresses both the (top-down) perspective of a 2°C-compatible CO_2 emission budget and how the related emission trajectories could be achieved from a bottom-up perspective."

5.2. Overview of modelling approach

The Vision report scenarios are developed using the EU reference scenario as documented in European Commission (2016a) as a starting point. The basis for constructing the new scenarios is identified as a combination of 'own modelling' and a consideration of other relevant projections. End-use sector energy demand along with industrial GHG emissions and non-CO_2 GHG emissions are built on existing deep decarbonisation scenarios informed by expert judgment. This information is aggregated and input to an integration model. The development of the power sector is based on modelling by Öko-Institut.

5.2.i) Geographical coverage

The analysis is undertaken at the aggregate EU-28 level.

5.2.ii) Sectoral coverage

All emissions except LULUCF in the EU emission inventory are included. Emissions from international air transport are included, but international maritime emissions and LULUCF emissions are excluded for lack of data/capacity.

5.2.iii) Role of bioenergy

The use of biomass is "restricted in order to comply with tight sustainability criteria". As a result of this cautious approach and of the assumption of improved energy efficiency, biomass

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consumption is actually lower in the Vision Scenario than in the reference scenario. Biomass energy does however continue to make modest contributions in all sectors.

5.2.iv) Consideration of biomaterials and cascading use

Based on the documentation available, the report does not appear to consider a largescale transition to the use of biomaterials, although other changes to lower carbon materials are assessed.

5.2.v) How is use of bioenergy determined?

The report assumes that all remaining liquid fuel demand for transport after electrification and efficiency improvements should be met by advanced biofuels and by electrofuels. The report divides this remnant market into 20% biofuels and 80% electrofuels. The size of this remnant is reduced by assuming that half of intra-EU flights are moved onto rail transport, but it is unclear how international aviation demand is modelled.

5.2.vi) Characterisation of 'negative emissions' technologies

The Vision report acknowledges the potential for BECCS as a net carbon removal technology, but is cautious about over-reliance on any CCS technologies. The report notes that technical problems still remain in effectively delivering CCS, that storage opportunities are finite, and that there is not yet an adequate regulatory framework in place. The report therefore adopts a general principle that, "CCS may only be used to avoid CO_2 emissions from industrial processes", and that, "CO_2 storage should consequently not be used for sectors in which sufficient emission abatement alternatives exist to the use of CCS (as is the case in the power sector)". Despite stating these general principles, some BECCS is assumed, associated with 14 $MtCO_2e$ sequestration out of a total 230 $MtCO_2e$ of CCS by 2050.

The report also does not assess the possibility of creating a net carbon sink through changing land management.

5.3. Assumptions on biomass availability

5.3.i) Feedstocks considered

The Vision report is not explicit about feedstocks beyond specifying that by 2050 all biofuels would be second or third generation. This implies that food-based fuels would no longer have a role to play. The report is not explicit about how second and third generation biofuels should be defined, but presumably it includes cellulosic biofuels in second generation and algal biofuels in third generation.

5.3.ii) Sustainability considerations

There are no specific sustainability criteria or land use governance requirements suggested for biofuels or biomass harvesting more generally. The report does however explicitly acknowledge the importance of sustainability oversight for the biomass supply,

5.4. Role of bioenergy in scenario outcomes

5.4.i) Bioenergy utilisation by sector and mode

As shown in Figure 8, total bioenergy consumption in the EU is assumed to increase only moderately compared to 2015, with about 20% higher bioenergy consumption in the reference than the Vision Scenario.

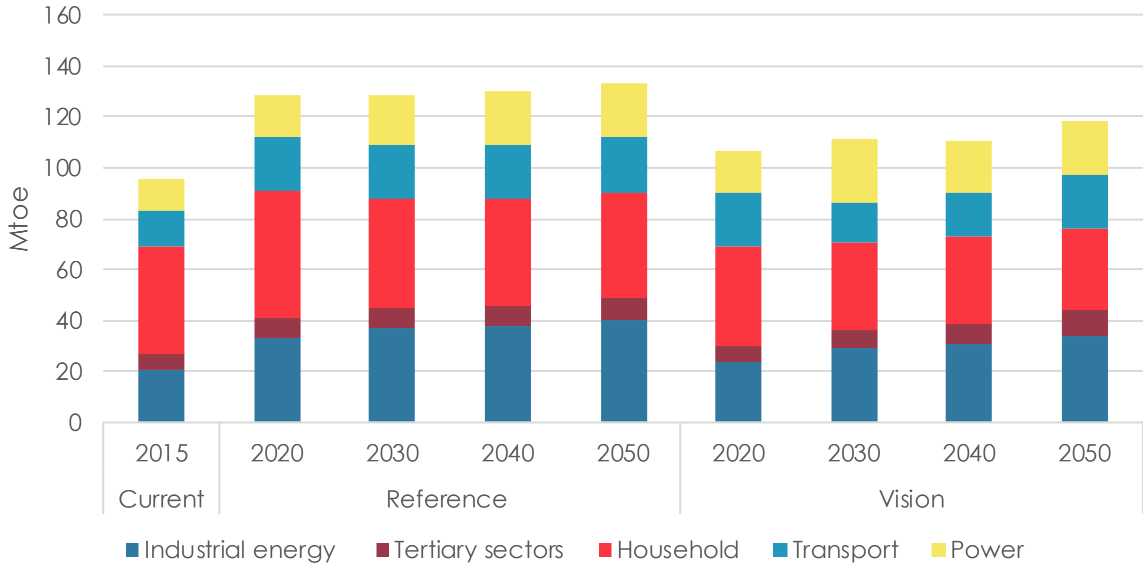

Figure 8. Final bioenergy consumption by sector

Biomass is the main renewable technology considered for industrial heat, where its use increases in absolute terms between now and 2050 in both scenarios becoming the largest final use consumer of bioenergy. In both scenarios, transport bioenergy consumption increases by 50% from 2015 to 2050, and biomass power increases by 75%. In the Vision Scenario, household bioenergy use reduces by 10 Mtoe.

Biomass use for domestic heating is assumed to be relatively constant in the reference scenario, and reducing slightly by 2050 compared to 2015 levels in the Vision Scenario. Biomass is the largest renewable energy contributor to residential energy consumption.

In the Vision Scenario it is envisaged that the second and third generation biofuels in road transport will assume a 20% share in 2050 (from around 5% today), most of which is used in freight transport. The split between second generation and third generation is not made explicit.

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5.4.ii) Role of imports

Biomass imports are considered in the modelling, but are very modest compared to total biomass use (about 6% in 2050).

5.4.iii) Implications for LULUCF?

There is no explicit assessment of the impact of biomass demand on land use, but this impact is implicitly limited by limiting total biomass use and considering only second and third generation biofuels by 2050.

5.4.iv) Regulatory recommendations

The Vision report contains several specific recommendations relevant to biomass use. These include:

1. Establishing a careful monitoring and management system to make the best use of the limited potential of sustainable biomass, bearing in mind the short- and medium-term as well as the long-term time horizon and appropriate cascades of biomass use (food, raw materials, energy);
2. International quality standards for the production of biofuels or biomass in general are an essential means of introducing high shares of such fuels in a way that is compatible with sustainability.
3. Setting an analytical, political and regulatory framework to assess and safeguard the environmental effects of novel fuels properly (including the effects from electricity and fresh water us or the direct and indirect land use change) for the domestic supply of biomass as well as fuel imports from other regions of the world;

The report also recommends with regard to electrofuels that, "From a policy perspective, power-generated fuels should not be subsidised. Instead, applying a quota system would be the preferable option. Thus, users would pay for additional costs and there would be a strong incentive to use more energy-efficient vehicles or switch to energy-efficient modes."

6. Net Zero 2050: from whether to how (Pestiaux et al., 2018)

6.1. Introduction

The Net Zero 2050 report was commissioned by the European Climate Foundation with a view to "building a vision and evidence base for the transition to net-zero emission societies in Europe and beyond, by mid-century at the latest." The report is based on a simulation model of EU emissions developed for the project, building on resources including the ClimateWorks Carbon Transparency Initiative. Three scenarios are presented in the report:

1. Shared efforts (comparable level of efforts across sectors and levers);
2. Technology (focus on electrification. efficiency, hydrogen and CCS);
3. Demand-focus (additional demand side changes are modelled to reduce overall energy, material and meat consumption).

6.2. Overview of modelling approach

The simulation model used by the report is the European roadmap model of the Carbon Transparency Initiative[2]. It is described as a 'techno-economic' simulation model. The model works by combining sets of 'levers' that would affect GHG emissions and/or energy demand, informed by but not driven by economic assessment. There is an online interface[3] that allows users to construct their own scenarios. The main outputs are GHG emissions and energy use, but for any constructed pathway capital requirements and ongoing expenses can also be assessed and impacts on energy trade balance and other externalities such as pollution can be considered. The model does not directly pick least cost pathways or predict the responses to a given carbon price, but does allow the estimated costs of constructed decarbonisation pathways to be compared.

6.2.i) Geographical coverage

The assessment is at the level of the EU-28.

6.2.ii) Sectoral coverage

The model covers all significant GHG emissions in the EU, including emissions from international aviation and shipping.

2 https://stakeholder.netzero2050.eu/

3 Ibid.

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6.2.iii) Role of bioenergy

The model includes bioenergy for industry, power and transport sectors. It outputs estimated emissions from Agriculture, Forestry and Other Land Use (AFOLU), total bioenergy demand and changes in land use associated with the constructed decarbonisation pathway.

6.2.iv) Consideration of biomaterials and cascading use

The model identifies co-products of 'wood transformation' and residues from agriculture and forestry as significant bioenergy resources. The three net zero scenarios all assume reductions in the direct use of food or energy crops for bioenergy feedstock.

6.2.v) How is use of bioenergy determined?

Bioenergy consumption is calculated on a bottom up basis by cross referencing assumed fractional use of bioenergy by each sector/sub-sector with modelled energy demand from that sector/sub-sector.

6.2.vi) Characterisation of 'negative emissions' technologies

Bioenergy with CCS is identified as a negative emissions technology, one of the negative emissions technologies that are necessary to achieve net zero without achieving zero emissions in all sectors.

6.3. Assumptions on biomass availability

6.3.i) Feedstocks considered

The CTI model identifies as potential biomass feedstocks: dedicated energy crops; agricultural residues; forestry residues; wood transformation co-products; post-consumption waste.

6.3.ii) Sustainability considerations

It is unclear what sustainability criteria have been used in assessing potential biomass supply, but by limiting the role of energy crops in favour of residues the sustainability risk of biomass use would be reduced. In the shared effort scenario, the report specifies that, "no additional dedicated biofuel/energy crops are necessary".

6.4. Role of bioenergy in scenario outcomes

The CTI model is intended as a tool giving users the opportunity to develop and compare decarbonisation pathways, and the Net Zero 2050 report "does not include the choice of an ideal scenario". The online model and report do however present four pre-set pathways for consideration: reference scenario (EUREF16); shared effort; demand-focus; technology. The reference scenario is tuned to the European Commission's EU Reference Scenario 2016[4], which is developed using the same suite of modelling tools as European Commission (2018a). The reference scenario is not consistent with EU climate commitments, but provides a benchmark against which to compare more ambitious scenarios. Below, we discuss the role of bioenergy in these four scenarios as presented in the CTI tool. Using the online tool we were not able to identify the additional consumption of biomass energy for industrial applications (steel, chemicals, cement and 'other'), but we have indicated the modelled level of replacement of fossil fuels with biomass fuels.

6.4.i) Bioenergy utilisation by sector and mode

In the EUREF16 scenario it is assumed that 7% of residual liquid road transport fuel demand is met by biofuels but no aviation biofuel is supplied. Between 10% and 50% of industrial fossil energy use is assumed to be replaced by biomass, depending on sub-sector. In this scenario, in 2050 there is 18 Mtoe of consumption of biogas and biofuels, 34 Mtoe of power from biomass and 43 Mtoe of heat for buildings from biomass.

In the shared effort scenario, it is assumed that 38% of residual liquid road transport fuel demand is met by biofuels and 33% of aviation fuel demand. Between 15% and 100% of industrial fossil energy use is replaced by biomass, depending on sub-sector. In 2050 there is 6 Mtoe of consumption of biogas and biofuels, 17 Mtoe of power from biomass and 17 Mtoe of heat for buildings from biomass.

In the demand-focus scenario 38% of residual liquid road transport fuel demand is assumed to be met by biofuels and 33% of aviation fuel demand. Between 10% and 50% of industrial fossil energy use is replaced by biomass, depending on sub-sector. In 2050 there is 8 Mtoe of consumption of biogas and biofuels, 17 Mtoe of power from biomass and 21 Mtoe of heat for buildings from biomass.

In the technology scenario it is assumed that 38% of residual liquid road transport fuel demand is met by biofuels and 33% of aviation fuel demand. Between 10% and 50% of industrial fossil energy use is replaced by biomass, depending on sub-sector. In 2050 there is 19 Mtoe of consumption of biogas and biofuels, 17 Mtoe of power from biomass and 11 Mtoe of heat for buildings from biomass.

6.4.ii) Role of imports

In the EUREF16 scenario, by 2050 7% of solid bioenergy is imported, with no import of liquid biofuels.

In the shared effort scenario, there are no bioenergy imports in 2050.

In the demand-focus scenario, there are no bioenergy imports in 2050.

In the technology scenario, by 2050 4% of liquid biofuels are imported, but no solid biomass.

4 https://ec.europa.eu/energy/en/data-analysis/energy-modelling/eu-reference-scenario-2016

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6.4.iii) Implications for LULUCF?

For the EUREF16 scenario there is a 4 million hectare expansion of energy cropping from 2010 to 2050, this is about 1% of total land use. In the other scenarios, the area of energy crops is presumed to shrink (to zero in the demand-focus and shared effort scenarios), but the overall forest area increases significantly (increasing by about 50%) at the expense of food crops and animals. The major sources of biomass for energy in these scenarios are residues, 'wood transformation co-products' and post-consumption waste. Dietary changes and afforestation have a much larger impact on land use in these scenarios than bioenergy consumption.

6.4.iv) Regulatory recommendations

The report identifies biomass CCS and afforestation as 'negative emissions' technologies to offset residual emissions in sectors that cannot reach zero emissions by 2050, but warns that there are limitations on the use of bioenergy with CCS.

7. ICF/Fraunhofer, Industrial Innovation: Pathways to deep decarbonisation of Industry (Fleiter, Herbst, Rehfeldt, & Arens, 2019)

7.1. Introduction

The Industrial Innovation report (Fleiter et al., 2019) contains modelling by consultants ICF and Fraunhofer ISI of scenarios for "the future evolution of energy demand and greenhouse gas emissions of the EU's industrial sector under varying assumptions with regards to technology innovation and diffusion". This report represents supporting analysis for the development of the European Commission's 'A Clean Planet for All' strategic vision.

7.2. Overview of modelling approach

The modelling is undertaken using the bottom-up FORECAST model, developed by Fraunhofer ISI. The model takes macroeconomic, cost data and policy assumptions as inputs and assesses resulting investment decisions, demand and associated emissions. Investment decision making is modelled as 'myopic' (rather than assuming perfect foreknowledge of future revenues) based on simplified decision rules such as payback times. The model includes characterisation of a wide range of emission mitigation options to reduce emissions in the sectors analysed. The report includes eight scenarios, of which six are designed to be consistent with >80% GHG emission reductions. One of these is bioeconomy focused (3c: BioCycle) while the last two scenarios are 'balanced' mix scenarios utilising the most cost effective technologies from the others.

7.2.i) Geographical coverage

The FORECAST modelling considers the EU Member States at the national level, but the results are largely presented only for the EU-28.

7.2.ii) Sectoral coverage

The model covers the industry, services and household sectors. It does not consider the transport sector or power generation.

7.2.iii) Role of bioenergy

Biomass boiler options are included for both steam and hot water generation for industrial processes, and for space heating/cooling.

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7.2.iv) Consideration of biomaterials and cascading use

The modelling includes 'circular economy and recycling' as one of five families of mitigation options. One of the scenarios considered (3c: BioCycle) specifically focuses on the bioeconomy and circular economy. Recycling and reuse assumptions are detailed by industrial sector and by scenario. For scenario 3c, biomaterials are considered as alternatives to concrete.

7.2.v) How is use of bioenergy determined?

FORECAST aims to model investment decisions related to the implementation of climate policy. Investment is determined 'myopically' based on 'known' economic data and policy in a given year. Facility utilisation is then (as we understand it) assessed in the context of sunk investment, determining total bioenergy use and biomass demand. Fossil fuel prices are assumed to increase to 2050, with heavy fuel oil prices rapidly doubling. This makes biomass (and other energy alternatives) more appealing on a cost basis. The modelling applies an increasing carbon price, varying by scenario. In the 3c: BioCycle scenario, this price goes to 200 €/tCO_2e by 2050. Biomass is treated as carbon neutral.

7.2.vi) Characterisation of 'negative emissions' technologies

Industrial CCS is included in the model, but there is no modelling of AFOLU.

7.3. Assumptions on biomass availability

7.3.i) Feedstocks considered

The study considers three biomass resources. Firstly, biomass already utilised for energy, primarily process residues such as from pulp and paper and the food industry, 96 Mtoe of which 20 are used by industry. Secondly, full EU "potentially sustainable" biomass supply (notably wood pellets), 125 Mtoe of which 21 Mtoe are assumed available for industry. The reference given for this biomass availability estimate may be incorrect or ambiguous, as we were unable to find documentation of the underlying assumptions. Thirdly, unlimited availability is assumed for international wood pellet imports. Imports are assumed to have a significantly higher price than domestic resources and thus the model fully utilises domestic resources before turning to international markets. It should be understood that this assumption of unlimited availability is made in the context of the size of EU industrial energy demand, and should not be understood as implying an unlimited global availability assumption for all sectors.

7.3.ii) Sustainability considerations

We were not able to find documentation of the assumptions on the EU domestic biomass potential.

7.4. Role of bioenergy in scenario outcomes

7.4.i) Bioenergy utilisation by sector and mode

The study only considers the industrial sector. Biomass demand ranges across scenarios modelled from 20 to 100 Mtoe (Figure 9). It is noteworthy that the use of biomass energy is minimised in the two mixed scenarios, suggesting that biomass for energy may not be cost competitive with many other industrial decarbonisation options, even with an assumption of carbon neutrality.

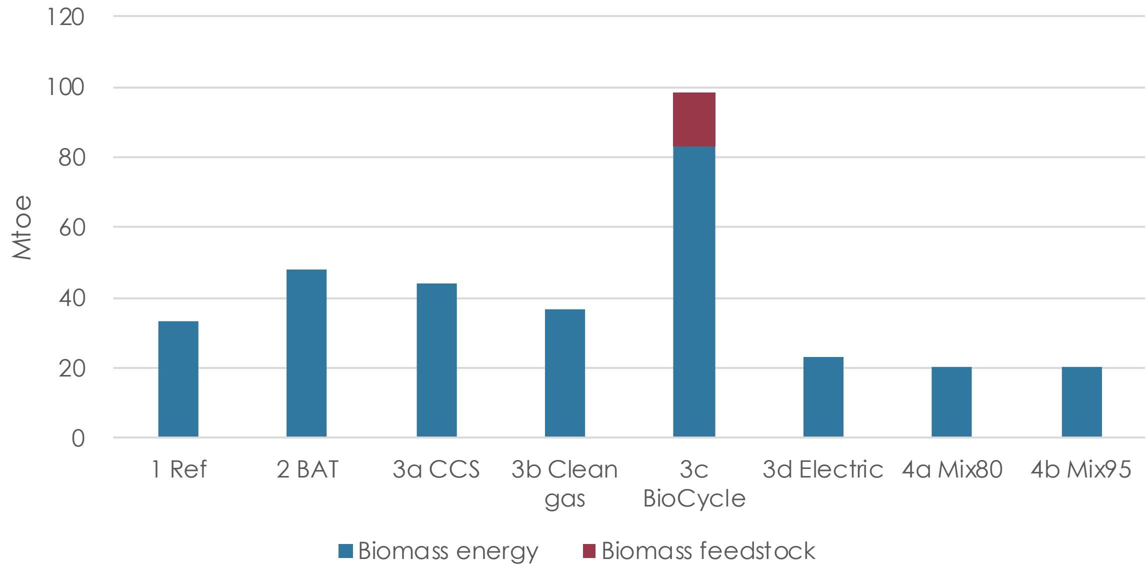

Figure 9. Biomass energy demand by scenario

7.4.ii) Role of imports

In scenario 3c: BioCycle the demand for biomass energy and biomass feedstock significantly exceed assumed domestic potential and thus imports would be required.

7.4.iii) Implications for LULUCF?

These are not discussed.

7.4.iv) Regulatory recommendations

The report concludes that some combination of innovative technology options are required to deliver deep industrial decarbonisation. The report calls for R&D support and for enhanced economic incentives.

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8. Global warming of 1.5 °C (IPCC, 2018)

8.1. Introduction

The IPCC's report on the impacts of global warming to 1.5 °C above pre-industrial levels was prepared in response to the declaration in the Paris agreement of an aspirational goal to keep warming to that level or lower. The report consists of five chapters prepared by teams of authors, the second of which details climate change mitigation scenarios understood to be consistent with limiting global warming to 1.5 °C. Scenarios are divided into 'archetypes' to allow different groups of scenarios to be compared: S1 – sustainable development scenarios; S2 – middle of the road scenarios; S5 high energy demand scenarios; LED low energy demand scenarios. Scenarios are further divided by whether they include an emissions overshoot by 2050 that requires additional net negative emissions by 2100.

8.2. Overview of modelling approach

The IPCC report is based on literature review of modelled mitigation pathways consistent with limiting temperature increase to 1.5 °C. There is therefore no single modelling approach for the report, although most pathways considered are generated using integrated assessment models (IAMs). The mitigation-modelling frameworks considered in the report are: AIM-CGE; BET; C-ROADS; DNE21; FARM 3.2; GCAM 4.2; GEM-E3; GENeSYS-MOD 1.0; GRAPE-15 1.0; ETP Model; IEA World Energy Model; IMACLIM; IMAGE; MERGE-ETL 6.0; MESSAGE(ix)-GLOBIOM; POLES; REMIND – MAgPIE; Shell World Energy Model; WITCH.[5] IAMs generally include equilibrium economic modelling and use carbon pricing as an internal driver for emissions reduction actions. The details of economic assumptions relating to carbon pricing (such as discount rates applied on costs and the assumed evolution of the carbon price over time) can drive significant differences in mitigation pathways between scenarios and models. The IPCC report notes that, IAMs "often struggle to capture a number of hallmarks of transformative change, including disruption, innovation, and nonlinear change in human behaviour", and these additional factors can limit the predictive power of IAM modelling. It is also noted that real costs for mitigation technologies cannot be reliably predicted. Examples given include real costs of nuclear power and CCS that have been higher than anticipated, and real costs of solar power that have reduced faster than anticipated.

8.2.i) Geographical coverage

All models considered by the IPCC report are global in scope.

5 See Forster et al. (2018). It was beyond the scope of this report to review each of these individually, and so the discussion is based only on the characterisation of the results by IPCC (2018), including in the supplementary information.

8.2.ii) Sectoral coverage

The models considered provide a characterisation of the whole economy, including AFOLU emissions and international aviation and shipping. Some of the IAMs model land use explicitly, others use stylised supply curves for the availability of bioenergy and similar emissions curves for the AFOLU emissions associated with given levels of bioenergy use.

8.2.iii) Role of bioenergy

All of the IAMs considered include bioenergy as an emissions mitigation technology. Some models limit bioenergy by making a 'food first' assumption (only land left over after meeting food demand is treated as available for bioenergy) while others allow competition for land between bioenergy and food.

All but two models include first generation biofuels, and all but one include second generation biofuels, mostly with an explicit consideration endogenous to the model. All models consider biomass electricity. Inclusion of biomass for heat is not summarised by the IPCC report.

8.2.iv) Consideration of biomaterials and cascading use

This is not discussed in the IPCC report or supplementary materials, and presumably varies by IAM.

8.2.v) How is use of bioenergy determined?

The approach to set bioenergy utilisation will vary across the IAMs. Most of the models considered construct climate change mitigation scenarios based on cost of mitigation options. Bioenergy use will therefore be determined by the competitive position of bioenergy as a CO_2 reduction technology as compared to other technologies. The economic characteristics of bioenergy as a climate mitigation tool will be strongly sensitive to assumptions about associated land use change emissions – models that do not consider land use emissions in the abatement cost of bioenergy, or that assume low/zero land use emissions associated with bioenergy use will assume greater bioenergy use than models that assume significant land use emissions that are included in the abatement cost calculation. All models that include explicit land use modelling include characterisation of emissions from land use changes.

8.2.vi) Characterisation of 'negative emissions' technologies

Most models considered explicitly include BECCS as a negative emission technology endogenous to the modelling, though three models do not allow for it and in two models it is added exogenously. About half of the models considered include afforestation/reforestation as a negative emission technology, and five include some characterisation of soil carbon enhancement options. The report notes that adding other cost-effective negative emission technologies (such as improved soil carbon management on agricultural land or the application of biochar to soils) would affect the demand for BECCS as a negative emission technology. This implies that current IAMs may be giving high-end estimates of cost-effective use of BECCS.

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8.3. Assumptions on biomass availability

8.3.i) Feedstocks considered

The report states that, the "Dominant bioenergy feedstocks assumed in IAMs are woody and grassy energy crops (2nd generation biomass) in addition to residues." Almost all models also consider first generation biofuels, and some models consider algal biofuels.

8.3.ii) Sustainability considerations

Sustainability considerations will vary by IAM and are not summarised for the IPCC report.

8.4. Role of bioenergy in scenario outcomes

The report notes that the 1.5 °C scenarios, "all share a substantial reliance on bioenergy under the assumption of effective land-use emissions control." This highlights a limitation of the IAMs, which is that sustainable land use management may be assumed by hypothesis without providing a clear pathway for such management rules to be adopted and enforced at the global scale. Assuming minimal land use change CO_2 emissions may contribute to low assumed CO_2 abatement costs for bioenergy, and therefore to higher use of bioenergy in the models. These results are invalidated if the underlying assumptions on land use management are not realistic[6], because this would increase the cost of CO_2 abatement with bioenergy. It is therefore important that discussion of the role of bioenergy in IAM results is always caveated by the assumption of "effective land-use emissions control".

8.4.i) Bioenergy utilisation by sector and mode

Total primary biomass energy demand (LHV of biomass resources consumed) is between 960 Mtoe and 7,450 Mtoe across scenarios, with a median of 3,600 Mtoe, equivalent to 26% of global primary energy supply and 8% of electricity generation. The median value is above the upper limit on sustainable biomass potential for 2050 of 2,900 Mtoe suggested by Searle & Malins (2015), suggesting that delivering biomass energy at the median level in the assessed studies may be difficult or impossible without causing significant land use change emissions and/or other negative sustainability impacts.

Final energy consumption (delivered energy as electricity, heat or liquid fuels) is divided into industry, buildings and transport in the report. At the median across scenarios, biomass contributes 390 Mtoe to industry, 380 Mtoe to buildings and 290 Mtoe to transport. Further detail is shown in Figure 10.

6 This issue is discussed further in the context of some now-outdated IEA modelling here: https://theicct.org/blogs/staff/iea-27-biofuels-and-cost-indirect-land-use-change

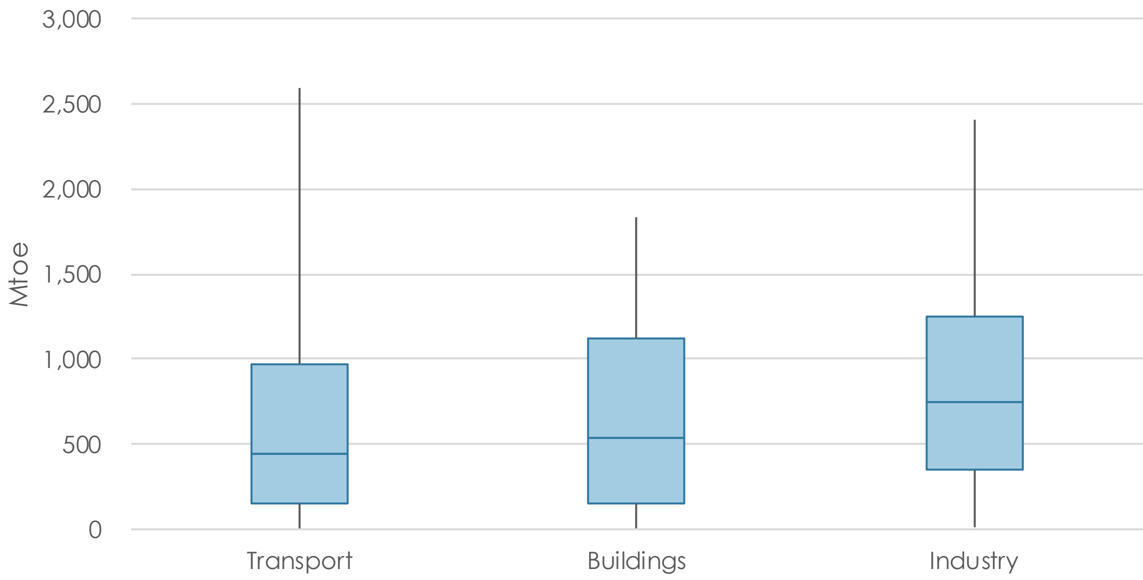

Figure 10. Final energy demand by sector across 1.5 °C scenarios, showing min, max, median and first and third quartiles

In the transport sector, biofuels meet of the order of 10% of transport final energy requirements in the median case. The IAM results are not presented split by mode, but IEA (2017) is cited as an example of a modal breakdown, as shown in Figure 11.

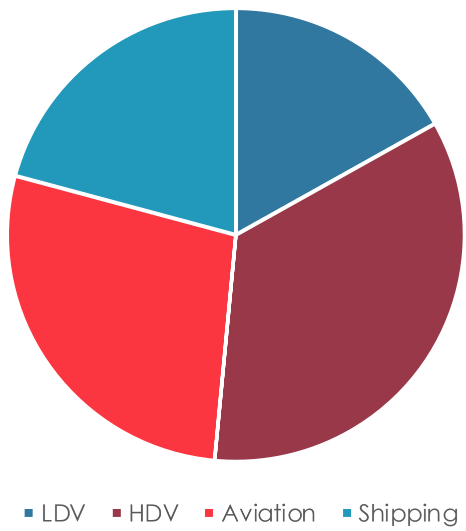

Figure 11. Biofuel deployment by mode in IEA (2017)

Bioenergy with CCS delivers significant sequestration by 2050 in the majority of scenarios

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that meet or exceed the 1.5 °C target. Across those scenarios, an average of 5.2 $GTCO_2e$ of sequestration is delivered through BECCS in 2050, and this is more than doubled by 2100. In 2050, this is equivalent to BECCS offsetting about half of residual CO_2 emissions from fossil fuels.

8.4.ii) Role of imports

The results are presented at the global level and the scale of assumed imports in the scenario modelling is not discussed. The report does note that trade in agricultural commodities can shift agricultural production between regions.

8.4.iii) Implications for LULUCF?

There is a tension in mitigation scenario modelling between minimising emissions from AFOLU and increasing availability of bioenergy. The land use implications of the 1.5 °C scenarios are significant, and vary considerably across scenarios and scenario types, as seen in Figure 12. The area of energy crops such as grasses and short rotation coppice expands in "all available pathways that assume a cost-effective achievement of a 1.5°C temperature goal in 2100".

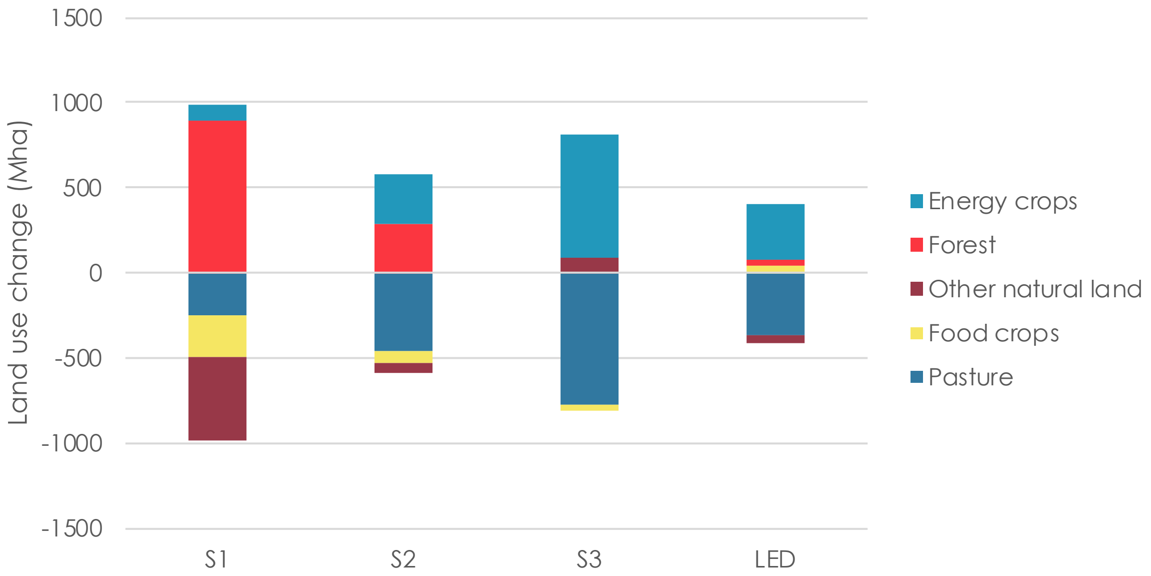

Figure 12. Land use changes compared to 2010 in selected 1.5 °C-consistent mitigation scenarios

Source: Figure 2.11 of IPCC (2018). S1 – sustainable development scenarios; S2 – middle of the road scenarios; S5 high energy demand scenarios; LED low energy demand scenarios.

There is a tension between afforestation/reforestation and energy cropping, with larger increases in energy cropping in scenarios with less forest expansion and vice versa. It should be understood that this dynamic does not only reflect a direct land competition between energy crops and forests, as with less net forest expansion more carbon removals with BECCS may be necessitated in a given model to meet carbon targets. All scenarios see reductions in pastureland, and most include smaller reductions in areas of food crops. This is sensitive to assumptions about crop yields – if forecast yield increases are not delivered, area of food crops may need to increase.

The cost of emissions abatement by reducing deforestation is sensitive to the ability to avoid displacement effects. If displacement of deforestation can be avoided, then anti-deforestation measures have low abatement cost and will be favoured by the IAM. If displacement cannot be avoided, then anti-deforestation measures have a higher net abatement cost and may not be chosen by the IAM.

The report highlights that there is potential for negative effects from increased bioenergy use due to the “substantial land and water footprint”, including biodiversity loss and increased food insecurity. The realisation of negative impacts would depend on measures to, “conserve land carbon stocks, limit the expansion of agriculture at the expense of natural ecosystems, and increase agriculture productivity”.

8.4.iv) Regulatory recommendations

The IPCC report discusses at some length the policy frameworks and other enabling conditions required to deliver mitigation scenarios consistent with 1.5 °C warming or less. The report notes the need for, “immediate and global land-use regulations for a comprehensive reduction of land-related GHG emissions (especially related to deforestation)”. As noted above, it is important to understand that the role of bioenergy in the 1.5 °C scenarios is dependent on land use management systems to avoid significant land use change emissions. Similarly, the report notes the need for policy to support afforestation, “some pathways rely strongly on a policy to incentivize afforestation and reforestation for carbon dioxide removal together with BECCS, which results in an expansion of forest area and a corresponding increase in terrestrial carbon stock.” It is also noted that increases in forest area accompanied by reductions in pasture area would represent a reversal of historical trends (at the global level at least) and that, distinct policy and government measures would be needed to achieve forest increases, particularly in a context of projected increased bioenergy use.”

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9. Global Energy System Based On 100% Renewable Energy (Ram et al., 2019)

9.1. Introduction

This report, a collaboration between LUT University in Finland and the Energy Watch Group, presents a 1.5 °C compatible scenario that involves a shift to 100% renewable energy and 'deep electrification' of transport and heat, which is described as "the first to present a 1.5°C scenario that is technology-rich, multi-sectoral, multi-regional and cost-optimal." It specifically avoids modelling the use of CCS technology or nuclear power on the basis that they are high risk.

9.2. Overview of modelling approach

The LUT Energy System Transition Model is an energy system optimisation model in which system development is determined on five year intervals optimised for cost given demand for power and heat, available technologies for energy generation and storage and relevant financial and technical parameters.

9.2.i) Geographical coverage

The model is global, divided into 9 regions (e.g. Europe, Eurasia, Sub-Saharan Africa) and further into 145 sub-regions allowing energy supply and demand to be balanced at the sub-regional level.

9.2.ii) Sectoral coverage

The model covers all sectors, split into power, heat, transport and industry.

9.2.iii) Role of bioenergy

Major bioenergy technologies are included in the energy system model, including biomass power and heat, biogas and liquid biofuels.

9.2.iv) Consideration of biomaterials and cascading use

Cascading use and opportunities for novel biomaterials are not discussed.

9.2.v) How is use of bioenergy determined?

For heat and power, the model undertakes least cost optimisation given assumptions about capital and operational costs for each technology (changing over time) to determine technology options. It is less clear how the role of liquid biofuels is determined, with jatropha oil identified as a possible sustainable biofuel source in a late chapter of the report the conclusions of which do not appear to be fully integrated into the reported results. By 2050, the report appears to consider only jatropha as a viable feedstock for liquid biofuels. Given the enormous uncertainty on the cost of jatropha agriculture, whether this result emerges from cost optimisation or from a simple model constraint it might be best understood as an exogenous decision.

9.2.vi) Characterisation of 'negative emissions' technologies

The modelling does not include negative emissions technologies, characterising CCS as 'high risk'. The model does assume the availability of direct air capture technologies to provide CO_2 for fuel synthesis.

9.3. Assumptions on biomass availability

9.3.i) Feedstocks considered

Biomass potentials are taken from Thrän et al. (2010), which identifies 720 Mtoe of biomass potential globally from wastes and residues. The central bioenergy scenario in this work assumes 200 million hectares of global land availability for energy crops, but it is noted that this assumes strong productivity growth for food crops and that the implementation of environmental restrictions on land conversion could reduce this significantly. In the bioenergy scenario the total assumed potential from energy cropping is 500 Mtoe. In the "Bioenergy with increased environmental and nature conservation restrictions" scenario it is assumed that no land is available for energy cropping after 2020. Availability of forestry biomass is assessed at between 860 and 1,400 Mtoe. Ram et al. (2019) follows the "Bioenergy with increased environmental and nature conservation restrictions" from Thrän et al. (2010) by assuming no 'good' agricultural land for energy cropping. It does however consider the possibility for biofuel cultivation on 'degraded arid' land, specifically jatropha oil, assuming a potential of 260 million tonnes of oil production on up to 700 million hectares of land, which would be associated with increased carbon sequestration. This relies on fairly aggressive assumptions on productivity improvement (quadrupling typical oil harvest by 2050).

9.3.ii) Sustainability considerations

Forestry material availability in Thrän et al. (2010) is assessed based on annual wood growth, with the report asserting that wood removals up to annual growth are sustainable. This characterisation makes no consideration of the opportunity cost of wood removals (bioenergy vs. carbon sequestration) and does not consider related sustainability concerns such as biodiversity support, soil carbon management and watershed management. Implementing "increased environmental and nature conservation restrictions" reduces forestry potential by about 25%. For agricultural straw, it was assumed that 20% could be sustainably available for energy use without impacting soil carbon formation and other uses.

The report does not discuss in any detail the sustainability implications of the rather dramatic

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suggested expansion of jatropha agricultural, except to assert that by targeting marginal/ degraded lands ILUC effects and competition with food could be avoided. The report does not discuss in any detail the necessary regulatory framework to direct jatropha production to such areas.

9.4. Role of bioenergy in scenario outcomes

9.4.i) Bioenergy utilisation by sector and mode

In 2050, biomass and waste contribute 6% of primary energy. Global biomass use for power is relatively modest in 2050 at around 50 Mtoe, with PV and wind the dominant global renewable power sources. The largest consumer of biomass for energy is heat production, which increases by about 60% at the global level to 550 Mtoe.

In transport, liquid biofuels (jatropha) play a minor role compared to electrification, hydrogen and electrofuels. By 2050 electricity dominates final energy consumption and the electricity supply is 100% renewable, mostly solar power (69% of global primary energy in 2050) and wind (18% of global primary energy in 2050). Biomass provides 6% of global primary energy in 2050 (only about 4% in Europe). Electricity prices are assumed to show large reductions. In Europe the report models a primary LCOE of 2.5 €cent/kWh and a delivered cost of 3.2 €cent/ kWh. The report states that with these relatively low electricity costs electrofuels can be cost competitive with liquid fossil fuels once a 2050 carbon price of 150 €/tCO_2e is applied. Primary energy consumption of biofuels reduces slightly from now to 2030. Liquid fuels are primarily used for aviation and shipping by 2050.

9.4.ii) Role of imports

The heavy reliance on electrification leads to reduce energy imports in Europe through the transition. Jatropha is characterised as a technology for local energy supply in regions with available degraded arid land, and not as an export opportunity.

9.4.iii) Implications for LULUCF?

The report largely avoids assuming large areas of energy cropping. The discussion of largescale cultivation of degraded land for jatropha implies hundreds of millions of hectares of land use change, albeit from presumably low value land status.

9.4.iv) Regulatory recommendations

The report calls for political support for a transition to 100% renewables, built on policy that is ambitious, transparent, well-defined and stable. The report mentions the possibility of tax exemptions for biofuels and of instruments such as feed-in-tariffs and renewable portfolio standards to encourage biomass for heat and power. There are no recommendations for managing biomass resources, except through the promotion of the jatropha production model.

10. Notes on other selected studies

10.1. Breaking new ground - Wind Energy and the Electrification of Europe's Energy System (Pineda, Fraile, & Tardieu, 2018)

This report by Wind Europe is based on analysis by DNV GL. It provides results for Europe taken from a global energy system transition model that is normally used as the basis for DNV GL's 'Energy Transition Outlook'[7]. For the Wind Europe study, the DNV GL 'most likely' assumptions were replaced with assumptions consistent with the EU delivering GHG emissions reductions of 80-95% by 2050. An 'accelerated electrification' scenario is based on assuming accelerated offshore wind power deployment and achieves a 74% GHG emission reduction by 2050 against the 1990 baseline, while a 'Paris-compatible' scenario goes further to deliver a 90% emission reduction by 2050.

In the Paris compatible scenario, biomass power supply reaches about 70 Mtoe, and a further 80 Mtoe of biomass energy are used in non-electricity applications. Biofuel use in transport halves compared to 2016 in the Paris compatible scenario as the vehicle fleet is electrified.

10.2. Eurelectric Decarbonisation pathways (Eurelectric, 2018)

In this report, Eurelectric develop scenarios in which electrification contributes to GHG emissions reductions for the EU of 80%, 90% and 95%. Biofuels are identified as part of the solution for parts of transport that cannot be electrified, alongside electrofuels, but relative contributions are not specified. Similarly, while biomass electricity is identified as a contributing power source, the biomass contribution is bundled with hydropower and geothermal power and therefore cannot be separately identified.

10.3. Low Carbon Pathways 2050 (Lloyd's Register & SCC, 2016)

This report considers the future of decarbonisation for international shipping using the GloTraM shipowner profit maximisation model. It presents three decarbonisation scenarios – high hydrogen, high bio and high offsetting. In the high bio scenario, about 90 Mtoe of biofuel is required by 2050, meeting around a quarter of the energy needs of international shipping. Biofuel demand is similar but slightly lower in the high offsetting case, but much lower in the high hydrogen scenario. The report notes that, "The amount of energy (fuel) that could be sourced from biomass in the future is highly uncertain and the results have a large sensitivity to this assumption." Marine is assumed to consume 2.42% of global biofuel consumption in 2050, with three levels of global use considered (from 900 Mtoe in the low case to 3,000 Mtoe in the medium case to 11,000 Mtoe in the high case). The medium case is about the same as maximum global primary bioenergy availability as suggested by Searle & Malins (2015).

The report assumes that biofuels would be brought into international shipping through the implementation of biofuel mandates. The high bio scenario requires about 100 Mtoe of biofuels annually by 2050.

7 https://eto.dnvgl.com/2019/index.html

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10.4. Energy [r]evolution (Teske et al., 2015)

This report for Greenpeace, the Global Wind Energy Council and SolarPowerEurope is presented as an alternative to the IEA WEO, built around a transition to 100% renewable energy by 2050. It presents a reference scenario based on the IEA WEO 2014 current policies, an 'energy revolution' scenario consistent with a 2 °C target for 2050 and a more ambitious 'advanced energy revolution' scenario with a faster introduction of decarbonisation technologies and greater role of behaviour changes.

By 2050, in the energy revolution scenario global biomass power generation increases to 260 Mtoe, biofuel consumption increases to 220 Mtoe and biomass use for heat increases to 920 Mtoe. The advanced energy revolution results are similar. The report is not explicit about the assumed sources of biomass, but notes that, "The use of biofuels is limited by the availability of sustainably grown biomass". The report provides a more detailed discussion of sustainability principles for bioenergy than other reports reviewed, suggesting explicitly criteria such as protection of biodiversity, natural capital and ecosystem services, cascading use and detailed LCA requirements.

11. Comparison of results

The reports reviewed above, and the scenarios within them, show a wide range of analytical approaches, premises and assumptions. Some studies attempt to explicitly model the lowest cost routes to deliver decarbonisation goals (e.g. the European Commission work). The IEA World Energy Outlook focuses on the potential results of current and future decarbonisation policies. The Net Zero 2050 model, in contrast, is designed to allow users to experiment with the results of innumerable combinations of policy and technology assumptions. Some scenarios are explicitly constructed to illustrate the implications of focusing on a single technology option – Ram et al. (2019) considers a system built around renewable electricity, and scenarios in the European Commission modelling focus in turn on electrification, a hydrogen economy, power-to-X, energy efficiency and the circular economy. It should not be surprising that with very different approaches we see very different scenarios being put forward. In all scenarios considered, however, there is some significant consumption of bioenergy assumed.

Figure 13 illustrates global primary bioenergy demand in several reviewed scenario. For the REmap study and the median value from the IPCC report the biomass required is above the 2,900 Mtoe estimated as the maximum potentially sustainable global biomass availability for energy in Searle & Malins (2015), suggesting that delivering those modelled levels of biomass for energy sustainably may not be possible.

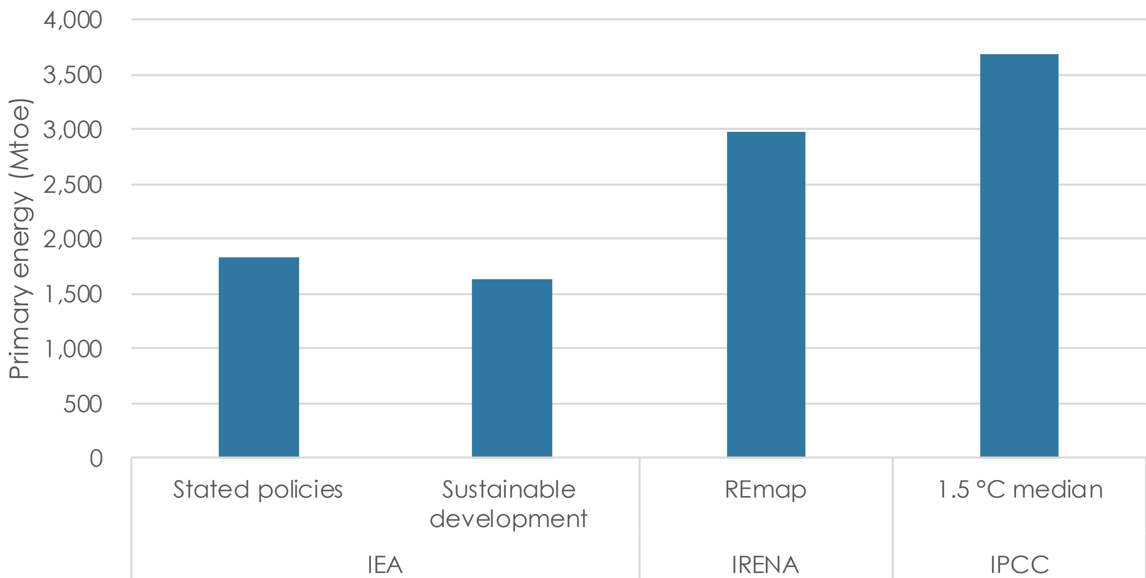

Figure 13. Global primary bioenergy demand in selected scenarios (2040 for IEA, 2050 for others)

The Searle & Malins (2015) upper -bound assessment is based on utilisation of all biomass residues that do not have existing uses and are not required to maintain soil quality, and on planting with energy crops all potentially productive land that does not have protected status, would not be needed for food production given a central projection of future food

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demand and yields, and is not currently forested. This category of potentially productive land is very broad, and includes areas that provide important ecosystem services and support for biodiversity that could be negatively affected by use of energy cropping (i.e. it is not limited to degraded or low value land). The estimate is controlled for cost of biomass production (some potential biomass production is assumed uneconomic) and for governance (it is assumed that in countries with weak governance it is unrealistic to assume all potentially sustainable biomass could be harvested). Given that this upper bound assumes massive expansion of managed land (900 million hectares of energy cropping) and would have serious implications for biodiversity and ecosystem services, even lower biomass consumption estimates may be difficult to achieve and raise serious sustainability concerns. While external factors (such as dietary change, stronger than expected productivity growth or lower than expected growth in food consumption) could allow greater availability, we can reasonably expect that delivering the level of biomass consumption required to meet any of these four scenarios would present major sustainability challenges, and in practice would be likely to result in some unsustainable outcomes. It must also be recognised that biomass for energy will be to some extent in competition with demand for biomass for bio-based products, further reducing sustainably achievable potentials.

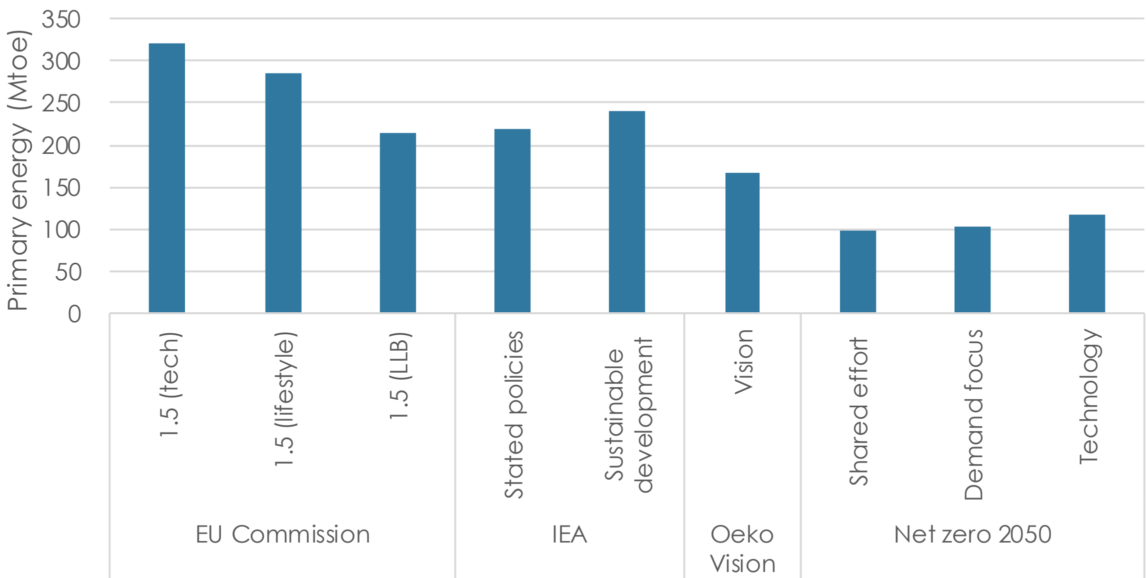

Figure 14. EU primary energy demand in selected scenarios (2040 for IEA, 2050 for others)

Figure 14 shows primary energy demand for some of the EU only-scenarios, and for the EU region in the IEA scenarios. Previous work for European environmental NGOs suggested a maximum sustainable biomass availability of about 150 Mtoe in 2030 (Transport & Environment & BirdLife International, 2016). This is based on a more restrictive assessment of potentially sustainable land availability from Allen et al. (2014) than that provided by Searle & Malins (2015). The level of biomass mobilisation required to realise any of the European Commission or IEA scenarios is at least 40% higher than this. These higher assumed utilisations reflect less stringent sustainability assumptions both for residue collection rates and for land conversion to energy cropping.

This highlights that even for biomass supply identified as 'sustainable' in any given assessment there may well be trade-offs with biodiversity and other ecosystem services.

Figure 15 and Figure 16 show that at the global level, most scenarios see heat (industrial heat and space heating) as the largest part of final bioenergy consumption. With no consensus on whether biofuels for transport will use more or less biomass resource than power generation.

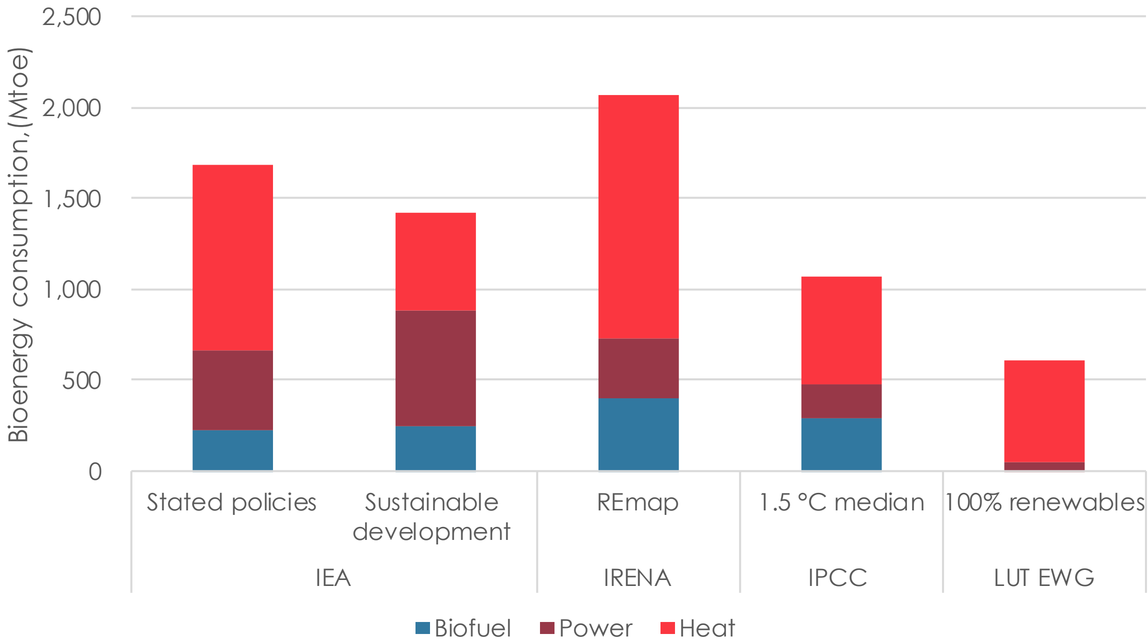

Figure 15. Global final bioenergy demand in selected scenarios

For the EU-focused scenarios, both the IEA World Energy Outlook and the European Commission 'Clean planet for all' scenarios have power as the larger final user of bioenergy (of course, in scenarios with significant combined heat and power production there is always a degree of balance between these energy outputs). Transport use is seen as more limited, which is partly explained by the high levels of passenger vehicle electrification assumed for Europe.

Within transport biofuels, there is a consistent emphasis on advanced fuels from cellulosic and lignocellulosic feedstock, and most studies explicitly or implicitly presume a transition away from food-crop based first generation biofuels. Emphasising advanced biofuels allows some of the sustainability issues associated with first generation biofuels to be more readily assumed away in the scenarios, but the reports fail to make concrete regulatory proposals for measures to prevent further expansion of first-generation biofuel production, and most fail to offer any specific suggestions to ensure sustainable biomass harvesting and collection for advanced biofuels. Sustainability governance will be important both for cellulosic energy crops, which may compete for agricultural land with food and feed crops, and for residues that may currently provide important ecological and agricultural services (Harrison, Malins, & Stephanie, 2016).

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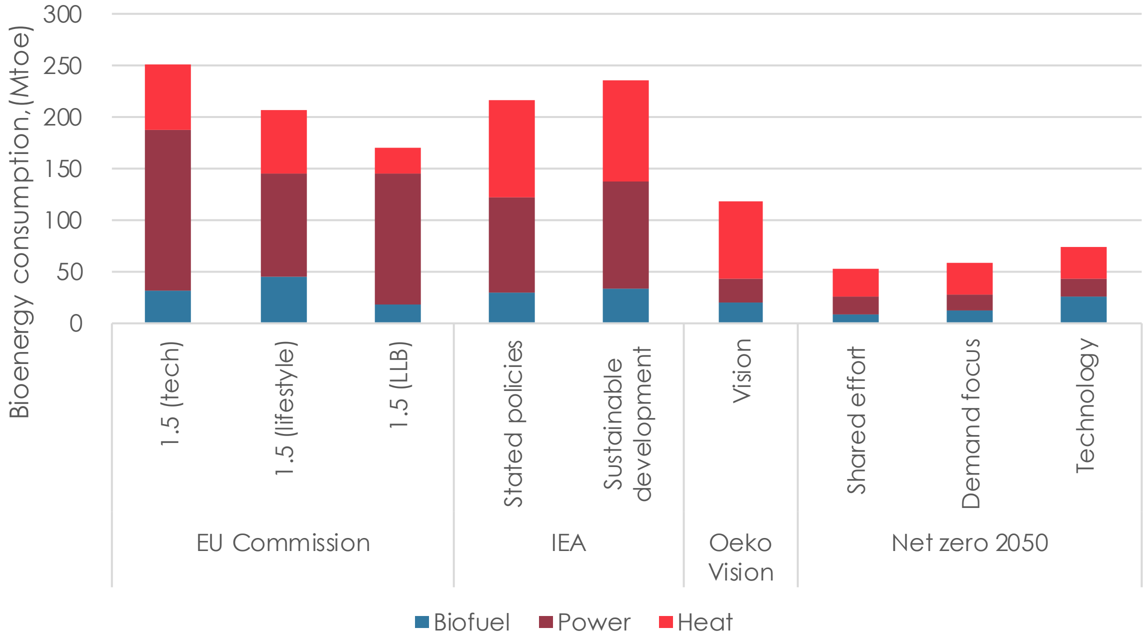

Figure 16. EU final bioenergy demand in selected scenarios

There is also significant potential looking forward for competition over biomass resources between energy use and materials uses, for instance for construction material, bioplastics and biochemicals. In some cases there may be a degree of potential complementarity, especially if principles of the circular economy are applied. For example, increased use of timber as a building material could support expanded commercial forestry, with correspondingly increased availability of forestry residues, and with increased average standing carbon stocks in the forest estate. Without the application of sustainable forestry principles, however, increased timber demand could also lead to illegal or unsustainable logging and reductions in total forest area. More generally, increased biomaterials production can be expected to compete with bioenergy for primary biomass resources, including traditionally lower value residual materials. This represents an additional pressure that is not consistently handled in the various scenarios for bioenergy potential.

12. Discussion

The world needs to dramatically reduce GHG emissions by 2050, and investments on which decisions are being made today will affect the energy transition, both because some facilities entering operation now will still be operational in 2050 and because faster deployment of novel technologies will make rapid scale up of those technologies by 2050 more achievable. In order to set policy effectively, governments need to have a sense of which technologies may have a role to play in 2050, and where policy focus should be. Hoping to support that decision making, a range of organisations including intergovernmental groups like the International Energy Agency and IPCC publish reports containing decarbonisation scenarios that could be consistent with targets to restrict average temperature changes below 2 °C or even 1.5 °C. Most of these scenarios show a role for bioenergy, but there is considerable range in the scenario results regarding the size of that role, and assumptions about how biomass could best be used. Some studies show increased biomass use in the most ambitious scenarios – in others, the use of biomass is actually reduced in the more ambitious scenarios as other technologies such as electrification are adopted. There is also disagreement about the level of risk posed by largescale expansion of biomass energy production, with some studies showing great caution on biomass availability while others assume that very large potentials can be achieved sustainably.

One argument made in favour of bioenergy (e.g. in IPCC, 2018) is that scenarios with significant deployment of bioenergy, and in particular bioenergy with carbon capture and sequestration, allow decarbonisation to be delivered at a lower cost to society. It should be understood however that all of these scenario studies make an assumption, sometimes explicit and sometimes implicit, that bioenergy is delivered in a way that minimises associated net CO_2 emissions from land use change and from carbon stock reductions. It is only true that bioenergy delivers cost effective GHG emissions reduction *if it is true that such emissions will be avoided*. This relates to the common assumption that bioenergy is fundamentally carbon neutral, on the basis that carbon released during combustion must recently have been absorbed from the air during plant growth. As numerous authors have pointed out (e.g. Baral & Malins, 2014; Berndes et al., 2016; Searchinger et al., 2009) this simple argument about carbon neutrality for bioenergy fails to acknowledge crucial details: the risk that equilibrium carbon storage in an ecosystem is reduced by biomass harvesting; the carbon debt incurred when harvesting trees that could take years to regrow; and the opportunity cost of using land for bioenergy that could be used to grow food or allowed to permanently afforest. Without proper management of biomass harvesting there is every risk that the carbon neutrality assumption will turn out to have been wrong.

In the discussion of sustainability in the various reports there is often a conflation between the statement that biomass *could* be produced sustainably and the prediction that biomass *will* be produced sustainably. There is considerable evidence that much of current modern[8] biomass use for energy is unsustainable (the use of palm oil for biodiesel is a particularly egregious example, but wood harvesting for pellets also remains controversial). The belief that biomass can be sustainably sourced ought to be a starting point to discuss how policy can be used to ensure that sustainable supply chains are developed and how unsustainable supply chains can be eliminated. It must not become an excuse to assume that the market will on its

8 Traditional biomass use is also generally recognised as less efficient, unhealthy and often unsustainable, and most scenarios assumes it is significantly reduced by 2050.

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own deliver biomass that is both low price and low impact. While all of the studies considered make at least a token gesture to recognising the importance of sustainable biomass harvest, it would be welcome if future iterations of these assessments were more explicit in discussing the regulatory framework that would be necessary to ensure that sustainability and carbon neutrality is not only possible but delivered. As has been seen over the last decade in the European Union, pursuing ambitious bioenergy targets without adequate regulatory measures to guarantee sustainability can easily result in unintended negative outcomes.

There is a very real risk that the existence of decarbonisation scenarios that have very ambitious levels of biomass demand could be taken as a justification for a laissez faire attitude to biomass sustainability, in the name of accelerating deployment. The opposite conclusion should in fact be drawn – the higher the level of biomass use being targeted the more important it will be to manage risks of unsustainable practices through regulatory action. These risks, and the imperative to manage them, will only be heightened by concurrent expansion of biomass demand for materials uses.

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