Economic Systems Research

ISSN: 0953-5314 (Print) 1469-5758 (Online) Journal homepage: https://www.tandfonline.com/loi/cesr20

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ECONOMIC SYSTEMS RESEARCH
https://doi.org/10.1080/09535314.2018.1564020

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ABSTRACT

The threats of climate change, food security, resource depletion and energy security are driving society towards a sustainable low-carbon future. Within this paradigm, biomass plays an invaluable role in meeting the food, feed, energy and material needs of future generations. Current EU thinking advocates biomass for high-value materials, which is not aligned with EU public policy support for 'lower value' bioenergy applications. 'High-technology' and 'no bioenergy mandate' pathways explore market conditions that generate a more equitable distribution between competing biomass conversion technologies and competing biomass and fossil technologies. In achieving greater equity, these pathways ease biomass market tensions; enhance EU food security; improve EU biobased trade balances; accelerate biomaterial sectors' output performance and favour macroeconomic growth. Moreover, an additional 80% increase in the oil price signals a tipping point in favour of first generation biofuels, whilst simultaneously boosting output in advanced material conversion technologies even more than the high-technology pathway.

ARTICLE HISTORY
Received 5 April 2018
In final form 22 December 2018

KEYWORDS
Bioeconomy; MAGNET; CGE; foresight study

1. Introduction

As the issues of resource depletion and climate change play an ever-increasing role in influencing the design and implementation of future policies towards a low-carbon future, there is widespread recognition in European Policy circles (European Commission [EC], 2012) that biomass usage has a key part to play within a circular (bio)economy model of sustainable prosperity and growth. A central tenet of the bioeconomy strategy is the principle of 'cascading' biomass usage (EC, 2012) that prioritises high-value-added material uses before eventual recycling and conversion to energy. This paradigm, however, is not aligned with European Union (EU) public policy, which at the current time promotes the use of

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Supplemental data for this article can be accessed here. https://doi.org/10.1080/09535314.2018.1564020

biomass for energy generation (e.g. OECD, 2014; Vis et al., 2016). As a result, this runs the risk of discouraging, or even crowding-out investments in, and production of, 'higher value' materials (Carus et al., 2011). For example, the increasing use of tall oil for biofuels, which is a co-product of the production of wood pulp, potentially limits its use as an input to biobased chemicals and materials (Omanukwue, 2014). Furthermore, taking the hotly debated topic of 'sustainability' (Euractiv, 2017), it is claimed that policy support for biomass in first generation biofuels as part of the Renewable Energy Directive (RED) is potentially a misappropriation of food crops, leading to environmentally harmful (indirect) land-use effects. Finally, an ongoing obstacle to the realisation of a truly sustainable and competitive (i.e. high-value) vision of a circular biobased chain of activities is the 'competitive-gap' that remains with established fossil-based technologies.

Employing a simulation model, this research seeks to evaluate the market impacts arising from a more economically efficient distribution of biomass across competing uses consistent with the EU's bioeconomy strategy (EC, 2012) as well as the closing of the 'competitive-gap' between biobased activities and rival fossil fuel alternatives. As a broad collective of sectors accounting for €2.2 billion in turnover and 18.6 million jobs (JRC, 2017), European biobased activity (i.e. agriculture, food, energy, industry) is a highly diverse collective with numerous interindustry linkages to the broader macroeconomy. Thus, any quantitative impact assessment must not only recognise the sustainability constraints for available biomass to biobased sectors but also competition between biobased and non-biobased activities for primary factors such as labour and capital. Furthermore, any credible analysis must explicitly consider available access to third-country markets to meet internal biomass requirements that arise from changes in public policy and/or market conditions.

Depending on the nature and scale of the research question, economic modelling representations of biomass supply and demand markets typically range from bottoms up representations of specific biomass conversion technologies, to multisector biobased partial equilibrium models and even economy-wide approaches akin to the computable general equilibrium (CGE) approach (Angenendt et al., 2018). Given the broad scope of this research, the tool of analysis employed here is a neoclassical multisectoral, multiregional CGE framework. To split out detailed sources and uses of biomass from the standard industry classification used in multisectoral economic analysis, is a data- and labour-intensive endeavour, which explains the dearth of focused biobased impact assessments within the broader macroeconomy.

Hoefnagels et al. (2013) and Van Meijl et al. (2018a) carry out a medium-term foresight analysis of the macroeconomic contribution of the bioeconomy in the Netherlands based on two axes of uncertainty: (i) trade access to biomass (e.g. sustainability criteria) and (ii) assumed rates of technology change in advanced generation biobased sectors. A key difference is that Van Meijl et al (2018a) explicitly incorporate much greater biobased activity detail in their study. Hoefnagels et al. (2013) focus on the large scale substitution of fossil resources by biomass for both energy and materials, whilst Van Meijl et al (2018a) incorporate more modest biomass policies into their scenarios coupled with enhanced biobased technical change assumptions garnered from a bottoms-up linear programming model of the Dutch energy and chemicals sectors. Whilst both studies concur that increased biomass trade openness and/or rapid technology bring economic benefits, Van Meijl et al. (2018a) conclude that blending mandates under the auspices of the RED incur economic inefficiency costs as fossil fuels are substituted by less efficient biomass conversion technologies.

With a level of explicit biobased activity coverage more akin to Van Meijl et al. (2018a), the foresight study of Philippidis et al. (2018a) examines the EU perspective through the construction a medium-term baseline. The study assesses two stylised bioeconomy 'narratives' or 'futures' and their implications for EU biomass usage and the trade-offs among various economic and environmental performance indicators. The authors conclude that EU bioeconomy growth and job creation is below full potential, largely due to assumed slower rates of EU technical change and steeper greenhouse gas reductions compared with third countries.

This research also employs a CGE framework. As in Hoefnagels et al. (2013) and Van Meijl et al. (2018a), one scenario assesses the role of technological progress as an efficient push for the development of nascent (higher value) biobased activities, although unlike the aforementioned references, this is carried out for the entire EU. Moreover, a further scenario examines the hitherto unexplored impact of removing EU bioenergy support as a means to foster more efficient alternative biomass uses. Finally, the competitiveness of the EU's biobased economy as a whole is examined through the key variable of fossil fuel price increases. With this scenario design, the concept of greater efficiency in biomass redistribution is examined on two levels, namely a redistribution of biomass to meet the needs of competing biobased applications (i.e. food vs. feed vs. energy vs. materials) and the market ingredients for narrowing the 'competitive-gap' which renders biobased activities as viable substitutes for incumbent rival fossil-based energy and industrial technologies. To the best of our knowledge, along with Van Meijl et al. (2018a), the explicit coverage of biomass sources and activities is the most comprehensive currently available for economy-wide studies of this type, whilst this paper further extends the representation of bioenergy with an advanced generation biokerosene technology. Finally, to more accurately represent the medium-term trends in EU biomass usage for energy, our baseline incorporates detailed shocks to capture EU energy market supply and demand trends accounting for competing fossil, biobased renewables, non-biobased renewables and nuclear technologies.

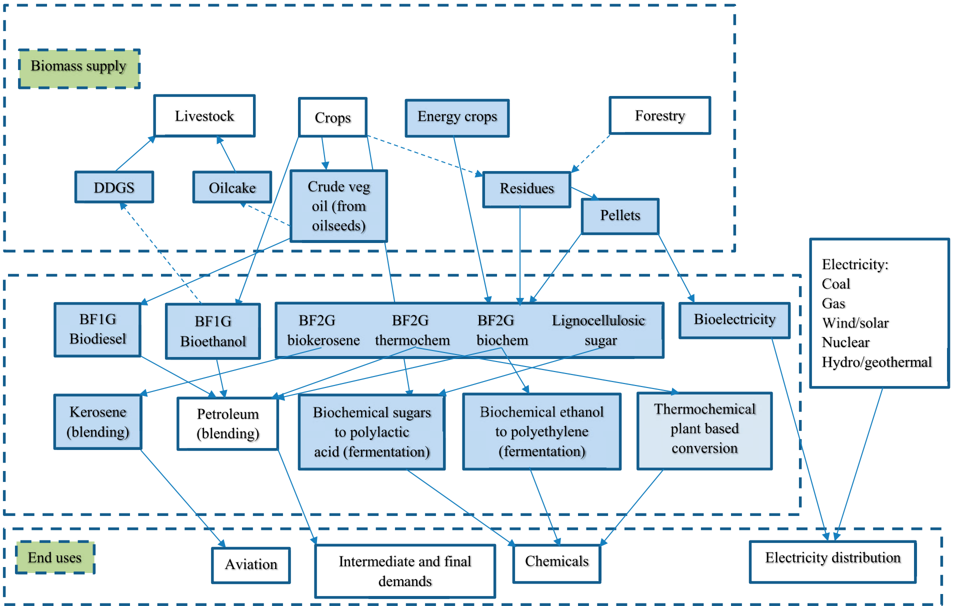
2. Materials and methods[1]

2.1. Database overview and aggregation

With its unrivalled coverage of countries (141 regions) and activities (57 sectors), version 10 of the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2016) includes detailed information on production, gross bilateral trade flows, transport costs and trade protection data, benchmarked against the year 2011. Within this data, biobased activities are disaggregated into 12 primary agricultural and 8 food processing sectors; forestry, fishing, wood products, and (with differing degrees of biomass content) textiles and a composite 'paper-publishing' sector. More contemporary uses of biomass for fuel and materials remain subsumed within their parent industry classifications. As an ongoing response, the coverage of the biobased activities in this study goes far beyond the typical classification of sectors commonly found in the standard classification of national accounts underlying

[1] For additional detail on the database, the modelling and the baseline scenario design and results for this study, see Philippidis et al. (2018b).

Figure 1. Overview of biobased sectors and linkages in MAGNET.



the GTAP database. Figure 1 shows the relationship between the 'new' biobased sectors (highlighted in blue) with the publicly available GTAP sectors (in white). The arrows indicate the direction of biomass, biobased energy and chemicals flows, whilst the dashed lines indicate where biobased by-products occur. The principal sources of data supply to capture these additional sectors in this study and a more detailed discussion of these sectors is available online in Philippidis et al. (2018b).

Table 1 presents a regional aggregation that reflects the EU focus of the study grouped into 12 representative geographical regions, whilst the rest of the world is also grouped into logical geographical clusters. The choice of commodities (Table 1) includes the most disaggregated representation of biobased activities currently available from the MAGNET model database, including numerous sources of biomass supply and biomass applications (i.e. food, feed, bioenergy and bioindustrial). To enhance the model treatment and baseline, further splits capture feed and fertiliser agricultural inputs and different energy sources (both fossil and renewable).

2.2. Model framework and closure

Based on the well-known GTAP CGE simulation model (Corong et al., 2017), this paper employs an advanced recursive-dynamic variant known as the Modular Applied GeNeral Equilibrium Tool (MAGNET – Woltjer and Kuiper, 2014).[2] In the academic literature,

[2] Many of the (nascent) biobased sectors have small initial output values reflecting their lack of commercial viability in the benchmark year of the study (2011). In designing our baseline to capture plausible structural changes in the economies over time, the resulting 'small-share' problem that resides in the family of convenient functional forms used in CGE analysis is problematic. As a result, to boost the progress of latent biobased technologies over time a multi-period recursive-dynamic treatment provides a superior treatment compared with a single-period comparative-static approach.

Table 1. Study disaggregation of commodities and regions.

Commodity disaggregation (66 commodities):
Arable and horticulture (9): paddy rice; wheat; other grains; oilseeds; raw sugar; vegetables, fruits and nuts; other crops; plant fibres; crude vegetable oil
Livestock, meat and dairy (7): cattle and sheep; wool; pigs and poultry; raw milk; cattle meat; other meat; dairy.
Fertiliser (1): fertiliser.
Other food and beverages (4): sugar processing; rice processing; vegetable oils and fats; other food and beverages.
Other 'traditional' biobased (5): fishing; forestry; textiles, wearing apparel and leather products; wood products; paper products and publishing.
Biomass supply (10): non-food energy crops; residue processing; pellets; by-product residues from rice; by-product residues from wheat; by-product residues from other grains; by-product residues from oilseeds; by-product residues from horticulture; by-product residues from other crops; by-product residues from forestry.
Biobased liquid energy (5): 1st generation biodiesel; 1st generation bioethanol; 2nd generation thermal technology biofuel; 2nd generation biochemical technology biofuel; biokerosene.
Biobased industry (4): lignocelluose sugar; biochemical (fermentation) conversion of sugar biomass to polylactic acid chemicals; biochemical (fermentation) conversion of bioethanol to polyethylene chemicals; thermochemical conversion of biomass to chemicals.
Biobased and non-biobased animal feeds (3): 1st generation bioethanol by-product distillers dried grains and solubles; crude vegetable oil by-product oilcake; processed animal feeds.
Renewable electricity generation (3): bioelectricity; hydroelectric; solar and wind.
Fossil fuels and other energy markets (10): crude oil; petroleum; gas; gas distribution; coal; coal-fired electricity; gas-fired electricity; nuclear electricity; electricity distribution; kerosene.
Other sectors (5): chemicals, rubbers and plastics; other manufacturing; aviation; other transport; other services.

Regional disaggregation (17 regions):
EU members (12): France; Germany; Italy; United Kingdom; Ireland; Austria, Rest of the Mediterranean (Spain, Greece, Portugal); Scandinavia (Denmark, Finland, Sweden); BeNeLux (Belgium, Netherlands, Luxembourg); Baltics (Latvia, Lithuania, Estonia); EU East (Poland, Czech Republic, Slovakia, Hungary); Rest of South EU (Bulgaria, Romania, Croatia, Slovenia, Cyprus, Malta).
Non EU regions (5): Rest of Europe; North America; Central and South America; African continent; Asia and Oceania.

MAGNET has featured as an impact assessment tool within a broad variety of areas including: land-use change (e.g. Schmitz et al., 2014); EU domestic support (e.g. Boulanger and Philippidis, 2015); Biofuels (e.g. Banse et al., 2008, Banse et al, 2011; Smeets et al., 2014); Food Security (Rutten et al., 2013) and Climate change (Van Meijl et al., 2018b).

A key strength of MAGNET is its' modular structure, which allows the user to activate those modules of relevance to the study focus. Thus, modules are activated that reflect (i) biomass sustainability considerations and (ii) behavioural assumptions and public policies of relevance to biobased activities. In (i), the supply of agricultural land and sustainable residues follows an asymptotic supply function. For (ii), technology nesting structures differentiate crop and livestock activities, land transfer is heterogeneous between alternative uses and EU agricultural policy is explicitly modelled (Boulanger and Philippidis, 2015). Fiscal neutral bioenergy policies (Banse et al., 2008; Banse et al., 2011) impose taxes on the downstream petroleum blending activity to finance biofuel providers to meet said targeted mandates. An environmental and energy module captures carbon taxes and physical limits on all greenhouse gas (GHG) emitting activities (Burniaux and Truong, 2002) and capital-energy substitution possibilities (Golub, 2013) in the refining and power generation sectors (e.g. electricity, petroleum). The model further assumes joint (i.e. Leontief) production technologies (see Figure 1), which acknowledges the important role of by-products. Thus, agricultural and forestry sectors also produce 'residues'; first generation bioethanol also produces distiller's dried grains with soluble (DDGS) animal feed, and crude vegetable oil, largely employed in first generation biodiesel production, also produces oilcake animal feed.

To improve the tracking of final demand patterns over medium- to long-term time frames, particularly in relation to food demand in regions with rapidly increasing per capita real incomes, calibrated income elasticity parameters are endogenously adjusted downwards in successive time periods with rises in real (PPP corrected) GDP per capita (Woltjer and Kuiper, 2014).[3] Finally, a medium- to long-term neoclassical model closure in all simulations is chosen, where regional savings drive investment demands, whilst imbalances on the capital account (i.e. regional savings less investment) are compensated by current account adjustments (exports minus imports), such that the balance of payments nets to zero.

2.3. Baseline and scenarios

A business-as-usual baseline scenario is developed distinguishing three periods: 2011–2015, 2015–2020 and 2020–2030. A detailed description of the main assumptions can be found online in Philippidis et al. (2018b).[4] In capturing the EU's RED, a 7% blending mandate for first generation biofuels is assumed by 2020, which is maintained until 2030. In the case of advanced generation biofuels, the mandates are increased in a time-linear fashion to 1.5% by 2030.[5] Furthermore, to represent the 'European Advanced Biofuels Flightpath' initiative to speed up the uptake of advanced biofuels to the aviation industry, a time-linear increase in the biokerosene blending mandate in the kerosene (blending) sector to 0.5% by 2030, is also assumed. In comparison with the baseline, 'high-technology', 'no-mandate' and 'competition-gap' pathways are explored to examine different prospects for increasing the efficiency of biomass allocation. In each case, these scenarios depart from the baseline in the decade 2020–2030.

The 'high-technology' (HT) scenario explores cost-competitive implications for advanced biochemical and thermochemical lignocellulose biomass conversion into biofuels and chemicals, which it is assumed, arises from aggressive EU-wide research and development. Following Van Meijl et al. (2018a), this scenario incorporates input-augmenting technological change in advanced biomass conversion technologies from a bottoms-up linear programming model of the energy and chemicals sectors for the Netherlands (see Philippidis et al., 2018b). The unregulated EU biofuels market scenario assumes that public policy support for the usage of biomass in energy is removed. Thus, the 'no-mandate' (NoM) scenario abolishes all RED first and advanced generation biofuel mandates and the biokerosene mandate, whilst public support for biomass in bioelectricity, is also eliminated.

Motivated by the possibility of a market shock to global oil markets (e.g. quota cuts by OPEC members, political instability in oil producing regions, reduced pumping capacity and/or market uncertainty), additional simulations based on the NoM scenario explore

[3] As a result, in regions/countries where real incomes are rising rapidly (i.e. China, India, Mercosur), a more realistic rise in food demands (vs. the standard GTAP treatment) moderates pressure on food prices, and by extension biomass prices and land rents.

[4] Within our EU focused baseline scenario, we do not include Brexit. This is because the final trade arrangement between the EU and the UK remains unclear at the current time ('soft' vs. 'hard' Brexit), which would leave our baseline assumptions open to pure speculation, and therefore subject to scrutiny. In reference to the results section, the reader should be aware that envisaged trade relations under a hard-Brexit future would have major implications for access to third country biomass, particularly for the UK.

[5] With a view to encouraging more advanced commercial biofuel technologies, the double counting of this mandate equates to a 'virtual' mandate of 3%.

the impact of higher global oil prices in closing the 'competitive-gap' between carbon-based and biobased rival technologies and subsequently, the impact on biomass allocation within the EU. Thus, compared with the assumed baseline oil price of $80 per barrel by 2030,[6] three scenarios examine an oil price rise of 30% ($104 per barrel), 50% ($120 per barrel) and 80% ($144 per barrel). These are labelled, NoM30%, NoM50% and NoM80%, respectively.

3. Results[7]

In this section, results are presented for the scenarios in comparison with the baseline for the period 2020–2030.

3.1. HT and NoM scenario results 2015–2030

3.1.1. Output and market prices

In macroeconomic terms, both scenarios generate very slight real EU GDP gains (approximately 0.03%), either due to the allocative efficiency gains from the removal of a market distortion (NoM), or due to technological improvements (HT). The production volume and market price impact from the HT and NoM scenarios are presented in Table 2. As a general comment, in both scenarios the relative impact on primary agricultural activities is confined, when observed, to first generation biofuel feedstocks of oilseeds and sugar beet. Similarly, in the food markets, the impacts are muted.

In the HT scenario, biochemical sector and transformed lignocellulose sugar output volumes improve by over 200% and 1500%, respectively (from small production bases). In the advanced generation biofuels and biokerosene sectors, the output volume rises are more moderate (5.3% and 4.2%, respectively) as the mandates are maintained.[8] In value terms (constant prices, 2011), these changes are equivalent to €362 million (biochemical conversion technologies), €24 million (thermochemical conversion technology), €157 million (lignocellulose sugar), €335 million (advanced generation biofuels) and €40 million (biokerosene).

In the HT scenario, output falls in biomass feedstocks from residues (−6.0%), pellets (−11.4%) and energy crops (−1.9%) are reported due to the assumed input-augmenting biomass conversion technologies. Furthermore, biomass substitution effects are in evidence. For example, the release of residues, pellets and energy crops from biochemical and thermochemical biomass conversion technologies, lignocellulose sugar, advanced generation biofuels sectors and biokerosene, to bioelectricity, leads to an output volume increase of 1.9% in the latter.

With assumed improvements in input–output efficiency, reduced per unit demand for lignocellulose biomass drives slight market price falls in these sectors. As a result, there are concomitant market price falls in vintage technologies such as bioelectricity and first generation biofuels, and a closing of the competitive-gap as evidenced by relative market price

[6] With the fall in fossil prices, this forecast is lower than the assumed oil price of $124 per barrel assumed in Van Meijl et al. (2018a).

[7] A full discussion of the baseline results can be found in Philippidis et al. (2018b).

[8] In a separate simulation, it was discovered that the impetus to output in these advanced generation biofuel sectors from high technological change was much smaller than the output loss from the removal of the mandates.

Table 2. EU output volumes and market prices vs. baseline (2020–2030, %).

	HT	NoM	HT	NoM
	Output volumes		Market prices	
I. Agriculture, fishing, forestry:				
Wheat	0.5	−0.5	−0.2	0.3
Other grain	0.7	0.6	−0.5	−0.1
CEREALS	0.6	0.1	−0.4	0.1
Oilseed	0.7	−6.7	−0.4	−3.2
Beet/cane sugar	0.3	−4.0	−0.9	−2.1
CROPS	0.6	−0.3	−0.5	−0.5
LIVESTOCK	0.3	0.2	−0.8	−0.6
AGRICULTURE	0.5	0.1	−0.6	−0.5
Fishing	0.0	0.0	0.0	0.0
Forestry	−0.2	−0.4	0.1	0.4
II. Food and feed industry:				
MEAT	0.2	0.1	−0.3	−0.2
DAIRY	0.2	0.2	−0.4	−0.4
FOOD	0.2	0.1	−0.1	−0.3
Feed	0.4	−0.9	−0.1	1.6
III. Lignocellulose biomass, processed intermediates and biobased by-products				
Energy crops	−1.9	−15.6	−1.3	−9.0
Residue	−6.0	−46.8	−0.8	−4.5
Pellet	−11.4	−54.5	−0.4	−2.5
BIOMASS	−6.1	−46.2	−0.8	−4.6
Crude veg oil	0.1	−16.9	−0.3	−5.3
FEED BYPROD	0.3	−16.8	0.0	11.8
IV. Bioindustry:				
Ligno. sugar	1561.3	26.1	−30.6	−2.6
Polyethylene	246.5	8.5	−23.0	−8.8
Polylactic acid	272.0	4.7	−25.1	−0.2
Thermochem	226.2	0.5	−12.1	0.0
V. Bioenergy				
Bioethanol 1G	1.1	−93.6	−0.3	−18.2
Biodiesel 1G	−0.1	−96.7	−0.2	−4.2
BF1G	0.0	−95.0	−0.2	−6.1
Thermal 2G	−4.1	−99.7	−36.8	−2.9
Biochem 2G	14.1	−99.7	−38.0	−3.2
BF2G	5.3	−99.7	−37.4	−3.0
Bkerosene	4.2	−98.5	−29.6	−4.6
Bioelectricity	1.9	−26.8	−0.5	−2.8

Notes: CEREALS include paddy rice, wheat and other grains activities. CROPS is an aggregate of all arable and horticultural activities in Table 1. LIVESTOCK includes cattle and sheep and pigs and poultry activities. MEAT includes cattle meat and other meat. DAIRY includes raw milk and dairy. FOOD includes all processed food activities in Table 1. BIOMASS includes all ten biomass supply commodities in Table 1. FEED BYPROD is distillers dried grains and soluble and oilcake. BF1G is first generation biodiesel and bioethanol. BF2G is both thermal and biochemical advanced biofuel technologies.

falls in advanced generation biofuels (37.4%), biokerosene (29.6%), lignocellulose sugar (−30.6%), biochemical conversion (−23.0% and −25.1%) and thermochemical conversion (−12.1%) technologies. Overall, in the HT scenario, the EU bioeconomy increases in volume by €4051 billion (2011 constant prices), of which much is due to the reallocation of (now) spare biomass into agricultural and food activities.[9]

[9] Bioeconomy is interpreted here as agriculture, forestry, fishing, food, bioenergies, bioindustry and associated lignocellulose feedstocks.

In the NoM scenario, first and advanced generation biofuels and biokerosene output volumes collapse. From an assumed EU average mandate of 8.5%, the blending rate falls to 0.3% (see Figure 3). In value terms, this scenario corresponds to a loss of (2011 constant prices) €11.4 billion in combined first and advanced generation biofuels and approximately €945 million in the biokerosene sector. Similarly, the removal of public policy support from bioelectricity also results in a sharp output volume fall of −26.8% (€4.6 billion). As a result, there are output contractions (Table 2) in upstream feedstocks sectors (i.e. oilseeds, sugar, cereals, crude vegetable oil, lignocellulose biomass) and biofuel by-product animal feeds (−16.8%). Indeed, also accounting for the contraction in upstream feedstocks, the EU bioeconomy supply-chain contracts €25.4 billion (2011 constant prices).[10]

Encouragingly, there is evidence of a levelling of the playing field as cheaper biomass is rechannelled into nascent biochemical biomass conversion (polyethylene polymers, polylactic acid polymers) and thermochemical biomass conversion technologies. Notwithstanding, in value terms, the relative increase is limited (€7 million and less than €1 million for the biochemical and thermochemical technologies, respectively). As expected, the removal of the biofuel mandates has a notable deflationary impact on biomass prices, with associated cost-driven market price falls in downstream first (−6.1%) and advanced generation (−3.0%) biofuels. With increased availability of cheaper biomass to bioindustrial uses, there are moderate reductions in production costs and, ultimately, market prices in these sectors. On the other hand, reduced availability of animal feed by-products, and manufactured animal feeds results in a relative market price rises of 11.8% and 1.6%, respectively, although this does not translate into a significant cost-driven increase in EU livestock prices due to the fact that 80% of animal feeds are sourced 'on-farm'.

3.1.2. Trade effects

Examining Table 3, both the HT and NoM scenarios imply reduced dependence on third-country sources of biomass, which in the context of reduced land-use, is environmentally beneficial. A further positive outcome is that EU meat, dairy and food security in general, as their respective EU trade balances improve slightly in both scenarios, due to the freeing up of additional biomass for food activities.

In the HT scenario, input efficiency gains imply reduced pellets intra-EU trade (−11.5%) and extra-EU imports (−17.1%), with associated rises in extra-EU exports (1.9%). Following the output rises reported in section 3.1.1 above, EU self-sufficiency in advanced generation biofuels and biokerosene improves dramatically (albeit from small bases).[11]

In the NoM scenario, intra-EU trade and extra-EU imports of the first generation, advanced generation and biokerosene biofuels are eliminated, which leads to a deterioration in the EU's energy security with increased dependence on fossil fuel alternatives. In value terms, the elimination of the biobased fuel mandates costs the EU an additional €415 million, €5133 million, €564 million and €459 million extra in coal, crude oil, gas and refined petroleum extra-EU imports, respectively (not shown). Examining the trends in the first generation biofuel feedstock sectors (i.e. oilseeds, crude vegetable oil and sugar

[10] See previous footnote.

[11] Owing the paucity of available data, it is assumed that advanced generation biochemical sectors and lignocellulosic sugars sectors are non-tradable. Instead they are classified as inputs to the aggregate chemicals sector (see Figure 1), which is traded. Total electricity output is tradable, to which bioelectricity contributes a component part.

Table 3. EU Trade volumes vs. baseline (2020–2030).

	Intra-EU trade				Extra-EU imports				Extra-EU exports			
	Baseline 2030 (€2011)	HT (%)	NoM (%)	NoM80 (%)	Baseline 2030 (€m 2011)	HT (%)	NoM (%)	NoM80 (%)	Baseline 2030 (€m,2011)	HT (%)	NoM (%)	NoM80 (%)
I. Traditional crop feedstocks:												
CEREALS	12,263	0.1	−0.1	−1.0	4,437	−0.9	0.5	−0.4	9,410	1.1	−0.2	1.4
oilseed	4,825	0.9	−9.0	−0.7	8,646	−0.5	−16.0	1.6	731	1.4	8.4	−4.0
Sugar beet	72	−0.1	−2.9	0.9	12	−2.9	−9.9	3.8	4	3.8	11.9	−0.8
II. Food and feed industry:												
MEAT	40,849	0.2	0,0	−0.1	6,345	−1.6	−1.4	−1.7	10,123	2.0	1.5	−4.1
DAIRY	29,565	0.1	0.1	−0.8	1,596	−1.5	−1.8	0.3	8,351	1.2	1.5	−0.6
FOOD	207,602	0.1	−0.3	−0.1	54,244	−0.4	−2.0	−2.1	99,679	0.5	0.9	−1.1
Feed	3,506	−0.9	−3.0	0.7	1,090	−1.2	2.8	0.5	2,015	0.1	−5.0	1.4
III. Lignocellulose biomass, processed intermediates and biomass by-products												
pellet	392	−11.5	−53.4	−35.2	141	−17.1	−73.2	−50.1	12	1.9	28.8	215.1
crude veg oil	5,593	0.3	−16.7	1.6	3,337	−0.8	−30.1	1.8	1,156	1.1	24.3	−1.0
FEED_BYPROD	1,791	0.3	−23.3	0.8	3,652	0.3	13.7	3.2	519	−0.4	−20.0	−11.6
IV. Bioenergy												
bioethanol 1G	11	1.0	−95.1	−74.8	193	0.0	−97.4	−74.9	61	1.0	54.6	344.0
biodiesel 1G	250	0.5	−98.8	−54.0	729	−0.1	−99.1	−56.6	74	0.8	24.4	914.1
BF1G	261	0.5	−98.7	−54.9	912	−0.1	−98.8	−60.4	179	0.8	30.9	656.5
thermal 2G	19	81.6	−99.8	−86.6	213	−67.1	−99.8	−88.3	3	379.2	11.3	833.4
biochem 2G	20	120.5	−99.8	−87.2	227	−62.5	−99.8	−89.0	3	411.5	12.4	757.0
BF2G	40	101.0	−99.8	−86.9	440	−64.8	−99.8	−88.7	6	395.3	11.8	793.7
bkerosene	10	63.4	−98.4	−94.2	53	−57.2	−98.6	−95.3	2	213.2	18.6	672.0

Notes: CEREALS includes paddy rice, wheat and other grains activities. MEAT includes cattle meat and other meat. DAIRY includes raw milk and dairy. FOOD includes all processed food activities in Table 1. FEED BYPROD is distillers dried grains and solubles and oilcake. BF1G is first generation biodiesel and bioethanol. BF2G is both thermal and biochemical advanced biofuel technologies.

beet) and pellets, intra-EU trade and extra-EU imports fall, whilst extra-EU exports rise (these trends are particularly marked in pellets trade). Importantly, EU cereals trade is not majorly affected by this policy. A reason for this is the rise in internal demand for cereals due to the rise in real incomes in the NoM scenario. In the case of first generation animal feed by-products and manufactured feeds, there is an additional reliance on extra-EU imports (13.7% and 2.8%, respectively) and a corresponding fall in extra-EU exports (20.0% and 5.0%, respectively).

3.1.3. Land use

According to the baseline, the EU28 land area will be approximately 1.8 million km^2 by 2030 (not shown). Of this total, approximately 46% is dedicated to each of livestock and crops (excluding oilseed and sugar beet) activities (Figure 2). The remaining 7.8% is mainly taken up by oilseeds (6.7%) and sugar beet (0.6%) as feed crops for non-biofuel usage. Conventional biofuel usage of oilseeds and sugar beet accounts for only 0.3% and 0.2% of the total EU land area, respectively, whilst lignocellulosic (non-food) energy crops for advanced biofuels account for only 0.1%.

As a result, neither scenario carries major implications for aggregate EU land usage when compared with the baseline (Figure 2 – lower panel), although at the margin, first generation biofuel policies have a non-trivial impact on oilseed (for biodiesel) and sugar beet (for bioethanol) cropping areas (Figure 2, lower panel). In the NoM scenario, first generation biodiesel and bioethanol land usage fall 5519 km^2 (-98.4%) and 3521 km^2 (-99.6%) respectively, whilst oilseeds and sugar beet for non-biofuels activities change by -457 km^2 (-0.4%) and 3064 km^2 (26.5%), respectively. Some of this land reduction is re-diverted into cereals (2479 km^2 – not shown), which drives the 0.4% land increase dedicated to crops, whilst the livestock sector also witnesses greater uptake of land (2699 km^2 or 0.3%). Interestingly, the usage of lignocellulosic energy crops in diverse advanced biomass energy and industrial technologies, means that even with the loss of EU support for advanced biofuels, the resulting land-use reduction is only 11% fall compared with the baseline.

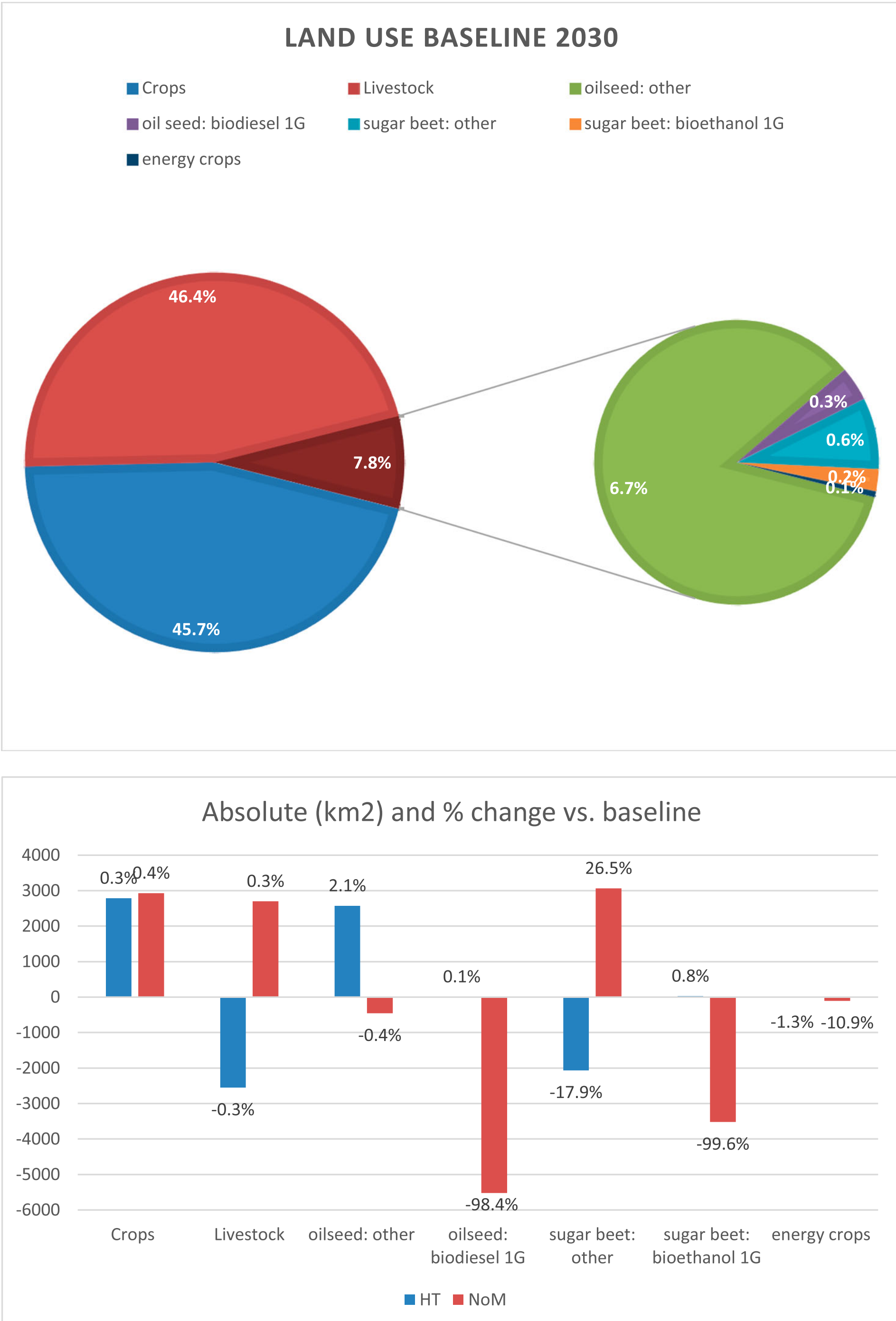
In terms of the third-country impacts which arise from the removal of the EU's biofuels mandates, dedicated land usage to biodiesel in 'North America' and 'South and Central America' falls moderately by 3940 and 820 km^2, respectively (results not shown). Similarly, bioethanol land usage falls 470 km^2 in 'South and Central America' (results not shown).

Under the assumption of strong technological improvements in advanced generation biobased energy and industrial sectors (HT), there is a reduced per unit demand for lignocellulosic biomass (i.e. residues, energy crops, pellets), although this only translates into a very moderate drop of 12 km^2 (-1.3%) in energy cropland usage compared with the baseline. On the other hand, with a slight improvement in the EU's real GDP in this scenario, a small relative rise in total EU land use (765 km^2) reflects the resulting demand driven growth for agri-food products.

3.2. Competitive-gap scenario – rising oil prices

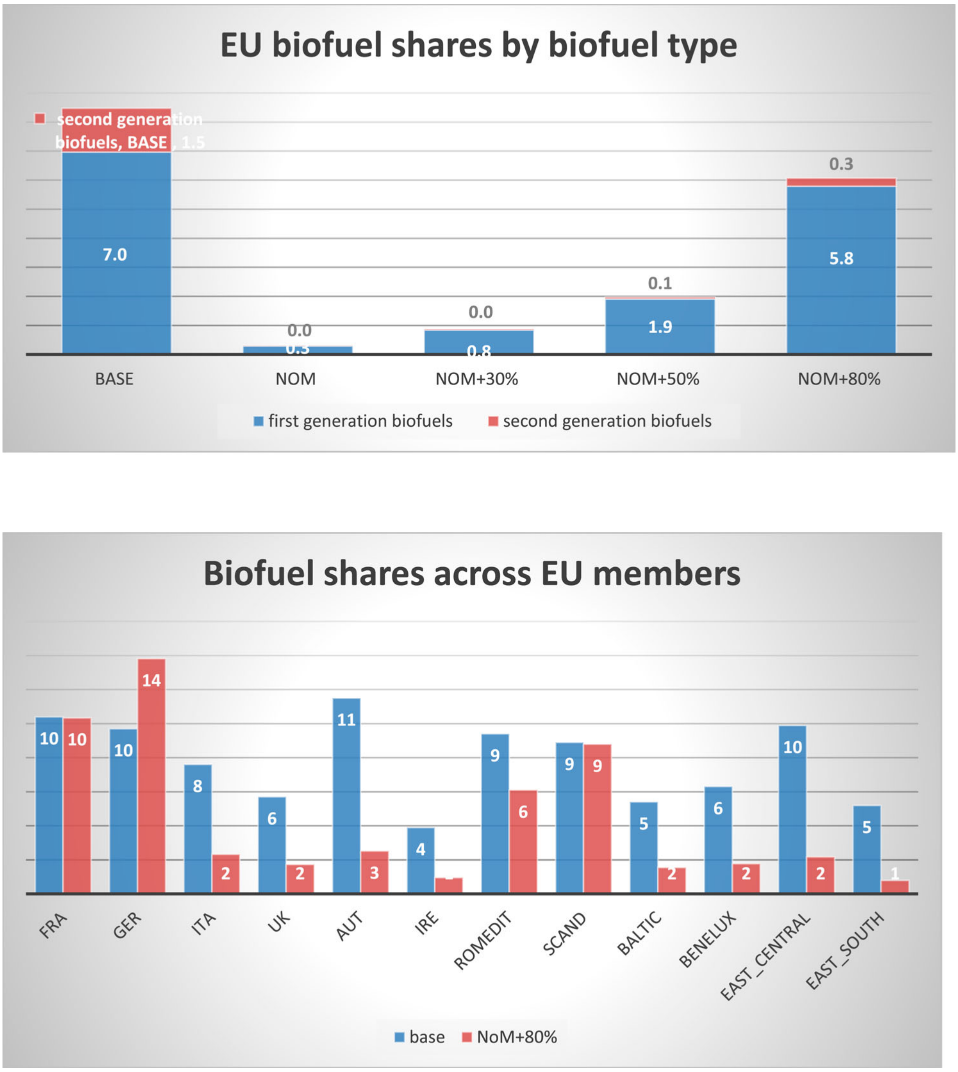
To illustrate the closing of the competitive-gap described in section 2.3, Figure 3 shows the impact of successively higher oil prices on first and advanced generation blending limits for the EU Member States (MS) and the EU aggregate. To meet the 7% first generation

Figure 2. EU land usage.



Notes: Crops is an aggregate of all arable and horticultural activities described in Table 1, except oilseeds and sugar beet. LIVESTOCK includes all primary livestock activities described in Table 1.

Figure 3. EU Member State 2030 blending limits in the baseline, no-mandate (NoM) and NoM oil price rise scenarios.



Notes: NoM30%, NoM50% and NoM80% are the 'competitive gap' scenarios with 30%, 50% and 80% higher oil price by 2030 compared with the baseline.

biofuel blending mandate, by 2020 the required bioenergy subsidy rate (not shown) indicates that biosubstitutes cost 2.2 times that of crude oil, which in the baseline, falls to a factor of 1.6 by 2030 (due to the assumed oil price rise in the baseline and no change in the mandate). For the 1.5% advanced generation biofuel mandate, the corresponding baseline cost-disadvantage figures for 2020 and 2030 are 4.4 and 4.0 times, respectively.

As the oil price rises even further above the baseline by 2030 accompanied by an elimination of subsidy support, the top panel in Figure 3 reveals gradual rises in the first generation blending shares reaching as high as 5.8% at the peak assumed oil price of \$144 per barrel. On the other hand, for advanced generation biofuels, even at \$144 per barrel, the

EU average blending rate of 0.3% remains way below the 1.5% mandate reported in the baseline.

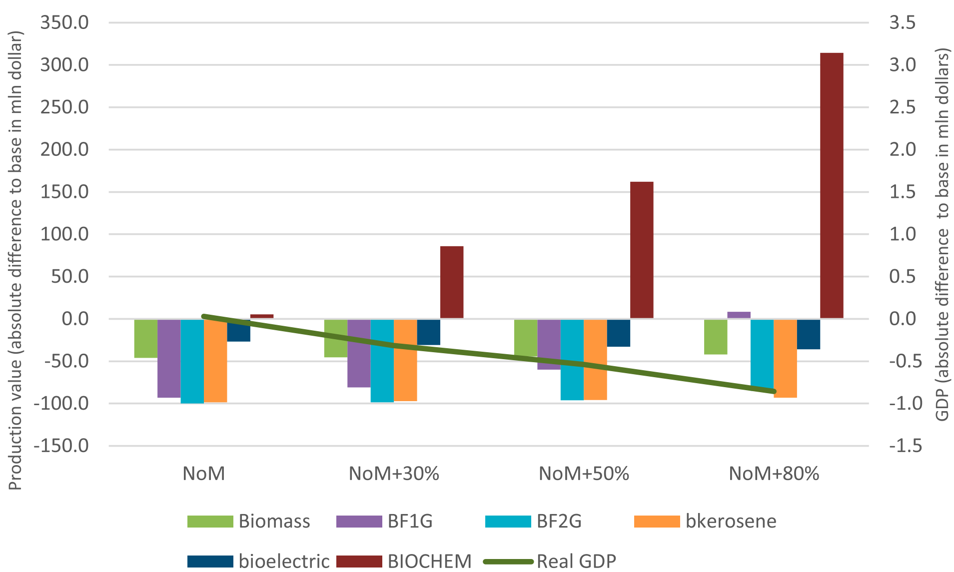
Examining the total (first generation and advanced generation) blending rates for the MS, at $144 per barrel France, Germany and Scandinavia equal or even surpass the baseline (subsidy supported) 2030 blending mandates. In the case of Austria, first generation biofuel production is almost entirely biodiesel, with a high dependency on North America imports. Thus, limited domestic capacity inhibits Austria's ability to increase its first generation biofuel production purely through the market mechanism.

3.2.1. Output volumes

In macroeconomic terms, by 2030, higher global fossil fuel prices of $104, $120 and $144 per barrel reduce relative EU real GDP growth by −0.3%, −0.5% and −0.9%, respectively (Figure 4). As EU growth slows, the EU retail price index also falls by −0.4%, −0.66% and −1.03%, respectively (not shown). With a slowing of real incomes and demand, there is a relative decline in EU28 bioeconomy activity output volumes in all three fossil fuel scenarios of −0.7% compared with the baseline (not shown). As noted in the previous section, at $144 per barrel (NoM80%), first generation EU28 biofuel output volumes are only 11% below the baseline, motivated largely by output expansions in Germany, France and Scandinavia (Figure 4), whilst corresponding advanced generation biofuel and biokerosene output remain 85% and 93%, below the baseline, respectively.

An important observation is the resulting push that the oil price gives to the biochemi-

Figure 4. Production volumes in EU28.



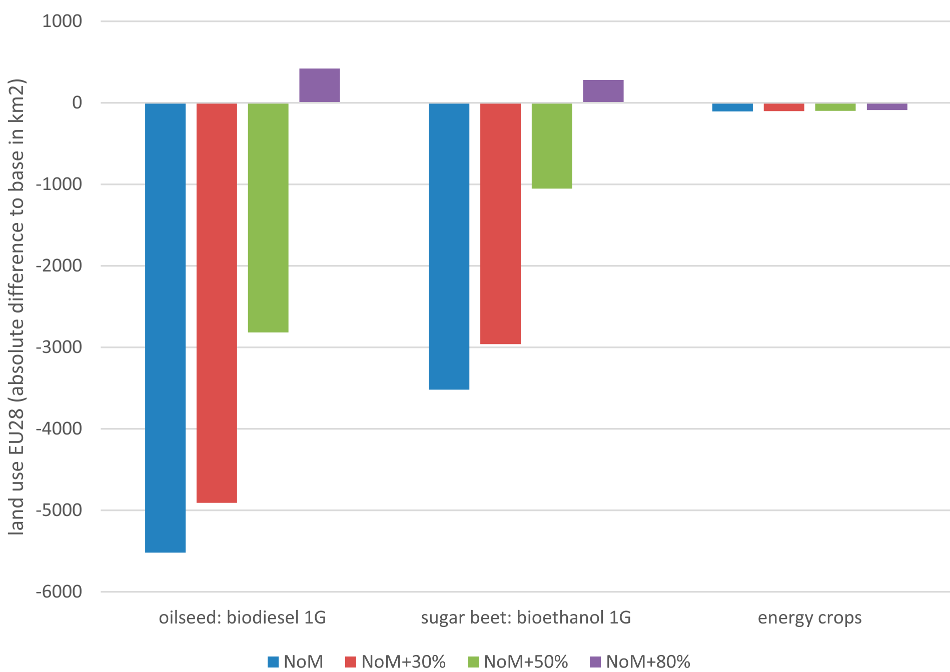
Notes: NoM30%, NoM50% and NoM80% are the 'competitive gap' scenarios with 30%, 50% and 80% higher oil price by 2030 compared with the baseline. AGRICULTURE includes all crop and livestock primary agricultural activities in Table 1. FOOD includes all processed food activities in Table 1. BIOMASS includes all 10 biomass supply commodities in Table 1. BF1G is first generation biodiesel and bioethanol. BF2G is both thermal and biochemical advanced biofuel technologies. BIOECONOMY includes all biobased activities in Table 1.

cal sectors largely driven by the rising relative price of fossil-based chemicals. Comparing with the baseline, the magnitude of the output increases in advanced biochemical and thermochemical conversion technologies is approximately 86% ($104 per barrel) to over 300% ($144 per barrel). A key point is that these output volume rises exceed even those reported in the HT scenario when comparing with the baseline.

3.2.2. Trade effects

At the highest oil price of $144 per barrel, crude oil and petroleum extra-EU imports fall 27% and 22%, compared with the baseline (not shown). As expected, compared with the NoM scenario, at the assumed high oil price, there is some recovery in intra-EU trade and extra-EU imports of biofuels (see Table 3). Following the production trends reported in Figure 4, intra-EU and extra-EU import trade in advanced generation biofuels and associated lignocellulose feedstocks (pellets) remains below the baseline. Third-country imports of crude vegetable oil and sugar feedstocks are slightly above the baseline to satisfy internal market requirements. As surplus internal production is dumped on world markets, extra-EU exports of first generation biofuels rise (from small bases) 657%, whilst extra-EU exports of advanced generation biofuels rise approximately 800%. Finally, in non-biofuel based trade, falls in real incomes (due to relative falls in macroeconomic growth), reduce the marginal propensity to import.

Figure 5. Land-use trends for biofuels.



Notes: NoM30%, NoM50% and NoM80% are the 'competitive gap' scenarios with 30%, 50% and 80% higher oil price by 2030 compared with the baseline.

3.2.3. Land usage

Examining Figure 5, land-use trends for biofuel uses present clear trends under each of the oil price assumptions. At the highest assumed oil price ($144 per barrel), relative land usage in both bioethanol and biodiesel rises by 281 and 421 km^2 above the baseline, respectively. This implies that land areas for food crops fall very slightly, whilst this land substitution effect is also driven by the macroeconomic contraction and resulting aggregate demand falls resulting from the increase in energy costs. Examining the land area for lignocellulosic energy crops for advanced biofuels, land-use reductions remain when compared with the baseline since the output volume of advanced generation biofuels is still some way below the baseline. Notwithstanding, comparing with the level playing scenario ($80 per barrel), one observes a slight recovery in the energy crops land area compared with the baseline from $-101\,km^2$ (NoM+30%) to $-89\,km^2$ (NoM+80%).

4. Conclusions

A number of commentators in the literature (e.g. OECD, 2014; Vis et al., 2016) observe a possible contradiction between the EU's current strategy towards the promotion of higher value biobased products (EC, 2012) and the existing emphasis on public support geared towards promoting biomass for energy.

This paper examines how market efficiency pathways (i.e. leveller playing field) impact on biomass use, and the associated market repercussions and trade-offs (i.e. food vs fuel, fossil energy vs bioenergy, bioenergy vs bioproducts, and biochemical vs petrochemical products). To this end, enhanced biobased efficiency narratives are identified and compared with a *status quo* baseline.

On a positive note, this study confirms that both the no-mandate (NoM) and high-technology (HT) narratives improve (marginally) the EU's macroeconomic growth performance. Furthermore, both pathways offer viable options for enhancing EU food security; improving EU biobased trade balances; providing a more sustainable model of biomass (reflected by lower biomass and biobased activity market prices); reducing environmental leakage (with reduced third-country land usage) and lastly, (particularly in the HT scenario) channelling biomass into higher value bioindustrial activities consistent with EU policy (i.e. cascading hypothesis).

In the HT scenario, rapid input-saving technological growth frees-up biomass usage that fosters agricultural, food and (as a result) bioeconomy sector growth compared with the baseline – estimated at €4051 billion (2011 constant prices). In the current paper, high-technology change assumptions are sourced from a specialist bottoms-up model. Whilst it is clear that positive outcomes are associated with innovative biobased solutions, further research on understanding the uncertainty surrounding promising technological advancements in biomass conversion technologies and their quantification within a CGE framework is wanting, especially where longer time frames (i.e. 2050) are concerned.

In the case of the NoM scenario, it is encouraging to note that even wholesale biofuel policy changes appear to have relatively limited impacts on EU land usage, a result also supported by previous literature (Babock, 2015). On the other hand, it is apparent that bioenergy sectors remain heavily reliant on EU patronage in order to remain viable, also supported by previous research (Araujo-Enciso et al., 2016), whilst rendering the EU more exposed to dependence on third-country sources for fossil fuels. Unfortunately, the NoM results also indicate that the EU bioeconomy output volume contracts compared with the baseline, despite the rechannelling of biomass for energy, into alternate uses. This result should, however, be considered as a worst-case outcome. Indeed, whilst nascent biochemical technologies are represented, an improved coverage of *existing* biochemical technologies represents a priority area for further research. Finally, in the animal feed market, the disruption to biofuel by-product animal feeds results in notable market price rises and greater third-country import dependence, although the overall impact does not imply any cost-driven price rises to EU livestock sectors, largely because on-farm feed crops constitute a large input share. In the model, the characterisation of animal feeds as aggregate inputs and the possible use of overly optimistic animal feed input substitution elasticities in livestock sectors, mask the potentially serious shortfall in essential protein-based feedstocks (i.e. soya), thereby exacerbating the EU's dependence on select (i.e. non-genetically modified) third-country trade (Euractiv, 2018).

Examining the competitive-gap scenarios, EU (and global) macroeconomic performance inevitably suffers under higher global oil prices, although this comes with the expectation of lower EU GHG emissions. Interestingly, with a 2030 bioenergy technology (cost-gap) improvement in dollars per barrel equivalent to $64 per barrel (i.e. 80% above the baseline), a near-tipping point is reached for first generation biofuels. More precisely, EU first generation biofuels practically compete with fossil fuel alternatives, without policy support. Banse et al., (2008) report that with 70% higher oil prices, unsupported first generation biofuel production remained only 4% below the benchmark year (2001), a result that is consistent with our study. This analysis also quantifies the market push required to generate a meaningful reallocation of biomass in the EU. Indeed, the rechannelling of lignocellulose biomass into advanced biomass material conversion technologies, generates an even greater output boost to nascent bioindustrial sectors than the assumed technological progress modelled in the HT scenario.

As with any modelling endeavour that attempts to capture real-world behaviour, a study of this nature inevitably carries limitations. With neoclassical CGE models, the standard structural caveats apply, chief among them being the deterministic (i.e. nonstochastic) behaviour of agents, the assumption of equilibrium market clearing, the stylised representation of investment, and the conditionality imposed on model results through the choice of model closure. Also, the parametric assumptions governing input substitution in the production nests remain invariant over the medium-term time horizon of the experiments, which introduces a degree of bias, particularly when examining technology shifts from fossil to biobased production, as explored in the competitive-gap scenarios.

Furthermore, treatment of other necessary ingredients (e.g. institutional, market risk, stakeholder engagement) to ensure a successful reorientation towards a more sustainable system of EU growth, are lacking or underrepresented. For example, Zilberman et al. (2018) comment on the role of governance in ensuring business friendly legal and regulatory conditions to foster optimal knowledge transfer and commercial viability of new biotechnologies. To promote the visibility of biobased material products in society, targeted consumer marketing campaigns spearheaded by public institutions that burnish both environmental and quality attributes would ensure greater market acceptability and sustained investment (Wesseler and von Braun, 2017; Zilberman et al., 2018). From a market uncertainty perspective, OECD (2014) observes that, akin to the petrochemical industry, biorefineries must be prepared to minimise risk during periods of fossil fuel price volatility through the development of biofuel/biochemical co-product platforms based on compatible biomass conversion technologies.

Finally, additional data-driven modelling developments are a priority. Further to the aforementioned need for greater biochemical activity splits, a representation of organic and municipal waste streams in (*inter alia*) biogas and bioheating is lacking. A more accurate depiction of sustainability in the model (i.e. resulting price changes) subject to expected rates of extraction and depletion, and an explicit treatment of forestry land, which has pertinence when examining issues of biomass availability (i.e. residues), indirect land-use change and greenhouse gas emissions, should also be considered as priorities for further research.

Acknowledgements

We would also like to thank the three anonymous referees and the editor for their very helpful comments and suggestions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was partly funded by an administrative arrangement between the Directorate General Research and Innovation (DG RTD) and the Joint Research Centre (JRC).

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