Modeling and Analysis

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Lignocellulosic biomass for chemicals and energy: an integrated assessment of future EU market sizes, feedstock availability impacts, synergy and competition effects, and path dependencies†

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Abstract: Lignocellulosic biomass is expected to play an important role in decarbonizing our economy. In this modeling study, we assessed the future role of biobased chemicals and energy from this resource in the EU up to 2030. The study's general outcomes indicate that biobased heat remains the largest biobased sector over this period, and biobased chemicals remain the smallest. A significant share of EU-domestic lignocellulosic biomass potential remains unutilized, even when feedstock availability is restricted. The technology mix for biobased heat, power, biofuels, and chemicals remains relatively stable in all cases, with a strong role for biobased combined heat and power (CHP). Several specific 'what if' analyses were done. These show that both restriction of feedstock potential and active mobilization of available potential affect overall costs of biobased options, illustrating the relevance of specific policies in bringing biomass potentials to the market. In feedstock-restricted scenarios, specific attention to advanced lignocellulose-based fuel technologies is essential to meet biofuel ambitions. Another analysis indicates that both competition and synergy effects occur between energy and chemical applications of biomass. This illustrates that biorefining and co-production of biobased chemicals

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and energy in integrated biorefineries is a better and more robust business than separated production. Finally, an analysis of the dynamics between lignocellulosic and crop-based biofuels reveals that the current capacity of the latter creates a need for a specific subtarget for lignocellulose-based biofuels before they can enter the market, and that crop-based biofuels may be gradually phased out, but with significant additional costs. © 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: lignocellulosic biomass; biobased energy and chemicals; integrated assessment biobased strategies

Introduction

According to all global assessments, biomass will be pivotal for decarbonizing our economy.[1,2] An advantage of this resource over other renewable options is that it can be converted into a wide array of energy carriers and into chemicals, thereby providing a substitute for the role of fossil feedstocks in the petrochemical sector.[3–5] Lignocellulosic biomass, in particular – woody material, straw, and other non-digestible feedstocks composed of (hemi)cellulose and lignin – is the focus of attention as this is abundantly available in the form of residues and is less susceptible to sustainability issues than cultivated agricultural crops used for bioenergy.[6] The use of biomass for chemical and energy applications is part of the EU's bioeconomy strategy.[7] For biobased chemicals, attention still seems to focus on R&D and raising awareness of policy,[8] without clear incentives for deployment. For applications of lignocellulosic biomass for energy, such incentives are already in place, with the Renewable Energy Directive (RED)[9] as the key policy framework. This directive contains, *inter alia*, country-specific targets for renewables in 2020 (adding up to 20% for the EU as a whole), towards which lignocellulosic biomass for power and/or heat are foreseen to pay an important contribution.[10] For advanced, lignocellulosic biofuels, the 2015 RED amendment[11] provides a specific indicative subtarget of 0.5% of total energy in transport in 2020.

The EU has been preparing its energy and climate policy framework for 2030, including a new Renewable Energy Directive. A draft of this REDII was published in 2016,[12] and consensus between the European Commission, Parliament, and Council was reached in June 2018.[13] Three relevant 2030 targets were set: 32% for renewable energy within the EU, 14% for renewables in transport for each member state, and 3.5% for lignocellulosic biofuels. In the debate on these policy developments there are several questions related to the future role of lignocellulosic biomass in our economy (see, e.g., Scarlat *et al.*[14]). These questions focus on biomass availability and sustainability (how much will there be?), on its optimal use (will there be enough for chemicals *and* energy, and how will these applications interact?), and on strategic considerations (what is an effective development pathway given current applications of non-lignocellulosic biomass in, e.g., transport?). Many of these questions were addressed in the EU project S2Biom (FP7, see www.s2biom.eu), which included a collection of technical data regarding potentials, conversion technologies, the development of strategic tools, and roadmap studies.

As part of the S2Biom project, the integrated assessment tool RESolve-Biomass was further developed to address several of the policy and strategy questions mentioned above at EU level. The general approach was to generate a reference scenario for the development of biobased energy and chemicals in the EU, and provide additional analyses going into several 'what if' questions. In this paper, we go into the following:

1. An important question is how quickly biomass feedstocks can be mobilized and brought to the market. To what extent do active policies, accelerating mobilization of EU biomass feedstock potentials, lead to lower overall costs? What impact would this accelerated mobilization have on the feedstock and technology portfolio?
2. Biomass feedstock potential is an ongoing point of scientific, societal, and political discussion. What happens to the role of biobased options if EU feedstock availability is limited in comparison to the default availability, e.g. through more restrictive sustainability policies?
3. Several stakeholders in the debate on biomass would like to use biomass only for chemicals and materials, and not for energy, as they foresee biomass scarcity and competition between applications. To what extent is there synergy or competition between these applications – in other words: do the demands for biobased energy and chemicals applications influence each other's marginal costs?
4. Many definitions exist for different types of biofuels. Here we mainly distinguish between biofuels from food crops such as vegetable oils and sugar/starch crops, using conventional, commercially available conversion

technologies (further identified as crop-based biofuels) and biofuels from lignocellulosic feedstocks (woody materials, straw), using advanced conversion technologies (further identified as lignocellulose-based biofuels). Conventional biofuels based on food crops have often been advocated as an essential stepping stone for more advanced biofuel production technologies based on lignocellulosic feedstocks. But if there are no specific subtargets, crop-based and lignocellulose-based biofuels also compete against each other in their contribution to meeting a biofuels target, with crop-based biofuels having the advantage of consisting of existing production capacity. To what extent does current capacity for these biofuels hamper the introduction of lignocellulose-based biofuels?

5. Other stakeholders argue that crop-based biofuels need to be phased out as soon as possible, as they claim that their sustainability will remain a point of contest. To what extent can lignocellulose-based biofuels already take over the entire biofuels market by 2030, fulfilling the foreseen role of biofuels in the entire mix of mitigation options, at the expense of crop-based biofuels? What impacts on feedstock mix and system costs would that have?

Modeling approach

RESolve-Biomass: key model architecture

The RESolve-Biomass model determines the least-cost configuration of the entire bioenergy production chain as a function of endogenously given demand projections for biofuels, bio-electricity, bioheat, and biobased chemicals (more specifically, chemicals made from lignocellulosic biomass), and given assumptions on supply chains, including biomass potentials and technological progress – see Fig. 1. By doing so, it mimics the competition among these four sectors for the same resources. The model is myopic and does not work with perfect foresight: it provides a pathway of annual least-cost solutions, taking into account standing production capacities of the year before. It focuses on biobased options only; interactions with other options for renewable electricity and heat are not part of the analysis. Although the model can technically work with a CO_2 price, thereby also indicating the impact of the EU-ETS, this was not applied in this study.

The RESolve-Biomass model includes raw feedstock production, processing, transport, and distribution. One of the features of the RESolve-Biomass model is the ability to link the national production chains to the international trade market. By allowing trade, the future cost of bioenergy and biochemicals can be approached in a much more realistic way than when each country is evaluated separately. An extensive description of the model and its key features can be found in Van Stralen *et al.*[16] Development and applications of the model in earlier research projects has been described extensively in Londo *et al.*[15]

In its current version, RESolve-Biomass covers the 28 Member States of the EU, and the Western Balkan countries, Moldova, Turkey, and Ukraine. The model allows for trade in feedstocks and final products by means of trucks, trains and short sea shipments within Europe. Import from outside Europe goes via ocean tankers. The only costs associated with international trade are transport costs (including handling), for which generalized distances between countries are used. Key model outputs are:

- the mix of chemicals, fuels, electricity and heat generated, and of related conversion technologies;
- the types of feedstocks applied for the full set of countries assessed, and also specifically for six European regions, the balance between use of domestic feedstocks and imports, and the amounts of remaining unused domestic feedstock potentials;
- market value of the various products generated from biomass (i.e. projected production volumes times current market values);
- system costs, i.e. total costs for feedstock production, logistics, and conversion, minus market value of the

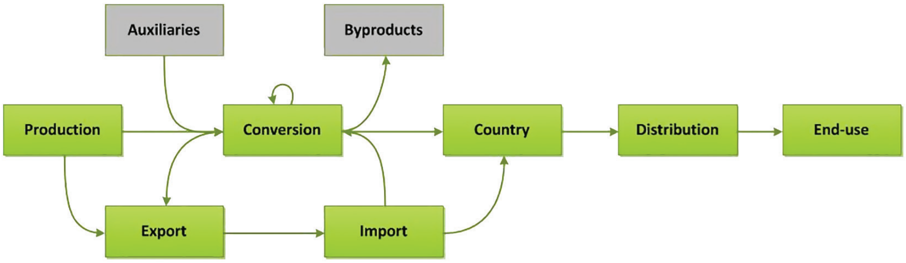

Figure 1. Schematic representation of the RESolve-Biomass model.[15]

products; this indicator is only to be used for a cost comparison between different model runs – the absolute numbers as such have limited meaning;

- marginal costs of some key products (i.e. production costs of the final unit of product needed to meet the demand).

RESolve-Biomass only analyzes biomass and bioenergy chains; the interplay between biobased energy routes and other options for energy production (renewable and nonrenewable) is not part of the analysis. The production levels of crop-based biofuels and application levels of various feedstocks for electricity and heat in the model were calibrated on available Eurostat data for 2005–2014.

Key inputs: biomass cost-supply data

European cost-supply data

The reference case for biomass availability is characterized by a policy environment in which the current sustainability policies are in place, and additional sustainability requirements are not limiting the size of feedstock. There is therefore no strong competition for resources and biomass feedstocks have low to medium prices.

For the EU-28 countries the required data were taken from the 'reference scenario' of the Biomass Policies project,[17,18] in which the current sustainability criteria for biofuels are implemented. In this analysis, interactions with the food and feed sectors and with lignocellulosic material-processing sectors were taken into account, both in terms of competition effects for feedstocks and for land, and in terms of synergies, e.g. through the mobilization of primary and secondary residues along the production chain for food, feed and lignocellulosic materials.

For interactions with agriculture for food and feed, this analysis was relatively detailed; for interactions with other forestry-based demands, this analysis was relatively simple. For example, future demand for stemwood was kept constant. Potential availability of forestry-based feedstocks may be higher in the future if stemwood demand increases and thereby co-mobilizes additional primary and secondary residues, but also lower if innovative technologies using primary and secondary residues for construction materials are further deployed (see Hildebrandt *et al.*[19]). Further methodological details are given in Elbersen *et al.*[18]

Beyond 2020, the 'reference scenario' is aligned with the 40% GHG reduction targets in 2030. For other countries included in the assessment, but which are not Member States of the European Union, the cost supply data has been taken from a JRC study on renewable energy potentials.[20]

The availability of biomass, slightly increasing between 2015 and 2030, is shown in Fig. 2. By 2030, the total potential adds up to almost 1 billion tonnes of dry matter. This potential for biomass availability is spread over a wide variety of categories, with the largest volumes in straw/stubbles, energy grasses and perennial crops, manure, primary forestry residues, saw mill residues, and other wood-processing industry residues. With cost data from the same project,[17,18] cost-supply curves were constructed, which for the major biomass feedstocks can be seen in Fig. 3.

Ex-EU import cost-supply data

Import cost supply data for crop-based and lignocellulose-based bioethanol, biodiesel, and wood pellets were taken from the IEE project 'biomass policies.'[21] Import cost supply data for used fats and oils (UFO) were taken from Spöttle *et al.*[22] and Pelkmans *et al.*[23] The import potential

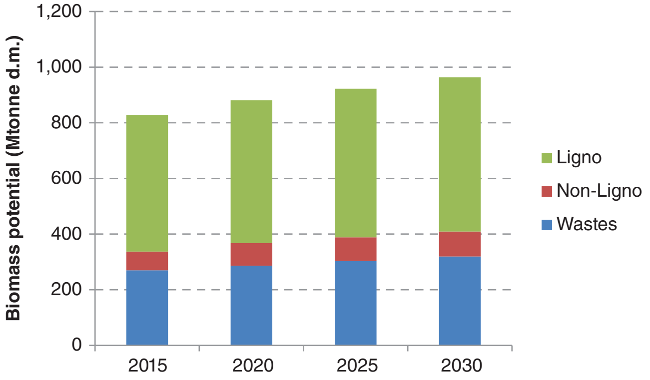

Figure 2. Total potential of biomass in the assessed region (in Mtonne dry matter) per feedstock type. Ligno: lignocellulosic crops and primary and secondary residues from forestry and agriculture; Non-ligno: nonlignocellulosic agricultural crops and primary and secondary residues; waste: postconsumer wastes.

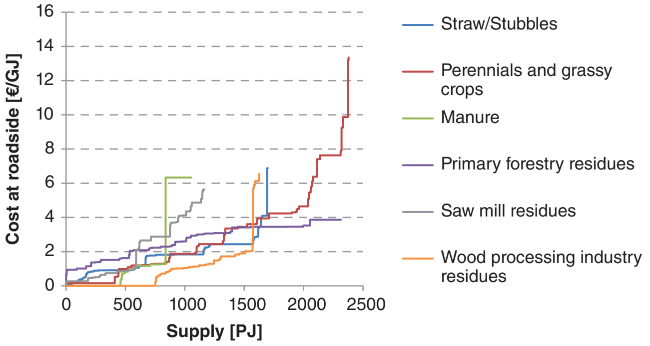

Figure 3. Cost supply curves for 2030 of the biomass feedstock types with the highest availability.

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for vegetable oils was estimated at 200 PJ. An overview of the import cost supply curves can be found in Fig. 4.

Key inputs: conversion technologies and logistics

The existing RESolve-Biomass database of technology performance and cost data was extensively updated on the basis of the newly collected technology data in the S2Biom project.[24,25] For the key technologies (of the >80 in total in the model), characteristics are summarized in Table 1.

Modalities for logistics of feedstocks, intermediates, and products were truck, train, and short sea shipping for intra-EU trade, bulk carriers for ex-EU imports, and truck for transport within a country. Costs per km were based on Hoefnagels *et al.*,[27] and were made dependent on oil price and labor costs per country.

Key inputs: Demand for biobased energy and chemicals

Another important input to ECN's RESolve-Biomass model is the future demand for bioenergy and biobased chemicals. For *bioenergy*, such data were readily available from several sources. A detailed description of heat, electricity, and biofuels demands is given in the S2Biom Deliverable 7.2b.[28] These demand projections up to 2030 were mostly taken from the Green-X model as used in the IEE project BETTER.[29] For the countries not included there, the respective National Renewable Energy Action Plans (NREAPs) were used as a basis for demand projections.[30] In Fig. 5, the bioenergy demand of the EU-28+ region in 2030 is shown per region; the growth pathway from now to 2030 (not shown) follows a relatively linear pattern.

For the future demand of *biobased chemicals*, much less information was available in the literature. In our analysis, we focused on five reference chemicals, for which demand is expected to be increasing sufficiently to create significant corresponding biomass demand: hydrogen, methane, ethylene, methanol, BTX (benzene, toluene and xylene), and PLA (polylactic acid) as a proxy for bioplastics. S2biom deliverable 7.2[31] provides an overview of this market analysis, based on two more detailed background reviews.[32,33] Figures 6 and 7 show the demand projections up to 2030 in five-year increments for the selected key biobased chemicals. For bioenergy as well as biobased chemicals, RESolve-Biomass itself converts final bioenergy demand into primary biomass demand, depending on the specific technologies applied.[31]

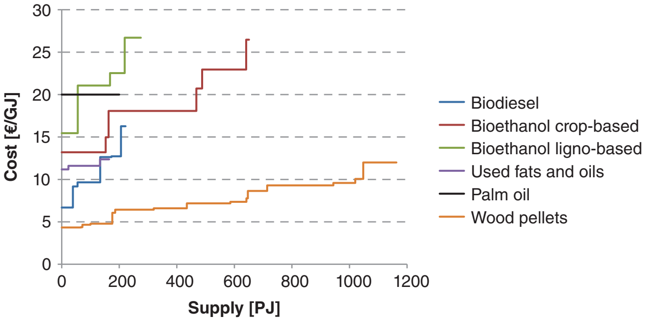

Figure 4. Cost supply curves for the imported feedstocks and biofuels for 2030.

Other assumptions for the analyses

Next to the reference scenario assessment, the five 'what if' questions were put up for additional analysis as follows (full details in Van Stralen *et al.*).[16]

Regarding question 1 (the effect of accelerated mobilization policies for biomass), the default model run constrains the growth of new feedstocks that are not yet applied for energy by an S-curve, reaching full use in 20 years. In a specific feedstock mobilization run, these constraints on feedstock availability were released, mimicking a situation with very active biomass mobilization policies. Impacts on feedstock mix, technology mix, and system costs were analyzed. On question 2 (the impact of restricted availability of EU-domestic biomass potentials), specific assumptions were made for each type of feedstock to create a feedstock restricted scenario, reflecting the susceptibility of the various types of feedstock to further sustainability disputes. See Table 2. Specific analyses were made on the following subquestions:

- With which additional measures can biofuels still deliver their expected share? This provides insight in possible additional measures that may be needed if feedstocks are to be restricted.
- If no such additional measures are taken, what is the maximum amount of biofuels that can still be produced under restricted biomass availability conditions, and to what extent can this shortfall in renewables production be compensated by other biobased options?

The competition and synergy effects of biobased energy versus biobased chemicals (question 3) were assessed by varying final demand from both sectors: one run was done without any demand for biobased chemicals, another run was done in which biobased energy demand was set to 50% of default values. The impact variable was the marginal cost of the applied biomass.

Table 1. Technology characteristics, performance and cost data for some key technologies in the model.

Technology	Intro year[a]	Covers sectors[b]	Efficiency first main product[c] (%)			Lifetime (years)	Investment costs (€$_{2010}$/kW)			Fixed O&M costs (€$_{2010}$/(kW*yr)[d]			Power/ size	Unit[e]
			2010	2020	2030		2010	2020	2030	2010	2020	2030		
Biomass IGCC	2023	E,H	40	45	50	15	915	915	1.006	46	46	50	90	MWth
Cellulose-EtOH	2015	T	39	39	39	20	3.673	Learning	Learning	363	Learning	Learning	200	ktonne year^{-1}
CHP using solid biomass >10 MW		E,H	35	35	35	35	871	933	1.058	44	47	53	100	MWth
CHP using solid biomass 0.5–10 MW		E,H	19	19	19	12	1.712	1.712	1.742	86	86	87	3	MWth
Co-digestion of manure		BG	60	60	60	12	898	714	586	56	44	36		
Direct co-firing coal-fired power plant		E	38	42	46	12	220	220	220	73	73	73	100	MWe
Ethanol + PLA production	2020	T	34	34	34	20	5.883	5.883	5.883	246	246	246	4	PJ_ethanol year^{-1}
Ethylene from ethanol	2015	C	61	61	61	20	3.879	3.879	3.879	536	536	536		
FT production	2023	E,H,T	50	50	50	20	1.894	Learning	Learning	192	Learning	Learning	550	GJ_FT h^{-1}
Gasification for BTX and SNG	2017	C,SNG	55	55	55	40	1.480	1.480	1.480	74	74	74	105	MWth_output
Indirect gasification for SNG (grid)		SNG	60	65	70	15	4.625	4.625	4.625	513	90	59	450	GJ h^{-1}
Large-scale pellet boiler (>= 5 MW)		H	90	90	90	15	350	350	350	18	18	18		
Local heating plant, straw (~5 MW)		H	91	91	91	20	611	611	611	132	132	132	5	MWth
Local heating plant, straw (~0.15 MW)		H	89	89	89	15	758	758	758	72	72	72	0,15	MWth
Local heating plant, wood chips (~5 MW)		H	87	87	87	20	478	478	478	19	19	19	5	MWth
Pyrolysis diesel production	2023	T	58	59	60	25	1.345	1.345	1.345	220	220	220	800	GJ_diesel h^{-1}
Pyrolysis oil production		E,H,T	62	65	68	25	649	649	519	32	32	32	53	GJ_oil h^{-1}
Starch-ethanol		T	55	55	55	20	1.060	Learning	Learning	433	Learning	Learning	100	ktonne year^{-1}
Sugar-ethanol		T	45	45	45	20	659	Learning	Learning	272	Learning	Learning	100	ktonne year^{-1}
Thermal conv solid biomass – power only		E	27	30	33	12	3.725	3.725	3.725	270	270	270	~10	MWe
Transesterification of oil seed		T	99	99	99	20	201	Learning	Learning	81	Learning	Learning	100	ktonne year^{-1}

[a] Technologies with an intro year mentioned are still under development and enter(ed) the market by this year. Intro years were based on the S2Biom review and dbase of conversion technologies,[24] on market information, and on our own expert views. Given the inherent uncertainties in novel technology development, these remain indicative estimations, In the intro year, the technologies have a maximum initial capacity related to market size (0.1–0.2%); in subsequent years, they have a maximum annual growth rate of 90% of standing capacity the year before.

[b] **Sectors:** E = electricity; H = heat; T = transport fuel; BG = biogas; SNG = substitute natural gas.

[c] **Efficiency definitions:** CHP plants: efficiency conversion of input (energy) to electricity (energy); ethanol + PLA production: total efficiency; ethylene from ethanol: efficiency of ethanol (tonne) into ethylene (tonne); transport fuel production: efficiency conversion of input (energy) into transport fuel (energy); gasification for BTX and SNG production: efficiency conversion of input (energy) into SNG (energy).

[d] **Investment and O&M costs:** 'Learning' in these columns means a specific approach for cost reduction through learning was adopted, see De Wit *et al.*[26]

[e] **Outputs:** MWth: thermal output; MWe: electricity output; ktonne year^{-1}: production output.

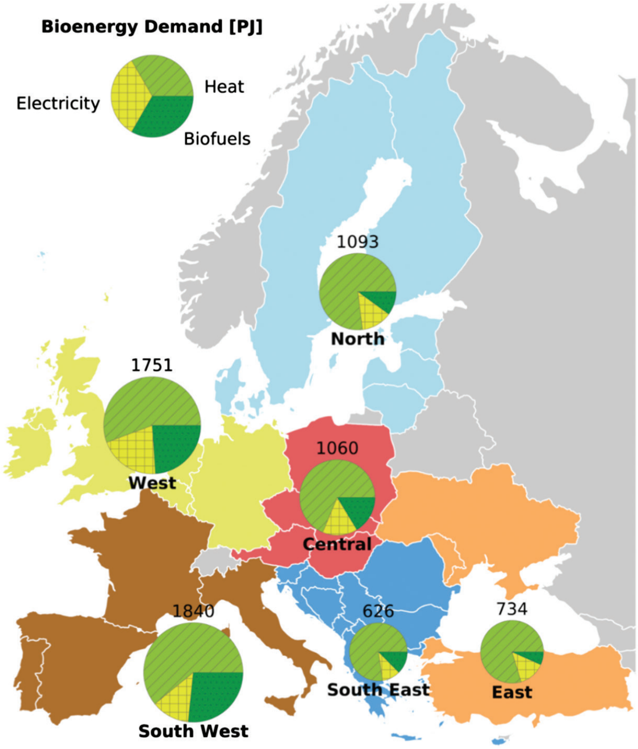

Figure 5. Total final demand for bioenergy in PJ in 2030 per region.

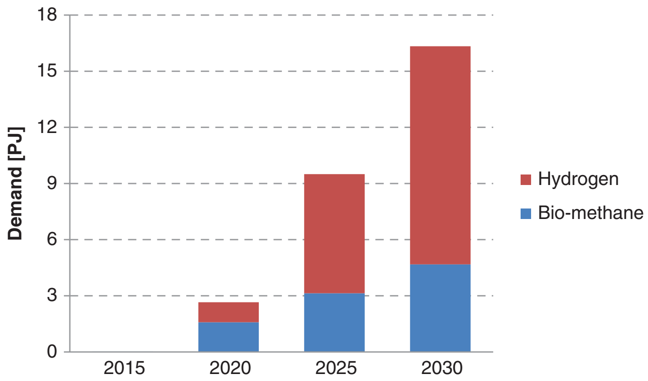

Figure 6. Demand projections for biobased chemicals hydrogen and methane until 2030 (PJ). This demand is in addition to the demand in Fig. 7.

In default mode, standing biofuel production capacity competes on the basis of variable costs against investments for new production capacity that have to be calculated on the basis of full costs. For question 4 (the potential lock-in effects of crop-based biofuels) we adapted this approach and let standing capacity compete on the basis of full costs too. This assumption is less realistic than the default one but provides insight into the extent to which standing production capacity forms a barrier for rapid changes towards new technologies. Furthermore, a constraint on the maximum rate by which standing capacity can be phased out was relaxed. The key impact variable was the contribution by 2030 of lignocellulose-based biofuels, and system costs.

For question 5 (what if crop-based biofuels are forced to be phased out by 2030?), specific runs were made (with all default model constraints in place), exploring what maximum phase-out rate for crop-based biofuels was technically possible in the model, while maintaining the externally given total production volume of biofuels (see

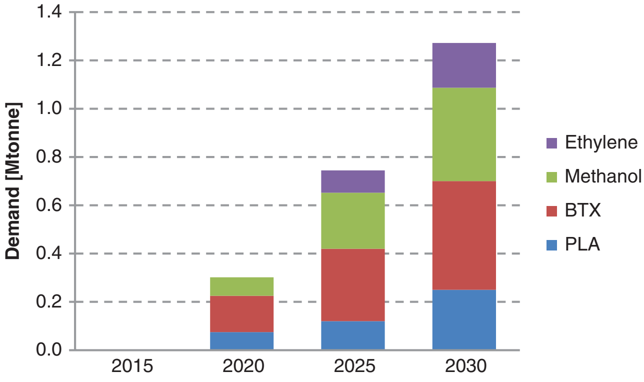

Figure 7. Demand projections for biobased chemicals ethylene, methanol, BTX (benzene, toluene, xylene) and PLA (poly-lactic acid) until 2030 (Mtonne). This demand is in addition to the demand in Fig. 6.

Table 2. Applied ratios between 'constrained' and 'reference' S2Biom scenarios in 2030, for various EU-domestic feedstock types.[16]

EU-domestic feedstocks:	Agricultural	Forestry/lignocellulose based
Primary products	Annual crops: 0 Perennial crops: 0.6	0.7
Primary residues	0.7	0.8
Secondary residues	0.8	0.9
Tertiary residues	0.9	1
Ex-EU imports		
Biodiesel	0.25[a]	
Bioethanol	0.5[b]	0.75
Vegetable oils	0	
Used fats and oils	0.9	
Wood pellets, chips		0.85

[a] Set higher than zero because partly produced from used fats and oils.
[b] Set higher than zero because partly produced from sugar cane.

Fig. 5). We also looked at impacts on feedstock mix and system costs.

Results

Base run, general outcomes

Feedstock use

Figure 11 (left) shows the overall exhaustion of lignocellulosic biomass potential for six EU regions. Overall, circa 50% of lignocellulosic potential remains unutilized in this run, varying between 25% and 70% among the regions. More detailed analysis of the types of lignocellulosic feedstock used indicates that most primary and secondary residues (forestry residues, saw-mill residues, and other wood-processing residues) used up to a significant share (> 80%) of their potential, whereas dedicated woody and herbaceous energy crops and manure have a low share of their potential used (~10%). Other feedstocks that are partly used but have significant remaining potential are straw and stubbles, and various waste streams.

In the north, the ratio between use and potential is highest of all regions. The strong position of northern regions in lignocellulosic biomass is also illustrated by the trade flows of a key lignocellulosic energy carrier, viz. wood pellets (Fig. 12, left). The north is the main net exporter of pellets, mostly from forestry wood-processing residues. All other regions are net imports of wood pellets.

Next to domestic biomass, significant amounts of resources are imported from outside Europe, for circa 15% of EU resource use in 2030, with an almost fourfold increase between 2015 and 2030. This import flow exists for three-quarters of biofuels and their feedstocks: crop-based biodiesel and bioethanol, vegetable oils, and used fats and oils. Around one-quarter, or just over 300 PJ, consists of wood pellets (see Fig. 8, left).

End-use market sizes

Regarding end-use markets, the biobased heating sector remains the largest of all biomass applications. In terms of biomass demand this is merely the consequence of the modeling inputs (see the section 'Key inputs: Demand for biobased energy and chemicals'), but the model outcomes indicate that this sector also remains the largest in terms of financial turnover (Fig. 9). Particularly biobased heat for industry increases significantly, while biobased heat for household decreases over time (see Fig. 10). Biofuels grow more strongly than biobased electricity, taking over the runner-up position towards 2030. Biobased chemicals also grow strongly but this sector remains significantly smaller (at least up to 2030) than the energy sectors; it remains merely in the same order as lignocellulose-based biofuels. The total additional amount of biomass needed to fulfil the demand for biochemicals is only 1–1.5% of the amount needed for bioenergy demand. Obviously, this additional demand can be accommodated without any significant impact on marginal biomass costs.

Technology mixes

In the three energy sectors, the technology mixes remain relatively stable in the base run: no new technologies are introduced on a significant scale – see Fig. 10. In heat and

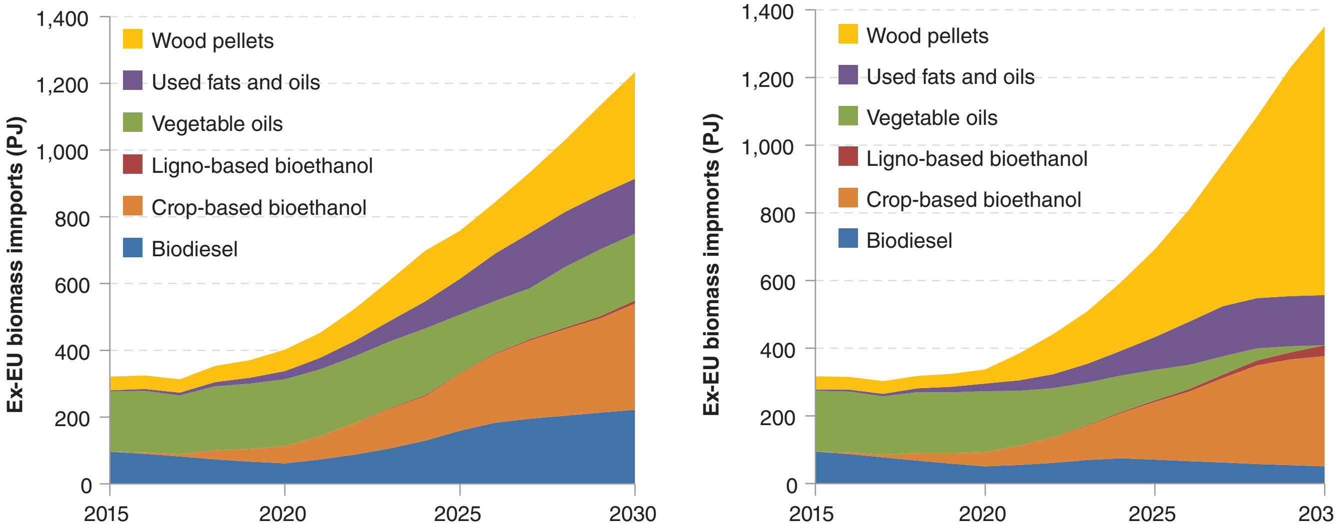

Figure 8. Size and shares of biofuel and biomass import streams, for the base run (left) and the feedstock restricted scenario with additional measures (right).

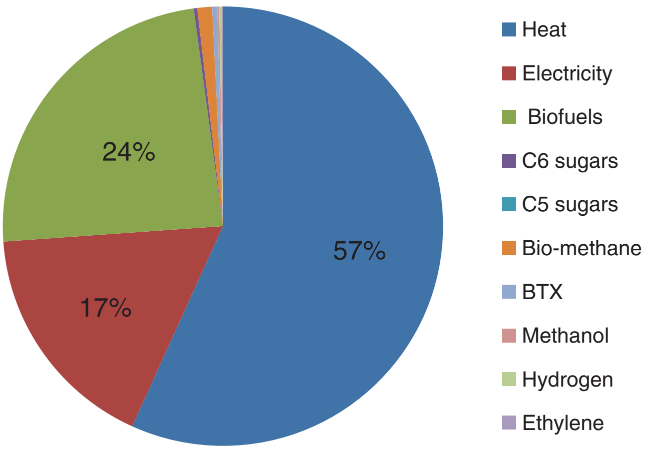

Figure 9. Shares in total market value of the various biobased products and energy carriers in 2030. BTX: benzene, toluene, xylene.

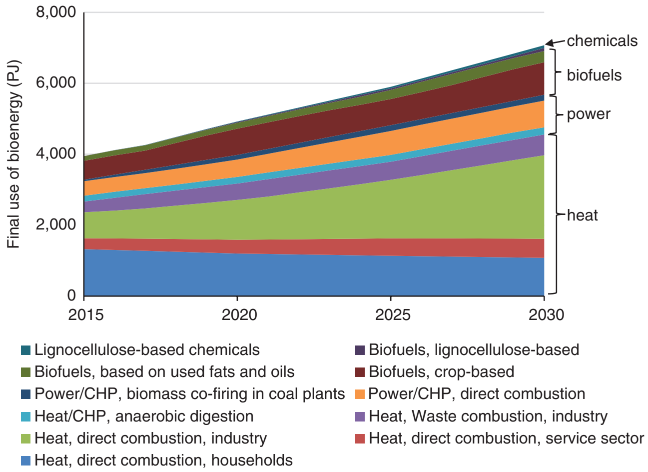

Figure 10. Technology mixes in the heating, power and biofuels sectors.

power, conventional combustion technologies accommodate the lion's share of the growth in their sectors; advanced options based on gasification or pyrolysis do not break through. Detailed analysis shows that biobased combined heat and power (CHP) becomes increasingly important: around 80% of biobased power production is in CHP, whereas circa 30% of biobased heat production is combined with electricity. In the biofuels sector, advanced technologies based on lignocellulose remain under 10% of total biofuels production (and under 1% of total energy demand in transport, excluding aviation). Among the advanced technologies, lignocellulosic ethanol provides roughly three times as much biofuel as lignocellulosic (Fisher–Tropsch and pyrolysis-based) diesel routes.

Q1: Accelerated feedstock mobilization

The effect of an accelerated mobilization of biomass, as a stylized effect of active biomass mobilization policies, is essentially twofold. In the first place, it leads to increased utilization of domestic feedstock, in particular of straw and landscape care wood, feedstocks that are underutilized in the base case. As a consequence, we see a reduction in the import of wood pellets and ethanol from outside Europe and slightly lower intra-European trade. The reduction of the trade flows of wood pellets is shown in Fig. 12 (middle). The underlying results also indicate that improved mobilization of feedstocks results in a higher share of lignocellulose-based biofuels, particularly of ethanol and pyrolysis diesel.

Secondly, the active mobilization of biomass reduces the overall cost for the biobased energy and chemicals system. The marginal costs of the applied biomass commodities decrease by 1–7%. The total costs of the system reduce by 1.7 billion euros per year, or less than 2%.

Q2: Impacts of feedstock potential limitation

If biomass availability (domestic and imported) is limited according to the factors specified in Table 2, and other assumptions are kept at default, the model yields to an infeasibility, i.e. the objectives for delivering the given amounts of biobased heat, power, fuels, and chemicals cannot be met. The critical factor here is the biofuel's objective: with biofuels from food crops (domestic and imported) strongly reduced, a substantial amount of currently available biofuels are not allowed any more, and advanced technologies based on lignocellulosic feedstocks cannot grow rapidly enough to compensate for this. On the first subquestion (what is needed to still meet the given biofuels target?), we found that a combination of two additional measures makes the model give a feasible outcome again: (i) accelerated mobilization of (lignocellulosic) feedstocks, consistent with the approach in question 1, and (ii) availability of lignocellulosic biofuel technologies three years earlier (2020 instead of 2023 for most). This illustrates the balance between very stringent measures limiting feedstock potential and measures actively to mobilize this potential, and to deploy in a timely way the advanced technologies that can convert lignocellulosic feedstocks into high-value biofuels.

On the second subquestion (if feedstock potential is limited, how much biofuels can still be delivered?), it appeared that the biofuels target needed to be reduced by almost 400 PJ (or almost 30%). It is quite striking that this shortfall

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in renewables production can still be compensated by additional realization of (lignocellulosic) biomass in the heat sector, partly because the conversion efficiency from biomass to heat is higher than from biomass to biofuels.

Figure 11 (right) presents the biomass consumption in comparison with the total biomass potential in 2030, for the restricted feedstock case with additional measures on feedstock mobilization and advanced lignocellulose-based technology introduction. In general, the ratio between biomass use and potential goes up; circa 25% of EU domestic potential remains unused (varying between 10% and 50% among the regions). In the east and southeast regions, the share of biomass potential used goes up most strongly in relative terms, by almost 25%, while in the Central region, this share increases by just more than 10%.

The mix of domestic lignocellulosic biomass types consumed also shows some specific changes compared to the base run: the application of lignocellulosic crops (woody and grassy) on agricultural land increases more than sixfold, manure increases tenfold, and landscape care wood increases twofold. Feedstock restriction does lead to some changes in intra-EU trade of wood pellets (see Fig. 12, right) but the clearest impact is the more than doubling of ex-EU pellet imports. Still, lignocellulosic imports consist of slightly over 10% of total lignocellulosic biomass consumption. In general, imports of biomass resources remain at circa 15%, just like in the base run. However, the mix of imports changes considerably (compare the left and right sides of Fig. 8): in the run with feedstock potential limitation, imports are dominated by a 60% share (almost 800 PJ) of pellets which grow about 20-fold between 2015 and 2030. The remaining part is mostly bioethanol.

The system costs of realizing all biobased objectives also go up in the restricted cases. Compared to the base run, these are 20% higher in the case with additional measures on feedstock mobilization and technology introduction, and more than 10% higher in the case with a shift from biofuels to biobased heat. The first number is the result of both the feedstock limitation and the additional measures to mobilize the still-available biomass potential; the second number indicates that biobased heat options are generally cheaper than lignocellulosic biobased fuels.

Q3: Biobased energy versus biobased chemicals: competition or synergy?

The question whether the demand for biobased chemicals impacts the costs of biobased energy applications is

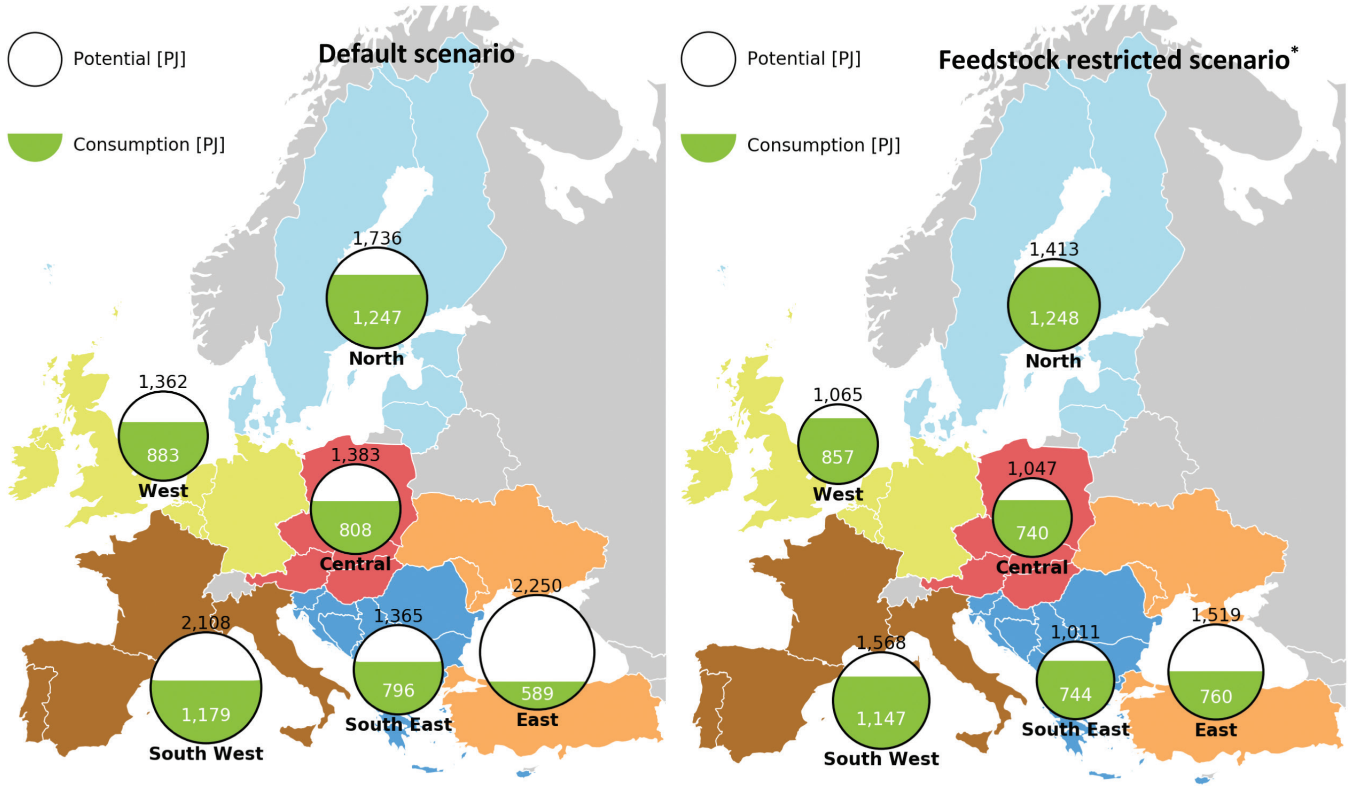

Figure 11. Lignocellulosic primary domestic biomass potential and the consumption amounts (including trade) for the six regions in Europe, for the base run (left) and the feedstock restricted scenario *with additional measures (right).

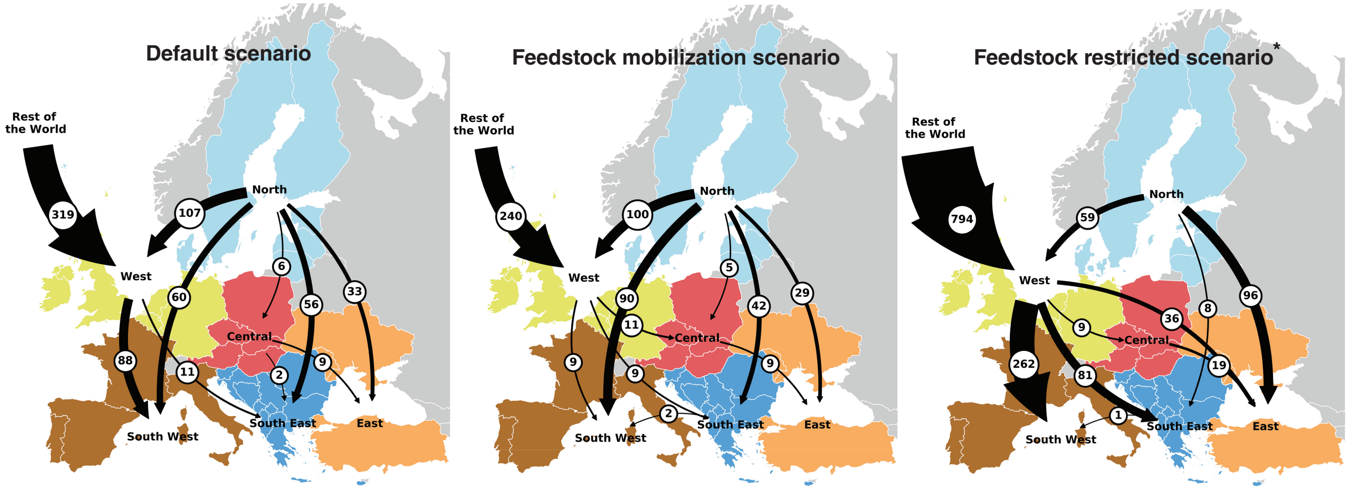

Figure 12. Wood pellet imports to EU and net trade among the regions in PJ in the base run (left), feedstock mobilization scenario (middle) and feedstock-restricted scenario *with additional measures (right).

relatively easily answered. The total additional amount of biomass needed to fulfil the demand for biobased chemicals is only 1–1.5% of the amount needed to fulfil the demand for bioenergy. In line with this, the full exclusion of demand for biobased chemicals in the model has an impact of less than 1% on the marginal costs of key feedstocks such as wood chips and pellets.

Regarding the question whether demand for bioenergy impacts the costs of biobased chemical applications, the picture is more complex and therefore interesting. The effect of a 50% demand reduction for biobased energy on the marginal costs of several biobased chemicals in 2030 is illustrated in Fig. 13. The effect on marginal costs of PLA, methane, hydrogen, and ethylene is significant (11–31% lower costs). For BTX and methanol, this effect is smaller (0–7%). This is because, in our definition of conversion technologies, both BTX and methanol production are integrated with biobased energy production. Biomethanol production produces heat as an important co-product, and BTX is (in terms of production volumes) a mid-temperature gasification co-product of biomethane production, which is mainly used as an energy carrier, not as a chemical. For these production processes, reduced demand for biobased energy leads to lower marginal costs for biomass feedstock but this effect is compensated by a lower value of the energy co-product. This illustrates how a synergic effect of biobased energy and chemicals

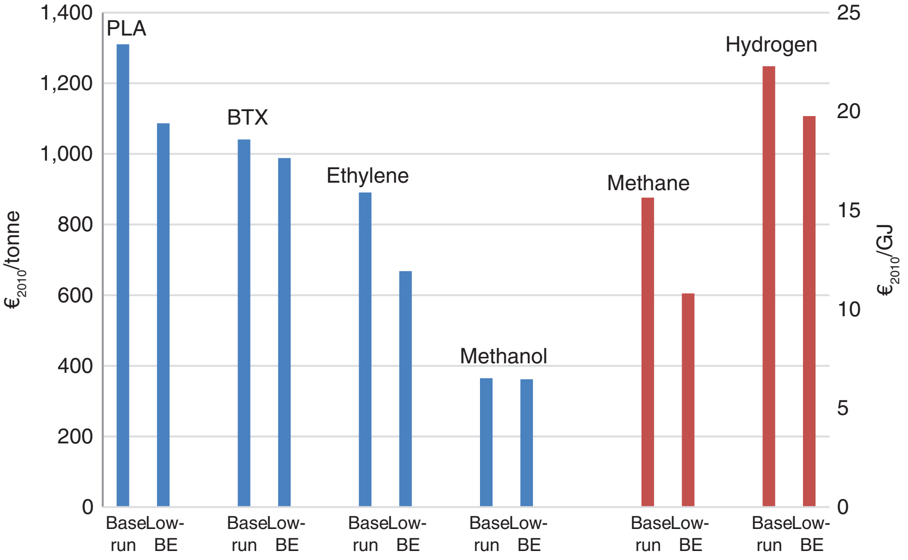

Figure 13. Effect of a low demand for bioenergy on the marginal costs of biobased chemicals in 2030.PLA: poly-lactic acid; BTX: benzene, toluene, xylene.

co-production takes away the competition effects between both applications. Or, in other words, biomass demand for energy does affect the competitiveness of biobased chemicals but not those for which production routes are integrated with biobased energy production. This also illustrates how cascading and biorefinery principles can improve business cases for both biobased chemicals and energy carriers.

Q4: Lock-in effects of crop-based biofuels

In the (hypothetical) model run in which standing and new biofuel production capacity compete with each other on the basis of full costs, we see that the amount of lignocellulose-based biofuels more than doubles, see Fig. 14. As a consequence, we also see a significant increase in consumption of straw and energy grasses and nonwoody perennial crops. The increase of lignocellulose-based biofuels mainly concerns diesel substitutes. Lignocellulose-based biodiesel can develop in this variant, so investment cost drops over time due to learning effects. The result is that the marginal cost for biobased diesel in 2030 are 10–20% lower in the variants with reduced lock-in effects. Another consequence of reduced lock-in effects is that they result in 6–7 billion euro per year lower system costs. However, this number is only valid if early retired installations for crop-based biofuels can be reused or retrofitted.

Q5: Forced phase-out of crop-based biofuels

The final question is 'to what extent it is possible to abandon crop-based biofuels (domestic and imported) while maintaining overall biofuel ambitions, and thus forcing lignocellulose-based biofuels to develop at their maximum rate?' Based on our model setup and assumptions regarding, e.g., maximum deployment of new technologies and feedstocks, it is possible to limit the amount of crop-based biofuels to 1.5% by 2030. Stronger reductions lead to infeasible outcomes in the model. Reaching the corresponding rapid development of lignocellulose-based biofuels is, however, still very ambitious. To be able to achieve such ambitions the following additional assumptions were made in the model analysis:

- The voluntary minimal percentage of 0.5% lignocellulose-based biofuels in 2020 was changed to a mandatory 1% share for that year.
- The model constraints were changed to allow a more rapid introduction of advanced lignocellulose-based technologies, to the maximum rates we consider possible.
- An ambitious and mandatory minimal percentage path of lignocellulose-based biofuels between 2020 and 2030 was laid out, and the introduction dates of non-ethanol lignocellulose-based production routes was set three years earlier than in the default run. In most of this study we assumed that the introduction year of DME, Fischer–Tropsch diesel, and pyrolysis diesel would be in 2023. For HTL diesel we assumed this to be in 2025. In the analysis in this section all these introduction years are set three years earlier.
- We introduced a mandatory reduction pathway for crop-based biofuels towards 1.5% in 2030.

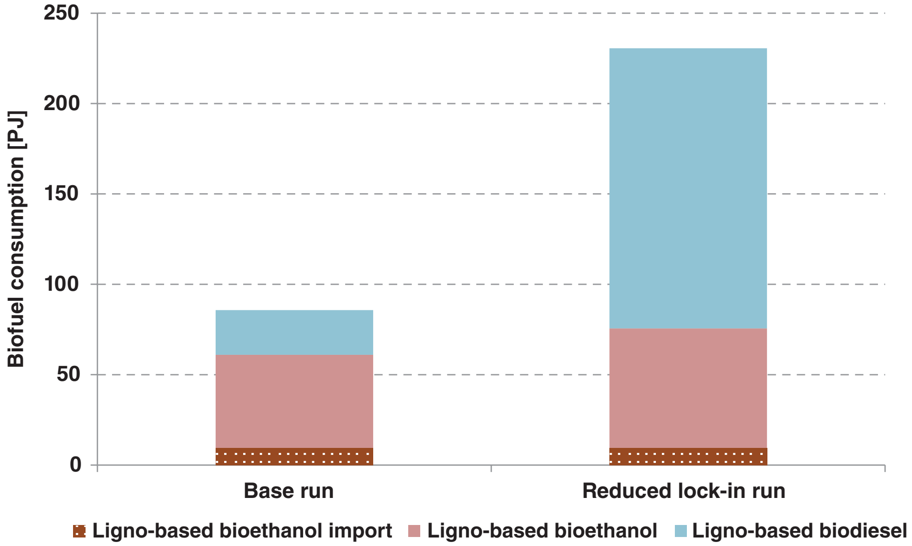

Figure 14. Consumption of lignocellulose-based biofuels in 2030 in the base run and its variant with reduced lock-in effects.

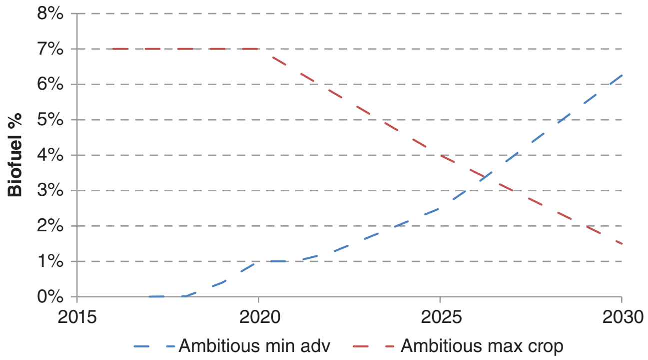

Figure 15. Corresponding developments of the shares of lignocellulose-based biofuels (dashed blue), and of crop-based biofuels (dashed red) in the run with forced phase-out of crop-based biofuels. The maximum deployment rate of lignocellulose-based biofuels limits the maximum reduction rate of crops-based biofuels.

Although biofuels based on used fats and oils are expected to play an important role in the period up to 2030, the availability of this kind of feedstock is a bottleneck for a strong contribution to the biofuels mix compensating for the reduction in crop-based biofuels. Most growth is therefore needed from lignocellulose-based biofuels, as is shown in Fig. 15.

In Fig. 16, the different amounts of biofuels is given in 2030 for the base run and for a ‘low crop-based run’ with a 1.5% cap on crop-based biofuels. One can see that, although lignocellulose-based diesel shows the largest increase in relative terms, lignocellulose-based ethanol shows the largest increase in absolute terms and will also have a larger total volume in 2030.

The transition to such a large share of lignocellulose-based biofuels also has a significant impact on the biomass consumption mix and on trade flows. There is a strong increase in lignocellulosic biomass consumption, of both domestic biomass and imported wood pellets, as shown in Fig. 17. However, the total amount of imports decreases due to a strong decline in liquid biomass imports.

A shift towards such a strong growth of lignocellulose-based biofuels also comes at a cost. Due to the market demand for lignocellulosic feedstocks, their marginal costs also rise strongly: wood pellets by almost 50%, biodiesel by 50%, and ethanol by 75%. Correspondingly, the total system costs increase by 5 billion euros per year in 2030. If crop-based biofuels are to be reduced in volume, these cost impacts suggest that it is probably cost effective to reduce the total contribution of biofuels towards the

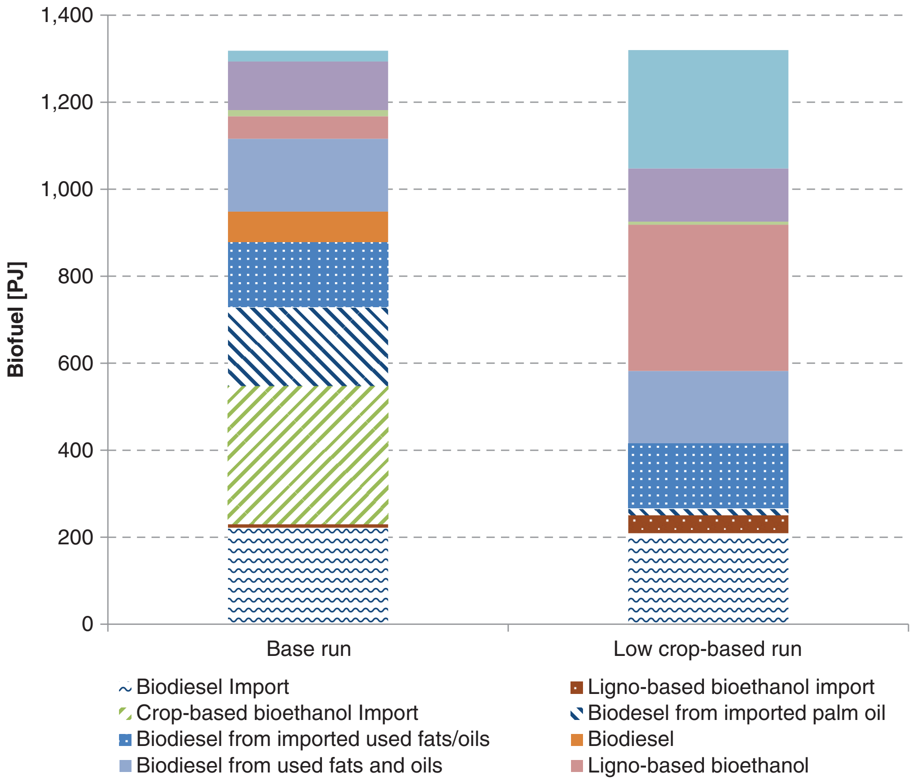

Figure 16. Biofuel volumes per category in 2030 in PJ for the base run and in run with a 1.5% cap on crop-based biofuels.

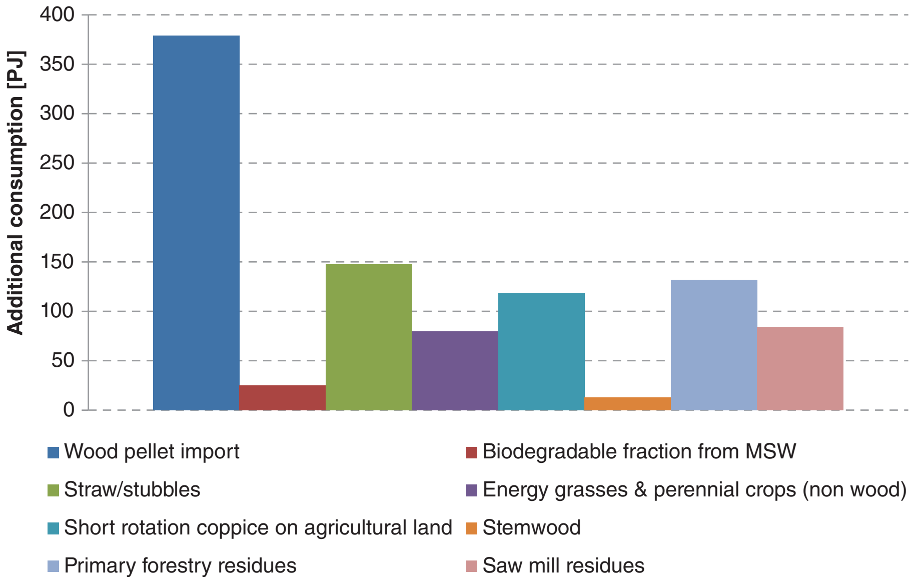

Figure 17. Additional consumption of lignocellulosic biomass in 2030 for the low crop-based run as compared to the base run. Only biomass categories that show a significant increase are shown.

energy and climate ambitions for 2030, and compensate this with other renewables and CO_2 mitigation measures. For the period beyond 2030, this picture may change again as lignocellulose-based biofuels reduce their costs due to learning effects and because these fuels probably need to play a significant role in the low-carbon end picture for transport.[1]

Discussion and conclusions

Our key impression from the base run is that our analytical tool is capable of assessing implications of both biobased energy and chemicals demand. This is consistent with the development history of the RESolve-Biomass model, which has been applied to a variety of settings and questions over more than a decade now.[15] The base run also indicates that feedstock and technology mixes are relatively inert: a rapid introduction of new technologies requires specific additional policies and does not come on by itself. The base run also indicates that biomass demand for chemicals will remain very small in comparison with the demand for energy, at least by 2030. An uncertain point in this analysis is the future biomass demand for chemicals. For example, Schipfer *et al.*[34] indicate significantly higher demand figures for cellulosic sugars and lignin by 2050, but also mention that these chains will probably be deployed significantly after 2025, and that reliable data are scarce. This will therefore need to remain a point of attention in future studies.

The answers to ‘what if’ questions 1 and 2 (more active biomass mobilization and reduced feedstock availability) illustrate the importance of the feedstock side of all biobased routes. Policies mobilizing actual biomass availability lead to a clear system costs reduction. If biomass availability is limited, policies to mobilize feedstocks and advanced lignocellulose-based technologies will be essential to reach the foreseen biofuel ambitions, and overall system costs still go up, consistent with earlier analyses.[35] This role of feedstock is an important element specific to biobased options compared with other renewable resources, as most generic support schemes for renewables (such as feed-in subsidies and quota obligations) only provide a market stimulus at the end of the chain. For biobased options, additional support in other parts of the supply chain will improve effectiveness, as was also qualitatively indicated by Smith *et al.*[36]

The answer to question 3 illustrates that both competition and synergy effects occur between energy and chemicals applications of biomass, the latter mainly when production of chemicals and energy carriers is combined. In general, biorefineries capable of (flexibly) serving various market outlets will improve synergy effects and be more robust towards price dynamics as well. This has already been observed in Brazil for sugar cane-processing plants able to flexibly produce sugar and ethanol.[37]

The results for questions 4 and 5 (on the dynamics between lignocellulose-based and crop-based biofuels) reveal that the current capacity of the latter creates a need for a specific subtarget on lignocellulose-based biofuels before they can enter the market. This is consistent with current efforts in the USA to force lignocellulose-based bioethanol into the market.[38] The results also suggest that crop-based biofuels may be gradually phased out, but only when considerable efforts have been made to ramp up lignocellulosic biofuels, and against significant additional costs. The extent to which the indirect land use change (ILUC) and other sustainability concerns that led to the introduction of a cap on crop-based biofuels can be addressed by other approaches, such as the development of low-ILUC safeguarding schemes,[23,39] was not part of this study.

The method and data applied in this paper inherently set limitations to the scope of the results. In the formulation of our conclusions, we have taken these into account; nevertheless they are worth explicit mentioning.

- These conclusions arise from a modeling exercise that focuses on biobased routes only with exogenously given targets; there is no interaction with other renewable options for production of heat and electricity, or with other routes for decarbonization of chemical production, power, heat, and transport. Particularly where results show differences in system costs, such interaction is relevant and deserves further attention, e.g. by using more integrated analytical tools.
- Within its scope, the RESolve-Biomass model optimizes on least-cost pathways for meeting given targets for biobased options, given various preconditions and constraints. This essentially means that the model analyses are merely useful to explore different scenarios and 'what-if' situations. They certainly do not predict what will happen in the real world, where policies are always imperfect and developments are influenced by more factors than costs alone (think of public perception, investment risks, etc.).
- As indicated above, our analysis of the interactions between biobased demand and the forestry sector was relatively simplified. New developments, particularly in the use of biomass as a direct resource for material in, for example, construction may have an impact on the availability of biomass for chemical and energy applications.
- Finally, model studies such as this strongly depend on input data quality. In this case, data on biomass availability, technology performance and costs, and on biomass demand from the different (energy and chemical) sectors are essential. While we are convinced that we have used a state of the art dataset, uncertainties in it inherently limited the extent to which we have drawn conclusions from the model outcomes.

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