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Future perspectives of international bioenergy trade

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ABSTRACT

According to the IEA World Energy Outlook 2012, primary demand for bioenergy will strongly increase up to the year 2035: the demand for biofuels and biomass for electricity is expected to triple. These changes will have an impact on the regional balance of demand and supply of bioenergy leading to both increasing trade flows and changes in trade patterns. The GFPM, TIMER and POLES models have been selected for a detailed comparison of scenarios and their impact on global bioenergy trade: In ambitious scenarios, 14–26% of global bioenergy demand is traded between regions in 2030. The model scenarios show a huge range of potential bioenergy trade: for solid biomass, in ambitious scenarios bioenergy trade ranges from 700 Mt to more than 2,500 Mt in 2030. For liquid biomass, the ambitious scenarios show a bioenergy trade in the range of 65 - > 360 Mt in 2030. Considering the currently very small share of internationally traded bioenergy, this would result in huge challenges and require tremendous changes in terms of production, pretreatment of biomass and development of logistic chains.

Contents

1. Introduction

According to IEA World Energy Outlook 2012, primary demand for bioenergy will strongly increase up to the year 2035, the

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demand for biofuels and biomass for electricity is expected to triple. Moreover, the patterns of bioenergy use are expected to change substantially. Power generation and production of biofuels for transportation will constitute a larger share of biomass use compared to the currently dominating traditional biomass. These changes will have an impact on the regional balance of demand and supply of bioenergy leading to a change in trade patterns as well. Studies in accordance with the IEA Bioenery show that world bioenergy production has grown exponentially in the past: from below 30 PJ in 2000 to 572 PJ in 2009 for biodiesel; from 340 PJ in 2000 to over 1540 PJ in 2009 for fuel ethanol. World net biofuel trade reached 120–130 PJ in 2009 [22] and increased from about 56 to 300 PJ between 2000 and 2010 for solid biofuel trade [23].

The IEA foresees that international trade of solid biomass for power generation and biofuels for transport increases about seven-fold from 6 Mtoe (251 PJ) in 2010 to about 40 Mtoe (1675 PJ) in 2035, or about one-tenth of bioenergy supply in the power sector [1]. The volumes, routes, fuels, logistics of bioenergy trade will hence look quite different as we are used today. However, different scenarios and models of the global bioenergy sector show a diverging picture of the future development of bioenergy use. The perspectives of bioenergy trade depend on the anticipated development path which is influenced by impacts regarding energy markets, technological development, energy and climate change policies. This publication discusses perspectives of international bioenergy trade in the coming decades, based on assumptions and results of models that cover international bioenergy trade An excerpt based on the presented results can be found in the International Bioenergy Trade Handbook [35].

The objectives of this article are (1) to assess how bioenergy trade is included in different energy sector models covering bioenergy, (2) to analyse the implications on bioenergy trade of different energy market scenarios and (3) discuss different perspectives of international bioenergy trade in various scenarios. The article is structured as follows: First, a brief overview of reviewed studies is given. Second, a more detailed description of models that have been identified as suitable for bioenergy trade analysis is presented. Third, a comparison of scenarios in selected models is presented, leading to an analysis of model based drivers of bioenergy trade. Finally, perspectives of bioenergy trade are discussed and conclusions regarding important bioenergy trade regions in the mid- and long-term time horizion are drawn.

2. Global energy models and the role of bioenergy trade

2.1. Literature and model overview

Many studies have been undertaken to assess the biomass potential to contribute to future energy supply. A limited number of studies is dealing with the gap between regional bioenergy demand, supply and bioenergy trade. Conclusions from these studies vary significantly. We have indentified 28 models which contain bioenergy trade in some form. The models are heterogenous with some focusing specifically on the trade of biomass products, while others are more general energy or trade models which also include bioenergy trade. A three-stage review process was carried out in order to identify models suited for in-depth analysis of biomass trade. Out of the 28 identified bioenergy trade models, 22 models were selected according to their potential to model global bioenergy trade on a sufficient regional resolution, data availability and explicit trade modelling.

The models identified for further analysis ("long-list") were characterised according to specific criteria regarding bioenergy trade, based on available literature and, where not specified in sufficient detail, a questionnaire was sent out to the respective modelling groups. The following criteria for model selection have been analysed: the extent to which the model does cover biomass trade and if regional or global trade patterns are assumed, sectoral coverage, geographical regional aggregation and scenario time frame. The summarised results of a selected model review are shown in Table 1. In most models a scenario timeframe until year 2100 is considered.

We have selected specific models to be analysed in terms of status of development and activity, assumptions regarding trade, scenario families, scenario assumptions, demand coverage, demand drivers and data availability.[1] Three models have been chosen for a detailed comparison of scenarios and model results: GFPM, TIMER and POLES, which will be described in the following sub-secrion. All three models are currently used in global policy analysis and are under continuing development and have sufficient spacial resolution to allow for a common aggregation. TIMER and POLES are global (bio)energy models with comparable scenario assumptions, whereas GFPM is a renown model, that offers a perspective from forest sector modeling (Table 2).

2.2. Selected models for bioenergy trade analysis

2.2.1. Timer

The TIMER model is a dynamic energy system model developed by the Netherlands Environmental Assessment Agency (PBL) [12]. It has bottom-up engineering information as well as top-down investment behaviour rules and technological change. It is part of the larger integrated assessment model IMAGE, from which it gets its biophysical data and in turn provides energy and industry related emissions. The simulation process is dynamic recursive on a year-by-year basis. Energy demand is determined from economic activity and population increase and is calculated over five sectors: Industry, transport, residential, services and 'other'. This energy demand can be met from a number of energy carriers which compete with each other on a relative cost basis. Thus demand for energy carriers including bioenergy is price elastic. Key elements of the model dictating the demand and supply of energy carriers include:

- Autonomous and price induced changes in energy intensity. Thus the demand of final energy is elastic to energy prices, simulating behavioural changes.
- Depletion costs of energy resources dictated by supply curves. In the case of biofuels supply is limited from land constraints and decreasing marginal crop yield due to use of lower quality land. These act as positive feedbacks on the price of energy carriers with increased (cumulative, in the case of non-renewable sources) use.
- Stock turnover of capital limits the rate of change of the energy system as installed capital has to completely depreciate.
- Technological learning reduces the cost of a conversion technology with cumulative use. This is based on the learning curve principle. This dynamic acts as a reductive force on the price of energy carriers.
- The Multinomial Logit function is used to determine the market shares which fuels take to meet the energy demand of each sector. Thus multiple fuels can be used in each sector where the

[1] The most actual version of the GLUE model that has been published in international scientific literature does only cover trade on a two region basis and has therefore not been considered in this study. The GLUE II model has, however, been recently improved in terms of regional resolution, but was not considered in the scope of this study due to availability of more recent publications. The analysis by Lamers does only take into account trade of liquid biofuels. The models by Heinimö and Hofnagels have a special resolution limited to a few countries or regions.

Table 1
Overview of selected models.

Model name first author	Short description	Coverage biomass trade (Interregional/global)	Sectoral coverage	Regional aggregation
GFPM Buongiorno, 2003 [2]	Partial equilibrium model	Global. Trade flows in the model were between each country and the world market rather than between individual countries.	Limited to the forest and forest biomass sectors; covers 14 principal categories of forest products	180 countries
IMAGE/TIMER MNP, 2006 [3]	Systems dynamic integrated assessment model	Bilateral trade available. N regions, N markets. Each region imports from wherever the lowest price is offered. Imports have transport costs, plus a factor determining how “open” they are to that region	Traditional biomass (no trade), modern solid biofuel, liquid biofuel	Global 26 regions
POLES Enerdata, 2013 [4]	Dynamic partial equilibrium hybrid model (top-down/bottom up), annual simulation	Biomass demand is modelled in transformation (power sector, inputs for biofuels production) and final demand (4 industrial sectors, 2 sectors for buildings).	– forest residues – short rotation crops – other energy crops,	Global 57 regions
		Biofuels demand is modelled in transport (road, air).	Distinction of 1st generation and 2nd generation biofuels.	
GLOBIOM Havlik, 2011 [5]	Global recursively dynamic partial equilibrium model	Global, trade flows on country level	23 biomass products	Global, 28 regions, more detailed resolution is currently developed
WEO IEA, 2012 [1]			3 biomass products	Global, 60 regions
EFI GTM Kallio 2004 [6]	Partial Equilibrium Model		36 products (6 wood, 4 rec.paper, 26 forest industry products)	Global; 60 regions, 31 in Europe
Lundmark Lundmark, 2010 [7]	Adopted Heckscher-Ohlin-Vanek trade analysis		3; roundwood, chips & particles, wood fuel	
IBSAL Sokhansanj, 2006 [8]	time dependent discrete-continuous model.	IBSAL does not have business trading but can model the movement of biomass from one region to another.		
IIASA/GGI-Scenario Database			primary energy biomass, electricity: Biomass	11 world regions
Witch Bosetti, 2006 [9]	A neo-classical optimal growth model with detailed energy input and endogenous technical change	no explicit trade between regions, analysis of country import and export data forest endowment (harvested volume of roundwood, forest area), real GDP, policy variable (RES-E targets), other factor endowment (pCap income)	traditional Biomass, biofuels, advance biofuels, Woody biomass power	12 world regions
MERGE Manne, 2004 [10]	General Equilibrium economic with bottom up energy representation	Yes, common pool	Final Energy: Electric, Non-Electric. These are served by biomass and biofuels respectively	Global, 9 regions
GCAM Edmonds, 1997 [11]	Integrated assessment model	Yes, common pool	Primary: Traditional, residues, dedicated crops. Secondary: Solid, liquid or gaseous biofuel	Global, 14 regions

Table 2
Corresponding TIMER and POLES scenarios.

S#	TIMER scenarios	POLES scenarios	EMF27
S1	OECD environmental outlook	Reference	G1
S2	Baseline	BAU	G4
S3	OECD environmental outlook Baseline with trade barriers (increase in transaction cost to make trade unattractive)	BAU+20% higher transaction costs on solid biomass and biofuels trade	–
S4	OECD 20$\$_{2005}$/t CO2 price	BAU+constant carbon price of 20 USD2005/tCO2 beginning with 2011, single value for all countries	–
S5	OECD 100$\$_{2005}$/t CO2 price	BAU+constant carbon price of 100 USD2005/tCO2 beginning with 2011, single value for all countries	–
S6	OECD 450 ppm	BAU+carbon price resulting in a long-term 450 ppm CO2e for all GHG, single value for all countries	G13
S7	OECD 650 ppm	BAU+carbon price resulting in a long-term 450 ppm CO2e for all GHG, single value for all countries	–

market shares depend on the relative costs of each energy carrier.

Advanced biofuels, as opposed to traditional, are included in the form of solid and liquid biofuels. In the TIMER model five crop types can produce biofuels: Lignocellulosic, maize, wheat, sugar, oil-crops. All these crops require land to grow which together with the crop yield sets the primary potential limit. Additional to crops, ‘residues’ are included whose potential and price is exogenously set [13,14]. Solid biofuels can be produced from lignocellulosic crops or residues and can be used for heat purposes in the industrial and transformation (power generation) sectors. Liquid biofuels can be produced from all primary sources except residues and can be used in the residential, services and transport sectors. The total potential of biofuels depends on land availability and respective crop yields as determined in the IMAGE model. The land potential for biofuels is the remaining land after accounting for urbanisation, agriculture, unsuitable land and reserve land for biodiversity purposes. The available land also has decreasing marginal crop yields based on soil quality data from the IMAGE model. Thus as a certain region increases its bioenergy production, marginal yields decrease while land prices go up. This forms the basis of regional bioenergy supply curves.

Trade of all secondary energy carriers (except electricity) is allowed. Thus modern solid and liquid biofuels are traded but not the primary sources. A country will import a fuel if its total cost (production+international transport) from any other region is lower than the cost of local production, that is, from the 26 regions, there are 26 possible markets. Thus regions which have low production costs due to low land prices and high crop yields tend to export to regions where land availability or yield have become constrained. Besides transport and transaction costs no further limits such as trade inertia or absolute limits on trade are included.

2.2.2. GFPM

The GFPM model is a spatial partial equilibrium model based on price endogenous linear programming [2]. In the analyses of bioenergy development, fuelwood demand in each country is represented by a price-elastic demand function with exogenously specified long-run shifts of demand based on scenario assumptions about global expansion in fuelwood consumption [15,16].

Demand for final products are defined by demand at last year's price and price elasticity of demand. Demand changes in each country due to changes in GDP and elasticity of demand with respect to GDP. The wood supply shifts exogenously according to a chosen scenario. The main database is the FAOSTAT [17] for production, prices and trade and the FAO global forest resource assessment for development of forest resources [18] and the World Bank Development Indicators [19]. Market forces simulated by the equilibrium calculation determine the direction of change of trade flow. However, institutional and other constraints limit the adjustment that can take place in any given year due to empirical obrservations that the ratio of exports or imports changes slowly over time (trade intertia). Effects of tarrifs change the cost of transportation.

The model is limited to the forest and forest biomass sectors and covers 14 principal categories of forest products of which fuelwood includes wood used for heating, cooking, power and fuel production. The model covers 180 countries of which 50 from Africa, 35 from North Central and South America, 50 from Asia and Oceania, and 45 from Europe and former USSR.

The GFPM and several applications are described in detail in Buongiorno et al. [2]. The current version of the model, together with the software data, and documentation are available at: http://fwe.wisc.edu/facstaff/buongiorno/.

2.2.3. Poles

The POLES model provides a complete system for the simulation and economic analysis of the sectoral impacts of climate change mitigation strategies. The POLES model is not a General Equilibrium Model, but a dynamic Partial Equilibrium Model, essentially designed for the energy sector but also including other GHG emitting activities, with the 6 GHG of the "Kyoto basket". The simulation process is dynamic, in a year by year recursive approach of energy demand and supply, with lagged adjustments to prices and a feedback loop through international energy prices that allow describing full development pathways from 2005 to 2100. The POLES model is jointly developed by JRC IPTS (European Commission), Enerdata and ADR-PACTE-EDDEN (Université de Grenoble); scenarios here were provided by Enerdata.

The model identifies 57 regions of the world, with 22 energy demand sectors and more than 40 energy technologies. The model provides dynamic cumulative processes through the incorporation of Two Factor Learning Curves, which combine the impacts of "learning by doing" and "learning by searching" on the technologies' improvement dynamics. There is an explicit breakdown of total land surface across main categories for each country/region of the model. Database on land categories mainly come from WRI and FAO. The main categories are: Agricultural land, Forest areas, Grasslands, Deserts (and other marginal lands), Inland water bodies, Built areas

Primary biomass resources have been divided into three categories, as such: Forest residues (cellulosic biomass), Short rotation crops (cellulosic biomass), Other energy crops such as sugar or bio-oil crops (non-cellulosic biomass). Non-cellulosic biomass is exclusively used as input for the production of 1st generation biofuels. Cellulosic biomass can be used as a transformed product in every consuming sector (including as input for 2nd generation biofuels).

The biomass potential is calculated as the product of the available area for bioenergy collection by the productivity of the biomass resource on this surface. Normalised cost curves, expressed as a cost in function of the % of potential used, are associated to the potentials on a regional basis.

Forest residues (as a bio-energy product) are collected on forest areas. Other energy crops come from a share of total agricultural area and a share of grassland. First generation biofuels are being progressively excluded over time and replaced by 2nd generation biofuels. Available area for short rotation crops is calculated in relation to total grassland areas. Normalised supply cost curves are used to calculate biomass cost from the percentage of the total potential that is used (elaborated from [20]).

Two biofuel types are distinguished in POLES: first generation biofuels and second generation biofuels (cellulosic ethanol). Demand in biofuels stems from road and air transport. Biofuel production technologies are explicitly modelled: domestic production costs are determined from fixed costs and variable costs; the variable costs include O&M costs, a moving average of the biomass price weighted by the biofuel process efficiency, and the subsidies to biofuel production.

An international biofuels market supplies importing countries. Commerce is one-way: imports start as soon as national production is unable to meet domestic demand and an exporting country ceases importing. Demand for each of the two biofuel types is met by a scrapped demand (taking into account equipment lifetime) and a share of the demand gap for biofuels. The competition of the biofuel types on the demand gap is driven by exogenous "technology maturity" or "infrastructure maturity" factors, the domestic production costs and, if relevant, the market price including transport costs for imported biofuels, with associated elasticities.

2.3. System boundaries, definitions and methodological questions of scenario comparison

In order to make model results comparable, 20 world regions have been defined, that allow for a grouping of individual model regions on a sufficient resolution. Note that the GFPM model uses a resolution on country level (180 countries) which have been individually assigned to the regions. Results of all three models are grouped according to this regional aggregation.

3. Selected scenario results

3.1. Scenario definitions

POLES and TIMER scenarios correspond closely to each other. The scenarios presented for the TIMER model are based on the OECD environmental outlook [21]. In all cases population growth, GDP growth, land availability and crop yields are constant. Since in the TIMER model energy demand is elastic to energy prices, total final energy demand variers across scenarios. The main scenario aspects are as following:

- Trade barriers: Transaction costs for bilateral trade are increased to such a level that interregional trade becomes unattractive. Thus bioenergy consumption is limited to local production
- $20\$_{2005}/tCO_2$ & $100\$_{2005}/tCO_2$: Global carbon tax is applied to the carbon content of fuels instantaneously in 2015 and remains throughout simulation period. Affects all energy consuming sectors and fuels.
- 450/650 ppm: Global carbon taxes are gradually applied uniformly across all fuels and sectors in order to ensure carbon concentration targets are met.

Compared to TIMER and POLES, GFPM has a different scope of modelling with a stronger focus on forestry products in general than on (bio)energy. It uses a more fundamental modelling approach that is driven by macroeconomic considerations and to a lesser extent by global (climate) policy assumptions. It does not extend to (non-forest) liquid biofuels. The following GFPM-Scenarios are analysed [16]:

- IPCC scenario A1B/ *high fuelwood demand*: Continuing globalisation, would lead to high income growth and low population growth, and thus the highest income per capita by the year 2060. 80% increase in biofuel demand up to 2030 from 2006.
- *Low fuelwood demand*: 20% increase in fuelwood demand up to 2030, other assumptions as in the high fuelwood demand scenario (50% of the fuelwood demand growth in scenario A1B). (Fig. 1)

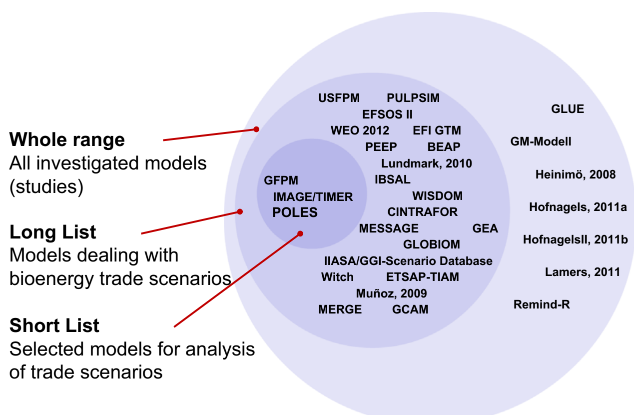

Fig. 1. Identified an selected models for bioenergy trade [24–34].

3.2. Scenario comparison

The model scenarios outlined above have been compared in terms of the following results:

- Global bioenergy demand and production,
- Bioenergy demand and production in 20 world regions
- Net trade balance of bioenergy in 20 world regions.

Key results of this comparison are shown in the following graphs. Fig. 2 shows that scenarios lead to a significant growth of bioenergy production and demand on a global scale. The current level of about 50 EJ (1.2 Gtoe) of world bioenergy production increases to a level of up to 150–170 EJ (3.6-4.1 Gtoe) in 2050 and 170–220 EJ (4.1–5.3 Gtoe) in 2070. However, it is not only the amount of bioenergy, also the structure of bioenergy use and mix of resources, fuels and conversion technologies changes.

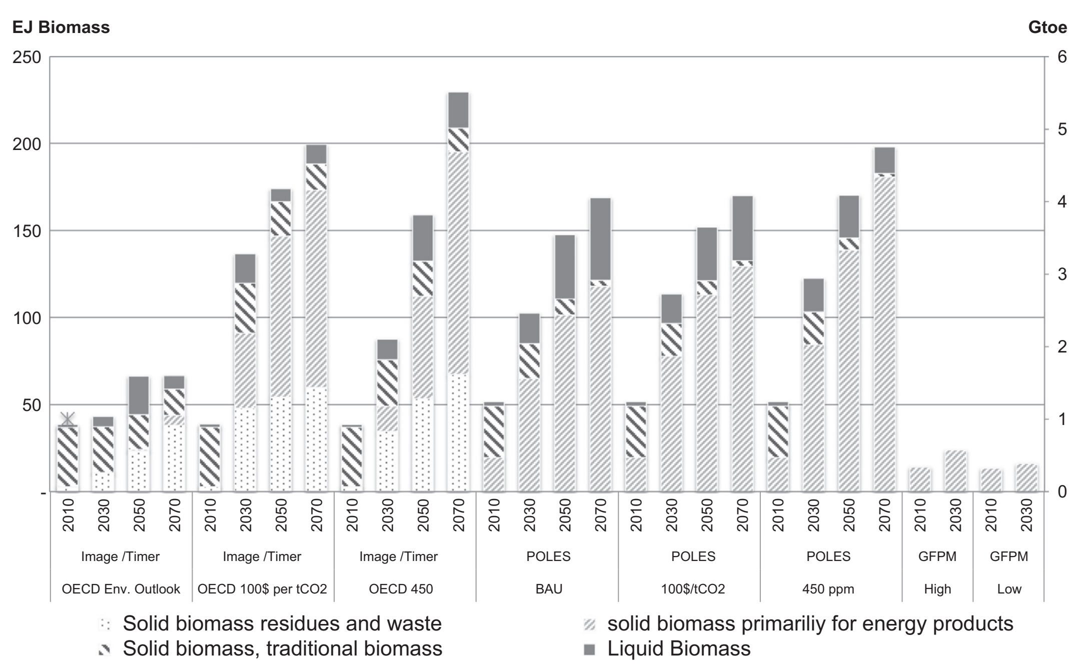

Fig. 2. World bioenergy production (equals demand) in selected scenarios *Note*: GFPM covers only forestry biomass and products. Traditional biomass is only distinguished in TIMER and is not considered in GFPM.

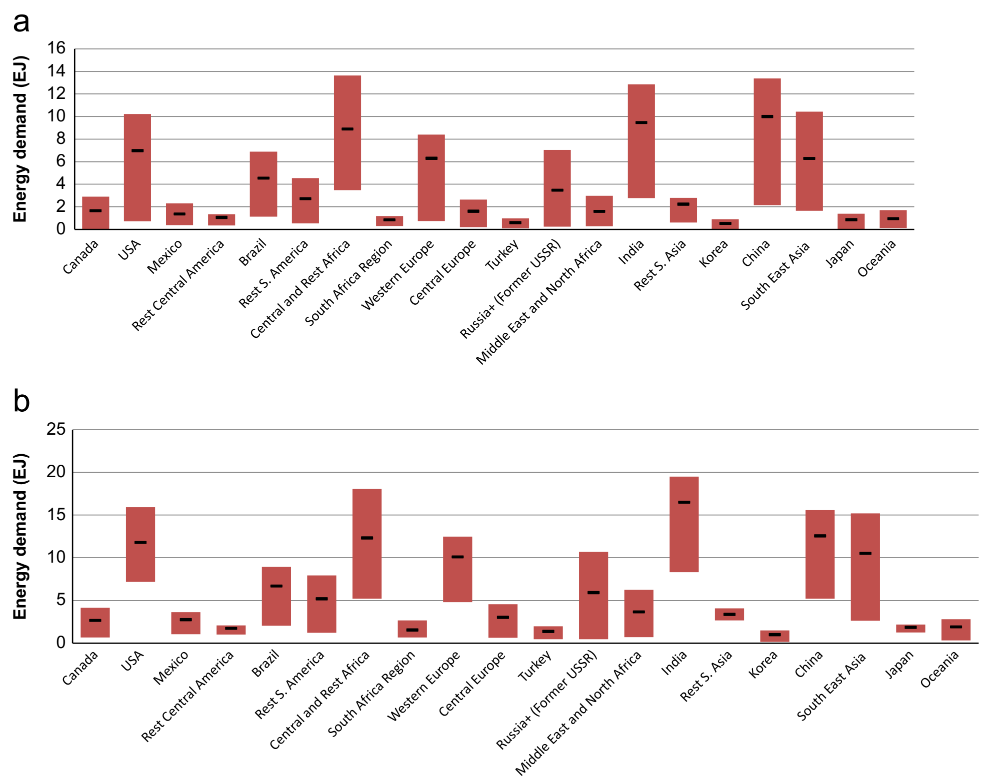

Fig. 3. (a, b) Range of total bioenergy *demand* in *moderate* scenarios by world regions. Upper graph: 2030, lower graph: 2050. Bars indicate the range of all scenarios, black lines the average of all scenarios. GFPM results are only included for 2030 and include only forestry products.

Traditional biomass reduces in all scenarios and step by step is replaced by "modern" (processed) biomass. The growth is clearly on solid biomass resources (the values for liquid biomass in the TIMER and POLES scenarios include second generation biofuels from solid biomass).

A few scenarios also indicate less growth in bioenergy demand (in particular, TIMER environmental outlook and other scenarios with low or moderate climate mitigation policies, that is, $20\$_{2005}$/t CO2 scenarios and 600 ppm concentration levels). Of course, also the regional distribution of supply and demand and thus trade balances vary among those scenarios. Thus, we distinguished moderate and ambitious bioenergy scenarios. The ambitious scenarios comprise those achieving the 450 ppm scenario or assuming a carbon price of $100\$_{2005}$ per t CO2, that is,:

- TIMER: OECD 450 ppm scenario, OECD $100\$_{2005}$ per t CO2 scenario
- POLES: 450 ppm, $100\$_{2005}$ per t CO2
- GFPM: high

The other scenarios are grouped as "moderate" bioenergy scenarios:

- TIMER: OECD environmental outlook, OECD EO trade barriers, OECD 650 ppm, OECD $20\$_{2005}$ per t CO2
- POLES: based on EMF scenarios G1 Reference, G4 BAU, BAU+ trade barriers, 650 ppm, $20\$_{2005}$ per t CO2
- GFPM: low

3.2.1. Scenario overview

3.2.1.1. Global bioenergy demand. Global overall bioenergy demand in moderate bioenergy scenarios is distributed more evenly than in the ambitious scenarios. In the average of the moderate scenarios the regions USA, Central and Rest Africa, Western Europe, India, China and South East Asia show a demand in the range of 6–10 EJ (140–240 Mtoe) and 10–16 EJ (240–382 Mtoe) in 2030 and 2050, respectively. In contrast, the ambitious scenarios are dominated by the demand in India and China (14–17 EJ and around 25 EJ in 2030 and 2050, respectively). China also shows the largest range within the investigated scenarios: Ambitious scenarios result in a range of 20 to more than 40 EJ in 2050. This overall increase of bioenergy demand is developing differently for liquid and solid fuels: The share of liquid biofuels on total bioenergy (sum of solid and liquid) for the median of the ambitious scenarios is 18% (2030) and 14% (2050). The following figures show the global distribution of bioenergy demand for solid and liquid biofuels in the median ambitious scenarios.

3.2.1.2. Bioenergy trade and trade patterns. In moderate scenarios, 0–20% and 7–26% of global bioenergy demand is traded between regions in 2030 and 2050, respectively. For solid biomass, this corresponds to an amount of 3 Mt–1500 Mt and 100Mt–2000 Mt in 2030 and 2050, respectively. These values only take into account TIMER and POLES scenarios since GFPM covers forest products only. In the scenario "high" of GFPM, in 2030 21% of global bioenergy demand from forestry products is traded between world regions. For liquid biomass, the range of bioenergy trade in moderate scenarios amount to 1–360 Mt and 12–820 Mt in 2030 and 2050, respectively.

In ambitious scenarios, 14–26% and 14–30% of global bioenergy demand is traded between regions in 2030 and 2050, respectively. In more detail, the model scenarios show a huge range of potential bioenergy trade: for solid biomass, in ambitious scenarios bioenergy trade ranges from 700 Mt to more than 2,500 Mt in 2030 and from 800 Mt to almost 4,200 Mt in 2050. These values only take into account TIMER and POLES scenarios since GFPM covers forest products only. In the scenario “high” of GFPM, in 2030, 25% of forest based global bioenergy demand is traded between world regions. For liquid biomass, the ambitious scenarios show a bioenergy trade in the range of 65 Mt to more than 360 Mt in 2030 and from 40 Mt to 520 Mt in 2050.

The results of the GFPM model analysis show that in a high bioenergy demand scenario, the global forest biomass consumption would increase by 80% from 2006 to 2030, with an even stronger increase in Europe and North America of 180% [16]. The endogenously predicted changes in forest stock imply future differences in future production of individual countries and international trade flows; The forest biomass production is expected to double in Europe towards 2030, with Germany, Russia and France as the major producers. An effect of doubling the growth rate of forest biomass demand is that world price of fuelwood and industrial roundwood to converge and wood would be reallocated from other uses, especially chemical pulp, to energy.

For comparison, trade volumes of liquid fuels (ethanol and biodiesel) did not exceed 5 Mt in 2011. Net woody biomass trade in 2010 amounted to roughly 18 Mt (mainly wood pellets fuel wood and wood waste). Thus, the model results show a huge increase of bioenergy trade in the coming decades in most of the scenarios (in particular in the more ambitious bioenergy scenarios).

For a proper interpretation of these results, one should take into account that these values underestimate the international trade that would actually occur for the following reasons: (1) trade streams are only reported between world regions; most of these world regions consist of a number of different countries with export and import activities between individual countries which are not estimated; (2) only net trade balances are reported; whereas in reality both import and export between two regions are observed.

3.2.2. Scenario details

In order to understand the differences between scenarios, drivers and a clearer distinction between different biomass fractions, this section displays selected reference scenarios of the three models in more detail

The following figures show the development of global world bioenergy production and the share of internationally traded bioenergy in selected scenarios of TIMER and GFPM. All values refer to modern biomass only, traditional biomass use is excluded (Figs. 3–9).

3.2.2.1. Moderate scenarios - selected model outputs. The GFPM A2 (slowdown of globalisation) shows the fastest fuelwood production in North America, South America and Europe, slower rate in Asia and Africa. By 2060, South America, Europe and Oceania are becoming net exporters. Prices of industrial roundwood and fuelwood would converge towards $71 per m3 by about 2025 (1997-dollars), ($9.9/GJ), increasing to $19.4/GJ in 2060. $140/m3 equals the real price of industrial roundwood in 1980.

Liquids: Due to the higher price of this fuel, demand only exists in regions with a high energy consumption: the United States, Western Europe, Japan and China (after 2030). Producing countries have little or no demand. Thus the model projects that over 80% of liquid biofuels are traded.

Solids: Trade of solids is initially limited to less than 1% due to local consumption of residues/waste. By 2050 this increases to 13%.

The TIMER scenario “OECD Environmental Outlook Baseline” shows a significant increase in demand of solid and liquid biofuels. In 2050 demand of liquid and solid biofuels are at 22.2 and 243.4 EJ respectively. For liquid biofuels, consistently more than 40% is traded peaking at 75% in 2020. Main exporters are Eastern and Western Africa, South America, Kazakhstan, Oceania. Whereas the main importers are USA, W. Europe, India, China, Japan. For solid biomass, international trade starts around 2020 and increases to 16% in 2050. Main exporters are Central Europe, Turkey, Russia, Kazakhstan, Indonesia. Main importing countries are South America, Western Europe, China, Japan.

The TIMER scenario “OECD Environmental Outlook with barriers on biofuel trade” is similar to the above baseline except that transaction costs for international trade of biofuels are increased to such an extent as to limit trade so that bioenergy consumption is limited to local production. The high transaction costs for trade of biofuels leads to importing regions continue consuming other

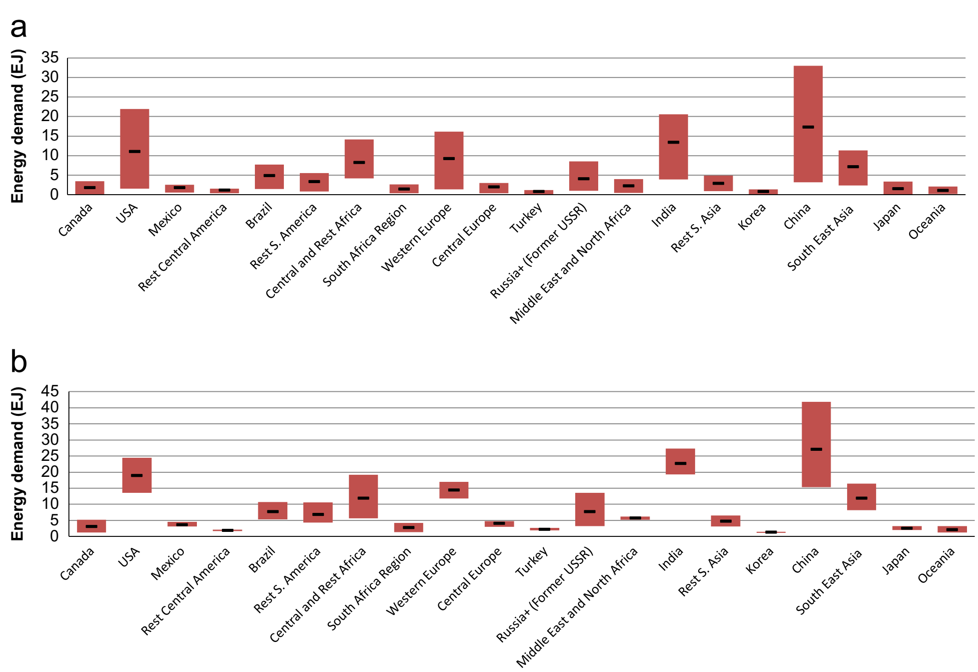

Fig. 4. (a, b) Range of total bioenergy *demand* in *ambitious* scenarios by world regions. Upper graph: 2030, lower graph: 2050. Bars indicate the range of all scenarios, black lines the average of all scenarios. GFPM results are only included for 2030 and include only forestry products.

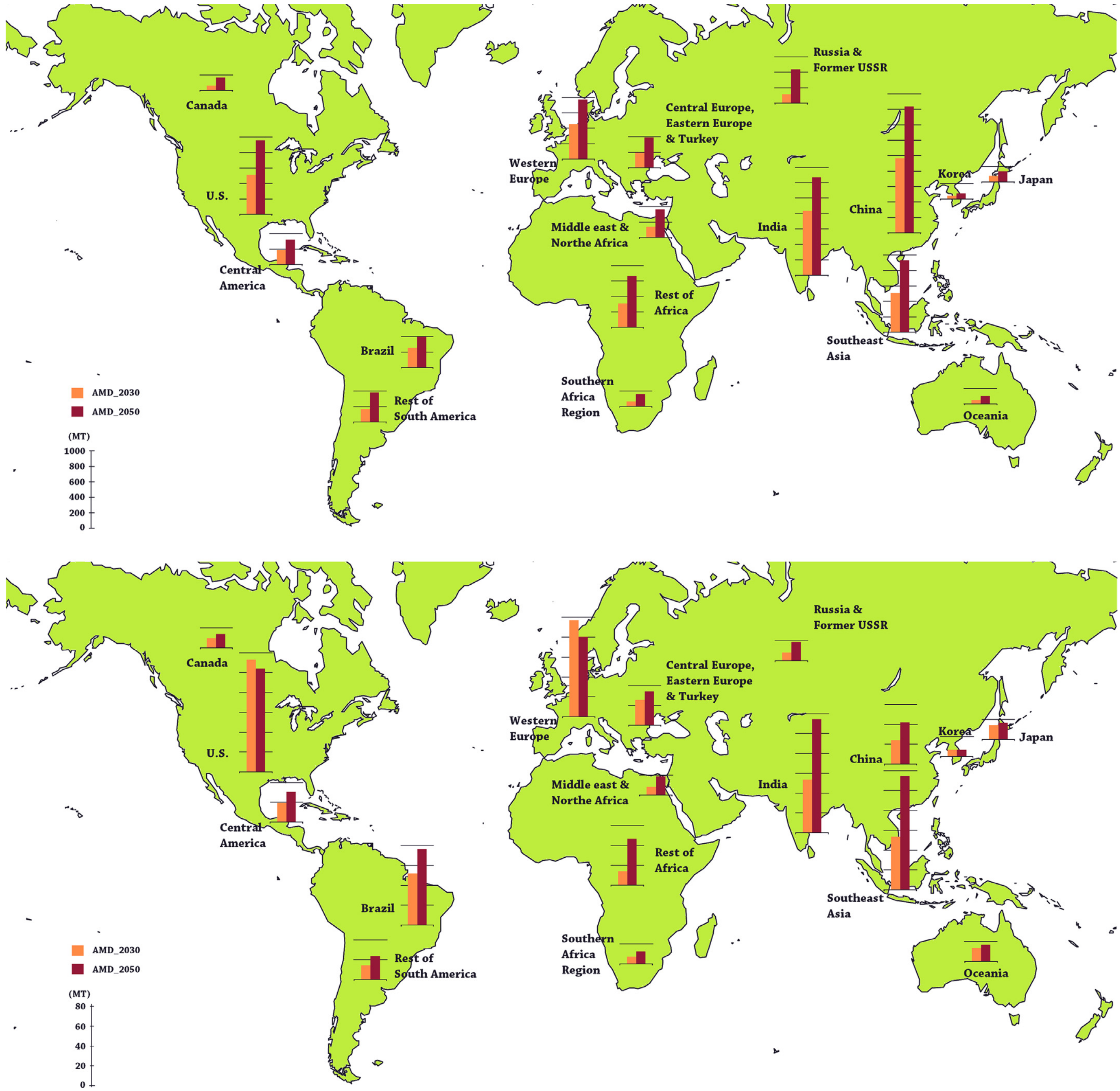

Fig. 5. Regional bioenergy demand in the median of *ambitious* model scenarios 2030 and 2050. Top: solid biomass, bottom: liquid biomass. (Unit: Mt).

fuels. However, the increased initial consumption of fossil fuels leads to price increases and thus by 2050 biofuel use and trade starts growing rapidly, especially for solid biofuels. In 2050 Demand of liquid and solid biofuels are at 3.1 and 23.8 EJ respectively. The reduced use of liquid biofuels in 2050 compared to the baseline is a clear display of path dependency. In 2030 liquid and solid biofuel production is 3% and 44% respectively of baseline, this limits the cost reductions (due to learning) which liquid biofuels require in order to become competitive and thus total biofuel price is higher.

3.2.2.2. Ambitious scenarios - selected model outputs. The results of the GFPM model analysis show that in a high bioenergy demand scenario, the global forest biomass consumption would increase by 80% from 2006 to 2030, with an even stronger increase in Europe and North America of 180% [16]. The endogenously predicted changes in forest stock imply future differences in future production of individual countries and international trade flows; the forest biomass production is expected to double in Europe towards 2030, with Germany, Russia and France as the major producers. An effect of doubling the growth rate of forest biomass demand is that world price of fuelwood and industrial roundwood to converge and wood would be reallocated from other uses, especially chemical pulp, to energy.

GFPM A1B, which implies continuing globalisation, assumes the fastest fuelwood production in North America, South America and Europe and a slower rate for Asia and Africa. An annual

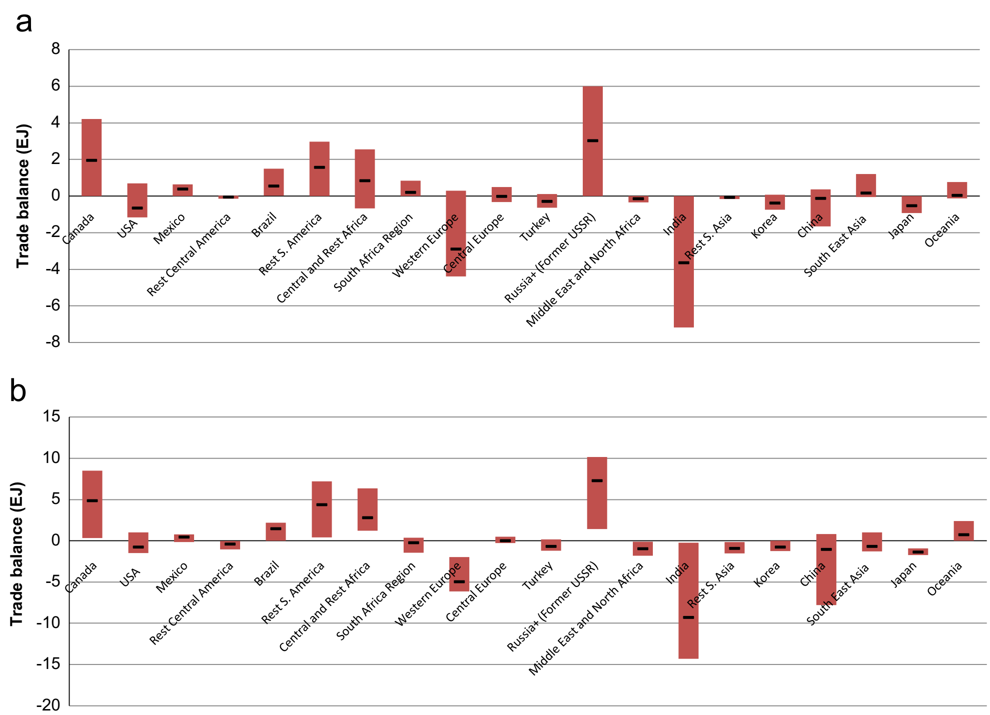

Fig. 6. (a, b) Range of *trade balance* of total bioenergy demand in *moderate* scenarios by world regions. Upper graph: 2030, lower graph: 2050. Bars indicate the range of all scenarios, black lines the average of all scenarios. GFPM results are only included for 2030 and include only forestry products.

growth from 2006–2060 of 6% in developed countries and 2.3% in developing countries takes place. Imports to Asia increase sharply especially after 2025. From 2030 to 2060, Oceania would be a major exporter, together with Europe and North America. Prices of industrial roundwood and fuelwood would converge towards \$83 per m3 by about 2025 (1997-dollars), \$11.5/GJ, increasing to \$400/m3 in 2060 (\$55.6/GJ) in 2060.

TIMER OECD-450 ppm: This scenario explores costs and required energy system investments in order to divert the baseline to a 450 ppm concentration level by 2100. As a result, demand of solid and liquid biofuels increases globally. The share of liquid biomass traded is slightly higher than in the baseline due to increased demand. The main exporting regions are the same, with a special focus on Brazil. For solids, the trade increases heavily to about 32% of global consumption in 2050. Exporters: Canada, S. America, E&W&S Africa, C. Europe, Kazakhstan, Russia, Oceania.

Due to ambitious CO_2 concentration stabilisation targets, the production of biomass is the highest in the 450 ppm scenario with about 140 EJ of modern biomass by 2050. On the other hand, the trade barrier scenario results in only about 30 EJ of modern biomass by 2050. This is about one-third less than the OECD environmental outlook baseline scenario. The share of internationally traded biomass on total modern biomass consumption is only about 20% in the trade barrier scenario versus 28% in the baseline scenario and more than 35% in the 450 ppm and the 100 €/t CO_2 price scenario.

These results show the relevance of bioenergy trade in the TIMER model. A moderate increase of trade barriers (increase of transaction costs of 20%) leads to a considerable reduction of bioenergy demand (of about 30% in 2050 compared to the baseline scenario).

In general, TIMER predicts very considerable exports of liquid and solid biofuel from Russia, Africa and Southern America. On the other hand the main importing regions are the USA, Western Europe, India and China. The reason for this is due to the supply and demand balances as well as the drivers of biofuel prices in TIMER. Exporting regions tend to have abundant land, and since the cost of land is the main cost component of biofuels (together with labour, transport, conversion and possible carbon taxes), the cost of biofuels produced in these regions is limited. Furthermore, these regions are not projected to have a very high final energy demand. The USA, Europe, China and India are all projected to be regions with very high final energy demand and their production potential is limited either by land or unfavourable crop yields and so local production cannot meet the demand. Furthermore, other energy carriers (oil, gas) are also expensive for these regions due to limited local reserves and an overall in their prices due to global scarcity. The combination of all these factors make trade flows of biofuels from South America to the USA, Russia to Europe and China and Africa to Europe and India the 'winning' combination.

Across the scenarios, the total use of biofuels and thus also the total volume of biofuels traded depends on how competitive it is vis-à-vis other energy carriers. Thus in cases where fossil fuels become very expensive early on (450 ppm, 100\$/tCO_2), consumptions as well as trade of biofuels increases. In the trade barriers scenario, since biofuels are limited to those produced locally, the global production of biofuels suffers significantly.

Figs. 10–12 show the growth in trade for all scenarios, relative to a common baseline trade volume in 2010, which amounts to 130 PJ for liquid biomass and 300 PJ for solid biomass fractions [22,23].

Quantities of exported biomass are rising in all scenarios (see Fig. 10). A trend toward a larger share of globally traded biomass in terms of globally produced and consumed biomass is evident after 2050 in all scenarios. All scenarios show an increase in total internationally traded biomass. The lowest growth rate occurs in the OECD Environmental scenario, with an six-fold (581%) increase of traded biomass from 2010 to 2030 and the highest growth rate in the OECD 100 $€_{2005}$ per t CO_2 scenario with an increase by about 12 fold (1186%). The trade barrier scenario assumes, that international biomass trade is developing only marginally until 2030 and barriers are overcome from 2050 on, leading to a steep increase in

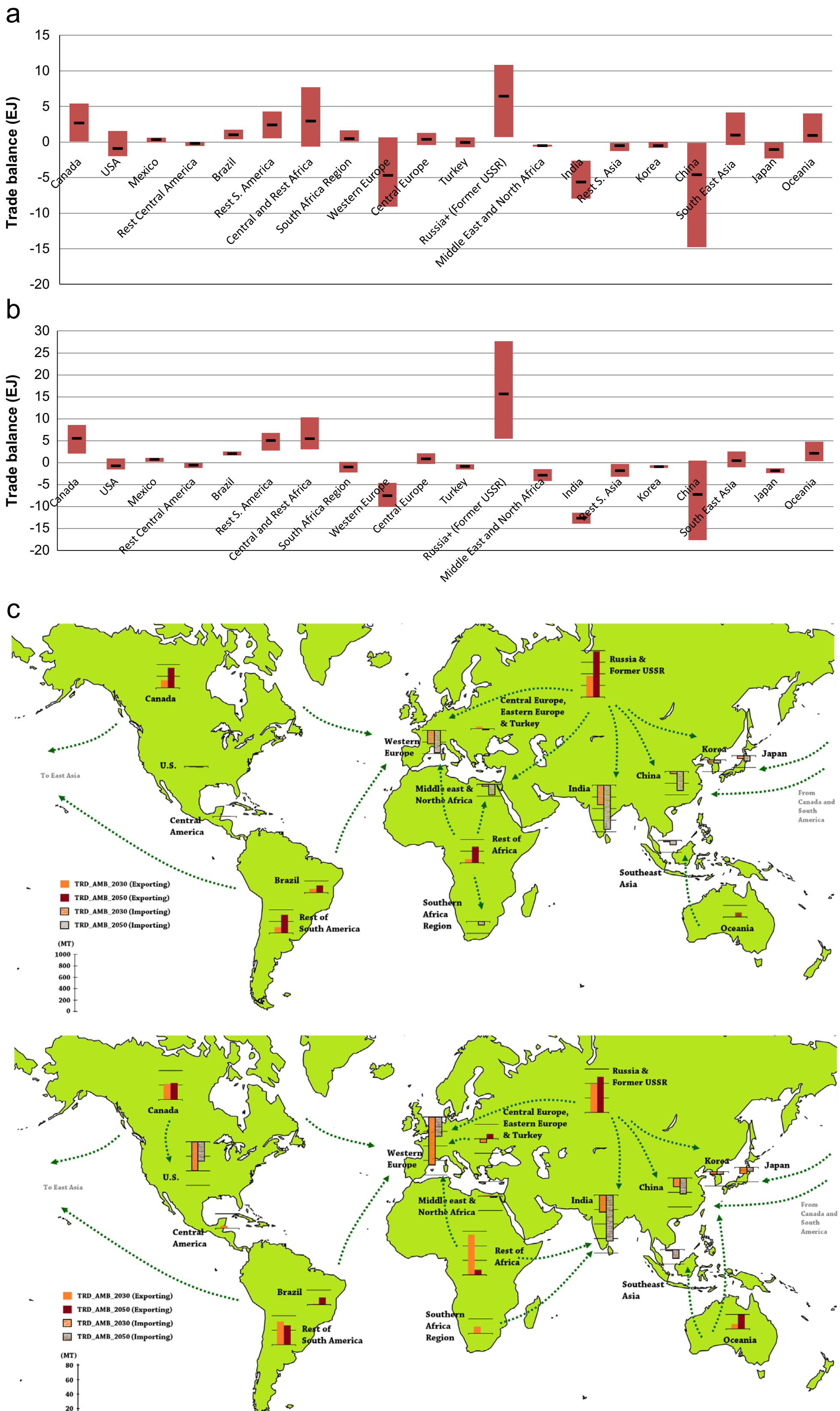

Fig. 7. (a, b) Range of trade balance of total bioenergy demand in *ambitious* scenarios by world regions. Upper graph: 2030, lower graph: 2050. Bars indicate the range of all scenarios, black lines the average of all scenarios. GFPM results are only included for 2030 and include only forestry products. (c) Regional bioenergy trade balances in the median of *ambitious* model scenarios 2030 and 2050. Top: solid biomass, bottom: liquid biomass. (Unit: Mt).

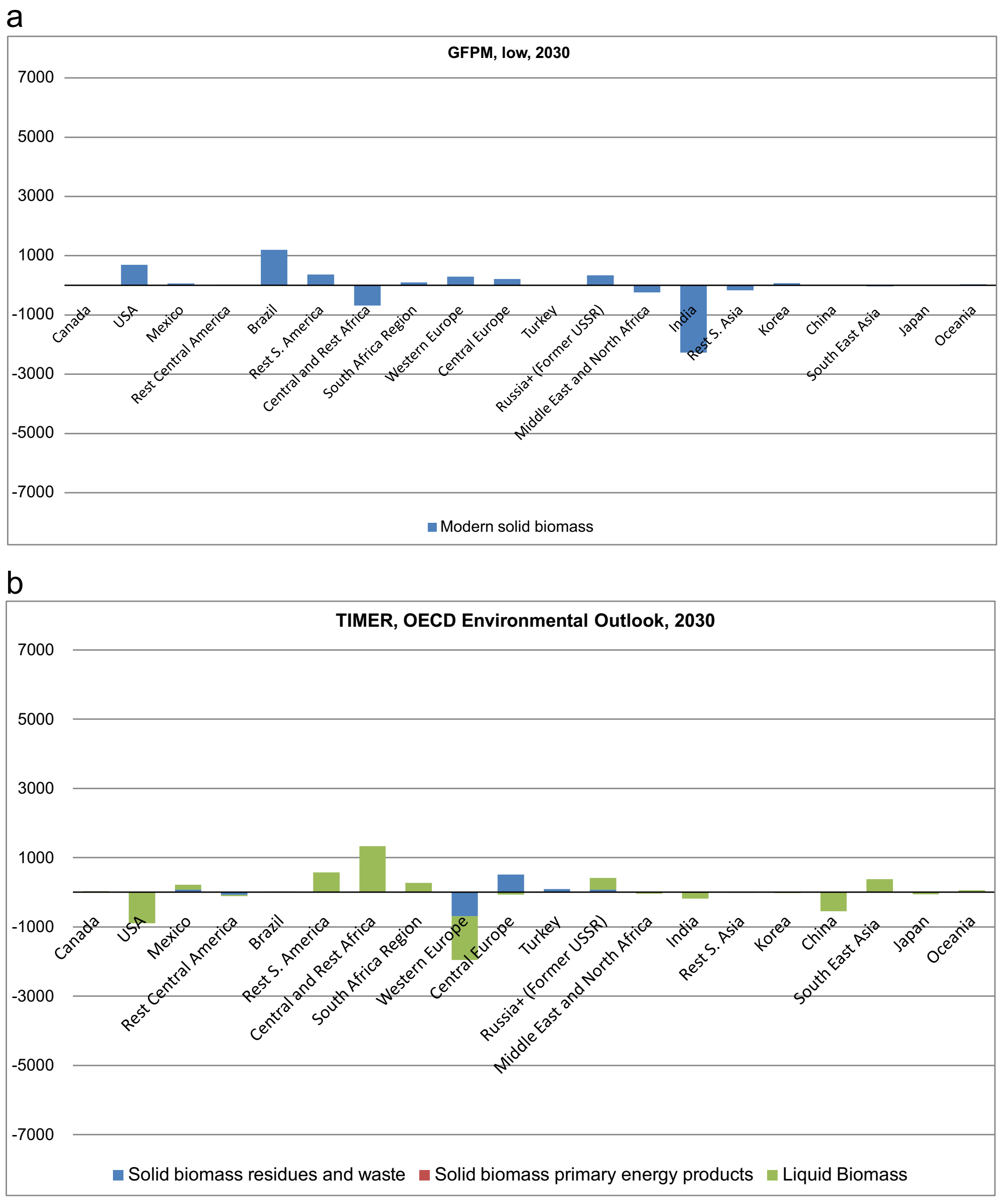

Fig. 8. (a) Trade flows 2030 per region in the GFPM reference scenario (EJ). (b) Trade flows 2030 per region in the TIMER OECD Environmental Outlook scenario (EJ).

relative terms. Total traded biomass is still below the figures in the remaining scenarios for 2050.

4. Synthesis and conclusions

In this article, a comparative investigation of selected model scenarios regarding bioenergy demand, production and the implication on bioenergy trade between world regions was carried out. Only a few number of global energy models explicitly simulate international bioenergy trade. Nevertheless, all global energy scenarios need to make an assumption on the future development of bioenergy trade. Mostly, this is only implicitly the case and is not clearly documented. A further continual investigation and integration of international bioenergy trade, emerging barriers and drivers into existing modelling frameworks is crucial for development of realistic scenarios regarding the future role of bioenergy in the future energy system. Major uncertainties in this respect are sustainability considerations, especially carbon balance of biomass, trade limitations as well as time and scope of policy implementation.

Those model scenarios with an ambitious increase of bioenergy demand imply a huge increase in bioenergy trade, an increase by a factor of 70 between 2010 and 2030 for liquid biofuels, and by a factor of 80 for solid biomass. It has to be taken into account that these results refer to trade between world regions. International trade within these regions (e.g. within Europe) would have to be added to these values. Such an increase would result in quantities of internationally traded biomass commodities which would be higher than the current total global bioenergy demand (i.e. larger than 50 EJ). Considering the currently very small share of internationally traded bioenergy, this would result in huge challenges and tremendous changes in terms of production, pretreatment of biomass and development of logistic chains. Although both liquid and solid international biomass trade has grown exponentially between 2000 and 2010, it is rather doubtful that this speed can be maintained and reach the levels of trade anticipated by the models. As an illustration, worldwide coal trade amounted to 1142 Mt in 2011 (world coal, 2013), that is, roughly the size that

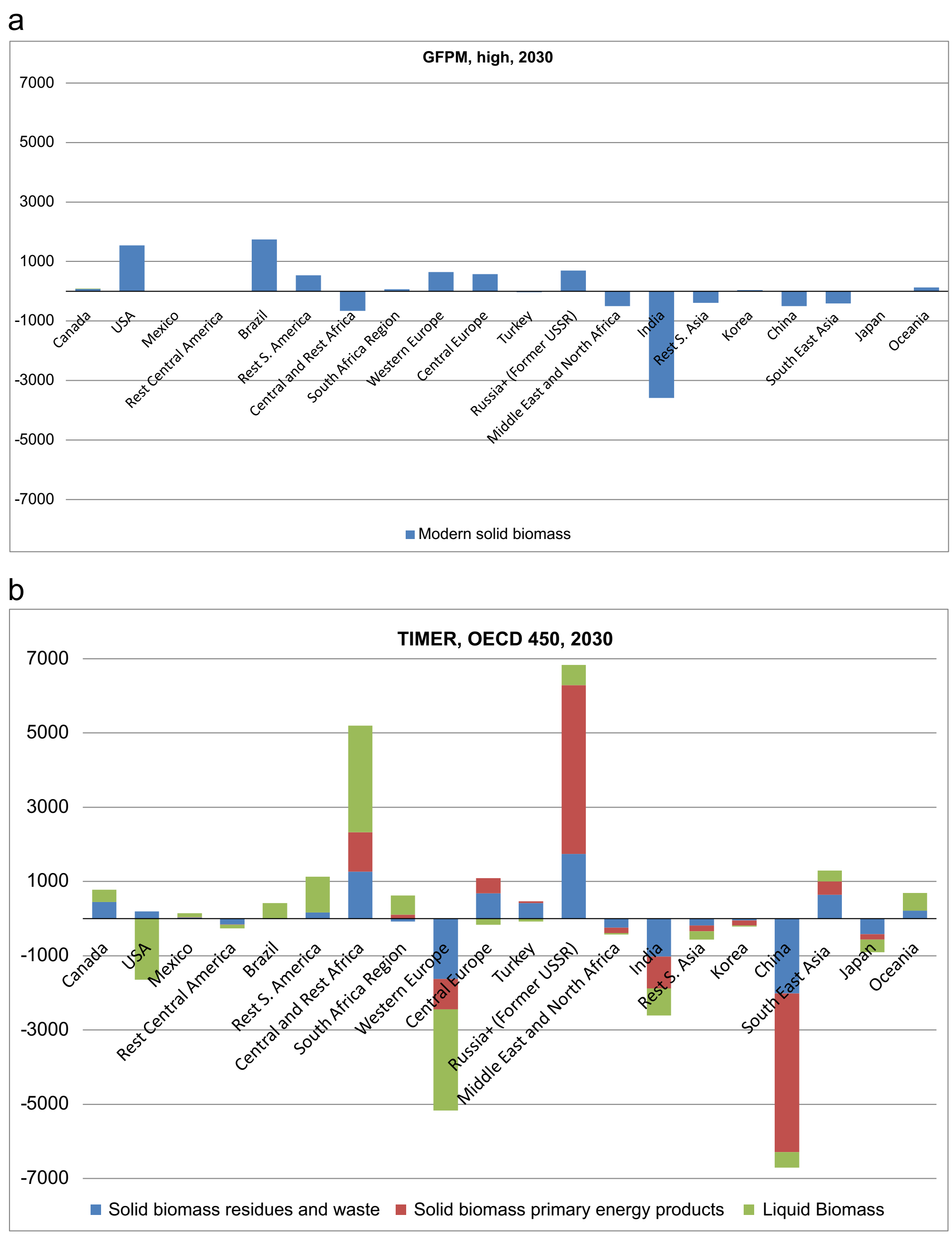

Fig. 9. (a) Trade flows 2030 per region in the GFPM high scenario (EJ). (b) Trade flows 2030 per region in the TIMER OECD 450 ppm scenario (EJ).

solid biomass would need to grow to within 20 years in the optimistic bioenergy use scenarios. However, coal infrastructures have been developed for over 200 years, coal does not require any pretreatment before transport, and logistics typically originate from large point sources (mines).

From the above, two conclusions can be drawn:

Conclusion 1: Current global energy models seem to overestimate the amounts of liquid and solid biomass that can be traded in especially the medium term (2030), as it would require extremely high annual growth rates, which could only be accommodated with very high investments in production facilities and logistics infrastructure. However, it should be taken into account that the models do not make predictions. They project based on biophysical trends and observed historic behavior under certain conditions and assumptions. The models tell what is potentially possible. Their objective is not to give advice how to overcome certain barriers. So, one reason of this overestimation could be that barriers for trade are not sufficiently covered in the models. If this is true, the question arises: How would global scenarios change if bioenergy trade barriers would be taken into account? To which extent would this change our picture of future global bioenergy use? So far, only a few number of global energy models explicitly simulate international bioenergy trade. Nevertheless, all global energy scenarios need to make an assumption on the future development of bioenergy trade. Mostly, this is only implicitly the case and is not clearly documented. A further investigation and integration of international bioenergy trade, barriers and drivers into existing modeling frameworks is crucial for a proper understanding of bioenergy in the future energy system. We strongly recommend that modellers investigate their model–specific assumptions and outcomes for international bioenergy trade, and analyse whether the required growth rates in international

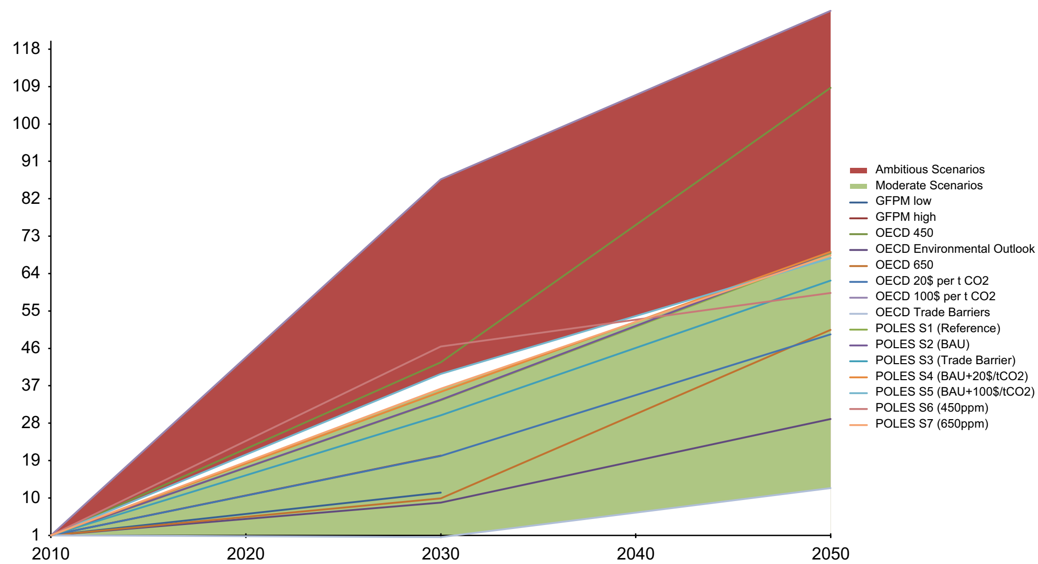

Fig. 10. Overview of growth in *total* global bioenergy trade per scenario (2010 = 100%).

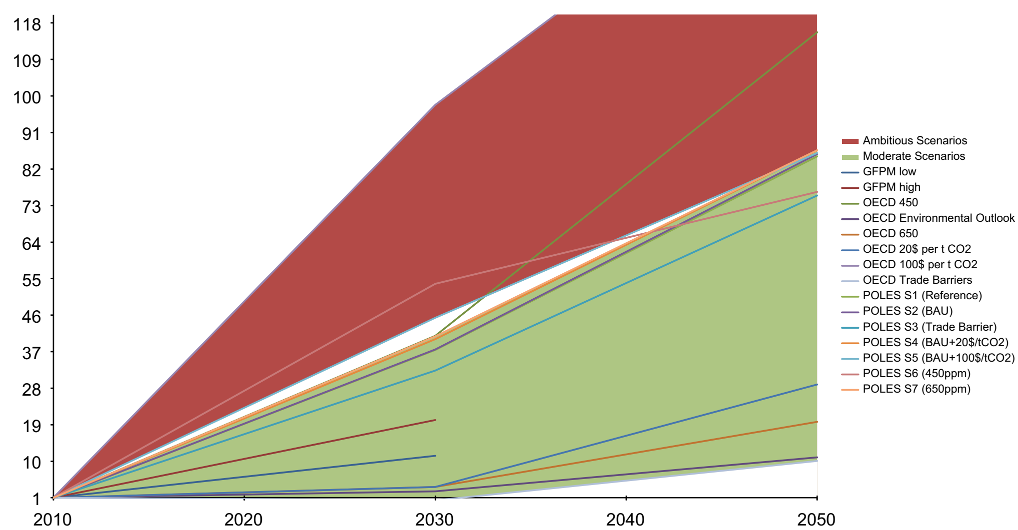

Fig. 11. Overview of growth in *solid* global bioenergy trade per scenario (2010 = 100%).

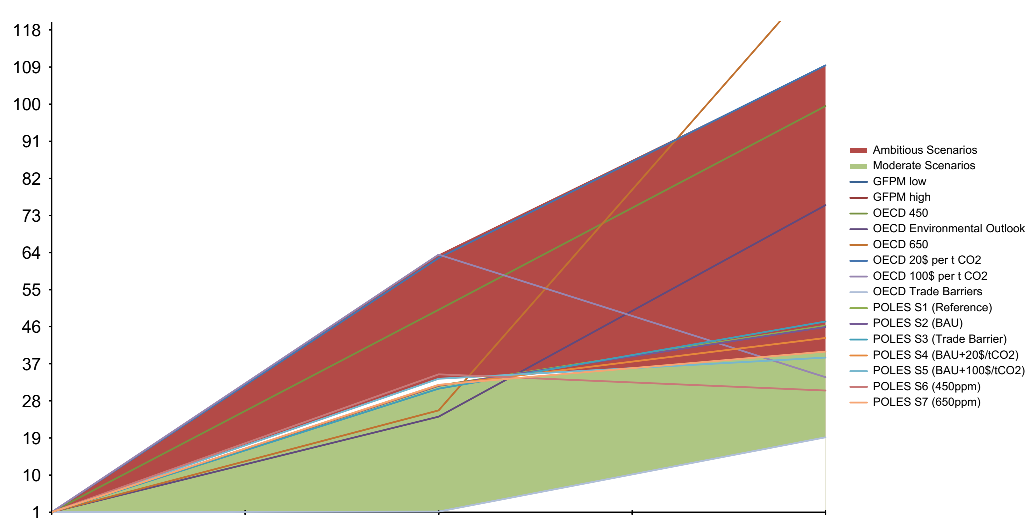

Fig. 12. Overview of growth in *liquid* global bioenergy trade per scenario (2010 = 100%).

bioenergy trade can be deemed realistic. Also users of the model results (e.g. industry, and policy makers that follow the IPCC reports) should be made aware of these model limitations.

Conclusion 2: The level of international bioenergy trade shown in the model scenarios is necessary to fill the anticipated regional gap between demand and supply. Without significant bioenergy trade between world regions, a much less pronounced growth of bioenergy is achievable. Hence, either major challenges regarding amongst other technical, logistical and economic aspects of international bioenergy trade will have to be solved, or the objectives of significant higher bioenergy use have to be reduced. Policy makers should thus realise that next to incentives to promote production and consumption of bioenergy also policies to support the (rapid) growth of bioenergy trade will need to be put in place.

The insight into future scenarios and perspectives of bioenergy trade revealed that substantial challenges for the future development of global and international bioenergy trade may be expected in the coming decades if a low carbon energy system is to be developed. Some of these, such as the development of logistics, the required investments to realise production and trade, and the need to govern sustainable production of bioenergy are addressed in this book. Others are still open for further research, for example, the implications of bioenergy trade for specific regions and for different biomass commodities in terms of social, ecological and economic impacts or the effect of fluctuating exchange rates, regional development of economic and policy side conditions.

4.1. Drivers of bioenergy trade in selected scenarios

It should be pointed out that model outcomes of trade flows depend on how a number of issues are included in the models. These include bioenergy availability and cost, bioenergy demand and bioenergy trade barriers and logistics. The details of how particular interregional trade-flows happen and what parameters drive/limit them require in depth knowledge of infrastructure-related parameters and are, if at all, only partially take into account in essentially all models. Our results point to the conclusion that these parameters should be investigated in more detail: Typically, when trying to mobilise potentials, the initial costs are much higher than originally anticipated – also because significant cost reductions can usually only be obtained with increases in scale. Biomass supply has in the short-run also a positive direct price-elasticity, meaning the increased volumes require a price increase in order to compensate the supplier for increased cost (more input, production on land with lower productivity, foregone revenues from deliveries to other industries etc). Transaction costs for bioenergy trade are rarely included in global models, and if so are included in a crude manner. Underlying assumptions and sensitivities may significantly affect the results. It is therefore deemed worthwhile investigating if the costs of transport should also be modeled as a function of scale and cumulative production.

Drivers for bioenergy demand (and trade) vary among the models considered in this study. Population growth and economic development are principal drivers behind overall energy consumption. In GLOBIOM demand is driven by population growth, GDP per capita, crop and livestock productivity. In GFPM demand for final products is defined by demand at last year‘s price and price elasticity of demand. Demand changes in each country due to changes in GDP and elasticity of demand from world GDP. The wood supply shifts exogenously according to a chosen scenario. Whereas in POLES the international solid biomass price is established through a cost curve (linking cost and biomass use with total biomass potential). The international liquid biomass price is established through world average biofuel production costs and added transport costs. Demand further is driven by population and GDP. Competition occurs over part of the demand each year, reflecting infrastructure lifetime and trade inertia.

The key drivers and barriers to be taken into account for model improvement and in future models could include:

- Barriers and drivers of bioenergy trade: Logistics, Trade policies, Sustainability requirements
- Regional balancing of supply and demand
  - Barriers and drivers of bioenergy demand (in current supply and demand regions): oil price, policies (e.g. quotas, subsidies, taxes), technological learning, GDP
  - Barriers and drivers of bioenergy supply, regional availability of biomass potentials
  - Regional development of bio-based industry
- Technological change: Change from traditional biomass to modern biomass
- Change in resource base

Further the supply of biomass resources is limited by overall regionally biomass potentials, that can be tapped to a certain extent. Assumptions on the regional potential can strongly affect trade patterns in the models.

4.2. Robust trends and trade patterns in all scenarios

The models and scenarios show considerable differences for bioenergy demand and for trade balances in different world regions. Nevertheless, the results shown above allow us to derive some robust trends and trade patterns:

In ambitious scenarios, the key potential future bioenergy export regions in 2050 are Russia and former USSR countries (40% of trade, 10% of global demand) and Canada, South-America, Central and Rest Africa, Oceania (40% of trade, 10% of global demand). This general pattern also holds for the moderate scenarios with slightly shifted figures: Russia and former USSR (33% of trade, 6% of global demand), Canada, South-America, Central and Rest Africa, Oceania (60% of trade, 12% of global demand). For the USA, there is a significant difference in the trade balance of liquid versus solid biomass. Where the scenarios show a quite balanced (or slightly positive) trade balance for solid biomass, the trade balance for liquid bioenergy is clearly negative.

Regarding the key future import regions in scenarios up to 2050, mainly India, Western Europe and China are dominating. In ambitious scenarios these three regions import more than two thirds of all global inter-regional trade: India (33% of trade, 8% of global demand), Western Europe, China (39% of trade, 9% of global demand). USA is a relevant importer of liquid biofuels, however this is partly compensated by exports for solid biomass. The moderate scenarios show a more balanced picture: India (42% of trade, 8% of global demand), Western Europe (33% of trade, 4% of global demand), several world regions holding a share of about 3–6% of global trade and about 1% of global demand, for example, Japan, China, South-East Asia and Rest of South-Asia, Middle-East and North Africa, USA, Korea, Turkey. For India, the scenario results are in a very close range, whereas for China a high difference between model results can be observed. This indicates the substantial uncertainties regarding biomass potentials and future exploitation of these potentials in China.

In the long-term (i.e. after 2030), the scenarios show a declining demand for liquid biofuels in Europe and the USA which reduces the imports from these regions.

In particular, the results regarding the relevance of Asia as importing region are also supported by [15] as well as IEA 2012. Raunikar et al. [15] propose that net exporters of forest biomass will be South America, Europe and Oceania.

However, one should keep in mind that the trade flows identified above are from models that are in first instance not made to analyse bioenergy trade. They are simply a consequence of where the models predict demand for and supply of biomass. When comparing the trends identified above with current actual trade flows, the following observations can be made:

- Russia and other former USSR countries, whilst possessing very large biomass resources, have so far only been a minor exporter of solid biomass, whilst trade in liquid biofuels is virtually non-existent. In between 2010–2012, wood pellet production capacities have been strongly expanded, especially in North-West Russia, but also in Russia's East (aiming to feed the East Asian markets) so this could indeed be a start of substantial solid biomass exports in the years to come.
- Canada has been one of the pioneers of solid biomass exports, and the expected major role as a biomass supplier fits current trends quite well.
- Latin America and Africa on the other hand virtually do not export any solid biomass at the moment, and are also not likely to so in any significant volume up until 2020. Thus, huge exports of solid biomass from these regions in the near and mid-term future are in reality rather unlikely. Significant barriers would have to be overcome and logistical, social, ecological and economic challenges would have to be solved. Exports of liquid biofuels from Latin America on the other hand are already significant (see chapter 2), and could likely expand further in the decades to come. For Sub-Saharan Africa, which has experienced a number of failed biofuel projects in recent years, this still remains to be seen.
- One market which (pending current and future policy developments) should increase its liquid and solid bioenergy imports further is the EU, as also the models anticipate. This is probably one of the most robust trends identified. The largest uncertainties are perhaps the future additional sourcing areas, that is, if South America and the African West coast may become important suppliers in the future as well.
- To some extent, India and China still remain wild cards. Both countries have shown little or no bioenergy imports or exports so far, partly due to the lack of strong supporting policies stimulating demand and at the same time limited amounts of agricultural land and forests that could be used to produce biomass for energy. Both countries have large potentials of agricultural residues, but these are likely to be used locally. It remains to be seen, if the large bioenergy imports expected by the model results will materialise. If so, from a logistical point of view it would make sense if India and China might increasingly source biomass from the east-coast of sub-Saharan Africa, while China might also utilise the forest biomass in East Russia. However, both bioenergy trade routes are virtually non-existent today, and thus would have to be developed from scratch. Again, any scenarios (implicitly) expecting large trade flows following these routes in the short and mid-term should be considered with caution.

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