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# Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints

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## Abstract

The expected use of solid biomass for large-scale heat and power production across North–West Europe (NW EU) has led to discussions about its sustainability, especially due to the increasing import dependence of the sector. While individual Member States and companies have put forward sustainability criteria, it remains unclear how different requirements will influence the availability and cost of solid biomass and thus how specific regions will satisfy their demand in a competitive global market. We combined a geospatially explicit least-cost biomass supply model with a linear optimization solver to assess global solid biomass trade streams by 2020 with a particular focus on NW EU. We apply different demand and supply scenarios representing varying policy developments and sustainability requirements. We find that the projected EU solid biomass demand by 2020 can be met across all scenarios, almost exclusively via domestic biomass. The exploitation of domestic agricultural residue and energy crop potentials, however, will need to increase sharply. Given sustainability requirements for solid biomass as for liquid biofuels, extra-EU imports may reach 236 PJ by 2020, i.e., 400% of their 2010 levels. Intra-EU trade is expected to grow with stricter sustainability requirements up to 548 PJ, i.e., 280% of its 2010 levels by 2020. Increasing sustainability requirements can have different effects on trade portfolios across NW EU. Excluding pulpwood pellets may drive the supply costs of import dependent countries, foremost the Netherlands and the UK, whereas excluding additional forest biomass may entail higher costs for Germany and Denmark which rely on regional biomass. Excluding solid biomass fractions may create short-term price hikes. Our modeling results are strongly influenced by parameterization choices, foremost assumed EU biomass supply volumes and costs and assumed relations between criteria and supply. The model framework is suited for the inclusion of dynamic supply–demand interactions and other world regions.

*Keywords:* 2020 targets, agripellets, bioenergy, EU policy, international trade, solid biomass, supply costs, sustainability, wood pellets

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## Introduction

As laid out in the Renewable Energy Directive (RED) 2009/28/EC, the European Union (EU) shall achieve a 20% share of renewable energy in final energy consumption across its Member States (MS) by 2020. The pathway to this goal is detailed via the individual MS' National Renewable Energy Action Plans (NREAP) providing the technology and sector trajectories including the respective policy frameworks. According to the NREAPs, biomass for electricity, heating, and cooling will supply around 42% of the total renewable energy target by 2020. The majority of this will be used in heating/cooling production (mostly in the residential sector) and come from solid biomass (AEBIOM, 2012). While the vast majority of the EU's solid biomass demand has been supplied domestically, the EU has also been a net importer for years. Actually, it has attracted most of the international biomass trade streams over the past decade (Lamers *et al.*, 2012). Wood chips, waste wood, and roundwood have been mainly imported from bordering countries, while wood pellets have been traded cross-continentally, foremost from North America and Russia. By 2012, imports from the United States and Canada reached around 3.2 Mtonnes, and just over 1 Mtonne

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from Russia and Eastern Europe (Lamers *et al.*, 2013b). The predominant EU market for these wood pellet imports is the industrial sector, i.e. large-scale (>5 $MW_{el}$) cofiring and dedicated heat and power installations. Due to the expected demand increase under current policy projections and limited regional resources (i.e., constraints regarding available land, in some cases high feedstock costs, and required time for mobilization), especially the northwestern countries in the EU are expected to remain net importers of solid biomass (at least) until 2020 (Kranzl *et al.*, 2013).

Sound environmental and social practices regarding the production and use of solid biomass can be safeguarded within the geographic boundaries of the EU via its judicial framework. At the same time, they also need to be guaranteed for extra-EU imports. While the RED prescribes minimum environmental requirements for liquid biofuels, it does not (yet) cover lignocellulosic biomass for heat and power production. To compensate this, initiatives by individual companies and MS, e.g., the UK (OFGEM, 2011; DECC, 2013b), have emerged recently.

Eligibility criteria for solid biomass may influence the eventual feedstock types and volumes available to pellet producers within or aiming to export to the EU market (Schueler *et al.*, 2013). Supply limitations may – given a stable or increasing demand – drive feedstock costs and define the cost-competitiveness of local vs. imported biomass. The price changes under different sustainability requirements will influence the economic viability of investments in bioenergy conversion facilities, e.g., co- or mono-firing installations. Thus, the uncertainty linked to potential EU sustainability criteria has a direct impact on the variability of existing and potential future investments in solid biomass production and conversion facilities, inside and outside Europe. Apart from the investor's perspective, it is also important for EU policy makers and energy companies to get a better understanding of the potential impact on trade patterns, biomass resource mix, and economics under different demand and supply, i.e., sustainability scenarios by 2020.

Past research, also with particular focus on EU imports (Al-Riffai *et al.*, 2010), has largely modeled international bioenergy trade implicitly, i.e., as part of agriculture or forest biomass trade streams for all purposes (foremost food and material) and from a macro-economic perspective (see e.g. Kranzl *et al.*, 2013; Matzenberger *et al.*, 2013 for an overview). The first integrated effort to model solid biomass for energy trade was done in the World Energy Outlook (IEA, 2012a), also via a macro-economic, global equilibrium approach. Such projections can provide indications for the general direction of trade flows on an aggregated temporal and spatial level. Top-down modeling efforts, however, miss a comprehensive analysis of actual market developments, such as – among others – existing and planned production capacities, raw material availability, logistics, and policy uncertainties (in the case of solid biomass mainly sustainability requirements). In particular, macroeconomic models often neglect time aspects, e.g., the delay between the establishment of a plantation and the first harvest, or the time between investment decisions and the (full) commissioning of a production or conversion facility. These aspects are important determinants of the volumes that may become available for international trade by 2020. The bottom-up modeling effort presented in this paper takes such temporal and logistical determinants into account and builds its trade projections for 2020 on latest policy developments and industry data. Similar models are used by consulting companies McKinsey and Pöyry (Pöyry, 2011). Their respective model frameworks and calibrations, however, are not disclosed or debated within the scientific arena.

The aim of this paper is to design a bottom-up global trade model for analyzing future solid biomass trade and demonstrate it via an assessment of trade streams towards (North-West) Europe by 2020. We also explore how sustainability criteria may influence solid biomass availabilities and costs. On the supply side, we cover forestry assortments, agricultural residues, and energy crops. Agricultural residues outside Europe are limited to corn, wheat, and palm oil production, i.e., commodities whose residues may become attractive as an energy feedstock (see Supporting Information for details). The extra-EU supply side is further limited to current key producing countries whose underlying agriculture sector is export-oriented, i.e., provides the necessary logistical basis. The wood pellet market developments are detailed for regions whose production is at least partly export-oriented toward Europe, e.g., the southeastern USA. Supply costs are derived geospatially explicit on a bottom-up basis, taking logistical infrastructure into account. The demand side is also modeled geospatially explicit. Specific attention is paid to current policy and industry expectations on a country-by-country basis within the EU. In addition, we also include rough scenarios for global developments, e.g., in Asia, to model potential international competition for tradable lignocellulosic biomass by 2020.

The next section presents our methodological framework, including the model itself, assumptions, calibration, and scenario details. Following, results are presented before the article closes with a discussion of our findings and a comparison to other studies. Detailed data and additional background material is provided in the Supporting Information.

## Materials and methods

### Modeling framework

Our modeling framework combines a geospatially explicit biomass transport model with a demand driven allocation model (Fig. 1). The modeling framework first generates a global cost per volume explicit origin/destination matrix for international solid biomass trade (Fig. 1). It builds on Hoefnagels *et al.* (2011c, 2013), who have applied GIS software to determine least-cost routes between a range of woody biomass supply and demand nodes based on existing transport networks and intermodal terminals for transloading (e.g., from a bulk ocean carrier to rail). The second part of the framework adds a linear programming problem that optimizes the allocation between all supply and demand nodes to reach minimum total biomass supply costs based on user defined demand/supply volumes per demand/supply node (Fig. 1). This allows for analysis of the implications varying supply and demand scenarios may have. It also enables the assessment of sustainability criteria on supply volumes and costs. Our cost–supply curves include production, processing, and logistic costs. Capital and operational expenses (CAPEX and OPEX costs) for the conversion and operation of existing or new power plants to co-fire biomass or the setup of pelletization plants, however, are not included.

Two different approaches have been used to calculate the cost and supply of biomass at supply nodes in the EU and outside the EU. In the EU, the total woody biomass supply per country is distributed among the regions in correlation to their surface area while the demand is linked to their population size. The supply and demand nodes outside the EU are based on existing and expected future trade routes (see Parameterization and Supporting Information). For each of these regions, export terminals (seaports) represent the export or import nodes of woody biomass. Free on board (FOB) prices of woody biomass in combination with the locations of these seaports, the distance to importing regions, the maximum ship sizes and shipping cost determine the total cost of supply of importing solid biomass from these regions. Hinterland logistics (toward or away from sea shipping terminals) are not modeled, but implicitly covered in FOB prices of biomass supply.

### Demand calibration

*EU demand*. We model different demand scenarios for the EU27 plus selected Asian countries. Our modeling focus is on NW Europe, as the key importing regions of internationally traded biomass, largely industrial type pellets and residues, have been Belgium (BE), Denmark (DK), the Netherlands (NL), and the United Kingdom (UK) (Lamers *et al.*, 2012; Goh *et al.*, 2013). These countries are also expected to see the largest demand changes regarding tradable, i.e., potentially imported, solid biomass due to their capacity increases for large-scale co- and mono-firing installations of solid biomass for electricity (and combined heat) generation (Beurskens & Hekkenberg, 2010; Sikkema *et al.*, 2011). The potential influences on future solid biomass trade under varying demand projections in these MS are critical to the outcomes of this modeling exercise. We therefore specifically investigate potential future policy and market developments in these countries plus Germany (DE), the largest single solid biomass consumer within the EU (although so far predominantly locally sourced).

As the exact policy context and thus potential price incentives cannot be precisely predicted for 2020, we do not speculate upon an individual country's buying power/capacity. This implies that, in our model runs, all countries are willing and able to pay the same price for biomass. The supply cost optimization is thus done for the demand side as a whole, although spatially explicit. Since no trade tariffs exist for solid biomass flows across the modeled countries/regions, we did not apply any in our model runs (although such factors could

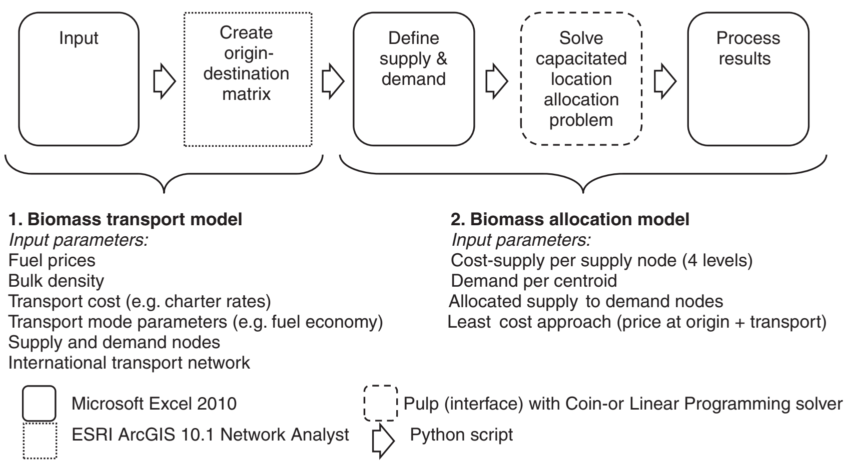


**Fig. 1** The BIT-UU modeling framework (Hoefnagels *et al.*, 2013) combines a global cost per volume explicit origin/destination matrix for international solid biomass trade (Biomass Transport Model) with a linear programming problem that optimizes the allocation between all supply and demand nodes to reach minimum total biomass supply costs based on user defined demand/supply volumes per demand/supply node (Biomass Allocation Model).

theoretically be included). The model runs result in country-to-country trade flows. For better comparison between scenarios, we aggregate these into intra- and extra-EU trade.

*Extra-EU demand:limiting global supply.* Also, local demand for potentially tradable biomass outside the EU is taken into account in our supply estimations. This explicitly covers the potential Canadian wood pellet demand by 2019 (Dale, 2013) and oil palm residue use within Malaysia and Indonesia. The largest possible competing demand for agricultural residues would be a large-scale commercialization of second-generation ethanol. It is however unlikely that the total low-cost corn stover supply, an expected 100 Mtonnes per annum within the USA alone (Gallagher & Baumes, 2012) (see Supporting Information), would be used and thus eliminate potential residue trade/exports by 2020; which we modeled at under 0.5% of this volume. Hence, we did not include a competition from this technology outside Europe in our simulations.

China is expected to significantly increase the utilization of biomass in power and heat generation units (Roos & Brackley, 2012) albeit exclusively from local agricultural and forestry residues (Cocchi *et al*., 2011; Pöyry, 2011). In our simulations, we expect competition for the EU in terms of tradable solid biomass most likely to emerge in Japan and South Korea where new policies are expected to increase the local demand for solid biomass. By 2020, Japan could face a supply gap of 3 million metric tonnes (Mtonnes) wood pellet equivalent (WPe; calculated with a lower heating value for wood pellet energy content: 17.6 GJ tonne$^{-1}$) (Iguchi, 2012). South Korea will probably only be able to produce 1 Mtonne WPe locally, leaving it with a net 4 Mtonnes WPe import demand by 2020 (Cocchi *et al*., 2011; Lee, 2012; Dale, 2013). While both countries source globally, a large share of their past import volumes originated within Asia (e.g. China, Vietnam, Malaysia) (Cocchi *et al*., 2011). Expectations are that this will remain the case. Vietnam alone may be able to produce 3 Mtonnes WPe from wood processing residues (Cocchi *et al*., 2011). Exact capacity developments in these producing regions are however unclear, but also expected to be of less importance to the EU market due to the regional demand. Hence, we did not include them in our modeling (Fig. 2).

*Extra-EU demand for internationally tradable biomass.* We assume that half of the future demand from South Korea (Pusan Harbor) and Japan (Yokohama Harbor) can be met from within Asia [e.g., Indonesia (ASW, 2013)] or supply regions we did not explicitly model (e.g., US West-Coast) (Fig. 2). The remaining demand would compete with the EU under our reference supply scenario (see Supply Scenarios). Under stricter criteria for solid biomass within the EU, however, the noneligible parts of total global production would still remain available for trade to other world regions. We assume that these volumes would suffice to satisfy the demand by Japan and South Korea.

## *Demand scenarios*

We run two different demand scenarios to cover a conservative and optimistic view on European renewable energy policy developments. Also, as a sensitivity analysis, we specifically model the EU demand projected via the NREAPs.

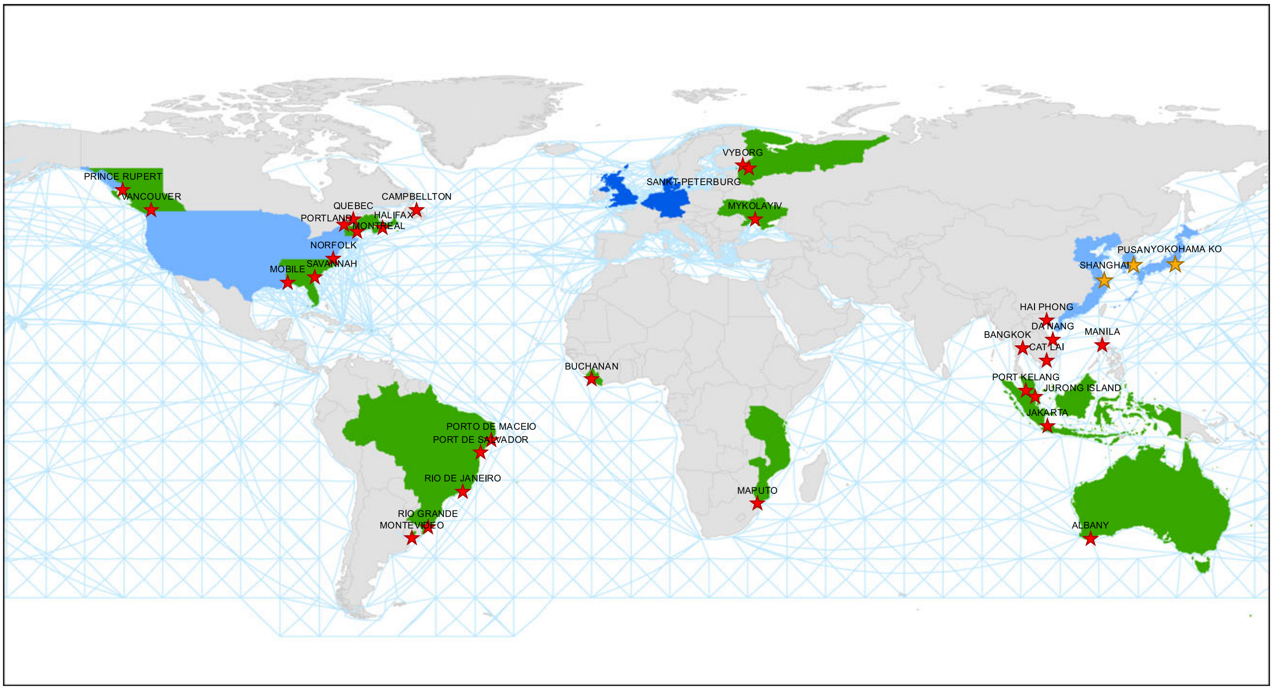


**Fig. 2** We defined specific global demand (blue) and supply regions (green) for solid biomass and respective harbors. The geospatially explicit origin/destination matrix between each demand/supply node is shown exemplarily for all open-sea transport route options.

*CON scenario: conservative policy/industry expectations.* The CON scenario postulates a continuation of past renewable energy support schemes causing most MS to miss their 2020 renewable energy targets. It is built on EU demand projections made with the Green-X model for the Re-Shaping project (Ragwitz *et al.*, 2012) where it is called Business-As-Usual.

*NPOL scenario: new policy developments.* The NPOL scenario covers new policy developments and announcements from industry across NW Europe. Information was collected in June/July 2013 from stakeholders directly involved in the respective MS policy discussions and from industry/investors (see Acknowledgments; to safeguard the anonymity of the respective parties, references to specific information pieces are only provided in case of publicly available, written information). While future policies are subject to change, the expected biomass electric capacity projections and the total primary biomass demand for the electricity and heat sector are expected to remain largely valid. For each of the five countries, the (grid-connected) heat production volume, i.e., the CHP fraction of the expected future electrical biomass generation capacity, was calculated via the relation between electricity and grid-connected heat generation in the respective MS' NREAP. The European MS other than BE, DE, DK, NL, and UK follow the choices made in the Green-X scenario which, similar to our NPOL assumptions, postulates a strengthening of national policies (SNP scenario in Ragwitz *et al.*, 2012) to meet the EU 2020 targets.

*NREAP scenario: sensitivity analysis.* The NREAP scenario is used in our sensitivity analysis. It postulates that NW Europe follows the projections made in the respective MS's NREAP for lignocellulosic biomass demand across the electricity, heat, and (advanced) transport fuel sector which are all higher, up to a factor of 200%, compared to the NPOL scenario except in the UK (Table 1). The demand projections for the rest of Europe are the same as in the NPOL scenario.

### Supply scenarios

To reflect the impact of potential future EU sustainability criteria on intra- and extra-EU supply, we run three supply side scenarios with different feedstock ranges eligible to satisfy the demand. In addition, we also run a sensitivity scenario under which only EU supplies may satisfy EU demand. Translating sustainability criteria into feedstock exclusions is a simplistic approach, and research suggests that mere exclusions may not reflect actual environmental impact levels, including carbon balances (Jonker *et al.*, 2013; Lamers *et al.*, 2013a,c). Nevertheless, feedstock exclusions, e.g., via black lists, are currently at the center of the debate on the sustainability of solid biomass use for energy in Europe. Our approach reflects this debate.

*RED scenario: RED on MS-level in NW Europe.* Our reference scenario assumes that the EC's proposition (EC, 2010) to MS to individually adopt solid biomass requirements similar to those for liquid biofuels in the RED remains valid. Across NW Europe, a national adoption of RED or similar criteria is indeed likely (the Dutch government is currently reviewing requirements for the NTA 8080 technical standard and certification scheme for sustainable biomass) and in case of the United Kingdom already proposed (OFGEM, 2011; DECC, 2013b). Alternatively to legal propositions on MS-level, energy utilities

**Table 1** Electric capacity and total solid biomass demand from dedicated mono- or co-firing installations in the NPOL and NREAP scenario

| | Solid biomass installations* | Co-firing capacity | NPOL scenario (2020) | | | | NREAP projections (2020) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | MWe (by 2010) | MWe (by 2012) | MWe | GWh† | Mtonnes WPe‡ | PJ‡ | MWe | GWh† | Mtonnes WPe‡ | PJ‡ |
| BE | 727 | 280 | 910 | 4341 | 2.6 | 45.8 | 2007 | 9575 | 5.8 | 102.1 |
| DE§ | 3179–3650 | (n/a) | 4313 | 22 112 | 13.3 | 234.1 | 4792 | 24 569 | 14.8 | 260.5 |
| DK§ | 1168 | (996)¶ | 1814 | 4788 | 2.9 | 51.0 | 2404 | 6345 | 3.8 | 66.9 |
| NL | 992 | 413–551‖ | 1306 | 6942 | 3.7 | 65.1 | 2253 | 11 975 | 7.2 | 126.7 |
| UK | 2097 | 208–338** | 3895 | 25 541 | 15.4 | 271.0 | 3140 | 20 590 | 12.4 | 218.2 |
| Sum | 8163–8634 | 1897–2165 | 12 238 | 63 724 | 38 | 668.8 | 14 596 | 73 054 | 44 | 774.4 |

Table 1 shows the current and expected solid biomass installation capacity and biomass use (primary) across the study region per country.
*Data provided by MS in their 2010 status reports to the EC for all solid biomass power installations (excluding biogas and bioliquid installations).
†Gross electricity generation.
‡Primary biomass demand (WPe: 'wood pellet equivalent' equals 17.6 GJ $tonne^{-1}$).
§Total installed capacity for solid biomass of all sizes (excluding biogas and bioliquid installations).
¶DEA (2012), total installed capacity for solid biomass of all sizes.
‖Agentschap (2013), the lower value is large-scale installations only, the higher value represents the total installed capacity (i.e. installations of all sizes).
**DECC (2013a), variation between 2011 and 2012 due to partial closure of Tilbury power station (RWE/Essent/npower) after a fire.
BE, Belgium; DE, Germany; DK, Denmark; NL, the Netherlands; UK, United Kingdom.

may themselves adopt criteria in-line with the RED (see e.g. Ryckmans, 2013). Assuming that the criteria would be solid biomass specific and a grandfathering option for existing production and trade routes be introduced, the criteria would not automatically lead to feedstock limitations, i.e., all solid biomass types may be traded in the RED scenario.

*RED+ scenario: RED plus carbon debt criterion.* Critiques claim that the RED criteria are not adequate for solid biomass; primarily as the suggested greenhouse gas (GHG) emission accounting rules (see also EC, 2010) would neglect a temporal imbalance between carbon sequestration and release from forestry biomass (Johnson, 2009; Searchinger *et al.*, 2009; Zanchi *et al.*, 2010). This concept, typically referred to as 'carbon debt', may be adopted by aforementioned initiatives on MS or company level in addition to the RED requirements. While it is not entirely clear how such a criterion may impact biomass supply, current propositions are e.g. to exclude roundwood including low-grade pulpwood via a feedstock black list. In this case, neither local nor imported wood pellets produced with this type of feedstock would be eligible. A political discussion on aforementioned points has already taken place e.g. in DK and NL. For producers and users of wood pellets alike, scenarios modeling an inclusion or exclusion of this forest assortment by 2020 is highly relevant, as most of the currently proposed additional wood pellet production capacity, especially plants of 250,000 tonnes annual capacity or higher, will at least be partly based on 'low-grade' roundwood (i.e. roundwood unsuitable for timber/wood products). Postulating that no land-use change occurs for the production of agricultural biomass, the much shorter rotation (and decay) times suppose that these residue streams may be exempt from an additional carbon debt criterion. Also, the establishment of short rotation forestry on agricultural land – postulating no direct or indirect displacement of other land use – generally tends to create net carbon benefits (Zanchi *et al.*, 2012; Agostini *et al.*, 2013; Jonker *et al.*, 2013; Lamers & Junginger, 2013).

*RED++ scenario: RED criteria for agricultural biomass, no additional forest resources.* In an extreme case, the discussion around carbon debt may lead to an exclusion of all forest biomass for the use in large-scale, nonresidential applications. This may be achieved via a temporal carbon criterion, but could also be linked, for instance, to the exclusion of biomass from 'primary forests'. Should the 'primary forest' definition of the RED also be applied to solid biomass, the majority of biomass from, e.g., Canadian or Russian forests would not be eligible for energy use as current forestry operations in these countries harvest stands which are theoretically in a 'natural condition', i.e., have not been harvested before and regrown. At the same time, forest management activities in Canada try to emulate natural disturbances and conserve features of natural ecosystems both at the stand and landscape levels. Therefore, even in managed areas, forests keep a high degree of naturalness (Thiffault, 2013). Nevertheless, a limitation to 'nonprimary' forests would not only apply to the roundwood but also any residue fraction used for energy; an aspect that is scientifically controversial (Lamers *et al.*, 2013c), especially because the same assortments may still be used for material purposes, e.g., pulp and paper. Essentially, the RED++ scenario assumes that no forest biomass may be used by large-scale, industrial applications except for the local use of processing by-products, e.g., black liquor, bark, shavings, or sawdust. Large-scale energy generation installations would need to rely exclusively on agricultural residue or crop streams, e.g., short-rotation coppice. Nevertheless, the scenario would allow the continuation of any previous, local use of forest biomass in residential heating appliances. This assumption is based on the widely distributed traditional wood use from smallholder forests, which is bound to continue under an EC sustainability scheme for solid biomass.

*RED++ NT scenario: RED++ scenario, no trade (i.e., no imports).* The sensitivity scenario excludes international trade, i.e., EU imports. While a mere ban of imports may breach WTO rules, trade could also be limited via additional GHG requirements, e.g., limiting ship transport emissions. This implies that large-scale installations may only source agricultural biomass from within the EU.

## *Parameterization*

*Extra-EU supply volumes and prices.* *Wood pellets:* Our prognosis of future wood pellet production trends is based on past production and trade volumes until 2012/2013 (Lamers *et al.*, 2012, 2013b), and market information data on plants currently proposed or under construction (e.g., Bioenergy International, 2010, 2013; Sackett, 2012; Biomass-Magazine, 2013). We also consulted various wood pellet market experts for anecdotal, informal market information (see Acknowledgments). While capacity increases are expected worldwide, we focused our analysis on southeast and northeast USA, Canada (West and East coast), north–west Russia, Brazil, Australia, and New Zealand, which are expected to remain or become wood pellet producers with a strong or major export focus towards Europe. Our capacity database is further detailed by the feedstock which will be used. Here, we distinguish between primary, secondary, and tertiary residues and pulpwood-quality roundwood (Fig. 3). The information basis for this differentiation is again largely market information, but also interviews with plant/proposal owners/investors.

As the EU has been and is expected to remain the key export region, we expect the investments in this sector until 2020 to be heavily influenced by the future EU sustainability criteria. Industry interviewees indicate that around 50% of the currently announced additional wood pellet plant capacities can be expected to eventually come online by 2020. In addition, load factor trends of global capacity and production (Bioenergy International, 2010, 2013) show that the capacity utilization factor of new wood pellet plants will be at around 50% on average across new installations. These assumptions generate wood pellet supply projections in the range of 14–15 Mtonnes by 2020 (Fig. 3) which are in line with an updated version of the EU import scenarios in Goh *et al.* (2013). Given a continuation of the observed capacity growth curves, they are also comparable to projections by Pöyry (2013), showing 21–27 Mtonnes tradable wood pellets by 2025.

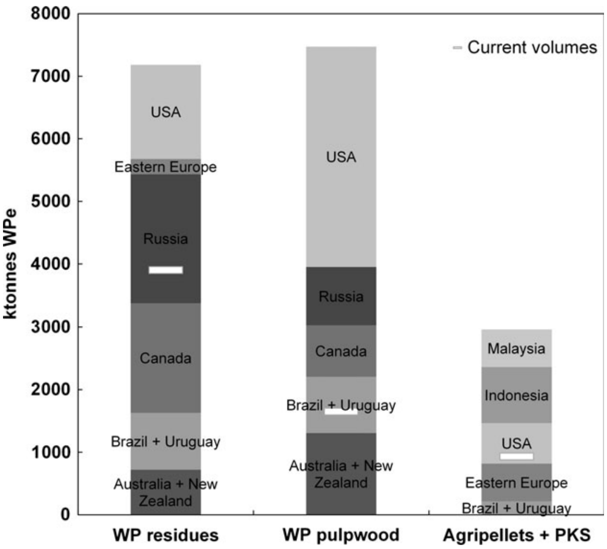


**Fig. 3** The total volume of residual agricultural biomass (in pelletized and raw form) lies in the range of 20–25% of our projected wood pellet volumes by 2020. The total extra-EU supply of wood pellets (WP) by 2020 is projected at just short of 15 Mtonnes. WP residues, wood pellets derived from primary or secondary residues; WP pulpwood, wood pellets made from pulpwood quality roundwood; PKS, palm kernel shells (traded in raw form).

*Agricultural residue streams:* The eventual development of agripellet supply chains will partly depend on future EU sustainability criteria (stronger requirements for forest biomass may spur growth in the agricultural sector, while additional criteria may also limit future agricultural residue supply, see e.g. Batidzirai & Faaij, 2013), but largely on technical requirements for trade and combustion and thus investments in pelletization technologies. Established infrastructure, an existing export-orientation of the underlying agricultural sector, and potentially past energy-related trade of agricultural residues were the key deciding factors for our choice of countries and feedstock. We explicitly model the potential supply from the United States (corn, wheat), Brazil (corn, sugarcane), Indonesia (oil palm), Malaysia (oil palm), and the Ukraine (sunflower, wheat) (see Supporting Information). An initial scoping of the theoretical upper sustainable agricultural residue potentials in aforementioned countries based on crop-residue ratios and expected future harvest volumes showed that the defining bottleneck will not be the available volumes but rather the number of pelletization plants and established logistic chains (see Supporting Information). This holds true even under high retention levels to, e.g., safeguard soil organic carbon levels (see Supporting Information).

Oil palm kernel shells (PKS) do not have to be pelletized prior to trade and were the only feedstock whose future tradable volumes we estimated via palm oil production trends (FAPRI, 2012) and past shipments (Lamers *et al.*, 2012). Due to the required investments in pelletization equipment, all other feedstock and country combinations are based on capacity trends. As there is little to no public information on such trends, our projections for 2020 build on 2010 data, which are extrapolated using the most recent developments (i.e., 2002–2012) in key wood pellet export markets. Few wood pellet production markets however date back 10 years or have reliable data available. We use the US wood pellet market as the main reference due to data availability and quality. Also, the United States is currently the key focus region for wood pellet investments and – since investment conditions etc. will be similar – could also become the largest single potential supplier of agripellets.

The total volume of residual agricultural biomass (in pelletized and raw form) lies in the range of 20-25% of our projected wood pellet volumes by 2020 (Fig. 3). This matches expert expectations (see Acknowledgments) on agripellet market growth. Primary reasons for this development are that agripellet production tends to be more difficult commercially than wood pellets due to feedstock variability of volumes over time (seasonality, rotations), i.e., a lack of consistent long-term supply guarantees, and quality (nutrients, alkalis, ash content).

*Supply costs:* Wood pellet FOB prices outside Europe (Table 2) are based on average prices per supply region as published between May and November 2012 in Argus Media (2012) and oil price developments towards 2020 (IEA, 2012b).

Due to the lack of official and consecutive trade data, agripellet FOB prices are calculated via farmer premiums and logistic cost formulas presented in Hess *et al.* (2009). For US corn stover, the shortest distance between the selected US harbors and the logistical centers of the main corn producing states (see Milbrandt, 2005) is the harbor in Mobile, Alabama (AL). A weighted overall distance was calculated via the corn production share per state (Milbrandt, 2005) multiplied by the distance between the logistical center of the respective state and Mobile, AL. Based on these logistical corridors, in general <10% of the distance has to be done by truck while the remaining share can be done via rail or ship. The FOB prices for Brazil include a 400 km average transport range of which the vast majority (80%) is done via truck/road.

The FOB prices for PKS are based on market information and personal interviews with former PKS traders (M. Wild, personal communication). The reference value at the farm gate is assumed to be 85 US$ tonne$^{-1}$ for both Malaysia and Indonesia (due to the strong geographic and economic linkages between both markets). While PKS will be traded in raw form and oil palm empty fruit bunches (EFB) need to be pelletized prior to international shipping, they are assumed to be able to largely use the same logistic chains from production locations to export harbors. Prior to pelletization, EFB need to be dried and milled. With a dry matter content of 65%, pre-processing and pelletization costs will make up approximately one-third of the total FOB prices of EFB and render them at a higher FOB export price than PKS (Table 2). The FOB prices of the different commodities are not varied across the supply scenarios as we do not model a demand-supply interaction.

## EU supply volumes and costs

There is inherent uncertainty about the exact biomass supply by 2020 within Europe. The EU primary biomass supply across

**Table 2** FOB prices per harbor modeled

| Harbor | Country/region | Pellet type | FOB (€ tonne$^{-1}$ WPe) | FOB (€ GJ$^{-1}$) |
|---|---|---|---|---|
| Albany | Australia | WP | 108 | 6.14 |
| Rio Grande, Porto de Maceio, Port de Salvador, Rio de Janeiro | Brazil | WP | 108 | 6.14 |
| Halifax (NS), Campbellton (NB) | East Canada (inland) | WP | 117 | 6.65 |
| Montreal (QC), Quebec City (QC) | East Canada (coast) | WP | 131 | 7.44 |
| Vancouver (BC), Prince Rupert (BC) | West Canada | WP | 105 | 5.97 |
| Auckland | New Zealand | WP | 108 | 6.14 |
| Sankt-Petersburg, Vyborg | North/West Russia | WP | 123 | 6.99 |
| Mykolayiv | Ukraine | WP | 123 | 6.99 |
| Montevideo | Uruguay | WP | 108 | 6.14 |
| Norfolk (VA), Portland (ME) | (North-) East USA | WP | 117 | 6.65 |
| Savannah (GA) | Southeast USA | WP | 108 | 6.14 |
| Mobile (AL) | Southeast USA | WP | 108 | 6.14 |
| Mobile (AL) | Southeast USA | CSP, WSP | 142 | 8.07 |
| Rio Grande, Porto de Maceio, Port de Salvador, Rio de Janeiro | Brazil | CSP | 154 | 8.75 |
| Jakarta | Indonesia | EFB | 150 | 8.52 |
| Port Kelang | Malaysia | EFB | 150 | 8.52 |
| Jakarta | Indonesia | PKS | 105 | 5.97 |
| Port Kelang | Malaysia | PKS | 105 | 5.97 |

Table 2 shows the different harbors (compare to Fig. 2) modeled within our analysis and their respective supply costs for different feedstock types.
FOB, free on board; WP, wood pellet (residue and/or pulpwood based); CSP, corn stover pellet; WSP, wheat straw pellet; EFB, oil palm empty fruit bunch pellet; PKS, oil palm kernel shell (raw, not pelletized).

our allocation runs, determining intra-EU volumes and costs, is based on the Green-X input database (Hoefnagels *et al*., 2011b). The dataset includes the economic-implementation potential of 20 different biomass resources per EU MS (Table 3). The economic implementation potential is interpreted as the potential that is economically feasible within a certain time frame taking policy incentives, institutional and social constraints into account (Smeets & Faaij, 2007; Dornburg *et al*., 2010; Chum *et al*., 2011; Batidzirai *et al*., 2012). A discussion of the potentials and costs of these and other biomass categories in GREEN-X per EU MS is provided as Supporting Information (see also Hoefnagels *et al*., 2011a). The regional distribution within the respective EU MS is based on the energy crop potentials per NUTS-2 region by de Wit & Faaij (2010). For forest biomass, it was assumed that the potential is equally distributed to the relative share of forest cover per NUTS-2 region (Eurostat, 2012). These shares are assumed to remain constant over time (Hoefnagels *et al*., 2011c). We exclude the Green-X resource base for organic waste and energy crops which are primarily destined for first-generation biofuels (e.g., wheat, maize) and biogas (Table 3). Thus, our modeling considers an exogenous, fixed demand for land by these sectors and feedstock options.

For reasons of model efficiency and to take historically grown local biomass use by industries and households into account, the solid biomass demand of some sectors is assumed to be partly met by domestic use (Table 3). This applies to three specific cases: the use of black liquor (an industry by-product in pulp and paper manufacturing) for the production of industrial heat and power (RES-$E_{industry}$), residential heating in household stoves (RES-$H_{residential}$), and second-generation transport fuel production from lignocellulosic material (RES-$T_{advanced}$). In all cases, the local demand is subtracted from the total potential supply (on NUTS-1 level). This implies that while it is included in the biomass allocation runs, it may only be used domestically. This avoids that biomass currently used domestically may become available for intra-EU trade and use in large-scale electricity generation within our allocation runs.

To further improve model efficiency, the EU supply is aggregated into four resource categories: Agriculture products (AP), Agriculture residues (AR), Forest products (FP), and Forest residues (FR). After the subtraction of predefined domestic use, the sum of the remaining potential and the weighted average supply costs (on NUTS-1 level) represent the EU cost–supply potential (Table 4). Due to the primarily local use, pelletization capacity is not a prerequisite or limiting factor to exploit EU biomass potentials. We do however include current pre-processing steps (e.g. bailing) in our supply costs.

## Results

### *Demand side developments*

The biomass demand in the CON and NPOL scenarios remains lower than the demand in the 2020 NREAP projections, except for DE and the UK (Fig. 4). The strongest absolute and relative increase as compared to 2010 is seen in the demand for industrial heat and

**Table 3** Coverage of Green-X biomass resource types and imported biomass per scenario

| | RED | RED+ | RED++ | RED++ NT | Predefined use (partial) |
|---|---|---|---|---|---|
| EU: agriculture products (AP, energy crops) | | | | | |
| AP1 (rape/canola, sunflower) | No | No | No | No | |
| AP2 (maize, wheat – seeds) | No | No | No | No | |
| AP3 (maize, wheat – whole plant) | No | No | No | No | |
| AP4 (short-rotation-coppice, e.g. willow) | Yes | Yes | Yes | Yes | |
| AP5 (miscanthus) | Yes | Yes | Yes | Yes | |
| AP6 (switch grass) | Yes | Yes | Yes | Yes | |
| AP7 (sweet sorghum) | No | No | No | No | |
| EU: agriculture residues (AR) | | | | | |
| AR1 (straw) | Yes | Yes | Yes | Yes | RES-$T_{advanced}$ |
| AR2 (other agricultural residues) | Yes | Yes | Yes | Yes | |
| EU: forest products (FP) | | | | | |
| FP1 (current use of wood chips, log wood) | Yes | Yes | Yes | Yes | RES-$H_{residential}$ |
| FP2 (complementary fellings – moderate) | Yes | No | No | No | |
| FP3 (complementary fellings – expensive) | Yes | No | No | No | |
| EU: forest residues (FR) | | | | | |
| FR1 (black liquor – current use) | Yes | Yes | Yes | Yes | RES-$E_{indudstry}$ |
| FR2 (forestry residues – current use) | Yes | Yes | No | No | |
| FR3 (forestry residues – additional) | Yes | Yes | No | No | |
| FR4 (demolition wood – current use) | Yes | Yes | Yes | Yes | |
| FR5 (processing residues – additional) | Yes | Yes | No | No | |
| Extra-EU: imported biomass | | | | | |
| Agripellets and PKS | Yes | Yes | Yes | No | |
| Forest residue pellets | Yes | Yes | No | No | |
| Pulpwood pellets | Yes | No | No | No | |

Table 3 provides an overview of the different biomass types covered across the supply scenarios from the Green-X database (and imported biomass below). It also shows the predefined use.

**Table 4** EU solid biomass potential and supply costs per resource category in PJ and Mtonne WPe

| | Total potential | Predefined use | Tradable potential | Supply cost* range |
|---|---|---|---|---|
| Agriculture products (AP) | 1122 PJ | 0 PJ | 1122 PJ | 8.47–11.88 € $GJ^{-1}$ |
| | 64 Mtonne WPe | 0 Mtonne WPe | 64 Mtonne WPe | 149–209 € $tonne^{-1}$ WPe |
| Agriculture residues (AR) | 1255 PJ | 170 PJ | 1085 PJ | 8.47–9.94 € $GJ^{-1}$ |
| | 71 Mtonne WPe | 10 Mtonne WPe | 61 Mtonne WPe | 149–175 € $tonne^{-1}$ WPe |
| Forest products (FP) | 2917 PJ | 1971 PJ | 946 PJ | 9.32–11.31 € $GJ^{-1}$ |
| | 166 Mtonne WPe | 112 Mtonne WPe | 54 Mtonne WPe | 164–199 € $tonne^{-1}$ WPe |
| Forest residues (FR) | 1497 PJ | 486 PJ | 1011 PJ | 4.03–4.89 € $GJ^{-1}$ |
| | 85 Mtonne WPe | 28 Mtonne WPe | 57 Mtonne WPe | 71–86 € $tonne^{-1}$ WPe |

Table 4 summarizes the total solid biomass potential within the EU per feedstock category.
*Supply costs include production and processing costs only.

power generation. While this represents an industry trend, it is also influenced by a stagnant or slightly declining share of the demand for wood in residential heating (Table S6).

*Supply side observations*

Granted requirements for solid biomass production similar to those defined under the RED and a market development in the wood pellet sector as currently indicated by capacity announcements (RED scenario), energy utilities could largely rely on existing supply streams but would need to incorporate a much larger volume of agricultural biomass over time. A continuation of the current feedstock selection in large-scale co- or mono-firing across NW Europe implies domination by wood pellets based on harvesting and processing residues, and to an increasing extent also pulpwood.

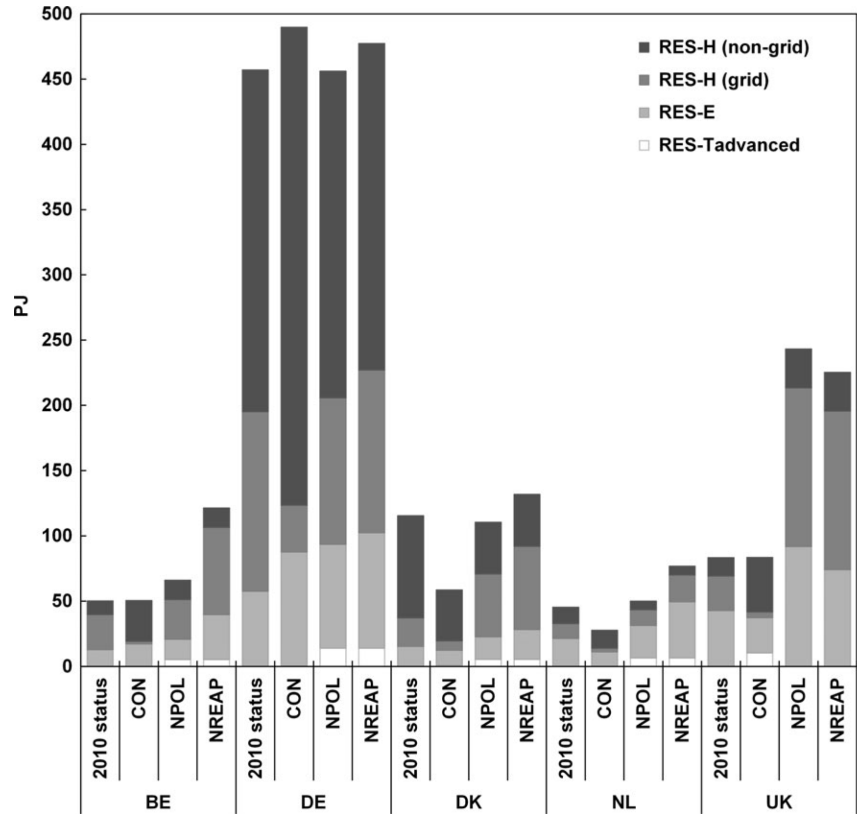


**Fig. 4** Primary solid biomass demand by end-use across NW Europe in 2010 and as projected for 2020 under a conservative scenario (CON), a new policies (NPOL) scenario, and the NREAPs scenario (excludes biogas and bioliquids).

The key change would be the increasing role of agricultural biomass, residues in particular (Fig. 5), whose overall share in electricity and heat generation has so far been marginal.

Due to the expected capacity restrictions for extra-EU biomass supply (Fig. 3), the MS will have to rely largely on intra-EU biomass to meet the 2020 targets (Table S6). The local biomass exploitation levels generally increase with additional sustainability requirements. With the exception of the predefined domestic supply from FP (for residential heating), the domestic streams will largely be FR including waste wood and AR streams (Fig. 5). This also implies that extra-EU trade is highest under lower criteria and intra-EU trade increases with more stringent sustainability requirements (Fig. 6). Extra-EU imports may increase to 221–236 PJ (RED) or 417–445% of their 2010 level. Intra-EU trade may reach 482–546 PJ (RED++ NT) or 243–277% compared to their respective 2010 level as quantified in Lamers *et al.* (2012).

### *Impact of increasing sustainability requirements*

The way this study simulates the impact of RED to RED+ is translated by excluding additional forest roundwood use and thus, e.g., pulpwood pellets. This has a smaller effect on intra-EU volumes as compared to extra-EU imports as little roundwood is used (apart from predefined residential heating) (Fig. 5). It will however cut imports to the EU by roughly a quarter (Fig. 6). These will be replaced by an additional use of AR and perennial crops (i.e., agricultural products, AP) of a similar cost range from within the EU (Figs 5 and 8). This can also be observed in the relatively small increase in total supply costs (by up to 2%) between the RED and RED+ scenario (Table 5). Naturally, the trade portfolio change has a more drastic effect on import dependent countries, foremost the NL and the UK. As shown in Fig. 8 (see Supporting Information for additional curves), the UK cost–supply curve moves by almost 5 Mtonnes WPe to higher priced biomass (largely intra-EU AR and AP).

In the RED++ scenario, the exclusion of forest residue usage (except black liquor and demolition wood, Table 3) drives up supply costs significantly (up to 25%) as cheaper supply from within the EU drops (Fig. 5). This shift is greatly noticeable in the overall weighted supply cost balance per scenario (Table 5) and is strongest for largely self-sufficient, local biomass users such as DE. This is exemplarily shown for an

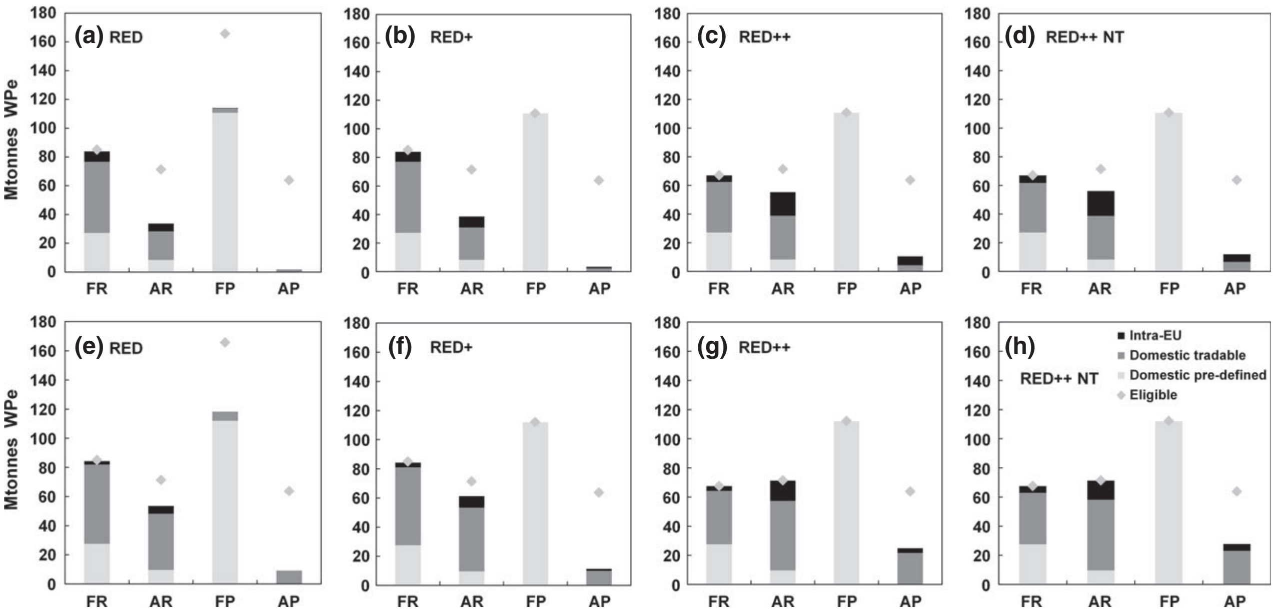


**Fig. 5** EU27 supply potential exploitation levels compared to the eligible supply volumes under the CON (upper row, a–d) and NPOL (lower row, e–h) demand scenarios. FR, forest residues; AR, agriculture residues; FP, forest products; AP, agriculture products.

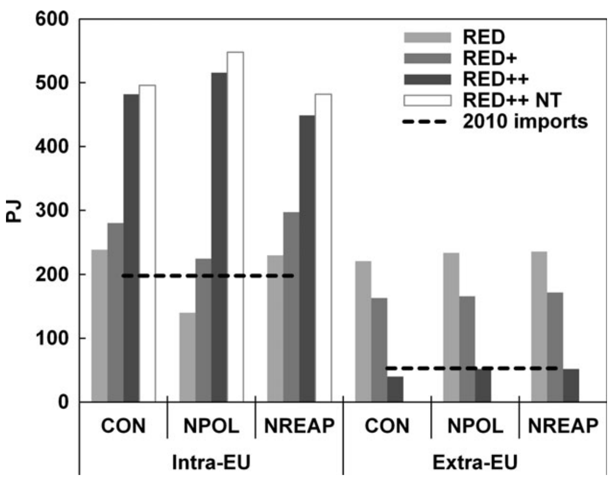


**Fig. 6** Absolute intra- and extra-EU trade volumes per scenario compared to 2010 values in Lamers *et al.* (2012).

NPOL scenario in Fig. 8. The reduction in domestic German FR use (under 50 € tonne$^{-1}$ WPe) needs to be replaced by domestic AP of over 150 € tonne$^{-1}$ WPe. Under the RED++ scenario, the exploitation of AR streams for energy reaches its maximum in the NPOL demand scenario (Fig. 5). The exclusion of extra-EU imports in a RED++ NT scenario then creates additional demand for AP such as willow, miscanthus, or switchgrass in the range of 40–52 PJ; although in a similar cost range than previously imported material (Table 5).

A key influencing factor for the differences in the supply portfolio of individual countries is the accessibility to extra-EU imports, i.e., the existence of sea and river harbors. International competition (in coastal regions) makes them fulfill some of their demand via sea and

**Table 5** Total annual weighted supply costs per scenario and country (million euro) excluding CAPEX and OPEX for power plant conversions or pelletization equipment

| | RED | RED+ | RED++ | RED++ NT |
|---|---|---|---|---|
| CON | | | | |
| BE | 495 | 489 | 557 | 536 |
| DE | 3976 | 4116 | 4511 | 4463 |
| DK | 391 | 391 | 409 | 409 |
| NL | 254 | 217 | 236 | 272 |
| UK | 645 | 637 | 755 | 716 |
| NW EU | 5761 | 5850 | 6468 | 6397 |
| NPOL | | | | |
| BE | 333 | 337 | 466 | 530 |
| DE | 2746 | 2645 | 3295 | 3205 |
| DK | 477 | 475 | 758 | 744 |
| NL | 515 | 550 | 724 | 752 |
| UK | 2164 | 2263 | 2622 | 2660 |
| NW EU | 6234 | 6270 | 7866 | 7892 |
| NREAP | | | | |
| BE | 763 | 762 | 903 | 935 |
| DE | 2940 | 2762 | 3133 | 3072 |
| DK | 631 | 641 | 647 | 680 |
| NL | 960 | 1173 | 1250 | 1249 |
| UK | 1754 | 1737 | 1917 | 1900 |
| NW EU | 7049 | 7075 | 7850 | 7835 |

Table 5 presents the total costs (results) per scenario run.
BE, Belgium; DE, Germany; DK, Denmark; NL, the Netherlands; UK, United Kingdom; NW EU, North-West Europe.

river ports and leaves the cheaper biomass for other inner-EU, i.e., landlocked demand nodes. This is fundamentally linked to our assumption of an equal paying capacity across all demand nodes and a supply-cost optimization for the demand side as a whole, i.e. not country-specific. BE, NL, and the UK are import dependent and reach their lowest overall supply costs in the highest import scenario, i.e. RED (Table 5, Fig. 7). This is due to the fact that their demand nodes, those in the UK in particular, would need to import biomass in any case; either from the EU mainland or any other world region. Therefore, in our modeling optimization, these countries/nodes will tend to out-compete other EU regions for international biomass supply. DE and DK are relatively less accessible for international imports and thus do not benefit from a larger (and cheaper) international supply as much as aforementioned countries. In addition, they both have a larger domestic supply – in relative fraction to the overall demand, and rely mainly on additional intra-EU supply volumes (e.g., via the Danube channel in the case of DE or the Baltic Sea in the case of DK).

Comparing the total cost–supply curves for NW Europe, it is clear that the predefined, low-cost domestic supply volumes are exploited similarly across all scenarios (Fig. 7). The key differences between the cost–supply curves lie beyond the 50 Mtonnes WPe mark, i.e., above 100 € $tonne^{-1}$ of WPe, when extra-EU imports start to compete with EU biomass, in particular domestic complimentary fellings (FP) and cultivated perennial biomass (AP) (see also Fig. 8 and Supporting Information). Eventually, almost all eligible parts of the extra-EU supply volumes are imported to the EU across our scenarios (Supporting Information). The exceptions are higher priced extra-EU agripellets, which are traded only under the most stringent trade scenario (RED++). In our scenarios, supply costs generally increase with more stringent sustainability criteria (Table 5); although small variations exist (Fig. 7). The intertemporal cost variations are exclusively related to the fact that the geospatially explicit optimization occurs for the whole demand side, i.e. Europe (EU27) and Asia, whereas the graphs only show results for NW Europe.

## Discussion

### *Robustness of our approach*

The modeling framework optimizes geospatially explicit cost–supply data and is able to simulate competition for different solid biomass types in a global setting. Its bottom-up design allows the inclusion of regionally explicit production and logistic capacity developments. The model structure is versatile and could be applied to different biomass markets and/or world regions. We applied it to the European context and a 2020 timeframe.

Our assessment of the potential future impacts of sustainability criteria on biomass supplies is based on feedstock exclusions. While this matches current EU discussions on feedstock blacklists, strictly speaking, it is a simplistic representation of criteria impacts on biomass supply. Eventually, policy makers will have to find a middle ground between an applicable yet scientifically robust mechanism. So far, little data are available and more research is required to appropriately model potential sustainability criteria impacts such as minimum GHG emission savings on biomass mobilization costs and volumes.

The individual modeling results depend on the underlying parameterization and foremost the assumed available biomass volumes and their respective costs. Our extra-EU supply parameters for wood pellets build upon the latest on the ground data and information

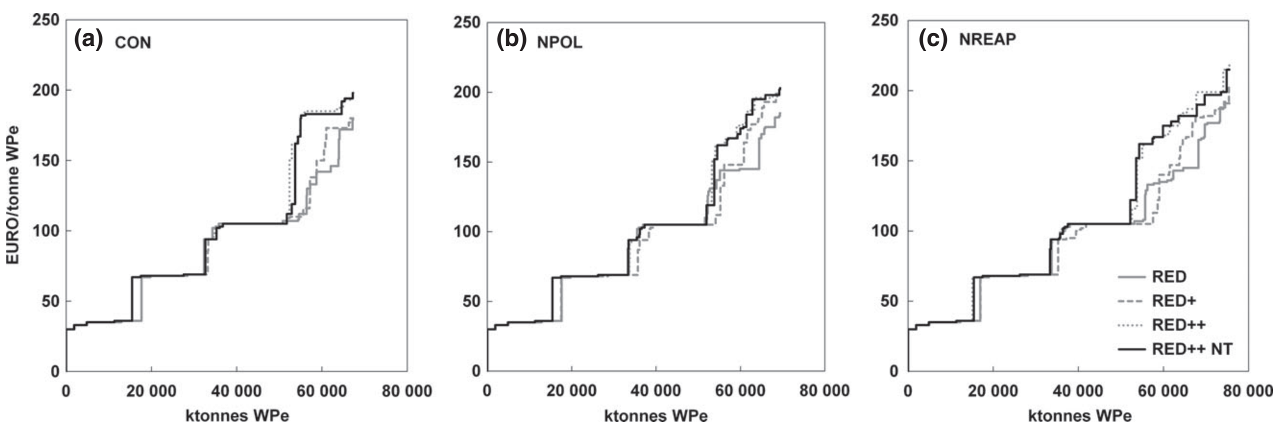


**Fig. 7** Cost–supply curves for lignocellulosic biomass across all sectors (as shown in Fig. 3) in NW Europe for all supply and demand scenarios.

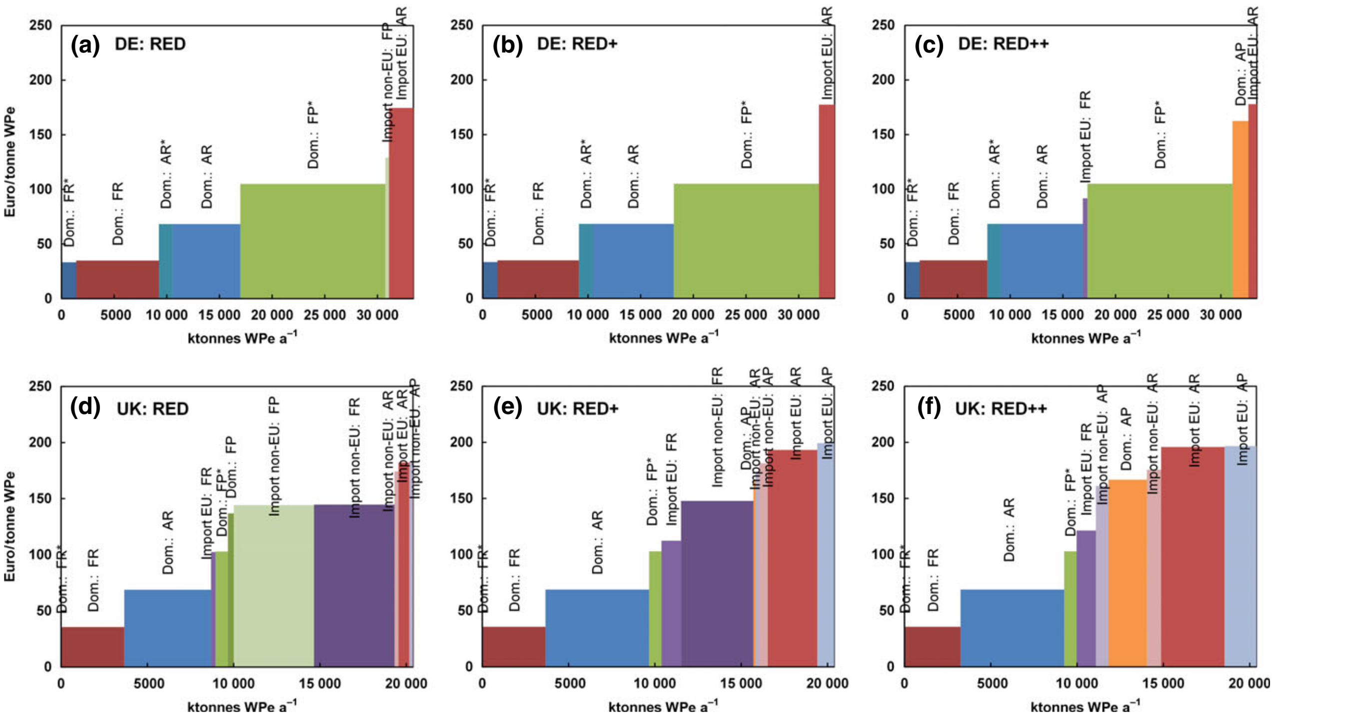


**Fig. 8** Cost–supply curves for Germany (DE) and the UK under an NPOL demand scenario. Dom. stands for domestic supply; *indicates predefined demand.

collected via involved market parties. The critical uncertainty in our runs is connected to a global lack of robust data on expected capacity developments for agriculture residue pelletization and FOB prices for agripellets. Within the EU, the Green-X database is the largest single influencing factor regarding our modeling outcomes (see Supporting Information for a detailed description of underlying Green-X assumptions and comparisons to other datasets). While the forest supply data are in-line with other studies in the field (Figs S4 and S5), the Green-X model does not contain a biomass crop production and land-use module and is therefore limited to predefined, potentially suboptimal agriculture crop mixes. For 2020, the Green-X agriculture dataset used in our modeling considers a business-as-usual case regarding the future energy crop costs and production levels (Figs S2 and S3). It may underestimate the potential future availability of low-cost lignocellulosic agriculture biomass within Europe by 0.9 EJ as compared to, e.g., de Wit & Faaij (2010) who projected potentially higher volumes of low-cost energy crops, roughly 4.2 EJ (1.8–6.8 EJ range), especially for Eastern Europe. Tapping these potentials until 2020, however, would require, e.g., a wider reform of the agricultural sector in Eastern Europe, and a rapid mobilization. This could although be influenced by policy makers to actively compensate unwanted extra-EU solid biomass imports with domestic biomass. Additional sensitivities to our results include the technological and economic development of large-scale second-generation transport fuel and/or biochemical production from lignocellulosic material, which would increase competition for the feedstock modeled, residues in particular. Also, we do not model dynamic interactions of land competition between lignocellulosic biomass and other feedstock types namely for first-generation biofuel and biogas. In this analysis, this demand is provided exogenously (in Green-X) and does not reflect potential future supply (e.g., yield improvements) or demand (e.g., policy) changes.

In this respect, our analysis does not model potential land-use change within Europe. Considering an exogenous, fixed demand for land by first-generation biofuels and biogas, however, limits the competition for land in our modeling runs to solid biomass sectors and feedstock options. Regarding the latter, it should be noted that not all agricultural residues are exploited within Europe (due to the higher costs); even in our highest demand scenarios (NPOL and NREAP). Independent of supply and eventually policy costs, a prioritization of these potentials could directly help mitigate or prevent land-use change. In addition, analysis, e.g., by de Wit (2011) suggests that Europe can absorb increased demand sustainably.

The analysis generally shows that NW Europe will remain the primary destination for extra-European biomass, in particular the UK, NL, and BE. The assumed demand for solid biomass differs between scenarios but is static; a necessary simplification to generate optimization runs within our model. The key demand for solid biomass however is based on co-firing capacity developments based on similar views by different parties. Nevertheless, it is not clear yet how policy schemes in the modeled demand regions and thus their buying power will develop. This will inevitably influence the competition for the available biomass resources and our individual country results (see Supporting Information) should be regarded as indicative and not absolute. The model cost-optimizes biomass supply for the whole demand side, suggesting that all biomass users are willing and able to pay the same price in 2020. This simplification suggests a harmonized policy scheme and may neglect potentially different incentives across NW Europe. At the same time, current (divergent) policy regimes indicate that the key demand regions for internationally traded biomass, wood pellets in particular, are going to be the UK and NL. Across our modeling results, both countries attract most of the international biomass streams.

The modeling differentiates between multiple geospatially explicit supply and demand nodes, but is unable to simulate individual supply contracts between biomass producers and users; which are still the most common form of biomass trade (in comparison to volumes traded, e.g., via biomass exchange platforms). This implies that our results may deviate from current business practice, i.e. import portfolios for specific countries, but remain valid on regional level. Also, in the past, intra-EU trade has been highly influenced by legal differences in, e.g., waste wood combustion requirements or national support schemes. While the model could cope with this, our cost-based optimization runs do not take such differences into account. The intra-EU trade volumes in the RED scenario although suggest that much of the traded volumes within Europe will be used locally rather than being exported to other MS – in case of equal legal frameworks and buying power.

Finally, the model is restricted to simulate competition between different solid biomass streams and origins. Neither does it cover a potential shift to other renewable energy technologies such as wind and solar, which may be enforced by stricter sustainability criteria for solid biomass. Nor does it entail learning effects (e.g., yield improvements) which could reduce biomass supply costs (see e.g. de Wit *et al*., 2010).

### *Comparison to other studies*

Our results are in-line with a recent evaluation of Europe's bioenergy potential by the European Environmental Agency (EEA, 2013) which explicitly modeled the use of EU biomass under different sustainability constraints, providing suggestions on the exploitation of forestry and agricultural resources based on these constraints. While our supply optimization is on cost basis and feedstock exclusions linked to criteria rather than GHG performance, it adds to the findings of EEA (2013) by providing cost–supply curves and capacity indications for achieving biomass use levels by 2020.

van Stralen *et al.* (2013) evaluated the role of biomass in the EU's 2020 energy mix for electricity, heat, and transport via the RESolve model. The authors concluded that the NREAP targets are ambitious (see also Atanasiu, 2010) and questioned whether they can be reached, especially under strict sustainability criteria. Our study indicates that while stricter criteria will increase the overall supply (and thus policy) costs, the EU will still be able to supply sufficient solid biomass to meet its targets in the electricity and heating sector plus second generation transport fuel. The key question will be how cost-effective the 2020 targets can be achieved and how policy makers will incentivize the mobilization of biomass.

At the same time, our simulations imply no additional competition for solid biomass by 2020, e.g., from biochemical production. In this, the RED supply scenario indicates the current chances of AR use in a competitive biomass environment. It shows that agripellets and PKS are competitive with forestry products. The RED++ scenario presents how far the EU targets could be reached via agricultural biomass (residues and products) alone. Excluding international trade options, our RED++ NT scenario also indicates an option via domestic resources only.

### *Implications*

While this analysis is focused on the trajectory until 2020, all recommendations are given for a timeline beyond 2020, especially due to the expected future role of solid biomass use for biochemicals and second-generation biofuels.

*For policy makers.* Restricting the eligibility of specific solid biomass fractions will create higher (policy) costs. Rather than applying biomass black lists, incentives for a hierarchical use of biomass (cascading) and stable framework conditions, i.e., a long-term, transparent strategy are needed. The lion's share of the EU biomass supply by 2020 will still be locally sourced (granted that it fulfills the suggested criteria set). The highest share of extra-EU imports by 2020 is reached under a RED supply scenario given NREAP demand levels (9% for the EU, 28% for NW Europe). Given current policy developments (NPOL demand scenario), import levels are likely to stay smaller. Generally, the bottleneck to a sufficiently large solid biomass supply to reach the EU's 2020 targets does not appear to be the sustainable biomass potentials (especially perennial crops) but rather the lack of exploitation capacity (e.g., pelletization facilities and connected logistics). This is particularly the case given stricter sustainability requirements and an increased use of AR.

*For industry and investors.* The policy uncertainty linked to the formulation of exact sustainability requirements brings feedstock and thus investment uncertainty. Currently, agripellet supply from outside the EU is limited by pelletization capacity. While this may change under stricter criteria, current price competitiveness suggests a higher use of intra-EU AR. Increased sustainability requirements may eventually also impact AR, their overall share is likely to increase by 2020 within the EU. This will have technical implications for current and new power plants. Fuel flexibility will be a determining factor. There are also technical preconditions of large-scale AR usage in the upstream parts of the supply chain, predominantly operationalizing the 'farmer to utility' collection and conversion section.

Generally, sustainability criteria increase the cost ranges of the available, i.e. eligible biomass, at least in the short-term. In the long-term, biomass supply costs may again drop due to supply chain or yield improvements. Eventually, the GHG default values (i.e. defined carbon savings per tonne of biomass) within the respective legislation may also drive the costs of specific biomass feedstock. In our scenarios, we assume that the conversion costs of power plants to use agripellets are the same as for wood pellets. This is, however, currently not the case.

Increasing sustainability requirements will require several key investments along the supply chain. Even under our reference supply scenario (RED), extra-EU trade increases by 450% as compared to 2010 levels. While this may shift to larger intra-EU trade under stricter requirements (e.g., RED++ scenario), harbor capacity and logistics will need to increase respectively. Also, an increased AR usage will require a larger number of pelletization plants (investments in capacity) for supply regions with longer shipping distances. Within the EU, simple pre-processing, e.g., bailing may be sufficient in most cases due to regional usage.

*For research.* Our model could be applied to regional or utility specific (cost) optimization strategies. Future model versions could also take dynamic cost–supply interactions (e.g., policy influenced) into account. Additional research may be needed to model a wider competition between solid biomass and other renewable energy sources in the context of GHG mitigation. Generally, it should be investigated whether a use of local, residual agricultural biomass is preferable over biomass imports from a GHG and wider stakeholder (in particular public and policy) perspective. The public perception of an increased agripellet usage may play a determining role. Clearly, there are trade-offs, e.g., rural development vs. competitively priced biomass imports (reducing overall policy and GHG mitigation costs).

An increasing role of AR in the future energy mix, potentially partly due to stricter criteria for forest biomass, could lead farmers to adapt their rotations or harvest shares. It will be critical to prevent overharvesting and contain e.g. soil carbon balances.

Furthermore, it should be evaluated how current biomass supply costs could be reduced in order to guarantee a stable supply, under strict sustainability criteria. For research and policy makers alike, it would be desirable to have detailed cost-breakdowns for both forestry and agriculture commodities to identify further cost reduction potentials, and implement cost-efficient policy trajectories. In this regard, future research should also investigate the dynamic relations between scaling and learning (including logistics, pretreatment technologies, and land management optimization) vs. (increased) sustainability criteria. First indications by Batidzirai (2013) show the potential dimensions and ranges of future cost savings, including AR. Reducing the cost of energy crop production could change the outcome of the above scenarios fundamentally. Nevertheless, the biomass would have to be mobilized by 2020 and at competitive costs to either other extra-EU or domestic biomass. Future research should evaluate what efforts are required to mobilize these potentials and how dedicated energy crops, such as short rotation willow, may compete with imported wood pellets.

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## References


AEBIOM (2012) *European Bioenergy Outlook – Statistical Report*. European Biomass Association, Brussels, Belgium. Available at: http://www.jotformeu.com/AEBIOMstatisticalreport/2012_European_Bioenergy_Outlook (accessed 6 June 2013).

Agentschap NL (2013) *Green Deal Duurzaamheid Vaste Biomassa*. Den Hague, The Netherlands. Available at: http://www.agentschapnl.nl/sites/default/files/2013/09/Rapportage%20Green%20Deal%20Duurzaamheid%20Vaste%20Biomassa%20(webversie,%20rapportage%20I%20-%202012).pdf (accessed 23 July 2013).

Agostini A, Giuntoli J, Boulamanti A (2013) Carbon accounting of forest bioenergy. In: *JRC Technical Reports* (ed. Marelli L). European Commission, Joint Research Centre, Institute for Energy and Transport, Ispra, Italy. Available at: http://iet.jrc.ec.europa.eu/bf-ca/sites/bf-ca/files/files/documents/eur25354en_online-final.pdf (accessed 29 March 2013).

Al-Riffai P, Dimaranan B, Laborde D (2010) *Global Trade and Environmental Impact Study of the EU Biofuels Mandate*. International Food Policy Research Institute (IFPRI), Washington, DC, USA. Available at: http://trade.ec.europa.eu/doclib/docs/2010/march/tradoc_145954.pdf (accessed 7 April 2012).

Argus Media (2012) Argus Biomass Markets. Argus Media Ltd, London, UK.

ASW (2013) Korean delegates see wood pellet potential in RI. In: *The Jakarta Post* (ed. Meidyatama Suryodiningrat), Jakarta, Indonesia. Available at: http://www.thejakartapost.com/news/2013/09/06/korean-delegates-see-wood-pellet-potential-ri.html (accessed 28 December 2013).

Atanasiu B (2010) *The Role of Bioenergy in the National Renewable Energy Action Plans: A First Identification of Issues and Uncertainties*. Institute for European Environmental Policy (IEEP), London, UK; Brussels, Belgium. Available at: http://www.ieep.eu/assets/753/bioenergy_in_NREAPs.pdf (accessed 3 November 2012).

Batidzirai B (2013) Design of Sustainable Biomass Value Chains – Optimising the Supply Logistics and Use of Biomass Over Time. PhD, Copernicus Institute, Utrecht University, Utrecht, The Netherlands.

Batidzirai B, Faaij A (2013) *Sustainable Biomass Resource Availability and Supply Strategies for Production of Synfuels – Feasibility of Maize and Wheat Residues Supply for Biomass Energy Application in South Africa*. Copernicus Institute, Utrecht University, Utrecht, The Netherlands.

Batidzirai B, Smeets EMW, Faaij APC (2012) Harmonising bioenergy resource potentials – methodological lessons from review of state of the art bioenergy potential assessments. *Renewable and Sustainable Energy Reviews*, **16**, 6598–6630.

Beurskens L, Hekkenberg M (2010) *Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States*. ECN, Petten, The Netherlands. Available at: http://www.ecn.nl/docs/library/report/2010/e10069.pdf (accessed 31 March 2011).

Bioenergy International (2010) *World Pellets Map*. Svebio, Stockholm, Sweden.

Bioenergy International (2013) *World Pellets Map*. Svebio, Stockholm, Sweden.

Biomass-Magazine (2013) Pellet Plant Producer List. Available at: http://biomassmagazine.com/plants/listplants/pellet/US/ (accessed 1 February 2013).

Chum H, Faaij A, Moreira J *et al.* (2011) Bioenergy. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (eds Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, Stechow CV), pp. 209–332. Cambridge University Press, Cambridge, UK; New York, USA.

Cocchi M, Nikolaisen L, Junginger M *et al.* (2011) Global Wood Pellet Industry and Market Study. IEA Bioenergy Task 40. Available at: http://www.bioenergytrade.org/downloads/t40-global-wood-pellet-market-study_final.pdf (accessed 16 January 2012).

Dale A (2013) Expanding demand and supply perspectives for the industrial pellet markets. In: *AEBIOM Conference* 17–19 June, Ekman, Brussels, Belgium.

DEA (2012) *Energy Statistics 2011: Data, Tables, Statistics, and Maps*. Danish Energy Agency, Copenhagen, Denmark.

DECC (2013a) *Energy Trends Section 6: Renewables*. Department of Energy & Climate Change, London, UK. Available at: https://www.gov.uk/government/publications/renewables-section-6-energy-trends (accessed 26 June 2013).

DECC (2013b) *Government Response to the Consultation on Proposals to Enhance the Sustainability Criteria for the Use of Biomass Feedstocks Under the Renewables Obligation (RO)*. Department of Energy & Climate Change, London, UK. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/231102/RO_Biomass_Sustainability_consultation_-_Government_Response_22_August_2013.pdf (accessed 4 September 2013).

Dornburg V, van Vuuren D, van de Ven G *et al.* (2010) Bioenergy revisited: key factors in global potentials of bioenergy. *Energy & Environmental Science*, **3**, 258–267.

EC (2010) *Report on Sustainability Requirements for the Use of Solid and Gaseous Biomass Sources in Electricity, Heating and Cooling*. European Commission, Brussels, Belgium.

EEA (2013) *EU Bioenergy Potential from a Resource-Efficiency Perspective*. European Environmental Agency, Copenhagen, Denmark. Available at: http://www.eea.europa.eu/publications/eu-bioenergy-potential/at_download/file (accessed 10 July 2013).

Eurostat (2012) *Data Explorer – nrg_1073a*. Eurostat, Brussels, Belgium.

FAPRI (2012) *World Agricultural Outlook*. Food and Agricultural Policy Research Institute, Ames, IA, USA. Available at: http://www.fapri.iastate.edu/outlook/2012/ (accessed 8 June 2013).

Gallagher PW, Baumes H (2012) *Biomass Supply from Corn Residues: Estimates and Critical Review of Procedures*. USDA, Washington, DC, USA. Available at: http://www.usda.gov/oce/reports/energy/Biomass%20Supply%20From%20Corn%20Residues-Nov-2012.pdf (accessed 9 March 2013).

Goh CS, Junginger M, Cocchi M *et al.* (2013) Wood pellet market and trade: a global perspective. *Biofuels, Bioproducts and Biorefining*, **7**, 24–42.

Hess JR, Kenney KL, Ovard LP, Searcy EM, Wright CT (2009) Commodity-Scale Production of an infrastructure-compatible bulk solid from herbaceous lignocellulosic biomass. In: *Uniform-Format Bioenergy Feedstock Supply System Design Report Series*. Idaho National Laboratory, Idaho Falls, ID. Available at: https://inlportal.inl.gov/portal/server.pt/gateway/PTARGS_0_4791_80492_0_0_18/EXT-09-17527_Complete_Report.pdf (accessed 5 May 2013).

Hoefnagels R, Junginger M, Panzer C, Resch G, Held A (2011a) Long term potentials and costs of RES – part I: potentials, diffusion and technological learning. In: *RE-Shaping (D10), Intelligent Energy – Europe*. Universiteit Utrecht, TU Vienna, Utrecht, The Netherlands, Vienna, Austria. Available at: http://igitur-archive.library.uu.nl/chem/2012-0320-200511/UUindex.html (accessed 10 September 2013).

Hoefnagels R, Junginger M, Panzer C, Resch G, Liebmann L, Held A (2011b) Long Term Potentials and Costs of RES – Online Database. Available at: http://www.reshaping-res-policy.eu/downloads/Long-term%20potentials%20and%20cost%20of%20RES%20-%20part%20I%20(Re-Shaping%20report,%202011).pdf (accessed 11 October 2013).

Hoefnagels R, Junginger M, Resch G, Panzer C (2011c) Long term potentials and costs of RES – part II: the role if international biomass trade. In: *RE-Shaping (D12), Intelligent Energy – Europe*. Universiteit Utrecht, TU Vienna, Utrecht, The Netherlands, Vienna, Austria. Available at: http://www.reshaping-res-policy.eu/downloads/WP5_ReportD12%20FINAL.pdf (accessed 7 June 2013).

Hoefnagels R, Cornelissen T, Junginger M, Faaij A (2013) *Capacity Study for Solid Biomass Facilities*. Universiteit Utrecht, Utrecht, The Netherlands. Available at: http://www.portofrotterdam.com/en/Business/rotterdam-energy-port/Documents/PoR%20Capacity%20study%20Trade%20Flows%20Final%20April%202013.pdf (accessed 7 June 2013).

IEA (2012a) Renewable energy outlook. In: *World Energy Outlook* (ed. Fatih Birol), pp. 211–240. International Energy Agency, Paris, France.

IEA (2012b) *World Energy Outlook*. International Energy Agency, Paris, France.

Iguchi H (2012) FIT and biomass demand in Japan. In: *CanBio Annual Conference*. Mitsubishi Corporation, Vancouver, BC, Canada.

Johnson E (2009) Goodbye to carbon neutral: Getting biomass footprints right. *Environmental Impact Assessment Review*, **29**, 165–68.

Jonker G-J, Junginger M, Faaij A (2013) Carbon payback period and carbon offset parity point of wood pellet production in the Southeastern USA. *GCB Bioenergy*, doi: 10.1111/gcbb.12056. Early view online.

Kranzl L, Daioglou V, Faaij A, Junginger M, Keramidas K, Matzenberger J, Tromborg E (2013) Medium and long-term perspectives of international bioenergy trade. In: *International Bioenergy Trade: History, Status & Outlook on Securing Sustainable Bioenergy Supply, Demand and Markets* (eds Junginger M, Goh CS, Faaij A), pp. 173–190. Springer, Berlin.

Lamers P, Junginger M (2013) The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels, Bioproducts and Biorefining*, **7**, 373–385.

Lamers P, Junginger M, Hamelinck C, Faaij A (2012) Developments in international solid biofuel trade – an analysis of volumes, policies, and market factors. *Renewable & Sustainable Energy Reviews*, **16**, 3176–3199.

Lamers P, Junginger M, Dymond CC, Faaij APC (2013a) Damaged forests provide an opportunity to mitigate climate change. *GCB Bioenergy*, **6**, 44–60.

Lamers P, Marchal D, Heinimö J, Steierer F (2013b) Woody biomass trade for energy. In: *International Bioenergy Trade: History, Status & Outlook on Securing Sustainable Bioenergy Supply, Demand and Markets* (eds Junginger M, Goh CS, Faaij A), pp. 41–64. Springer, Berlin.

Lamers P, Thiffault E, Paré D, Junginger HM (2013c) Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. *Biomass and Bioenergy*, **55**, 212–226.

Lee HW (2012) Biomass demand in Korea. In: *CanBio Annual Conference*. Drying Engineering Inc., Vancouver, BC, Canada.

Matzenberger J, Daioglou V, Junginger M, Keramidas K, Kranzl L, Tromborg E (2013) Future Perspectives of International Bioenergy Trade. IEA Bioenergy Task 40. Available at: http://bioenergytrade.org/downloads/t40-trade-perspectives-summary-2013.pdf (accessed 3 September 2013).

Milbrandt A (2005) A geographic perspective on the current biomass resource availability in the United States. In: *Technical Report*. National Renewable Energy Laboratory, Golden, CO, USA. Available at: http://www.nrel.gov/docs/fy06osti/39181.pdf (accessed 7 April 2013).

OFGEM (2011) *Renewables Obligation: Sustainability Criteria for Solid and Gaseous Biomass for Generators (greater than 50 kilowatts)*. UK Office of the Gas and Electricity Markets, London, UK. Available at: http://www.ofgem.gov.uk/Sustainability/Environment/RenewablObl/FuelledStations/Documents1/Solid%20and%20Gaseous%20Biomass%20Guidance%20FINAL.pdf (accessed 26 September 2012).

Pöyry (2011) International trading – global pellet market outlook to 2020. In: *Interpellets*. Pöyry Management Consulting (London) Ltd., Stuttgart, Germany.

Pöyry (2013) View on the Atlantic Basin industrial pellet market up to 2025. In: *World Biomass to Power Markets*, Amsterdam, The Netherlands.

Ragwitz M, Steinhilber S, Breitschopf B *et al*. (2012) *RE-Shaping: Shaping an Effective and Efficient European Renewable Energy Market*. Intelligent Energy – Europe, ALTENER, Karlsruhe, Germany. Available at: http://www.reshaping-res-policy.eu/downloads/Final%20report%20RE-Shaping_Druck_D23.pdf (accessed 27 June 2013).

Roos JA, Brackley AM (2012) The Asian wood pellet markets. In: *General Technical Report PNW-GTR-861*. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA. Available at: http://www.fs.fed.us/pnw/pubs/pnw_gtr861.pdf (accessed 8 July 2013).

Ryckmans Y (2013) *An Introduction to IWPB*. Laborelec, Belgium. Available at: http://www.aebiom.org/conference/wp-content/uploads/file/2013%20AEBIOM%20Conference/Presentations%202013/130617-IWPB%20General%20Presentation%20with%20principles.pdf (accessed 28 July 2013).

Sackett J (2012) Proposed and Existing Woody Biomass Facilities in the Southeastern US. Southern Environmental Law Center. Available at: http://www.southernenvironment.org/uploads/fck/file/biomass/biomass_facilities_map_table_071012.pdf (accessed 2 February 2013).

Schueler V, Weddige U, Beringer T, Gamba L, Lamers P (2013) Global biomass potentials under sustainability restrictions defined by the European Renewable Energy Directive 2009/28/EC. *GCB Bioenergy*, **5**, 652–663.

Searchinger TD, Hamburg SP, Melillo J, Chameides W, Havlik P, Kammen DM *et al*. (2009) Fixing a Critical Climate Accounting Error. *Science*, **326**, 527–528.

Sikkema R, Steiner M, Junginger M, Hiegl W, Hansen M, Faaij A (2011) The European wood pellet markets: current status and prospects for 2020. *Biofuels, Bioproducts & Biorefining*, **5**, 250–278.

Smeets E, Faaij A (2007) Bioenergy potentials from forestry in 2050. *Climatic Change*, **81**, 353–390.

van Stralen JNP, Uslu A, Dalla Longa F, Panoutsou C (2013) The role of biomass in heat, electricity, and transport markets in the EU27 under different scenarios. *Biofuels, Bioproducts and Biorefining*, **7**, 147–163.

Thiffault E (2013) Mobilizing sustainable forest bioenergy in Canada. In: *BE-Sustainable Magazine* (ed. Maurizio Cocchi), pp. 10–12. Available at: http://issuu.com/besustainablemagazine/docs/be-sustainable_magazine_issue_2 (accessed 23 July 2013)

de Wit M (2011) Bioenergy Development Pathways for Europe – Potentials, Costs, Environmental Impacts. PhD dissertation. Utrecht University, Utrecht, The Netherlands. Available at: http://igitur-archive.library.uu.nl/dissertations/2011-0915-201509/wit.pdf (accessed 5 March 2012).

de Wit M, Faaij A (2010) European biomass resource potential and costs. *Biomass and Bioenergy*, **34**, 188–202.

de Wit M, Junginger M, Lensink S, Londo M, Faaij A (2010) Competition between biofuels: modeling technological learning and cost reductions over time. *Biomass and Bioenergy*, **34**, 203–217.

Zanchi G, Pena N, Bird N (2010) The upfront carbon debt of bioenergy. In: *Report for Birdlife International*. Joanneum, Graz, Austria. Available at: http://www.birdlife.org/eu/pdfs/Bioenergy_Joanneum_Research.pdf (accessed 7 April 2012).

Zanchi G, Pena N, Bird N (2012) Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, **4**, 761–772.

## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Table S1.** Conversion and calculation factors.
**Table S2.** Top ten countries regarding agricultural residue availability by 2020 (PJ).
**Table S3.** Expected biomass co-firing capacity developments in Belgium.
**Table S4.** Expected biomass co-firing capacity developments in the UK.
**Table S5.** Pelletization capacity for the production of agri-pellets for trade (ktonnes WPe).
**Table S6.** EU total biomass use per supply and demand scenario (PJ).
**Figure S1.** US corn stover cost–supply curves.
**Figure S2.** Supply potential of dedicated energy crops in the EU27 for Green-X (columns) and REFUEL (markers) for the same crop type production mix from Hoefnagels *et al.* (2011a).
**Figure S3.** Farm gate cost-supply curves for bioenergy crops in the EU27 in Refuel and Green-X for the same crop type production mix from Hoefnagels *et al.* (2011a).
**Figure S4.** Cost-supply curves of forestry products (primary and secondary), agricultural residues and waste in Green-X from Hoefnagels *et al.* (2011a).
**Figure S5.** Total forestry potential (calibrated for the EU27) of stemwood and primary forestry residues (left) and secondary forestry residues (right) from Hoefnagels *et al.* (2011a).