Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

Sourcing overseas biomass for EU ambitions: assessing net sustainable export potential from various sourcing countries

Thuy Mai-Moulin, Lotte Visser, Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands
Kevin R. Fingerman, International Institute for Sustainability Analysis and Strategy, Darmstadt, Germany and Humboldt State University, Arcata, California, USA
Wolter Elbersen, Berien Elbersen, Gert-Jan Nabuurs, Wageningen University and Research, Wageningen, The Netherlands
Uwe R. Fritsche, International Institute for Sustainability Analysis and Strategy, Darmstadt, Germany
Inés Del Campo Colmenar, CENER – National Renewable Energy Centre, Sarriguren (Navarra), Spain
Dominik Rutz, International Institute for Sustainability Analysis and Strategy, Darmstadt, Germany
Rocio A. Diaz-Chavez, Imperial College London, South Kensington Campus, The United Kingdom
Axel Roozen, Mathijs Weck, Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands
Leire Iriarte, International Institute for Sustainability Analysis and Strategy, Darmstadt, Germany
Luc Pelkmans, VITO NV, Mol, Belgium
David Sanchez Gonzalez, CENER – National Renewable Energy Centre, Sarriguren (Navarra), Spain
Rainer Janssen, WIP Renewable Energies, Munich, Germany
Martin Junginger, Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands

Received June 12, 2017; revised November 10, 2017; accepted November 28, 2017
View online at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.1853; *Biofuels, Bioprod. Bioref.* (2018)

Abstract: Low-cost sustainable biomass availability in the European Union may not be able to meet increasing demand; exploring the option of importing biomass is therefore imperative for the years to come. This article assesses sustainable biomass export potential from Brazil, Colombia, Indonesia, Kenya, Ukraine, and the United States by applying a number of sustainability criteria. Only biomass types with the highest potential are selected, to take advantage of economies of scale, e.g. pulpwood, wood waste, and residues in the United States, and agricultural residues in Ukraine. This study found that, except for the United States, pellet markets in the sourcing regions are largely undeveloped. The export potential depends strongly on pellet mill capacity and assumed growth rates in the pellet industry. Results show that the United States, Ukraine, Indonesia, and Brazil offer the highest biomass export potential. In the Business As Usual 2030 scenario, up to 204 PJ could potentially be mobilized;

Correspondence to: Thuy Mai-Moulin or Lotte Visser, Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands. E-mail: t.p.t.mai-moulin@uu.nl (Mai-Moulin); L.Visser2@uu.nl (Visser).

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.
This is an open access article under the terms of the Creative Commons Attribution NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

in the High Export scenario this could increase to 1423 PJ, with 89% of the potential being available for costs ranging from 6.4 to 15 €/GJ. These potentials meet the European Commission requirements for a 70% reduction in greenhouse gas emissions set in the Renewable Energy Directive. The total export potentials do not reflect the net possible import potentials to the European Union, as biomass could be imported to other countries where there is a demand for it, where less strict sustainability requirements are applied, and which are proximate to the sourcing regions, notably South Korea, Japan, and China. © 2018 The Authors. *Biofuels, Bioproducts, and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: sustainable biomass potential; sustainability criteria; wood pellet price; GHG emissions; energy policy; supply chain analysis; sourcing country; biomass trade

Introduction

In recent years, many countries have made efforts to reduce greenhouse gas (GHG) emissions and to become less dependent on fossil energy supply through increasing renewable energy production.[1,2] One means of achieving those objectives is to increase the share of bioenergy, and as a result the role of biomass and bioenergy has become increasingly apparent in the energy mix in most EU countries and other developed regions in the last decade. In December 2015, in the Paris Climate Agreement, 196 nations agreed to introduce measures and policies to reduce GHG emissions globally and to decarbonize the global economy. As of today, 152 countries have ratified the agreement in which developing renewable energy sources, including biomass and energy efficiency, will play a key role.[3]

At present, many countries are increasingly deploying and implementing renewable energy options, including bioenergy.[4] The European Union (EU) has collectively set a target to reach a share of 20% renewables in the final energy mix by 2020 and at least 27% by 2030. Japan, the largest importer of biomass outside the EU, has set a 22–24% renewables target share by 2030[5] whilst South Korea, the second largest importer of biomass outside the EU, aims for an 11% share of renewable energy in the overall energy mix by 2035.[6] Globally, biomass is the largest renewable energy source, and will continue to play a significant role in decarbonizing the energy system.[7] Wood pellets, e.g. pre-processed products from various solid biomass feedstocks, have been used increasingly for power generation in many countries in recent decades and can provide a stable source of low-carbon electricity. Biomass used for heat has grown more slowly due to limited policy support. Renewable energy in the EU, in general, will be increasingly market oriented and untapped potential needs to be exploited.[1,2,5,8,9]

To safeguard sustainable production and use of solid biomass for bioenergy as identified in various national renewable energy targets in the EU,[4,5,6] sustainability requirements are to be applied. Within the EU, the European Commission (EC) issued a proposal for the new Renewable Energy Directive in 2016 to reinforce the existing EU sustainability criteria for bioenergy by extending their scope to cover biomass and biogas for heating, cooling and electricity generation.[8] Sustainability requirements of solid biomass used for heat and power production have already been implemented in a number of EC Member States such as Belgium, Denmark, the Netherlands and the United Kingdom, the main importers of solid biomass in the EU.

The EU is currently the largest producer and net importer of wood pellets.[10,11] In 2015, 20.3 Mt wood pellets were consumed, of which 7.2 Mt were imported. By 2020, EU wood pellet imports from third countries are expected to be in the range of 15–30 Mt.[11] EU imports of wood pellets from non-EU countries in 2014 mainly came from the US (59%), Canada (20%) and Eastern European countries (19%).[12] In most scenarios with ambitious climate change mitigation targets, solid biomass use in the next decades is expected to increase.[7,13–15] These scenarios show that that, by 2030, the main exporting regions will likely be the same as today: United States, Canada, and Russia. By 2040, top-down models indicate a broadening of the main exporting regions, with an increasing role for Latin America, Oceania, and Africa.[13,14]

With increasing demand for wood pellets and other solid biomass in the EU but also in other parts of the world such as Japan, South Korea, and India, additional domestic and imported resources will be needed. Focusing on domestic but also on new non-EU import regions is rational as this could reduce the energy dependence of Europe on particular regions and could help to mobilize unused, sustainably sourced, residual resources. This article focuses on

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

sustainable solid biomass potential, particularly residual biomass sources, in non-EU regions. It follows a bottom-up approach and takes sustainability constraints, current alternative local use of biomass, and other local barriers into account.

Main objective

The main objective of this paper is to investigate six selected prospective international sourcing regions with promising sustainable biomass potentials that may be mobilized and exported to the EU between 2020 and 2030. This investigation includes the following tasks:

- Assessment of sustainable export potentials: an initial review of lignocellulosic biomass potential in various countries revealed that a number of countries have high agricultural potential and/or forestry residues and land availability for bioenergy crops. Six different case-study regions were selected based on data availability and local contacts; high expected biomass potentials; promising logistic infrastructure and intercontinental transport; variation of socio-economic and environmental constraints. The six case studies, on five different continents, are Kenya, Indonesia, Colombia, Brazil, the United States, and Ukraine.
- Analysis of the cost and GHG emissions along the supply chain: cost supply curves and GHG supply curves were generated for biomass produced in the six case study regions and transported to the port of Rotterdam in the Netherlands.

Methodology

The potentials assessed in this analysis include the technical potential of lignocellulosic biomass, the sustainable potential calculated by including sustainability criteria, the sustainable surplus potential, which considers domestic demand in sourcing countries, and the export potential, which is the amount of sustainable biomass that could be available for export to other world regions such as the EU (Fig. 1). A general and comparable assessment approach for potentials was applied in all case-study regions, allowing for a comparison of sustainable export potential, based on similar criteria[17] (Fritsche et al., accepted for publication).[18]

To qualify the lignocellulosic biomass that can be mobilized for exports, a number of pre-requisites were formulated:[18]

- ***Sustainable sourcing*** is a precondition for all exported lignocellulosic biomass, and for all domestically sourced biomass the sustainability principles and criteria that are already implemented in the EU are considered.
- ***Local demand for both energy and material purposes has priority over export***. Thus, domestic demand for biomass should be satisfied first before exploring exporting options. This avoids distortions of local markets.
- ***Emissions from the entire supply chains of biomass*** should lead to substantial chain reductions in comparison to the fossil-fuel equivalence.

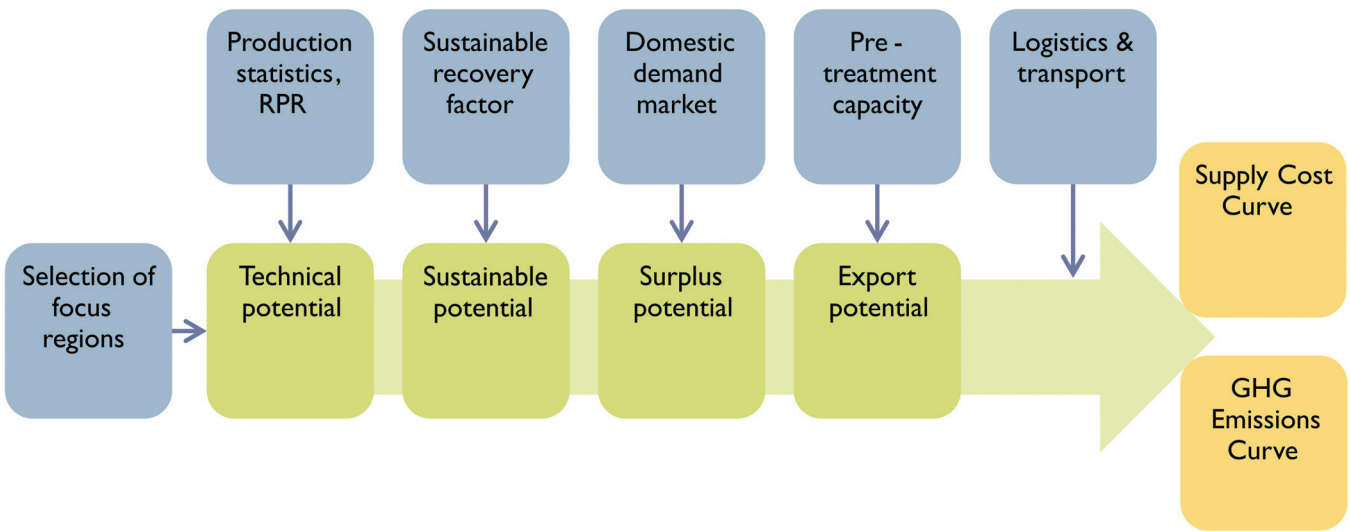


Figure 1. Methodology to calculate the different potentials.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

- ***Performance-based sustainability requirements*** need to be applied to the entire value chain (including production and logistics) up to the import harbor.

The following section briefly discusses the methodology applied to calculate the potentials, supply chain costs, and supply-chain GHG emissions (Fritsche et al., accepted for publication).[16]

Methodology to calculate potentials

The first methodological step was the selection of the case-study regions with the highest biomass potential within different countries, and the potential mix of biomass resources to be analyzed per region (see Fig. 1 and Appendix A for more details).

In the six case studies, different feedstocks were included, following local opportunities (Table 1). Primary agricultural residues are residues generated in the field during harvesting processes, whereas secondary residues are generated at the processing stage. Primary forestry residues are residues originating from harvesting or forest-management practices, such as logging residues and thinnings, typically left behind in either natural or plantation forests. Secondary forestry residues originate from the processing of forest products and include, for instance, saw-mill residues. Dedicated energy biomass is the production of either energy crops such as switchgrass or miscanthus, or forestry biomass, dedicated to the production of (solid) biofuels.[19]

Kenya was the first case study in which the methodology was applied, including an investigation of all types of biomass, agricultural residues, energy crops, and forest residues. This case study, however, showed very limited potential from energy crops and forest residues, after which it was concluded that the remaining case studies would focused on the most promising potentials in the respective regions. For the Brazil case study, the availability of agricultural and forestry statistics allowed for the inclusion of both these feedstock types. In Indonesia, more than 50% of the land is covered by natural forests, which are protected for biodiversity reasons. Considering the sustainability risks in Indonesia, only residues from certified palm plantation areas or land under governmental support were included.[20] In Colombia, although more than half the land is covered by forests, the potential for forestry biomass is assumed to be low because most of the forests are biodiversity-rich, protected areas. For this reason, the Colombian case study focused solely on agricultural residues (Elbersen et al., accepted for publication).[21] In the case of the Ukraine, there was access to detailed data on the potential for energy crops.[22] For other case studies this data was not available. In the US case study the calculated potential was based on existing practices. By far the largest share of pellets produced in the case study region in the United States is produced from forestry residues and forestry products such as roundwood. The US case study therefore focused on these residues.[23]

In the second step, the **technical potential** was calculated, which follows the definition of potentials in the Biomass Energy Europe project,[24] and is defined as *the terrestrial biomass considered available under the current techno-structural framework conditions with current technological possibilities (such as harvesting technologies, infrastructure and accessibility and processing technologies), while also taking into account spatial confinements due to other land uses (such as food, feed and fiber production, and nature reserves).* The technical potentials (P_T) in the different case-study regions were calculated using Eqn (1) based on production statistics of agricultural and forestry products combined with residue-to-product ratios (RPR), or from literature on the production of solid biomass or residues per hectare.

$$P_T = A_i \times Y_i \times RPR \times E_i \quad (1)$$

where A_i is the crop area of crop *i* in the case-study region, Y_i represents the yield of crop *i* in the case-study region, RPR is the residue-to-product ratio, and E_i is the energy content of crop i in the case-study region (LHV).

Table 1. Feedstocks included in case-study countries.

		Brazil	Colombia	Indonesia	Kenya	United States	Ukraine
Agricultural residues	Primary	X	X	X	X		X
	Secondary		X	X	X		
Forestry residues	Primary	X				X	X
	Secondary	X					X
Dedicated energy biomass	Agriculture						X
	Forestry					X	

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

The **sustainable potential** (P_S), *defined as the share of the technical potential that meets environmental, economic, and social sustainability criteria,*[24] was calculated in the third step. An assessment was made per region and feedstock, based on literature and local expert opinions, of the sustainable land availability and sustainable recovery factor (SRF) of residues and energy crops. By applying restrictions on the harvestable area and removable biomass shares, the sustainable potential was calculated using Eqn (2). The basic sustainability requirements included in all case studies are closely aligned with the requirements of the Renewable Energy Directive (RED).[25] Additional specific requirements were included in some case studies based on data availability and relevant local sustainability criteria. The residue-to-product ratio, energy content per feedstock, and sustainable recovery factors used per case-study country and feedstock are presented in Appendix B.

$$P_S = PT \times (1 - L_S) \times SRF_i \quad (2)$$

where L_S is the fraction of land excluded because of sustainability criteria (such as high biodiversity areas) and SRF_i represents the sustainable recovery factor of crop *i* in the case study region, the factor of residues that can be extracted while meeting sustainability criteria.

The **surplus potential** (P_{SS}) was calculated in the fourth step. *This was defined as the potential that could be available for export to other regions, after subtracting current and expected future local demand for biomass for material and energy applications, covering industrial and residential use.* Based on local expert opinions, the percentage of primary and secondary residues used locally was subtracted from the sustainable potential to form the sustainable surplus potential. The local demand in the different case studies is presented in Appendix C:

$$P_{SS} = P_S - LD_i \quad (3)$$

where LD_i represents the local demand of crop *i* in the case-study region.

In the fifth step, the **export potential** (P_E) was calculated, *defined as the potential that could be exported, taking into account requirements such as the availability of transport infrastructure and pre-treatment plants.* Lignocellulosic biomass needs to be pre-treated and densified before it can be transported across long distances. This is done, among other reasons, to reduce safety risks related to self-heating and microbial hazards, but also to improve handling properties and reduce the cost and energy requirements of transport. As default pre-treatment technology, pelletization of woody and agricultural biomass was assumed as this is the pre-treatment technology most commonly used for solid biomass.[26] The future pelletization capacity was estimated by analyzing current capacities (if any) and growth curves of production capacity in the respective countries and by considering potential capacity growth rates. The availability of pellet production facilities was taken into account as a limiting factor to calculate the export potential:

$$P_E = MIN\,(P_{SS}, CY_P) \quad (4)$$

where CY_P is the pelletizing capacity in the case-study region.

In the final step, to calculate the costs and GHG emissions of exported biomass, transport routes from case-study regions to the EU were designed and calculated. The port of Rotterdam was chosen as the import point, because of its central location in the EU and the good port facilities, making it an interesting potential import hub for biomass energy carriers. Based on the export potential, the cost of delivering biomass to the port of Rotterdam, and the emitted GHG emissions, were calculated, including feedstock cultivation, pellet production, inland transport, and transport to Rotterdam. Cost supply curves and GHG supply curves were generated to account for differences between different supply regions and feedstocks.

Supply-chain cost calculation

Supply-chain costs were calculated using Eqn (5) by taking several components along the chain into account, while combining country-specific data and uniform cost assumptions.

$$C_D = C_P + C_{Tdf} + C_{Pt} + C_{Tdp} + C_{Ti} + C_H \quad (5)$$

where C_D is the total production cost of biomass residues, C_P is the cost of feedstock production, C_{Tdf} is the cost of domestic transport from the fields to pre-treatment facilities, C_{Pt} represents the cost of pre-treatment, C_{Tdp} is the cost of domestic transport from pre-treatment facilities to the export location, C_{Ti} is the cost of international transport from export locations to the port of Rotterdam, and C_H represents the cost of handling and storage.

Most of these cost parameters were taken from the literature. In some cases, field research and interviews with experts provided country-specific parameters. The cost factors used in the different case-study countries can be found in Appendix D.

The transport cost to the pre-treatment facilities (C_{Tdf}) was calculated by including road transport over 50 km.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

The production cost of pellets (C_{Pt}) is based on Ehrig et al.[27] Cost of some consumables, such as spare parts, was included based on Pirraglia et al.[28] The cost structure of pre-treatment is assumed to be similar in the different case studies. In most of the case study countries, there is no large-scale pellet production yet, making it difficult to assess potential cost; the decision was therefore made to base the cost for all countries on the same data sources. A number of country-specific cost factors are included in all case studies, such as the cost for electricity, labor, and feedstock. In the Colombian case study, data limitations prevented the calculation of cost based on country-specific factors. Instead, total pelletization costs are assumed based on the other case studies.

The cost of transporting pellets to export ports was calculated by taking the distance from weighted centers of regions to export ports. For most case-study regions this was done based on a first-level administrative division (typically state level); for the United States, this was done on a second-level basis (i.e. county level). Road transport was assumed in most of the case studies, as rail networks are often not developed, or very poorly developed. For the Ukraine and the United States, rail transport is a viable option for some locations. For these two countries, it was possible to calculate the transport cost in more detail by making use of the existing BIT-UU model.[29] The BIT-UU model is a GIS-based biomass transport model with an intermodal network structure of road, rail, inland waterways, short sea shipping in Europe, and ocean shipping. The model combines linear optimization of the allocation between supply and demand nodes with global input data on cost for transport of lignocellulosic biomass. The cost of international transport (C_{Ti}) was calculated by making use of the BIT-UU model where possible. For countries that are not included in this model, these costs were calculated through a web-based sea-freight calculator.[30]

Supply chain GHG calculation

To determine GHG emissions for each stage of the supply chain, global warming potentials were estimated from electricity, fuels, and materials use. The calculation of GHG emissions closely followed the EC approach.[2] When actual data were not available, default values provided by the EC and other references were applied.[2,31]

The GHG emissions are calculated according to Eqn 6:

$$E = E_{ec} + E_s + E_p + E_{dt} + E_{it} \quad (6)$$

where E_{ec} is the emissions from cultivation (applied only for energy crops), E_s represents the emissions from nutrient replacement (including emissions from production and use of fertilizer to compensate for biomass removal which leads to the emissions of GHGs via chemicals use), E_p are the emissions from pre-treatment (including chipping, drying and pelletization), E_{dt} are the emissions from domestic transport, and E_{it} are the emissions from intercontinental transport to the port of Rotterdam.

Analysis of potential GHG savings was made by comparing emission avoidance in relation to production of electricity and heat from fossil resources. In order to compare the emission savings with fossil fuel alternatives, the RED was used. Where forest or agriculture residues are considered, the required GHG emission savings in the EC are in principle at least 70% compared to fossil fuel alternatives. However, lower savings can occur for short-rotation coppices (e.g. eucalyptus in tropical countries), in case of low fertilizer use in agriculture, and when natural gas is used for drying pellets.[31] It is therefore considered to be good practice for existing bioenergy installations to achieve GHG savings of at least 70% compared to the fossil fuels comparators. This equates to lifecycle emissions of less than or equal to 12.8 gCO_{2eq}/MJ_{el} for electricity and 34.1 gCO_{2eq}/MJ_{el} for generated heat. In the more ambitious EC pathway the GHG savings should be 80% lower, equal to 10.6 gCO_{2eq}/MJ_{el} for electricity and 28.4 $gCO_{2eq.}/MJ_{el}$ for generated heat in a co-firing heat-and-power plant (CHP).[31,32] (An industrial CHP using conventional hard coal for electricity production has GHG emissions of 261.5 $kgCO_2$equivalent/GJelectricity. A CHP based on ORC technology has an electrical and thermal efficiency equal to 16.3% and 69.6%, based on low heating value of wood pellets.)

Scenario development

One of the key aims of the analysis presented in this paper was to investigate future markets and opportunities for sustainable biomass feedstocks. This depends on aspects such as technological and economic developments and changes in climate, energy, agricultural, and business policies. To anticipate the possible changes in biomass trade, and market developments, two scenarios were designed for 2020 and 2030.

The Business as Usual (BAU) scenario was based on a continuation of historic and current trends. The BAU scenario was built on current and expected policies in climate and environmental policies in the sourcing regions. Historic feedstock production trends in most countries show an increase in production area and yield. These trends were assumed to continue in the BAU scenario. The sustainable potential calculations were based on current

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

feedstock extraction rates, taking into account existing sustainability restrictions. The domestic demand for different feedstocks was estimated using statistics where possible, and in consultation with local field experts otherwise. The BAU scenario takes into account trends in local use, for instance local use of residues for energy production. Continuation of pellet production capacity growth trends is applied in the BAU scenario where possible. In case the growth of production capacity is unclear, the growth of pellet plant capacity is based on worldwide growth estimates.

The high export (HE) scenario explored options under which larger volumes of sustainably produced biomass might become available for export. These may include an assessment of possibilities to increase the yields of biomass production, of additional land availability for biomass production, and of reduced local demand for biomass. Agricultural and forestry production was assumed to follow optimistic growth trends, including improved yields as a result of better management practices and higher fertilizer use.

For the calculation of the surplus potential, the lower ranges of expert assessment of local demand of feedstock were used. The growth rates for pellet plant capacity were assumed to be higher in the HE scenario. As a maximum growth rate, recent historic growth rates in the United States are taken, which showed a very high increase from 160 ktonne in 2006 to 4800 ktonne in 2013.[33] The growth rates in specific case-study countries are modeled to US growth rates, starting from the period with similar total production volume.

Case study assumptions and specific adaptations

The calculation of potentials in each case study was largely determined by the availability of statistical data, literature and access to local experts. Assumptions were made based on literature and expert consultations. In some case studies, it was necessary to diverge from the general methodology due to data limitations or case-specific situations, which justified an adapted, more suitable, approach. The most important case-specific adaptations to the general methodology will be discussed below.

In Brazil, the technical potential was restricted by land suitability, consisting of technical and non-technical constraints, according to Verstegen, Van der Hilst and Woltjer.[34] This entailed the partial inclusion of certain restrictions in the additional technical potential towards 2030. This restriction had a larger effect in the HE scenario, considering the assumptions of larger increases in yields and agricultural areas.

In Colombia, the calculation of the sustainable potential fully excluded oil palm trunks and leaves, as experts deemed collection to be prohibitively costly. This could limit the sustainable potential by more than just the residue fraction needed to cover sustainability criteria. Furthermore, as reliable information about pellet production capacity was not available, pellet plant capacity was not considered as a limiting factor (Elbersen et al., accepted for publication).[21] For this reason, the only results shown for Colombia were the surplus potentials, and not the export potentials. Cost supply curves were calculated based on the surplus potentials.

In Indonesia, the yield of agricultural crops in the HE scenario was assumed to be higher than in BAU and increased over time until 2030. At the same time, the rate of residue removal was supposed to increase, as fewer residues are needed for soil protection and to maintain soil organic carbon levels as a result of improved crop management.[35]

In Kenya, as in the Colombia case study, pellet production capacity was not considered as a limiting factor because data about pellet production was not available. Similarly, cost supply curves were calculated based on surplus potentials.

In Ukraine, agricultural production has varied strongly in past years. Future investments in the agricultural sector in Ukraine are uncertain due to the difficult political and economic situation resulting from the Ukrainian Revolution of February 2014. The assumption was made that the total agricultural production volume remains unchanged both in the BAU and the HE scenario. The amount of residues needed to maintain SOC levels was modeled by applying the Rothamsted Carbon model to calculate the soil carbon balance.[36–38] The model input was taken from the MITERRA-EUROPE model. The database used in this model is on the NUTS 2 level and includes relevant data such as land use, crop type, soil type, and topography.[39] Data on soil organic carbon levels was retrieved from the European Soil Database.[40] In the HE scenario, the assumption was made that the residue removal rate increases gradually until 2030 as a result of improved management practices, and the application of fertilizer, except for those regions in which the removal rate is 0%.[22,41,42] In Ukraine, a significant potential for dedicated energy crops was assumed, based on a study by Van der Hilst et al.[22] This study analyzed the bioenergy production potential in Ukraine as well as related GHG balances of land-use change. In this study the demand for

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

food and feed was calculated in a BAU and progressive scenario, in 2020 and 2030, as well as the land required to meet this demand. The bioenergy potential was calculated based on the production of switchgrass on land still available after accounting for this existing demand.

In the United States,[43] the focus is on the south east of the US, which is the most important pellet exporting region within the US. Pellet production was based on forestry feedstocks, including logging residues, mill residues, and pulp logs, making up only a small percentage of the total wood market.[44] By applying sustainability criteria only for wood used for energy purposes, the risk of leakage exists; wood sources meeting the criteria can be (re-) allocated to biomass purposes, whereas non-sustainable sources could be used for other purposes not covered by sustainability schemes.[17] This effect is to be avoided in order to ensure overall sustainable harvest practices. A slightly different approach was therefore used in the US case study. In the calculation of the sustainable potential, only the biomass used for pellets is limited by the sustainability criteria. In the calculation of the surplus potential, however, the assumption was made that the entire domestic demand for biomass, that is the existing wood market, must also meet the sustainability criteria.[17] The availability of pellet equipment was not included in the calculation of the export potential. The pellet market in the United States is well developed; large historic growth rates have shown that the industry is capable of responding quickly to market developments. The pellet plant capacity was therefore considered to develop in response to market developments and was not included as a limiting factor in the calculation of export potential.[17]

Data collection

Data for the calculation of the different potentials was gathered from a combination of sources. Statistical data on agricultural and forestry production was combined with data from literature, for instance, on sustainable restriction. Regionally specific data was used as much as possible to calculate the different potentials. Data from literature was, where possible, supplemented by assessments from experts in the case-study regions.

The technical potential in all case studies was based on production statistics on a state level, or higher resolution. The sustainable potential was in some cases based on regionally specific input, such as in the Ukraine and US case studies. In other case studies, such as in the Brazil study, data availability made it necessary to use default values for the entire case study. Data on the domestic demand of different crops was largely based on personal communications with local experts, and was assumed to be similar for all regions.

Sensitivity analysis

The calculation of potentials, costs, and GHG emissions in the different case studies involved several assumptions and the use of uncertain data. The two different scenarios reflect the uncertainty in the future development of biomass potentials, costs and GHG emissions. To further analyze the impacts of data uncertainty, sensitivity analyses were carried out for the supply potentials, supply costs, and supply GHG emissions by varying several factors that strongly impacted the calculations.

The preferred method of obtaining minimum and maximum values for selected parameters is from the available literature. If no data could be found in the literature, a three-tier uncertainty system was applied, with low, medium, and high levels of uncertainty reflected in different uncertainty ranges of 10%, 25% and 50% for export potentials and costs; and of 5%, 10% and 20% for GHG emissions. The uncertainty for GHG emissions was assumed to be lower because, in practice, there is less fluctuation in the three impacting factors used for GHG emissions calculation (nutrient substitution, local transport and electricity use). In order to assess the level of uncertainty, interviews with experts, where possible from the specific case study regions, were used.

Results

First, to show the results of applying the different methodological steps to calculate the export potential, the results from one case study are highlighted. To this end, the case study of Brazil is considered to be a good example for several reasons. Most importantly, the availability of locally collected data allowed for the application of all the steps of the general methodology. Furthermore, the domestic use of biomass, specifically for energy production, is increasing in this country. This results in clear differences between the scenarios and timelines as the domestic demand is increased. The situation in Brazil therefore shows the effect of applying different constraints, while varying these constraints in different scenarios.

An analysis of the overall results of all the six case studies will then be shown, focusing on the differing export potentials under different timelines and scenarios, as well as the respective cost supply curves and the GHG supply curves.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Results from the Brazil case study

The technical potential of agricultural and forestry residues shows the importance of sugarcane residues, especially from São Paulo state, accounting for 43% of the total technical potential (see Appendix E for a map of all included states). The sustainable potential was calculated by applying a sustainable recovery factor (SRF); see Eqn 2. Sustainable recovery factor values for Brazil were obtained from literature research, and for sugarcane, cross-checked through interviews with local experts (Roozen A, personal communication).[45–52] The SRFs obtained from the literature were derived from field experiments investigating the effects of residue removal on soil nutrient balance, soil erosion rates, and soil organic carbon percentages. The chosen SRFs represent a removal rate at which these sustainability indicators are not negatively impacted. The SRFs are impacted by local conditions, such as soil type, slope, and climate; there is, however, no data available on geographically specific SRF factors. To overcome this problem, a default SRF was used for the entire case-study region, drawing from literature on sustainable residue removal in Brazil.[52] This default can be considered conservative; case studies on the removal of rice, soybean, and corn residues in Brazil show removal rates that are higher than the default removal rates used in this study (Cervi, unpublished).[53–55]

The residue recovery limitation does not apply to processing residues such as bagasse, rice and coffee husks, and orange peels, which can be 100% utilized. The sustainable recovery factors of the different feedstocks can be found in Appendix C. As the use of sugarcane bagasse is not restricted by sustainability criteria, the relative contribution of sugarcane to the sustainable potential is even larger, with sugarcane bagasse accounting for 56% of the total potential (see Fig. 2).

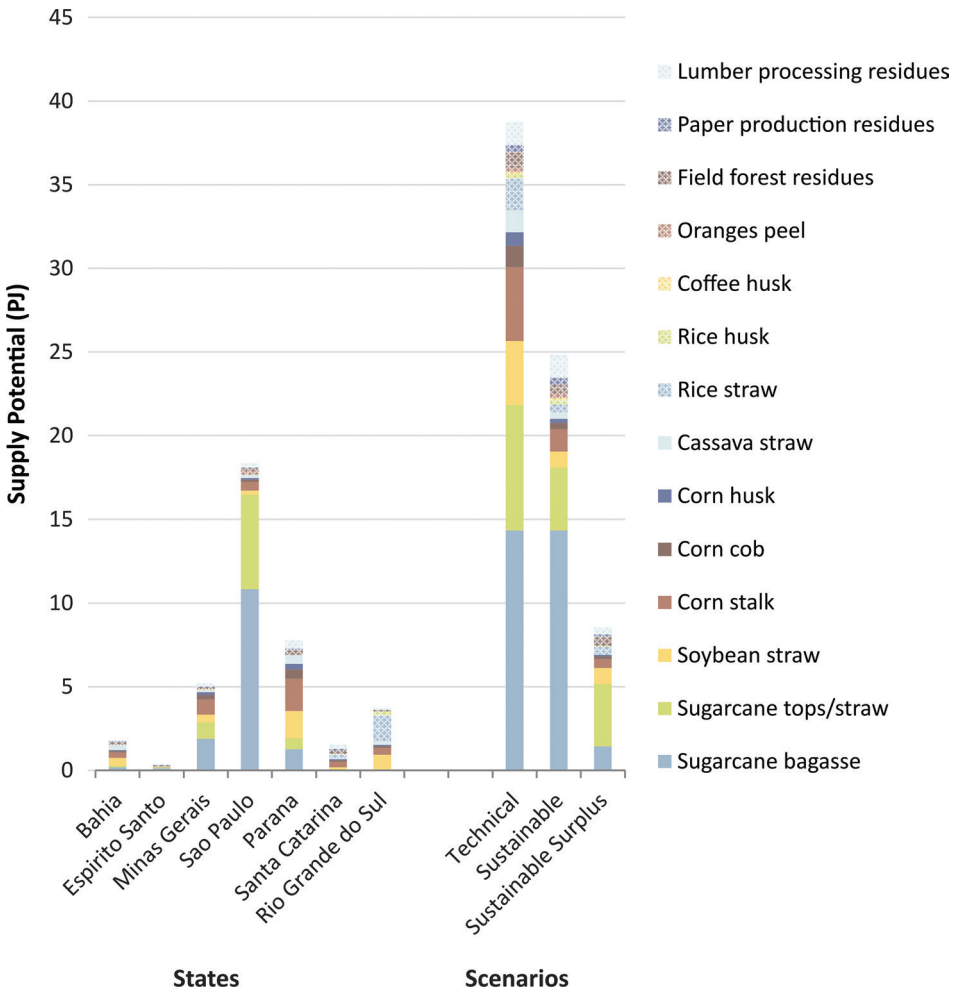


Figure 2. Technical potential current scenario in Brazil, per feedstock and region; technical, sustainable, and sustainable surplus current scenario in Brazil.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Figure 2 shows the sustainable potential and sustainable surplus potential of the different residues in Brazil. Sugarcane bagasse is already used predominantly for the production of local electricity and heat. Currently 90% of the bagasse is used locally to provide electricity and heat to sugarcane mills, and excess electricity to the power grid (Roozen A, personal communication). The demand for local residues used to produce electricity is expected to increase significantly based on the expected increased contribution of bioelectricity to Brazil's energy needs from 3% to 18%.[56]

Considering this strong pull towards local use of sugarcane bagasse, the assumption was made that the remaining residues that can technically be harvested will, in the future, be used locally as well. The additional assumption was made that residues that do not meet the quality standard required for local production of electricity or heat, will not meet the criteria required to produce pellets either, and are therefore considered unavailable. The local use of sugarcane bagasse was therefore assumed to increase to 100% in the BAU 2030 scenario.

Sugarcane straw has predominantly been burned in the fields in the past. In recent years, federal governments, with São Paulo being the first, have banned this practice to limit damage to the environment and surrounding villages.[57] The common practice changed to piling up the sugarcane stalks in the fields. Partial straw removal from the fields for additional electricity production is beginning to take place. These trends, as considered by local experts, will result in increased local use of residues towards 2030.[58] To account for the uncertainty in these developments, domestic demand is varied: demand was assumed to increase from 0% in the current situation towards 50% in the BAU scenario, and 25% in the HE scenario in 2030. After considering the domestic demand for residues, the total sustainable surplus potential was reduced to just 17% of the sustainable potential in 2030 in the BAU scenario and 31% in the HE 2030 scenario.

The last limitation applied was the availability of pellet plant capacity needed to densify the residues. The current potential was calculated based on the capacity of existing plants.[59] The capacity in the case-study regions is currently 630 ktonnes per year. A capacity factor of 80% was used to calculate the actual pellet-producing capacity. This is considered optimistic because, in reality, pellet plants often run at lower capacity because of supply limitations.[60]

As data about expected growth rates of pellet production capacity was not available, estimations about future capacity in the BAU scenario were based on world-wide pellet capacity developments expected between 2015 and 2023.[61] This growth was expected to continue until 2030. For the HE scenario the assumption was made that the pellet plant capacity increases with growth rates modeled after the historical pellet capacity growth in the United States.[33] This results in an annual export potential of 71 PJ in the BAU scenario and 411 PJ in the HE scenario in 2030.

The newly added pellet capacity was assumed to be divided according to the surplus potential in each state. Until 2020, pellets were assumed to be produced from forestry residues; the sustainable surplus forestry potential exceeds the pellet plant capacity. After 2020, agricultural residues were assumed to make up a share of 30% of the additional pellet production capacity, increasing in some states where there is a limited supply of forestry residues.

Limiting factors

The extent to which specific constraints limit the various potentials varies between case studies, reflecting, amongst other things, differences in sustainability concerns, domestic uses of biomass and the maturity of wood pellet production markets. In this section, the main limiting factors per case-study country are discussed.

In Brazil the potential is limited by the local use of sugarcane residues for the generation of heat and electricity, corn stover and cassava straw for cattle feed, rice and coffee husk for chicken bedding, and orange peel for citrus pulp pellets (Roozen A, personal communication).[62–67] A lack of railway infrastructure increases the cost of pellet export and the export potential is limited by the lack of pre-treatment technology; the existing pellet capacity is very small in Brazil and the focus is on ethanol instead of pellets.[59]

In Colombia the potential is reduced by the use of palm residues for compost production and the use of sugarcane bagasse for co-generation to generate process energy in sugar and ethanol mills. Poor infrastructure limits the mobilization of field residues, increasing the cost of transporting pellets from inland areas. High mineral and moisture content of residues limits the production of pellets. A lack of pellet plant capacity limits the export potential in general, no pellet plants exist in Colombia as of yet, and data on pellet capacity development is lacking (Elbersen et al., accepted for publication).[21]

The potential from Indonesia is limited by the local use of palm residues for electricity production at palm-oil mills and the use of palm fronds as fertilizer at palm-plantation sites. Sustainability concerns of expanding palm plantation areas, especially at areas not under governmental support, result in excluding these areas from the sustainable potential. No pellet plants exist in the investigated regions in Indonesia, limiting the export potential. At the

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

same time, capacity is assumed to grow at a fast pace, considering the possibility of integrating pellet production in existing and growing oil mills.[35]

In Kenya, avoiding soil erosion and nutrient depletion is an important issue, resulting in a low SRF. The use of agricultural residues for cattle feed, and forest residues for cooking, reduces the surplus potential. Large distances from production regions to the Mombasa port, and poor quality of infrastructure, increase the cost of exporting pellets. No pellet plants exist in Kenya and no data is available on pellet capacity development, limiting the export potential.[68–70]

In some regions in Ukraine the SRF factor is low. In many regions 100% of the maize straw can be removed, with stubbles, chaff, and below-ground carbon being sufficient to maintain SOC levels. Removal levels for barley straw are generally low, however – below 45%. Levels for rapeseed, sunflower, and wheat vary between 0% and 100% per region. Historic growth rates of pre-treatment capacity are low, therefore pellet capacity is assumed to remain a strong limiting factor.[71]

In the United States, sustainability requirements are considered to apply to the entire US wood market, forming the main limiting factor. This is in order to avoid nutrient depletion and biodiversity loss and to avoid unsustainable shifts in harvest practices.[17]

Combined case study results

Results show a very large technical potential for lignocellulosic biomass supply in 2030, especially in the form of energy crops from the Ukraine and agricultural residues from Brazil, as seen in Fig. 3. Due to several restrictions applied in this study, the sustainable, sustainable surplus, and export potentials are considerably smaller. In the BAU scenarios, the local demand for biomass forms the largest restricting factor, with the pre-treatment capacity being an important limitation as well. In the HE export, the limited increase over time of pre-treatment capacity forms the main limitation.

The overall export potential increases strongly in the HE scenario towards 2030, due to the high assumed annual growth rates of pellet production capacity. In 2030, in the HE scenario, Brazil contributes 26% to the total potential, Indonesia 20%, the United States 29%, and Ukraine 14%. As the export potential could not be assessed in the case studies of Colombia and Kenya, these countries are left out of consideration.

Cost supply curves

When looking at the cost supply curves (Fig. 4 and Fig. 5) there is a large difference between the case studies. The least expensive lignocellulosic biomass can be imported from Ukraine, the cheapest residues being 6.4 €/GJ. Delivery costs from Indonesia (from 11.8 €/GJ) and Brazil (from €10.8/GJ) are significantly higher. The cost of lignocellulosic biomass from the United States in the HE scenario starts off reasonably low at €7.8/GJ and stays under 15 €/GJ for 400 PJ (about 89% of the total export potential).[17] The steep increase in costs towards the end of the

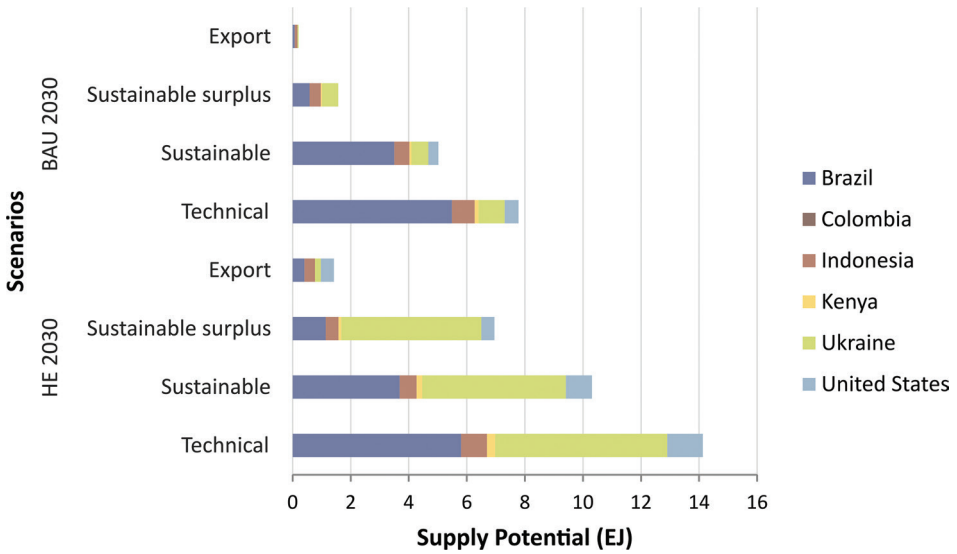


Figure 3. Technical, sustainable, sustainable surplus and export potentials in the different case study countries – BAU 2030 and HE 2030.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

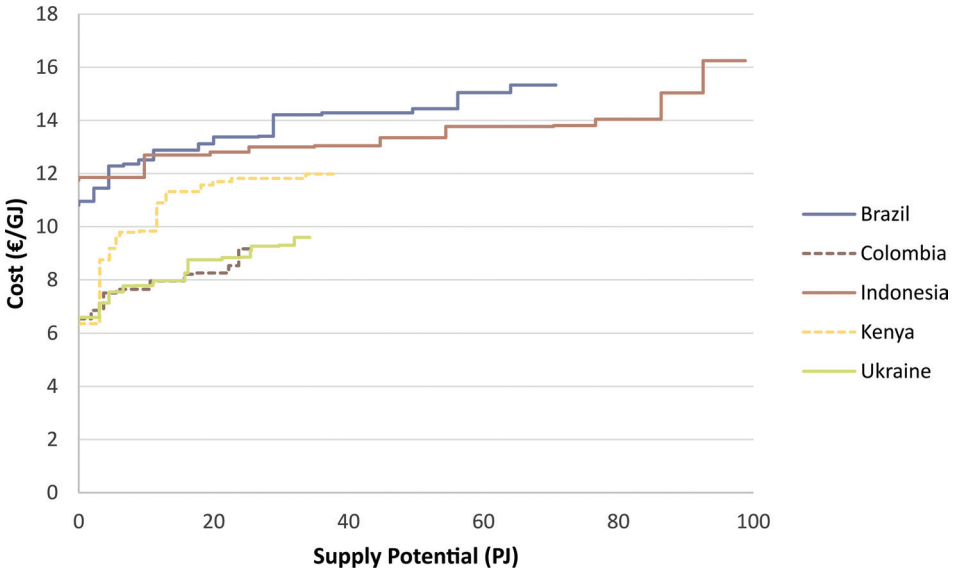


Figure 4. Cost supply curves of export potential (Brazil, Kenya, Ukraine – solid lines) and sustainable surplus potential (Colombia, Kenya – dashed lines) delivered to the Port of Rotterdam in the BAU 2030 scenario.

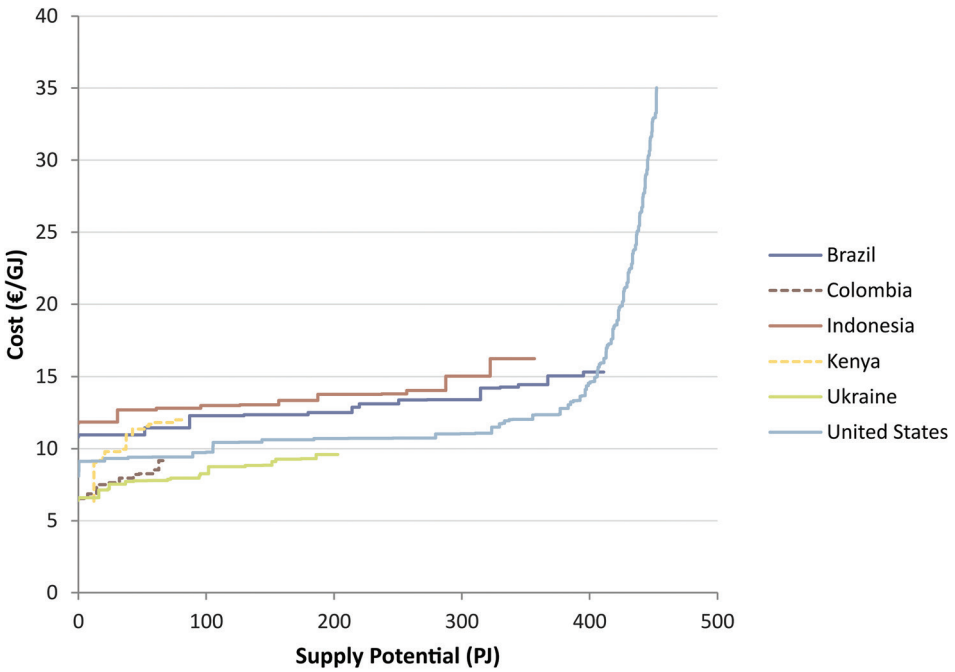


Figure 5. Cost supply curves of export potential (Brazil, Kenya, Ukraine, United State – solid lines) and sustainable surplus potential (Colombia, Kenya – dashed lines) delivered to the Port of Rotterdam in the HE 2030 scenario.

US cost supply curve is the result of the modeling of costs of forest thinnings from areas with poor or no road access. Increased 'distance to road' results in very expensive biomass, which in reality would not likely be harvested, but is still available for use.[17,72] The US case study furthermore includes incremental costs for additional feedstock supply, resulting in a sharp increase in feedstock cost towards the maximum supply potential as identified in this case study.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Greenhouse gas emission curves

The calculations of GHG emissions show that average emissions from the United States are the lowest, emissions from Kenya, Ukraine, Brazil and Colombia are higher, but the highest values are for Indonesia (Fig. 6). In the Colombia case study, the emissions of pre-treatment were assumed to be zero as residues were considered to be used for the production of energy for plant operation and maintenance activities, which resulted in no GHG emissions. In practice, there are still emissions due to diesel use for machinery and the use of electricity from the national grid in the pre-treatment plants. In order to easily compare the results with other case studies, a GHG emissions factor from electricity production was taken into account in Colombia, following the BioGrace II default values.[32]

With shorter intercontinental transport routes to the import harbor of Rotterdam, Ukraine has the lowest international transport emissions. Indonesia has the highest transport emissions, due to the long transport distance to the EU. The emissions from local transport are highest in Kenya and Brazil. In both countries, the state of infrastructure is poor and the distance between sourcing regions to the export harbors is large. Emissions from pre-treatment plants are highest in the United States and Ukraine, mainly due to the high electricity emission coefficients in those countries. Emissions from nutrient substitution are highest in Indonesia and Ukraine due to higher fertilizer use to substitute the removed residues for soil organic carbon. The United States is the only country where cultivation and harvesting are taken into account, since the collection of forest residues is a well-regulated activity in which emitted GHG emissions are recorded.

In both BAU 2030 and HE 2030, the potential supply from all the case studies meets the current 70% and proposed 80% cut-off reference for heat as set by the current and recasted EC Renewable Energy Directive (34.1 and 28.4 kg CO_2/GJ respectively in co-firing heat and power plants). When using the current 70% cut-off reference for electricity (12.8 CO_2/GJ), as defined in the current RED,[8] all potentials from Indonesia and most potentials from Kenya and Brazil are above the GHG reduction limit for heat production, as can be seen in Fig. 7. When using the proposed 80% reference for electricity (10.7 CO_2/GJ) in the recasted RED, 80% of total potentials are not qualified to be exported to the EU. The share of the potential that does not meet this threshold will not likely be mobilized to the EU in the future if strict GHG emission reductions are applied.

Sensitivity analysis

Sustainable surplus potential

The uncertainty analysis is based on the sustainable surplus potential, because this was assessed for all the countries. The export potential as calculated in this study depends solely on the pelletization capacity as limiting factor and would therefore not show the impact of varying parameters. The three factors that have the highest impact

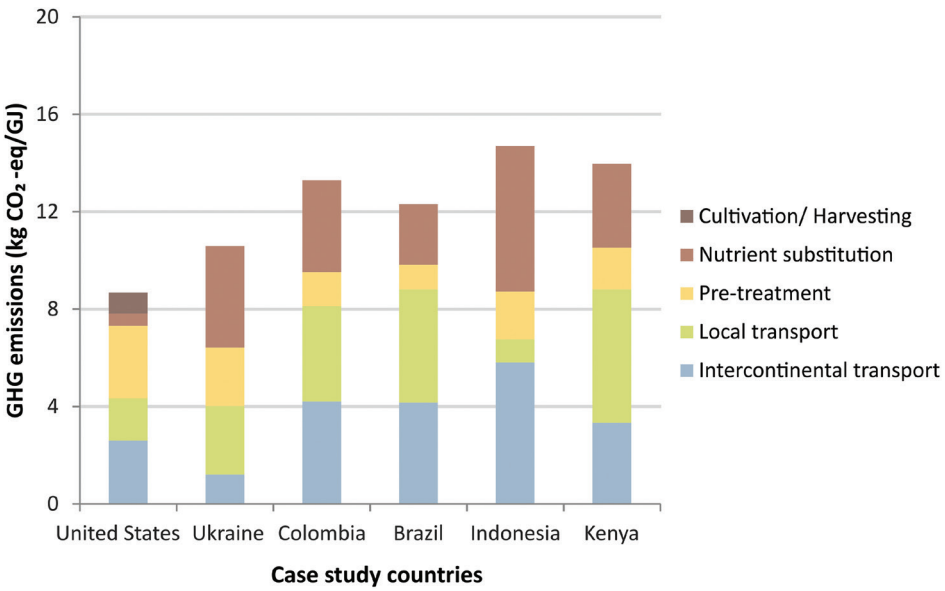


Figure 6. Average GHG emissions of solid biomass supply chains in different case study countries.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

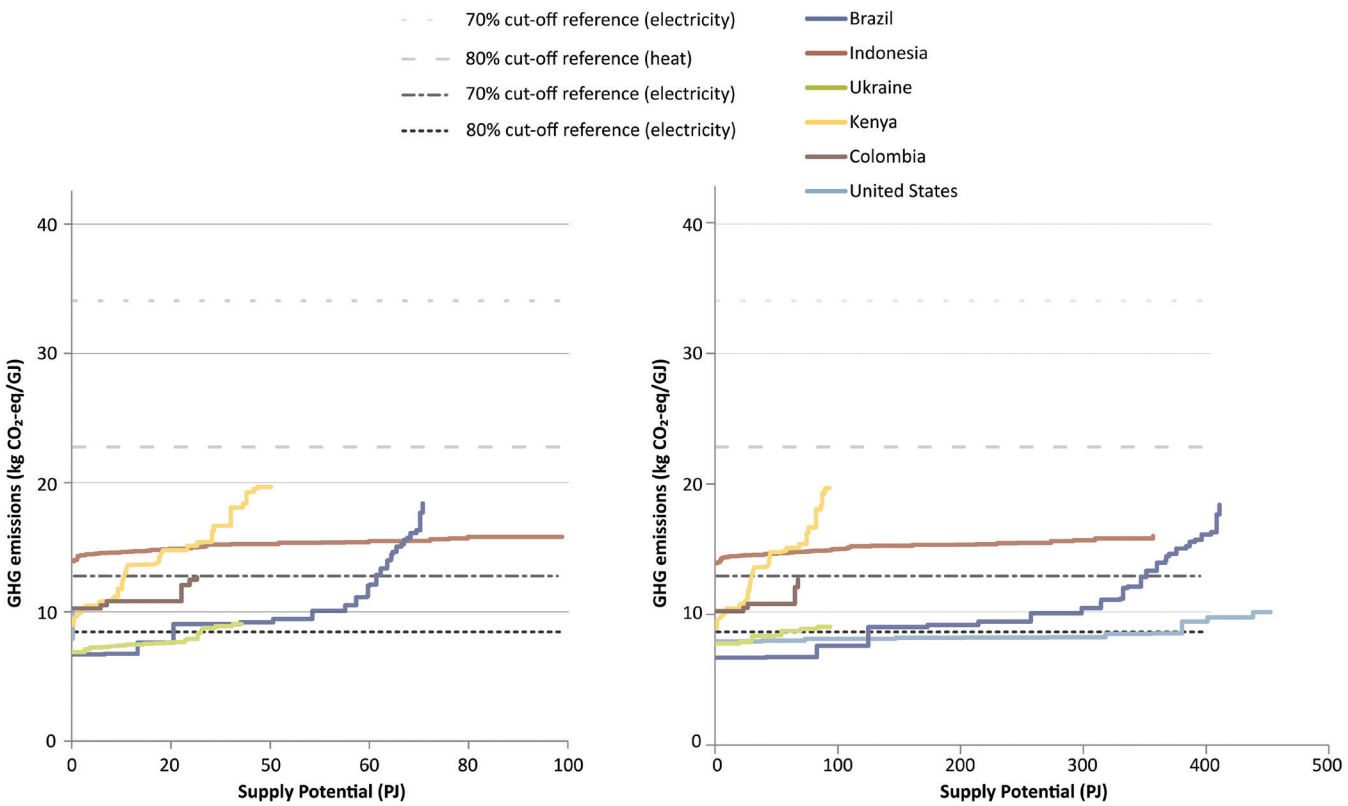


Figure 7. Greenhouse gas supply curves of export potential (Brazil, Kenya, Ukraine, United States – solid lines) and sustainable surplus potential (Colombia, Kenya – dashed lines) delivered to the Port of Rotterdam – BAU 2030 (left) and HE 2030 (right).

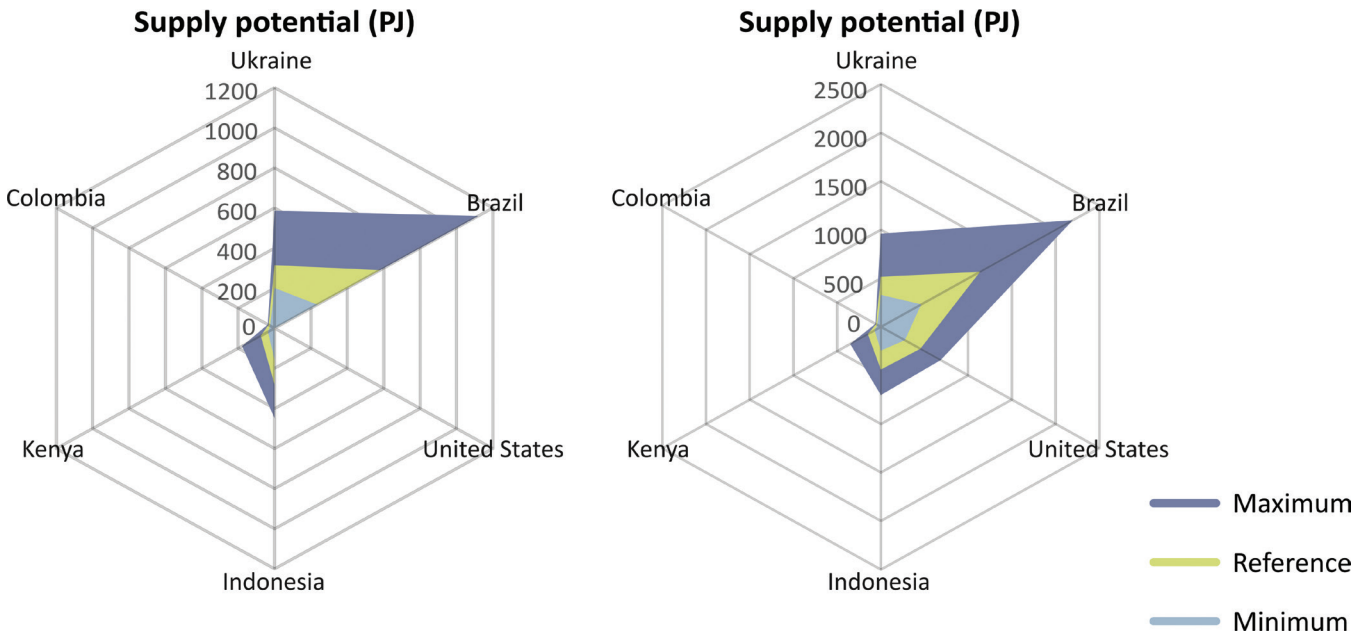


Figure 8. Total surplus potential uncertainty ranges of the six case studies – based on the BAU 2030 potential (left) and HE 2030 potential (right).

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

on the sustainable surplus potential, the RPR, the SRF, and the LD, were varied in this sensitivity analyses.

For the Ukraine case study, the RPR is varied with the highest and lowest value within Europe,[73] resulting in a variation between 81–137%. For the SRF, a lower value was used based on a European commission report, resulting in a potential of 91% of the reference potential.[73] For the LD, as the lower end of the range, the reference value was used combined with the assumption that residues are traded across regions. The higher end of the range uses an alternative estimate from the European Commission of 14.5% instead of 31%, resulting in a variation between 87–133%.[73]

The RPR variation in Brazil for all crops was modeled after data of the range of Cassava availability, between 144 and 257% of the product.[63] The SRF in Brazil is highly uncertain, as referenced by a variation of corn stover removal in literature between 20% and 100%.[74,75] Alternative sources also provided data on sugarcane tops and straw SRF values of 65% of the reference value and soybean straw SRF values of 144% of the reference values.[76] To reflect this large uncertainty, a variation of 50% for non-process residues was used. The availability of residues was varied with 35% based on assumption used by Portugal-Pereira et al.[76]

For the US case study it was not possible to assess the data uncertainty in the literature, since the parameters were the result of several overlapping, spatially explicit datasets. It was not possible to use literature to assess the data uncertainty at this detailed spatial level. The pellet-production industry is well established in the United States, so the uncertainty of residue availability as well as the demand for paper, paperboard, and panels is considered low. The RPR and LD are therefore varied by 10%. The SRF is considered somewhat more uncertain, considering the difficulties of determining local sustainability

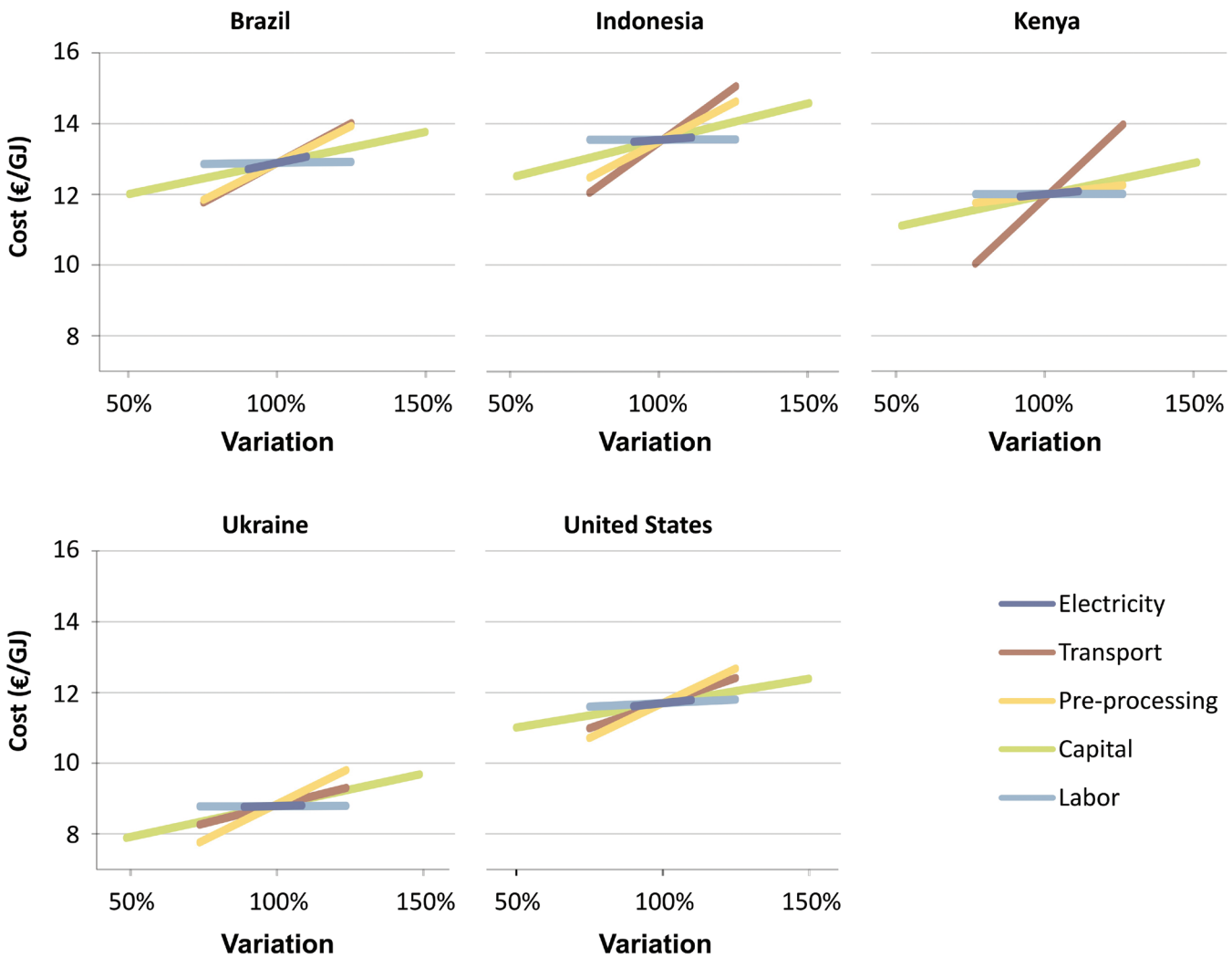


Figure 9. Sensitivity of five case studies (excluding Colombia) for different cost parameters.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

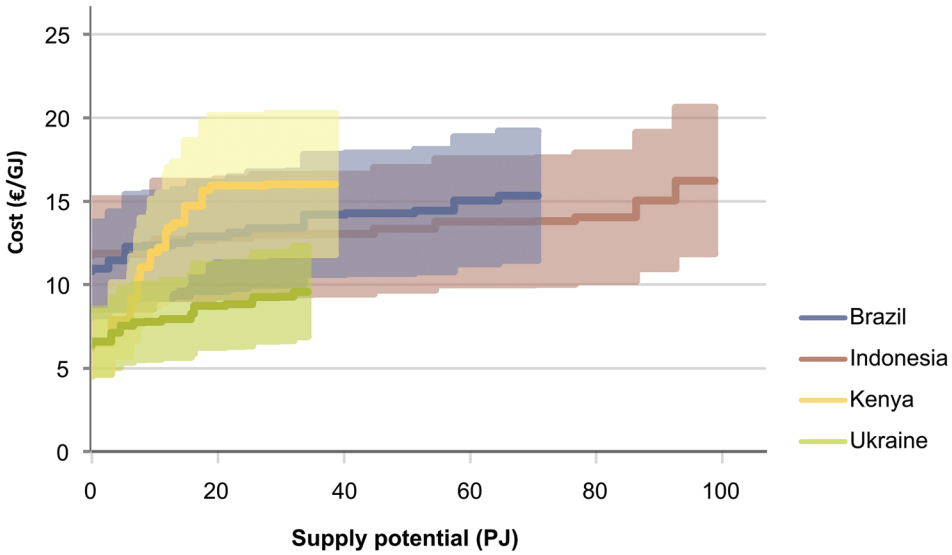


Figure 10. Uncertainty ranges cost supply curves – BAU 2030.

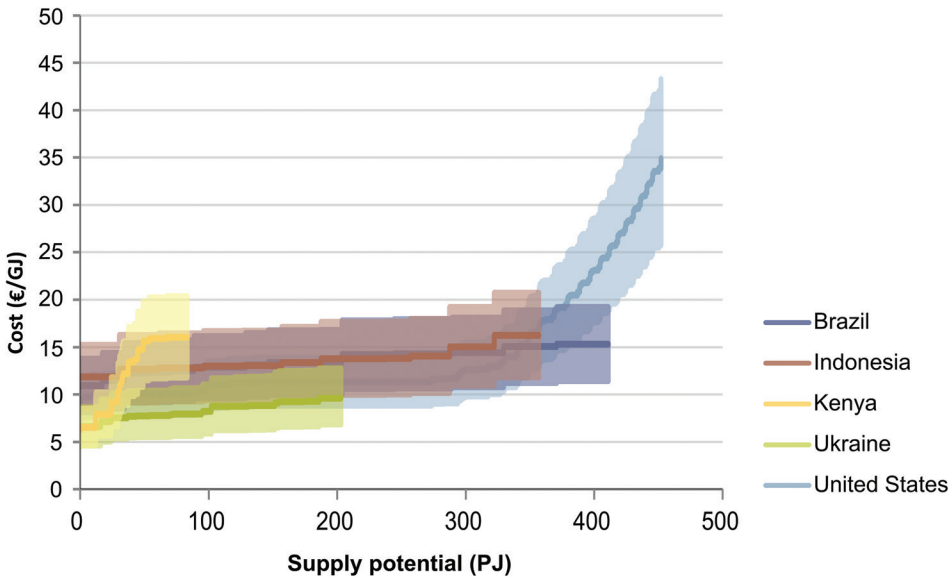


Figure 11. Uncertainty ranges cost supply curves – HE 2030.

concerns based on a high-level spatial analyses. As a result, the SRF is varied by 25%.

In Colombia, the RPR and SRF values of palm and sugar cane residues are clearly undetermined as residues are estimated based on the total quantity per ha in Colombia. Those values are considered based mainly on the studies of palm residues in Indonesia and Malaysia, with ranges of 82–127% and 74–112% respectively. Local demand was estimated based on the project field interviews with a range of 86–114% (Elbersen et al., accepted for publication).[21]

In Kenya, interviews with representatives of Ministries of Agriculture and Energy as well as meetings with farmers in various regions of the country have resulted in an average RPR range of 82–127% and LD range of 77–136%.[77] Regarding the SRF, no data were available for Kenyan case studies. However, SRF references were taken into considerations from Mozambique and South African data with similar local conditions of agricultural cultivation and harvesting.[68,69,78]

For the Indonesian case study, the average RPR was estimated based on studies of palm-oil residue potentials for both Indonesia and Malaysia (of similar climate and agricultural conditions),[79,80] resulting in a variation between 80–124%. Regarding the SRF value, a range of 74–112% was applied based on the studies on palm oil residues used

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

in both Indonesia and Central Kalimantan.[80,81] Based on studies on Malaysian local use of palm residues, the LD was varied between 94% and 115%.[82]

The combined effect of varying the parameters on the potentials in the BAU 2030 and HE 2030 scenarios is shown in Fig. 8.

Costs

There are large degrees of uncertainty in the use of different cost factors. It was not possible to assess the cost factors through detailed field research in the different case studies or literature review. To show the impact of cost assumptions, five varying parameters were considered: electricity cost, transport cost (from pre-treatment facilities to import ports), pre-processing cost (including cost of feedstock, collection and transport to pre-treatment facilities), pellet plant capital cost, and labor cost. The cost of electricity is considered relatively less uncertain, and is varied by only 10%. Capital cost of pellet plants is considered the most uncertain, as mentioned in expert interviews, and is varied by 50%. The other factors are varied by 25%.

Figure 9 shows the impact of changing different parameters in the different case studies. Colombia was not included because this cost calculation could not be based on country-specific parameters. Cost calculation in the United States includes incremental feedstock cost, resulting in a sharp increase towards the end of the cost supply curve. For the sake of showing the sensitivity to impacts on the largest part of the United States' cost supply chain, and to align these results with the methodology followed in the other case studies, a cut-off is applied at 15 €/GJ, corresponding to 89% of the total potential. The results of sensitivity analyses of the different case-study countries can be found in Appendix H.

The combined effect of varying the different parameters (varied with respectively 10%, 25% and 50% as explained above) is shown as a cost-supply curve uncertainty range for the BAU 2030 scenario in Fig. 10 and for the HE 2030 scenario in Fig. 11.

GHG emissions

The three key factors impacting the GHG emissions that strongly depend on local conditions are nutrient substitution, transport emissions and electricity production emissions.[32,64,65,83,85–87] Research and consultation with stakeholders were also carried out to investigate to what extent

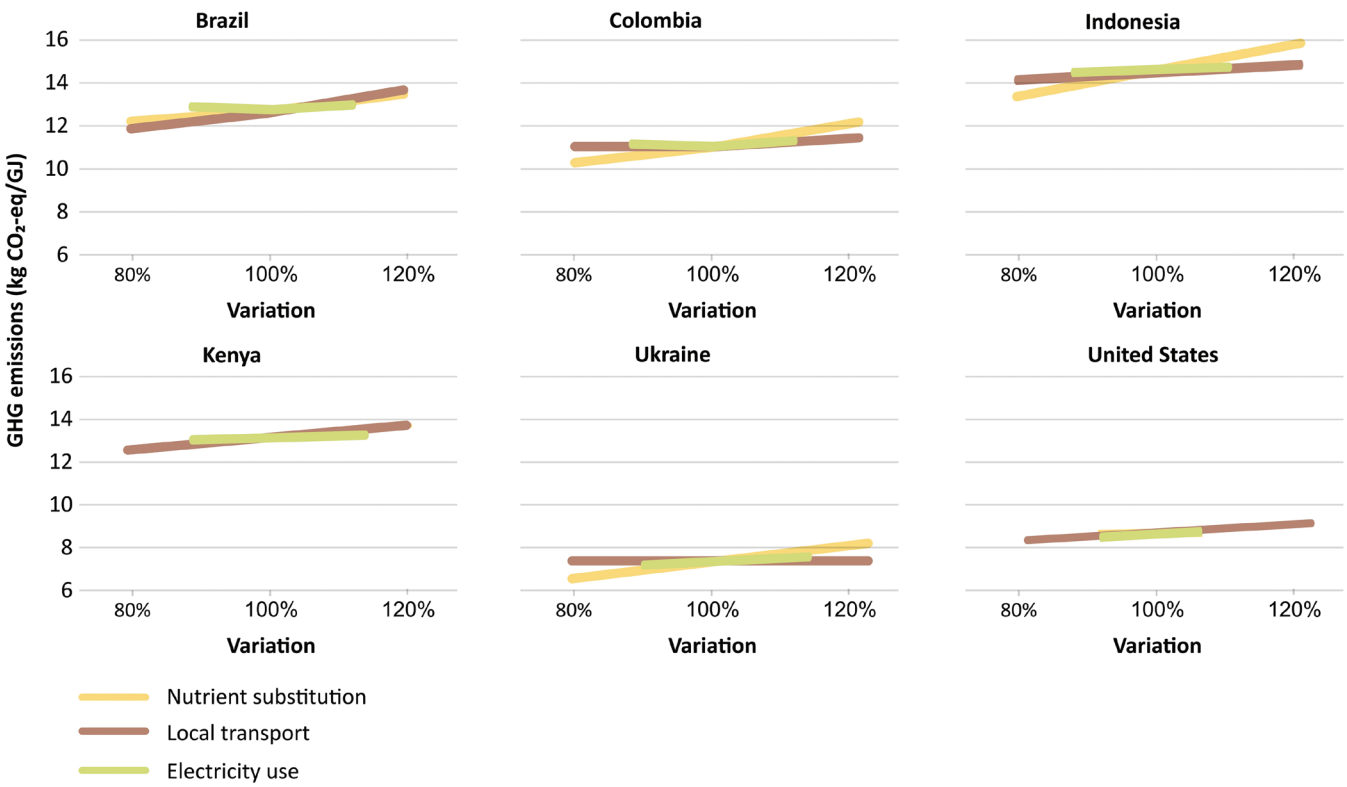


Figure 12. Sensitivity of six case studies for different GHG emissions parameters.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

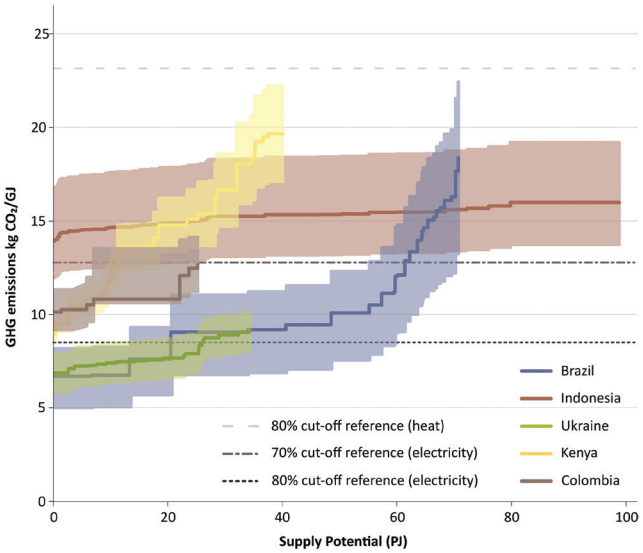


Figure 13. Uncertainty ranges GHG emission curves – BAU 2030.

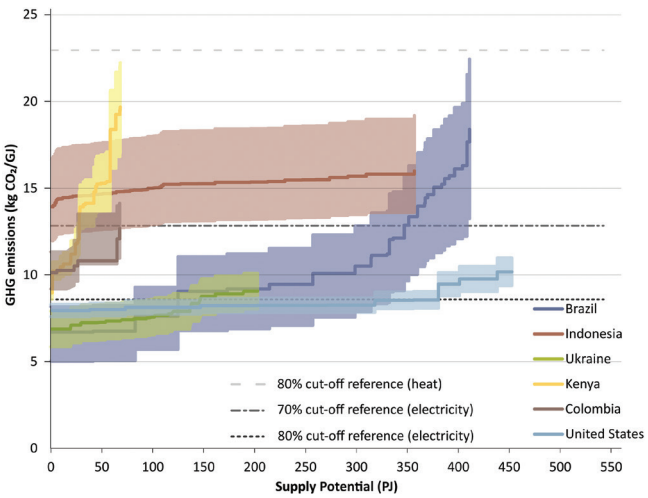


Figure 14. Uncertainty ranges GHG emission curves – HE 2030.

ranges of these factors reflect changes in GHG emissions. The study then considered that in Ukraine, Indonesia, Kenya, Brazil and Colombia, variation in nutrient substitution and local transport is ± 20% (low: –20% and high: +20%). This is explained by using nutrients to boost crop yields; and a low quality of infrastructure, which results in high GHG emissions per kilometer. Electricity use has a range of ±10% (low: –10% and high: +10%), which reflects changes in electricity use in the sourcing regions. With a similar consideration for local transport in the United States, transport emissions are also set at ± 20%. However, nutrient substitution is currently not applied for the use of forest biomass in the United States, also electricity emission factor is less uncertain, so they are set at 5% for comparison and uncertainty analysis.

The results of sensitivity analysis for the different case study countries can be found in Appendix I. The combined effects of GHG emissions are presented in Fig. 12. Figure 13 and Fig. 14 show the total GHG emission uncertainty ranges for the five case studies in the BAU 2030 (no export potentials available for the United States under this timeline) and for the six case studies in HE 2030. In the current situation, the largest part of the export potentials from the sourcing countries meet the EU 80% GHG emission reduction for heat production and 70% GHG emissions reduction for electricity production, as can be seen in Fig. 13. Figure 14 shows that most potentials would be eliminated under the strictest EU GHG emissions limit if three impacting factors are all included (except for some parts from Ukraine, the US and Colombia). Figure 14 also indicates that if lower nutrients, less fossil fuels, and grid electricity are used in the local supply chains, a higher quantity of biomass qualifies for export from Ukraine, the United States, and Colombia.

Discussion and conclusions

Discussion

Future export perspective

In the United States, given the interlinkages between the pellet industry and the conventional (in particular sawmilling) wood industry, the pellet industry can only flourish if the traditional industry flourishes.[87] The pellet industry is expected to expand significantly if the conventional forest product use increases, as this would lead to increasing levels of low-quality round-wood and residues becoming available. However, these dynamics are not explicitly accounted for in the present analysis. Domestic demand, together with EU sustainability constraints, also plays an important role in determining whether export potentials will be available from the United States. In the BAU 2030 case, due to higher local demand and stricter application of sustainability requirements for sustainable biomass exported to the EU, export potentials are equal to zero. In the HE 2030 scenario there is high availability of biomass for export. In order to reach these export quantities, pelletization capacity needs to be expanded, requiring trust by the industry that demand (in the United States, the EU or other export markets) will steadily increase.

In Ukraine, forest residues are not included in the potential estimation as in practice they are not mobilized and there are no incentives to change this situation. The quality of the road networks in Ukraine limits accessibility to

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

certain areas, especially during certain weather conditions. This is included in the calculation of cost supply curves in the form of high transport cost per kilometer, but is not included as a limiting factor for the calculation of potentials. The lack of pellet plant capacity in Ukraine strongly limits the export potential. Investments in the bioenergy sector in Ukraine, as a result of increased demand for solid biofuels in Europe, could reduce this barrier. However, the current political situation may hinder investments.

In Brazil, potentials increase from the current situation towards 2030. Current agricultural practices of leaving large amounts of residues in the field, if positively changed by collecting part of those residues, could add to the surplus potential over time. If the bioenergy sector in Brazil develops, it could make a significant contribution to socio-economic developments in Brazil strengthen the renewable energy sector in both Brazil and the EU.

In Colombia, the investigation indicated that more investments in the bioenergy sector would be needed. Calculated potentials are lower than actual potentials as a result of excluding inland regions where transport costs are too high. Investments in accessible infrastructure would increase the potential for solid biomass mobilization both for local and export uses. In Indonesia, palm residues such as fronds or empty fruit bunches are currently largely left as waste in the fields and at oil mills. Palm residues are currently free of charge; in the future, feedstock cost might be added once palm residues become commercialized. Costs might also be higher if the certification of the Roundtable on Sustainable Palm Oil would be implemented to provide sustainability compliance of palm plantation. It was difficult to predict local consumption of palm residues in Indonesia. It is considered likely that palm residues will be largely attributed to export due to the established supply chains of the palm industry. Local households could mobilize other local alternative energy carriers such as rice straw and husk and corn stover.

In Kenya, aggregate biomass potentials decrease over time as food demand, woody biomass deficit, and livestock nutritional needs are projected to increase towards 2030. Some agricultural yields in sub-Saharan Africa are projected to decrease, caused predominantly by lack of water, soil loss, and land degradation.[88] Proper farming practices could help to boost agricultural production and thereby also result in more residue production. Kenya is not considered a suitable country for energy crop cultivation as many attempts failed to boost biofuel production in the country. There is resistance from local NGOs; there are conflicts between locals, and governmental corruption is an issue. Overall, Kenya does not seem to be a suitable export country until these issues are resolved. This could differ for other sub-Saharan countries. For example, in another study, van der Hilst and Batidzirai find substantial biomass export potentials for Mozambique while applying a similar methodology.[19,78]

This study found that, in certain regions, the poor state of infrastructure, logistic conditions, and pre-treatment capacity limits the availability of solid biomass to be mobilized for export. These barriers furthermore result in high costs and high GHG emissions in some regions. If these challenges are to be overcome, costs and GHG emissions will be reduced and access to feedstocks in remote regions could be achieved, leading to the availability of higher export potentials, with more competitive costs and lower GHG emissions.

If sustainability requirements, are being implemented or established in certain countries, the market price and global trade of solid biomass might change from one country to another. Countries with no or loose sustainability requirements will more likely import certain shares of biomass compared to countries with strict sustainability requirements. More research is necessary to more accurately predict the future global trade of solid biomass for the bioenergy sectors in different countries.

Differences in local demand for biomass feedstock, sustainability criteria, and different levels of market maturity result in different levels of feedstock availability for export. For easy comparison of costs and GHG emissions, the assumption was made that most feedstocks are suitable for pelletization. In reality, agricultural residues may require additional pretreatment compared to biomass originating from forestry (e.g. washing to remove corrosive elements), or may require pre-treatment through pyrolysis or torrefaction. Those assumptions may also lead to lower or higher biomass availability for export, as well as changed cost supply curves and emissions supply curves.

As a result of limited data availability and difficulties in consulting local stakeholders regarding national policy focus and local markets, results need to be interpreted with a degree of uncertainty. Market prices for biomass used for bioenergy production were not stable in the last two years and it is difficult to predict market trends in the future.

Other global demand for biomass

So far, this paper has implicitly assumed that all export potentials are available to the European Union. However, the demand for solid biomass for bioenergy is predicted to increase elsewhere too, until 2030.[7,13] Matzenberger et al.[14] have studied three global integrated assessment models, GFPM, TIMER and POLES, and have assessed the (implicit) global biomass trade streams in these models. This study shows that Europe will still be the main

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

importing region for bioenergy by 2030. At the same time there are emerging countries competing for lignocellulosic biomass resources with the EU, notably India, Japan, and South Korea. The latter two have recently started to import biomass for energy. Simply based on the geographic vicinity, it is possible that the Indonesian resource potentials will be used in East Asia rather than being exported to the EU.

While this study has focused on the six case studies, initial investigations of potentials have indicated that countries such as Canada, Russia, Mozambique, Argentina, Vietnam, India and China also have high potentials of lignocellulosic biomass for both local use and export. Canada produces 48 PJ of wood pellets/year and 90% of this quantity is currently exported.[89,90] Canada also implements sustainable forest management, aiming to meet environmental, social, and economic requirements for lignocellulosic biomass, and is currently a leader in third-party certified forests.[90] Russia is an exporter of wood pellet and has high potential resulting from its large forest industry,[14,15] although the current political situation has limited its export capacity. According to van der Hilst and Batidzirai,[19,78] Mozambique has potential for up to 2.7 PJ of combined agricultural and forestry residues as well as potentials of 1.6–7.0 EJ from energy crops. Although local uses of food and feed have not been carefully investigated in this study, Mozambique probably has the potential to export biomass.[19,69,78] Vietnam is currently the leading export of wood pellets to South Korea and Japan, with more than 18 PJ of wood pellets exported in the last three years,[89] and is currently the highest exporting country of solid biomass in Asia.

From this perspective, further investigation in these countries together with this study will provide a more comprehensive overview of the potential global trade of solid biomass. Given the existence of additional demand for biomass in other world regions and potential additional exporters to the EU not included in this paper, the projected biomass import potentials in this study should be seen as examples to illustrate the order of magnitude and conditions for import, not as solid projections.

Conclusion

Results for the six case studies have shown that the sustainable export potential of lignocellulosic biomass is currently limited. However, depending on specific country conditions, the study also shows that sustainable export potentials may increase in the future in most countries, particularly in the HE scenario.

Ukraine, Indonesia, and Brazil may become promising sourcing countries in the future as potentials increase from 18, 0 and 9 PJ in the current situation to 203, 356 and 411 PJ respectively in the HE 2030 scenario. On the other hand, potentials in the United States decrease to almost zero in 2030 in the BAU scenario when sustainability criteria are applied to the whole forest sector instead of just the pellet sector. Such assumptions were not made in the other case studies. When sustainability criteria are only applied to the pellet sector, the export potentials from the south-east United States may become the largest of all case studies increasing to 452 PJ in the HE 2030 scenario. Potentials in Kenya and Colombia increase only moderately compared to other countries from 20 and 29 PJ in the current situation to 68 and 93 PJ respectively in the HE 2030 scenario.

The feasibility of importing lignocellulosic biomass to the EU is limited by costs. When comparing the estimated costs of solid biomass export from the different sourcing countries with the global average market prices in the last five years, it can be seen that this is one of the main limiting factors. The costs of solid biomass from Ukraine are relatively low, ranging from 6.4 €/GJ to 11.8 €/GJ. This can mainly be explained by the shorter transport distance from Ukraine to the port of Rotterdam. Interestingly, Colombia is three times farther from the Netherlands than Ukraine but costs from Colombia are calculated to be between 6.5 and 9.2 €/GJ as a result of cheap feedstock and low pellet-production cost. In the United States, the costs range between 7.4 €/GJ to 35.0 €/GJ; the high end of the range is the result of the increased cost of collecting residues when approaching the maximum potential, resulting in 89% of the potential ranging between 7.4 €/GJ and 15.0 €/GJ and the other 10% ranging between 15 €/GJ to 35.0 €/GJ. As a result of long-distance intercontinental transport, as well as expensive inland transport, Brazil and Indonesia bear higher cost ranges, from 10.8 €/GJ to 15.3 €/GJ and 11.6 €/GJ to 16.2 €/GJ.

The market price of wood pellets in the Netherlands between 2009 and 2016 ranged between 6.3 €/GJ to 8.0 €/GJ, which is considered representative for the international wood pellet market value.[91] It can be seen that lignocellulosic biofuels from the six case-study countries are not likely to be exported under the low-end of this price range. Under the high-end price, a small potential of 15.7 PJ in the BAU 2030 or 94.4 PJ in the HE 2030 could be exported. In both scenarios this can be attributed to potentials from Ukraine. In all other case studies, calculated supply costs exceed 8.0 €/GJ. If the market price were to increase to 10 €/GJ, the import potential meeting this threshold would increase to 34.2 PJ in the BAU 2030 scenario and 308 PJ in the HE 2030 scenario.

This study also shows that GHG emissions are currently not a critical issue in the countries investigated for biomass to be qualified for export to the EU. The potentials from all the six countries comply with the requirements

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

for 70% GHG reduction compared to fossil fuel-based heat and electricity production, as recommended in the EU.[83] This can be explained by the fact that the largest part of the potentials is mobilized from agricultural and forest residues where emissions from cultivation are exempted. Pre-treament plants partly use lignocellulosic biomass to produce electricity for their operations. Pre-treatment emissions are therefore also partly exempted.

If the requirements of GHG emissions are strengthened up to an 80% reduction, as identified in the proposed RED,[8] only the potentials in the United States, Ukraine and Colombia, and part of the potentials in Kenya and Brazil, meet the sustainability requirements for heat production. The potentials are particularly limited regarding biomass used for electricity production, in this case only part of the potentials from the United States, Ukraine, and Brazil meet the reduction criterion. This is mainly due to intercontinental and local transport, which accounts for a large share of the GHG emissions, especially from countries far away from the European Union. In Indonesia, Ukraine and Kenya, large amounts of fertilizers need to be used for nutrient substitution, which also causes higher total emissions.

Despite these constraints, it can be concluded that substantial sustainable biomass export potentials currently exist, and one of the biggest constraints is currently to mobilize these potentials. The results presented in this study were used in the BioSustain study, research at EU level to analyze potential future intra-EU and extra-EU biomass supply scenarios. The BioSustain results show that the potential from the case studies included in the Biotrade2020+ study could cover 32% of the extra-EU demand for biomass in 2020 and 69% in 2030.[92]

Acknowledgements

This paper was written within the framework of the Intelligent Energy – Europe (IEE) project Supporting a Sustainable European Bioenergy Trade Strategy, IEE/13/577/SI2.675534. Special thanks are given to A. Dardarmanis, MSc student of Utrecht University to carry the data collection in Kenya, the advisory board of Biotrade2020plus project, who helped provide comments on individual case studies. Advice from various local stakeholders and experts was also very much appreciated. The acronym of the project is BioTrade2020plus. Project information is available at: http://www.biotrade2020plus.eu/.

References

1. IRENA, *Renewable Energy Prospects: United States of America, REMap 2013 Analysis.* [Online]. Abu Dhabi (2015). Available at: http://www.ourenergypolicy.org/wp-content/uploads/2015/06/IRENA_REmap_USA_report_20151.pdf [April 11, 2017].
2. European Commission, *Commission Staff Working Document – State of Play on the Sustainability of Solid and Gaseous Biomass used for Electricity, Heating and Cooling in the EU.* [Online]. (2014). Available at: https://ec.europa.eu/energy/sites/ener/files/2014_biomass_state_of_play_.pdf [December 25, 2017].
3. *United Nations Framework Convention on Climate Change, Paris Agreement.* [Online]. (2015). Available at: http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm [December 25, 2017].
4. REN21, *Renewables 2016 Global Status Report.* [Online]. (2016). Available at: http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report.pdf [February 7, 2017].
5. Ministry of Economy Trade and Industry, *Settlement of FY 2016 Purchase Prices and FY 2016 Surcharge Rates under the Feed-in Tariff Scheme for Renewable Energy.* [Online]. (2016). Available at: http://www.meti.go.jp/english/press/2016/0318_03.html [March 24, 2017].
6. Ministry of Trade, *Industry and Energy, Korea Energy Master Plan – Outlook and Policies to 2035.* [Online]. (2014). Available at: http://www.motie.go.kr/common/download.do?fid=bbs&bbs_cd_n=72&bbs_seq_n=209286&file_seq_n=2 [December 30, 2017].
7. International Energy Agency (IEA), *World Energy Outlook 2016.* [Online]. (2016). Available at: https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExecutiveSummaryEnglish.pdf [May 9, 2017].
8. European Commission, *Proposal for a Directive of the European Parliament and of the Council – on the Promotion of the Use of Energy from Renewable Sources.* European Commission, Brussels (2016).
9. Ministry of Environment, *Import of Solid Refuse Fuel (SRF) to be Permitted with more Stringent Quality Test.* [Online]. (2014). Available at: http://www.me.go.kr/eng/web/board/read.do?menuId=21&boardMasterId=522&boardId=338239 [March 13, 2017].
10. Eurostat, *International Trade in Goods in a Nutshell.* [Online]. Available at: http://ec.europa.eu/eurostat/web/international-trade-in-goods/statistics-illustrated [April 6, 2017].
11. Pelkmans L, Devriendt N, Junginger M, Hoefnagels R, Resch G, Matzenberger J, *et al., Benchmarking Biomass Sustainability Criteria for Energy Purposes.* Study carried out for the European Commission, Directorate-General for Energy 2011/TEM/R/190. [Online]. (2012). Available at: https://ec.europa.eu/energy/sites/ener/files/documents/2014_05_biobench_report.pdf [June 1, 2017].
12. Granath J, *The Global Wood Pellet Market.* [Online]. Williamsburg: Pellet Fuels Institute (2015). Available at: http://www.pelletheat.org/assets/docs/2015_Conference/speaker_presentations/2015_pfi_conf_presentation_granath_monday_900.pdf [December 30, 2017].
13. Lamers P, Jacobson J and Wright C, *Expected International Demand for Woody and Herbaceous Feedstock.* [Online]. Idaho Falls (2014). Available at: https://www.osti.gov/scitech/servlets/purl/1177235 [December 30, 2017].
14. Matzenberger J, Kranzl L, Tromborg E, Junginger M, Daioglou V, Sheng Goh C, *et al.* Future perspectives of international bioenergy trade. *Renewable Sustainable Energy Rev* **43**:926–941 (2015).
15. Rose SK, Kriegler E, Bibas R, Calvin K, Popp A, Vuuren DP Van *et al.,* Bioenergy in energy transformation and climate management. *Clim Change* **123**:477–493 (2014).

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

16. Fritsche et al., To be published in this Special Issue – more information can be requested through corresponding authors.
17. Fingerman et al., Opportunities and risks for sustainable biomass export from the south-eastern United States to Europe. *Biofuels, Bioprod Bioref* (2017).
18. Pelkmans et al., Long term strategies for sustainable biomass imports in European bioenergy markets. *Biofuels, Bioprod Bioref* (2018).
19. Batidzirai B, Smeets EMW and Faaij A PC, Harmonising bioenergy resource potentials—Methodological lessons from review of state of the art bioenergy potential assessments. *Renewable Sustainable Energy Rev* **16**(9):6598–630 (2012).
20. Facts and Details, *Land and Geography of Indonesia*. [Online]. (2015). Available at: http://factsanddetails.com/indonesia/Nature_Science_Animals/sub6_8a/entry-4078.html [May 30, 2017].
21. Elbersen et al., To be published in this Special Issue – more information can be requested through corresponding authors.
22. Van der Hilst F, Verstegen J, Zheliezna T, Drozdova O, and Faaij APC, Integrated spatiotemporal modelling of bioenergy production potentials, agricultural land use, and related GHG balances; demonstrated for Ukraine. *Biofuels Bioprod Biorefin* **8**(3):391–411 (2014).
23. Biomass Magazine, *Pellet Plants* [Online]. (2017). Available at: http://biomassmagazine.com/plants/listplants/pellet/US/Operational/ [April 11, 2017].
24. Torén J, Dees M, Vesterinen P, Rettenmaier N, Smeets E, Vis, M. *et al., Biomass Energy Europe – Executive Summary, Evaluation and Recommendations.* [Online]. (2011). Available at: http://www.eu-bee.eu/_ACC/_components/ATLANTIS-DigiStore/BEE_D7.1_Executive Summary_1_0be20.pdf?item=digistorefile;247980;837&params=open;gallery [December 30, 2017].
25. European Union, Regulation (EU) No 1307/2013 of the European Parliament and of the Council of 17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation . (2013). Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:347:0608:0670:EN:PDF [December 30, 2017].
26. European Biomass Association (AEBIOM), *AEBIOM Statistical Report 2016.* Brussels: European Biomass Association (2016).
27. Ehrig R, Behrendt F, Wörgetter M and Strasser C, *Economics and Price Risks in International Pellet Supply Chains.* Springer, Cham Heidelberg New York Dordrecht London (2014).
28. Pirraglia A, Gonzalez R and Saloni D, Techno-economical analysis of wood pellets production for US manufacturers. *BioResources* **5**(4):2374–2390 (2010).
29. Hoefnagels R, Resch G, Junginger M and Faaij A, International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union. *Appl Energy* **131**:139–157 (2014).
30. Sea Freight Calculator, *Sea Freight World.* Available at: http://www.seafreightcalculator.com/ [30 December, 2017].
31. Giuntoli J, Agostini A, Edwards R, and Marelli L, *Solid and Gaseous Bioenergy Pathways: Input Values and GHG Emissions.* Luxembourg (2015).
32. Biograce II, *BioGrace-II Publishable final report*. [Online]. (2015). Available at: biograce.net/img/files/BioGrace_-_Final_publishable_report.pdf [December 30, 2017].
33. Southern Environmental Law Center, *Wood Pellet Plants and European Export – Southeast Wood Pellet Plants.* [Online]. (2015). Available at: https://www.southernenvironment.org/uploads/maps/southeastUSwoodepelletproduction_mapandtable.pdf [December 30, 2017].
34. Verstegen JA, Van der Hilst F and Woltjer G, What can and can 't we say about indirect land-use change in Brazil using an integrated economic – land-use change model? *GCB Bioenergy* **8**:1–18 (2015).
35. Boer R, Nurrochmat DR, Ardiansyah M, Hariyadi, Purwawangsa H and Ginting G, Reducing agricultural expansion into forests in Central Kalimantan – Indonesia: Analysis of implementation and financing gaps. [Online]. (2012). Available at: https://pcfisu.org/wp-content/uploads/pdfs/FINAL-REPORT-CCROM-Reducing_agricultural_expansion_into_forests_23_May_2012-2.pdf [June 9, 2016].
36. Coleman K, Jenkinson DS, Crocker GJ, Grace PR, Klír J, Körschens M *et al.,* Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma* **81**(1–2):29–44 (1997).
37. Farina R, Coleman K and Whitmore AP, Modification of the RothC model for simulations of soil organic C dynamics in dryland regions. *Geoderma* **200–201**:18–30 (2013).
38. Jenkinson DS and Coleman K, The turnover of organic carbon in subsoils. Part 2. Modelling carbon turnover. *Eur J Soil Sci* **59**(2):400–413 (2008).
39. Velthof GL, Oudendag D. and Oenema O, Development and application of the integrated nitrogen model MITERRA-EUROPE. [Online]. (2007). Available at: http://content.alterra.wur.nl/Webdocs/PDFFiles/Alterrarapporten/AlterraRapport1663.1.pdf [Septemer 16, 2015].
40. European Soil Data Centre, European Soil Database Derived data. [Online]. (2013). Available at: https://esdac.jrc.ec.europa.eu/content/european-soil-database-derived-data [January 9, 2017].
41. Gelten R, Spatial assessment of the environmental impacts of wheat and switchgrass bioethanol chains in Ukraine. Master thesis. [Online]. (2010). Available at: https://dspace.library.uu.nl/handle/1874/191522 [December 30, 2017].
42. Smeets EMW and Faaij APC, The impact of sustainability criteria on the costs and potentials of bioenergy production – Applied for case studies in Brazil and Ukraine. *Biomass Bioenergy* **34**(3):319–333 (2010).
43. Hoefnagels R, Searcy E, Cafferty K, Junginger TCM, Jacobson J and Faaij A, Lignocellulosic feedstock supply systems with intermodal and overseas transportation. *Biofuels Bioprod Biorefin* **8**(6):794–818 (2014).
44. Fletcher K, *Report Concludes US Pellet Exports no Threat to Southern Forests.* [Online]. (2015). Available at: http://biomass-magazine.com/articles/12604/report-concludes-us-pellet-exports-no-threat-to-southern-forests [March 6, 2017].
45. Lindstrom MJ, Effects of residue harvesting on water runoff, soil erosion and nutrient loss. *Agric Ecosyst Environ* **16**(2):103–112 (1986).
46. Papendick RI and Moldenhauer WC, Crop residue management to reduce erosion and improve soil quality – Northwest. [Online]. Agricultural Research Service (1995). Available at: https://archive.org/details/cropresiduemanag40pape [August 4, 2015].
47. Graham RL, Nelson R, Sheehan J, Perlack RD and Wright LL, Current and potential US corn stover supplies. *Agron J* **99-1**:1–11 (2005).
48. Gavrilescu D, Solid waste generation in kraft pulp mills. *Environ Eng Manage J* **3**(3):399–404 (2004).

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

49. Briggs DG, *Forest Products Measurements and Conversion Factors: With Special Emphasis on the US Pacific Northwest.* College of Forest Resources, University of Washington, Seattle, WA (1994).
50. de Paula Protásio T, Bufalino L, Tonoli GHD, Guimarães Junior M, Trugilho PF and Mendes LM, Brazilian lignocellulosic wastes for bioenergy production: characterization and comparison with fossil fuels. *BioResources* **8**(1):1166–1185 (2013).
51. AEBIOM, European Bioenergy Outlook 2014 – a growing sector in figures. European Biomass Association (AEBIOM), Brussels, Belgium (2014).
52. Carvalho JLN, Noguierol RC, Menandro LMS, Bordonal R de O, Borges CD, Cantarella H *et al.,* Agronomic and environmental implications of sugarcane straw removal: a major review. *GCB Bioenergy* **9**(7):1181–1195 (2017).
53. Denadai MS, Guerra SPS, Bueno O de C and Lancas KP, Custo do enfardamento de palha de milho em diferentes percentuais de recolhimento. *Eighth International Bioenergy Conference,* São Paulo, November pp. 5–7 (2013).
54. Leitão FM da L, Perez NB, Trentin G, Sisti RN, and Nunes CLR, Avaliação comparativa de variedades de arroz irrigado cultivadas sob pivô central na Regiao da Campanha do Rio Grande do Sul, in *II Simpôsio de Iniciaçao Cientifica da Embrapa Pecuária Sul* [Online]. (2012). Available at: http://ainfo.cnptia.embrapa.br/digital/bitstream/item/72337/1/leitao-final.pdf [March 13, 2016].
55. Mansur PTB, *Viabilidade do Confinamento de Bovinos com Feno de Resíduos Culturais de Soja no Sistema Triângulo.* Fundaçao Getulio Vargas Escola de Economia de São Paulo, São Paulo (2014).
56. UNICA, *Sugarcane Industry in Brazil.* [Online]. Available at: http://sugarcane.org/resource-library/books/Folder and Brochure.pdf [December 30, 2017].
57. SugarCane, *SugarCane Best Cultivation Practices.* [Online]. Available at: http://sugarcane.org/sustainability/best-practices [May 10, 2016].
58. Cervi W, Potential of Sugarcane Straw to Bioelectricity – A Spatial Assessment. *Manuscr Prep*.
59. Bioenergy International, World of Pellets 2014. Stockholm: SBSAB/Bioenergy International Magazine (2014).
60. Wood Pellet Association of Canada*, Canadian Wood Pellet Production.* [Online]. Available at: http://www.pellet.org/production/production [December 30, 2017].
61. KMEC Engineering, *Building of Pellet Plant promote the Market Development.* [Online]. Available at: http://www.biomasspelletplant.com/news/building-of-pellet-plant.html [December 30, 2017].
62. Emprese de Pesquisa Energética, *Balanço Energético Nacional – Year 2013*. [Online]. (2014). Available at: https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2014.pdf [March 20, 2015].
63. Ferreira-Leitão V, Gottschalk LMF, Ferrara MA, Nepomuceno AL, Molinari HBC and Bon EPS, Biomass residues in Brazil: availability and potential uses. *Waste Biomass Valorization* **1**(1):65–76 (2010).
64. Missagia B, Agricultural and forestry residues for decentralized energy generation in Brazil. Brandenburgischen Technischen Universität Cottbus [Online]. (2011) Available at: https://opus4.kobv.de/opus4-btu/files/2440/Diss_Missagia.pdf [February 14, 2016].
65. Da Silva SS, and Chandel AK, Biofuels in Brazil – Fundamental Aspects, Recent Developments, and Future Perspectives Cham Heidelberg New York Dordrecht London, Springer (2014).
66. Mayer FD, Salbego PRS, Almeida TC De, and Hoffmann R, Quantification and use of rice husk in decentralized electricity generation in Rio Grande do Sul State, Brazil. *Clean Technol Environ Policy* **17**(4):993–1003 (2015).
67. Citrosuco, *In Our Process the Orange is Used in the Following Way.* [Online]. (2015) Available at: http://www.citrosuco.com.br/en/products.php#NFC [June 13, 2015].
68. USDA Foreign Agricultural Service, 2013 Kenya Annual Sugar Report [Online]. (2013). Available at: http://s3.amazonaws.com/ProductionContentBucket/pdf/20130430083027878.pdf [October 17, 2016].
69. Batidzirai B, Design of Sustainable Biomass Value Chains. Utrecht University, Utrecht (2013).
70. Andole O, The State of Solid Waste Management in Kenya [Online]. (2016). Available at: http://www.envr.tsukuba.ac.jp/~sustep/dl/160412_02.pdf [February 1, 2017].
71. Bioenergy, Ukrainian Biomass Pellet Market. [Online]. (2014). Available at: http://ukraineagrovalley.com/site/files/Biomass_Pellets_Market.pdf [October 26, 2017].
72. Perlack RD and Stokes BJ (leads) *US Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry* Oak Ridge National Laboratory, Oak Ridge, TN (2011).
73. ECOFYS, Maximising the yield of biomass from residues of agricultural crop. [Online.] (2016). Available at: https://ec.europa.eu/energy/sites/ener/files/documents/Ecofys - Final_ report_ EC_max yield biomass residues 20151214.pdf [May 29, 2017].
74. Regis M, Leal LV, Galdos MV, Seabra JEA, Walter A and Oliveira COF, Sugarcane straw availability, quality, recovery and energy use : A literature review. *Biomass and Bioenergy* **53**:11–19 (2013).
75. Wilhelm WW, Johnson JMF, Hatfield JL, Voorhees WB and Linden DR, Crop and soil productivity response to corn residue removal: a literature review. *Agron J* **96**(1):1–17 (2004).
76. Portugal-Pereira J, Soria R, Rathmann R, Schaeffer R and Szklo A, Biomass and Bioenergy Agricultural and agro-industrial residues-to-energy: Techno- economic and environmental assessment in Brazil. *Biomass and Bioenergy* **81**:521–533 (2015).
77. Mai-Moulin T, Dardamanis A and Junginger M, *Assessment of Sustainable Lignocellulosic Biomass Potentials from Kenya for export to the European Union 2015 to 2030.* [Online]. (2016). Available at: http://www.biotrade2020plus.eu/publications-reports.html [December 30, 2017].
78. Van der Hilst F, Verstegen J, Karssenberg D and Faaij APC, Spatiotemporal land use modelling to assess land availability for energy crops – illustrated for Mozambique. *GCB Bioenergy* **4**(6):859–874 (2012).
79. Kheang LS, Subramaniam V and Ngatiman M, Oil Palm Biomass - Energy Resource Data. Kuala Lumpur, Malaysian Palm Oil Board (2012).
80. Paltseva J, Searle S and Malins C, *Potential for Advanced Biofuel Production from Palm Residues in Indonesia.* [Online]. (2016). Available at: http://www.theicct.org/sites/default/files/publications/ICCT_palm residues_2016.pdf [December 30, 2017].
81. Suharno DI, Dehen DYA, Barbara DB and Ottay MJB, *Opportunities for Increasing Productivity & Profitability of Oil Palm Smallholder Farmers in Central Kalimantan.* [Online]. (2013). Available at: https://climatepolicyinitiative.org/wp-content/uploads/2015/04/Opportunities-for-Increasing-Productivity-Profitability-of-Oil-Palm-Smallholder-Farmers-in-Central-Kalimantan-Full-Report1.pdf [December 30, 2017].
82. Abdullah N and Sulaim F, The oil palm wastes in Malaysia. *Biomass Now – Sustain Growth Use.* [Online]. (2013). Available

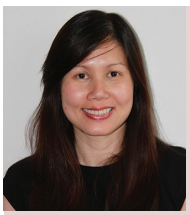
© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

at: http://www.intechopen.com/books/biomass-now-sustainable-growth-and-use/the-oil-palm-wastes-in-malaysia [December 30, 2017].

83. European Commission, JRC Science and Policy report - Solid and gaseous bioenergy pathways: input values and GHG emissions. Luxembourg; (2015).
84. The World Bank, *Electric Power Consumption (kWh per Capita).* [Online]. (2014). Available at: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC [September 19, 2017].
85. The World Bank, Fertilizer Consumption (Kilograms per Hectare of Arable Land). [Online]. (2014). Available at: https://data.worldbank.org/indicator/AG.CON.FERT.ZS [September 19, 2017].
86. PBL Netherlands Environmental Assessment Agency, *Trends in Global CO_2 Emissions 2016.* The Hague (2016).
87. Wear DN and Greis JG, *The Southern Forest Futures Project: Technical Report.* [Online]. (2013). Available at: https://www.srs.fs.usda.gov/pubs/44183 [December 30, 2017].
88. Kenya National Bureau of Statistics, *Kenya Facts and Figures.* [Online]. (2015). Available at http://www.knbs.or.ke/index.php?option=com_phocadownload&view=category&id=20&Itemid=1107 [March 24, 2017].
89. Murray G, Emerging Pellet Markets in Asia. *Wood Pellet Assoc Canada* [Online]. (2016) Available at: https://www.canadianbiomassmagazine.ca/images/Emerging-Pellet-Markets.pdf [January 11, 2017]
90. Murray G, Canadian Bioenergy Situation and Opportunities in Canada's Wood Pellet Sector. [Online]. (2017). Available at: https://www.canadianbiomassmagazine.ca/images/canadian%20bioenergy%20situation%20and%20opportunities%20in%20canadas%20wood%20pellet%20sector.pdf [23 June, 2017]
91. Biomass Magazine, Market price trend of wood pellets (2009-2020) [Online]. (2016). Available at: http://biomassmagazine.com/articles/13796/futuremetrics-offers-wood-pellet-demand-spot-pricing-estimates [April 6, 2017].
92. BioSustain, Biomass supply potentials for the EU and biomass demand from the material sector by 2030 - Technical Background Report of the "BioSustain" study: Sustainable and optimal use of biomass for energy in the EU beyond 2020.
93. Nogueira LAH, Lora EES, Trossero M and Frisk T, Wood energy: Resources and wood energy fuels. In: Dendroenergia : fundamentos e aplicações. ANEEL. Brasília pp. 24–45 (2000).
94. Hassuani SJ, Leal MRLV and Macedo I de C, Biomass power generation – Sugar cane bagasse and trash, in *Biomass Power Generation – Sugar Cane Bagasse and Trash* ed. by Hassuani SJ, Leal MRLV, Macedo I de C. PNUD – Programa das Nações Unidas para o Desenvolvimento CTC – Centro de Tecnologia Canavieira, Piracicaba, Brazil, pp. 24–26 (2005).
95. Miles TR, Miles TRJ, Baxter LL, Bryers RW, Jenkins BM and Oden LL, *Alkali Deposits found in Biomass Power Plants – A Preliminary Investigation of their Extent and Nature,* Vol. II. Springfield, VA (1995).
96. Bhattacharya SC, Pham HL, Shrestha RM and Vu QV, CO_2 emissions due to fossil and tradition fuels, residues and wastes in Asia. *Workshop on Global Warming Issues in Asia,* Asian Institute of Technology, 8–10 September 1992, Bangkok, Thailand (1993).
97. Coelho ST, Monteiro MB, Karniol MR and Ghilardi A, *Atlas de Bioenergia do Brasil.* São Paulo [Online]. (2008). Available from: https://www.scribd.com/document/40479685/Atlas-Bioenergia-CNEBIO [January 20, 2017].
98. Forster-Carneiro T, Berni MD, Dorileo IL and Rostagno MA, Resources, conservation and recycling biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. *Resour Conserv Recycl* **77**:78–88 (2013).
99. Aguiar L, Márquez-Montesinos F, Gonzalo A, Sánchez JL and Arauzo J, Influence of temperature and particle size on the fixed bed pyrolysis of orange peel residues. *J Anal Appl Pyrolysis* **83**: 124–30 (2008).
100. Coelho S and Escobar J, Possibilities of sustainable woody energy trade and impacts on developing countries: Country Case Study Brazil. [Online]. Sao Paulo: Centro Nacional de Referência em Biomassa - CENBIO (2013). Available from: http://www.iinas.org/tl_files/iinas/downloads/CENBIO_2013_Brazil-Case-Study_GIZ.pdf [June 5, 2015].
101. Tomaselli I, Otimização da gestão de resíduos e o desenvolvimento florestal. In: II Encontro Nacional de Gestão de Resíduos, 4–6 May, 2011, Curitiba: ENEGER; (2011).
102. Boundy B, Diegel SW, Wright L and Davis SC, *Biomass Energy Data Book – Edition 4.* [Online]. Knoxville, Tennessee: Oak Ridge National Laboratory (2011). Available at: cta.ornl.gov/bedb [June 6, 2017]
103. Bortolin TA, Trentin AC, Peresin D and Schneider VE, Estimativa da geração de resíduos florestais no Brasil. *3º Congresso Internacional de Tecnologias para o Meio Ambiente*, 25–27 April 2012, Bento Gonçalves (2012).
104. BID-MME, *Evaluacion del Ciclo de Vida de la Cadena de Produccion de Biocombustibles en Colombia.* [Online]. (2012). Available at: www.fedebiocombustibles.com [March 20, 2012].
105. Leyssens G, Trouve G, Schönnenbeck C and Cazier F, Energetic performances and environmental impact of the combustion of cardboard / sawdust in a domestic boiler. *FUEL* [Online]. (2015). Available at: http://dx.doi.org/10.1016/j.fuel.2014.01.034 [December 30, 2017].
106. ECN, *Phyllis 2 – Database for Biomass and Waste.* [Online]. Available at: https://www.ecn.nl/phyllis2/ [December 14, 2014].
107. Escalante Hernández H, Orduz Prada J, Zapata Lesmes HJ, Cardona Ruiz MC and Duarte Ortega M, Atlas del Potential Energético de la Biomasa Residual en Colombia. [Online]. Available at: https://biblioteca.minminas.gov.co/pdf/ATLAS POTENCIAL ENERGETICO BIOMASA RESIDUAL COL. UPME.pdf [May 16, 2015].
108. Ramírez N, Arévalo A, and Garcia-Nunez JA, Inventario de la biomasa disponible en plantas de beneficio para su aprovechamiento y caracterización fisicoquímica de la tusa en Colombia. *Rev Palmas* **36**(4):41–54 (2015).
109. Biopact, *Crop Residues: How much Biomass Energy is Out There?* [Online]. (2006) . Available at: http://news.mongabay.com/bioenergy/2006/07/crop-residues-how-much-biomass-energy.html [November 23, 2014].
110. Jiang D, Zhuang D, Fu J, Huang Y and Wen K, Bioenergy potential from crop residues in China: availability and distribution. *Renewable Sustainable Energy Rev.* [Online]. **16**(3):1377–1382 (2012). Available at http://dx.doi.org/10.1016/j.rser.2011.12.012 [December 30, 2017].
111. Terrapon-Pfaff J, Fischedick M and Monheim H, Energy potentials and sustainability – the case of sisal residues in Tanzania Energy potentials and sustainability – the case of sisal residues in Tanzania. *Energy Sustainable Dev* **16**(3):312–319 (2012).

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

112. SAACKE, *Liquids with Low Heating Value.* [Online]. (2012). Available from: www.saacke.com/fileadmin/Media/Documents/pdfs/EN/Brochures/0-0750-0020-02_Ansicht.pdf [December 30, 2017].
113. Terrapon-Pfaff JC, Linking energy- and land-use systems: energy potentials and environmental risks of using agricultural residues in Tanzania. *Sustainability* **4**:278–293 (2012).
114. Cubero-Abarca R, Moya R, Valaret J and Filho MT, Use of coffee (Coffea arabica) pulp for the production of briquettes and pellets for heat generation. *Ciência e Agrotecnologia* **38**(5):461–470 (2014).
115. Senelwa K and Sims REH, Opportunities for small scale biomass-electricity systems in Kenya. *Biomass and Bioenergy* **17**:239–55 (1999).
116. Office of Energy Efficiency and Renewable Energy, *Bioenergy Technologies Office* [Online]. Available at: https://www.energy.gov/eere/bioenergy/bioenergy-technologies-office [December 30, 2017].
117. Argonne National Laboratory, *Greet Model.* [Online]. Available at: https://greet.es.anl.gov [December 21, 2014].
118. Jenkins BM, Baxter LL, Miles Jr. TR and Miles TR, Combustion properties of biomass. *Fuel Process* **54**:17–46 (1998).
119. Geletukha G and Zheliezna T, *Prospects for the Use of Agricultural Residues for Energy Production in Ukraine.* [Online]. Kyiv (2014). Available at: www.uabio.org/activity/uabio-analytics [December 30, 2017].
120. IINAS - International Institute for Sustainability Analysis and Strategy, EFI - European Forest Institute, and JR - Joanneum Research, *Forest Biomass for Energy in the EU: Current Trends, Carbon Balance and Sustainable Potential.* Prepared for BirdLife Europe, EEB, and Transport and Environment. [Online]. (2014). Available at: http://www.birdlife.org/sites/default/files/attachments/IINAS_EFI_JR_2014_Forest_biomass_energy_EU.pdf [December 30, 2017].
121. BioGrace-II, *The BioGrace-II GHG Calculation Tool for Electricity, Heating and Cooling Products.* [Online]. (2015). Available at: http://www.biograce.net/app/webroot/biograce2/content/ghgcalculationtool_electricityheatingcooling/overview [December 30, 2017].



Thuy Mai-Moulin
Thuy Mai-Moulin is a junior researcher at the Copernicus Institute, Utrecht University. Her works focus on sustainable bioenergy supply chains, sustainability requirements for solid biomass use, and sustainable bioenergy trade and markets to support the development of the biobased economy.

Lotte Visser
Lotte Visser is currently working as a PhD candidate at the Copernicus Institute at Utrecht University. Her research examines supply-chain costs of lignocellulosic feedstocks and focuses on logistics costs and supply-chain optimization strategies.

Kevin R. Fingerman
Dr Kevin R. Fingerman is an assistant professor of environmental science and management at Humboldt State University. His research employs life-cycle assessment, simulation, and spatial modeling tools to evaluate the impacts of bioenergy and transportation energy systems. He holds MSc and PhD degrees from UC Berkeley's Energy and Resources Group.

Wolter Elbersen
Dr Wolter Elbersen is senior researcher at Wageningen Food & Biobased Research where he works on biomass mobilisation and setting up sustainable biomass supply systems. He has worked on these issues in Colombia, Suriname, Ukraine and Malaysia. Currently he is the National Task Leader for IEA Task 43 on Biomass Feedstocks for Energy Markets.

Berien Elbersen
Dr Berien Elbersen is a senior researcher on land use and integrated environmental assessment at Wageningen UR – Environmental Research. Her areas of expertise include biobased economy, agricultural policy, land use planning, agriculture and environment.

Gert-Jan Nabuurs
Prof Dr Gert-Jan Nabuurs is a professor of European forest resources at Wageningen University and Research. His background is in strategic European scale forest resource analyses and forest management under climate change, addressing, for example, wood availability, carbon sequestration, biodiversity, and their synergies.

Uwe R. Fritsche
Uwe R. Fritsche is a physicist, who worked since 1984 at Öko-Institut where he focused on international activities, sustainable use of biomass, and land. Since 2012, Uwe has been the scientific director of IINAS. His expertise is in life-cycle assessment and sustainability; he is the national team leader for IEA Bioenergy Task 40, and has provided expertise to the FAO, GBEP, GEF, IEA, UNEP, and UNIDO.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Inés del Campo
Inés del Campo has an MSc in chemical engineering. She works in the biomass department of CENER as R&D engineer leading advanced biofuel and bio-based product-related projects. She coordinated BioTrade2020plus and is now working on other EU projects as coordinator, technical coordinator, and partner. These include ButaNexT, BIOrescue, and BRISK2.

Dominik Rutz
Dominik Rutz is head of the bioenergy and bioeconomy unit at WIP Renewable Energies. Since 2005, he has been an expert at WIP on renewable energies and more specifically on bioenergy. He graduated in environmental science as well as in consumer science. His main field of experience includes the technical and non-technical analysis of bioenergy and its supporting policies worldwide.

Rocio A. Diaz-Chavez
Dr Rocio A Diaz-Chavez is a research fellow at the Centre for Environmental Policy of Imperial College London and MSc tutor for the distance learning MSc of the Centre for Development Environment and Policy at SOAS. Her research interests are on sustainability assessment (economic, environmental social and political/institutional) with application on renewable energy, particularly bioenergy projects, in Latin America, Africa, Asia and Europe, and integrated systems for producing food, fiber, fuel, and fodder (including biorefineries), and climate-change impacts.

Leire Iriarte
Leire Iriarte has a PhD in bioenergy and is a senior expert on sustainability assessment of biomass systems in the EU, developing countries, and global contexts. Her areas of expertise include sustainable bioenergy policies and standards, biomass potentials, GHG emissions balances, and land-use-related issues.

Luc Pelkmans
Luc Pelkmans is technical coordinator of the IEA Bioenergy Technology Cooperation Program and member of the Dutch Advisory Commission on sustainability of biomass for energy. He graduated with an MSc in mechanical engineering in 1994 and worked for VITO from 1996 until 2017 as project manager on alternative transport fuels and drivetrains, biofuels, bioenergy, and biobased economy.

David Sanchez Gonzalez
David Sanchez Gonzalez leads different project activities related to biomass energy, both national and international, since 2000. As an agricultural expert focusing on bioenergy, his main research lines are biomass resource assessment and logistic supply, and solid biofuels production. From 2012, as a head of biofuels service in CENER's biomass department, he is leading the execution of RTD activities.

Rainer Janssen
Dr Rainer Janssen is managing director projects at WIP Renewable Energies and senior expert in biomass. He specializes in the production, distribution and market penetration of biomass energy and biofuels, with special emphasis on innovative technologies, research and innovation policies, market research, and public awareness.

Axel Roozen
Axel Roozen MSc is a graduate from Utrecht University where he received his master's degree in energy science. His master's thesis focused on the sustainable lignocellulosic biomass potential of agricultural and forestry residues in Brazil. As part of his master's thesis, he visited Brazil where he gathered information from sugarcane producers and experts within the biomass sector regarding the sustainable removal rates of agricultural residues and local mobilization barriers.

Mathijs Weck
Mathijs Weck MSc is a graduate from Utrecht University where he received his master's degree in energy science. His master's thesis focused on the sustainable lignocellulosic biomass potential of agricultural and forestry residues in Ukraine. As part of his master's thesis, he spent some time in Ukraine, gathering data from relevant stakeholders in the agricultural sector and the wood-pellet sector regarding sustainability constraints and domestic demand.

Dr Martin Junginger
Prof Dr Martin Junginger holds the Bio-Based Economy chair at the Copernicus Institute, Utrecht University, and works on, among other fields, sustainable biomass production, supply chains, conversion, and end use for energy and materials. He is a task leader of IEA Bioenergy Task 40 on sustainable biomass markets and international trade to support the biobased economy.

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Appendix

Appendix A. Classification of feedstocks

Agricultural resources	
Primary	Crop residues from major crops – corn stover, small grain straw, and others Grains (corn and soybeans) used for ethanol, biodiesel, and bio products Perennial grasses Perennial woody crops
Secondary	Animal manures Food/feed processing residues
Tertiary	Municipal solid waste and post-consumer residues and landfill gases
Forest resources	
Primary	Logging residues from conventional harvest operations and residues from forest management and land clearing operations Removal of excess biomass (fuel treatments) from
Secondary	Primary wood processing mill residues Secondary wood processing mill residues Pulping liquors (black liquor)
Tertiary	Urban wood residues – construction and demolition debris, tree trimmings, packaging wastes and consumer durables

Appendix B. RPR and LHV values and SRF

	Feedstock	RPR (t/t)	LHV (MJ/kg) (%)	SRF (%)
Brazil	Sugarcane tops/straw	0.34[94]	17.38[95]	50[46]
	Sugarcane bagasse	0.30[94]	17.71[96]	100[47]
	Soybean straw	1.40[94]	12.38[96]	25[48]
	Corn stalk	0.78[97]	17.45[46]	30[48–50]
	Corn cob	0.22[65]	16.28[47]	30[48,50–52]
	Corn husk	0.20[47]	12.00[96]	30[48,50–52]
	Cassava straw	0.80[94]	17.50[96]	30[48,50–52]
	Rice straw	1.48[94]	16.02[96]	25[48]
	Rice husk	0.22[94]	14.17[98]	100
	Coffee husk	0.21[94]	17.71[95]	100
	Orange peel	0.50[99]	17.11[100]	100
	Field residues	0.15[101,102]	19.05[103]	52.5[53]
	Paper and cellulose production residues	0.117[50,51]	18.18[52]	100
	Sawmill and furniture industry residues	0.3825[65,98,104]	18.18[100]	100
		RPR (t/t)	HHV (MJ/kg)	SRF (%)[105]
Colombia	Sugarcane trash	3.26[106]	18.69[107]	50–70[a]
	Oil palm shell	0.22[108]	21.5[109]	83–92[b]
	Oil palm fiber	0.63[106]	19.2[109]	83–92[b]
	Oil palm empty fruit bunch	1.06[106]	17.9[109]	83–92[b]
	Sugarcane bagasse	2.68[106]	19.37[107]	100
		RPR (%)[81,84]	LHV (MJ/kg)[81]	SRF (%)[81,84]
Indonesia	Palm EFB	21.07	18.88	95
	Palm shell	4.29	20.09	85
	Palm fiber	15.42	19.06	85
		Dry quantity(t/ha)		
	Palm frond	10.88	15.72	100
	Palm trunk	2.48	17.47	100

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Appendix B. Continued

		RPR (t/t)[70,72,110–112]	LHV (MJ/kg)[70,81,113–115]	SRF (%)[70,81,113–115]
Kenya	Bagasse	0.38	12.93	40
	Sugarcane stalks and leaves	0.22	16.61	9
	Molasses	0.04	8.50	100
	Sisal ball	4.10[c]	14.85	83[c]
	Sisal bogas	19.80[d]	14.85	100[d]
	Coffee husk	0.24[e]	14.10	83[e]
	Coffee pulp	2.42[e]	0.01	100[e]
	Coconut husk	1.10	17.66	100
	Rice straw	2.19	13.45	3
	Rice husk	0.29	16.17	100
	Offcuts and chips (share in timber waste)	57,5%[71,116]	19.2[106,117–119]	81
	Sawdust (share in timber waste)	19,5%[g, 71]	16.8[106,116–118]	0
		RPR (t/t)	LHV (MJ/kg)	SRF (%)[f]
Ukraine	Barley	0.8	13.6[120] (wet)	0–100
	Maize	1.3	7.6[120]	0–100
	Rapeseed	1.8	14.3[120]	0–100
	Sunflower	1.9	5.7[120]	0–100
	Wheat	1	13.3[120]	0–100
	Primary forestry residues		16.0	0–75
	Secondary forestry residues		17.9	0–75
		RPR	LHV (MJ/kg, wet)	SRF (%)[74]
US	Mill residue	[g]	6.95	100
	Logging residue	[g]	6.95	50–67[a]
	Softwood biomass	[g]	6.95	[h]
	Hardwood biomass	[g]	6.95	[h]
	Other removals	[g]	6.95	50

[a]Varies per scenario.
[b]Varies per scenario, total for oil-palm residues (including empty fruit bunch, fiber and shell).
[c]This price is calculated based on data from Real Vipingo sisal estate in Kilifi County. Each year 300 ha is harvested; 3000 plants are produced per ha, with a sisal ball weighing 20 kg. Fiber production was 5100 t in 2014.
[d]The lower limit of sisal bogas RPR is provided by Real Vipingo's estate measurements.
[e]Data from Kofinaf (coffee mill) in Kiambu County.
[f]Varies per region in Ukraine, calculated using spatial data on soil type, production intensity, crop type, and climate.
[g]Calculated using spatial date on forest product removal (on county level) from the US Forest Service Timber Products Output (TPO) database (USDA-USFS 2015).
[h]Varies per region in the United States, calculated using spatial data on protected areas of conservation significance, rarity-weighted species richness and forest types (taking into account exclusion of gum-cypress and a 10% exclusion of oak-pine forest types).[121]

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Appendix C. Local demand (share not available) (%)

		Current	2020 BAU	2020 HE	2030 BAU	2030 HE
Brazil	Sugarcane bagasse	90	100	90	100	90
	Sugarcane tops/straw	0	0	0	50	25
	Soybeans straw	0	10	0	30	0
	Corn stover	60	60	50	60	30
	Cassava straw	100	100	100	100	100
	Rice straw	0	0	0	0	0
	Rice husk	75	85	67	100	67
	Coffee husk	100	100	100	100	100
	Oranges peel	100	100	100	100	100
	Forestry field		0-15	0-5	0-40	0-25
	Paper & cellulose production		75	70	85	70
	Lumber processing		75	70	85	70
Ukraine	Combined residues (straw)	31	31	15.5	31	15.5
Colombia	Sugar cane trash	0	5	10	20	10
	Palm EFB	36	10	15	10	15
	Palm shell	9	3	10	5	10
	Palm fibre	25	2	10	5	10
Indonesia	Palm frond	0	0	10	10	15
	Palm trunk	0	0	10	10	15
	Palm EFB	10	10	15	15	20
	Palm shell	10	10	15	15	20
	Palm fibre	10	10	10	15	20
Kenya	Bagasse	0	0	0	0	0
	Sugarcane stalks & leaves	6	4	4	6	6
	Molasses	50	50	50	50	50
	Sisal ball	0	0	0	0	0
	Sisal bogas	0	0	0	0	0
	Coffee husk	100	100	100	100	100
	Coffee pulp	100	100	100	100	100
	Coconut husk	17	16	16	16	16
	Rice straw	0	0	0	0	0
	Rice husk	7	5	5	7	7
	Off-cuts & chips (share in timber waste)	21	18	18	21	21
	Sawdust (share in timber waste)	100	100	100	100	100
US	Forest biomass	69	73	63	76	57

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Appendix D. Cost factors & country specific cost factors

			Brazil	Colombia[a]	Kenya	Indonesia	Ukraine	United States
Feed-stock	Moisture content (fresh)	%	50	50	50	73	50	50
	Moisture content (dry)	%	8.5	8.5	8.5	7	8.5	8.5
	Cal. Value after drying	MJ / kg ar (LHV)	16.35	16.35	16	16.35	16	16
	Interest rate (IRR)%		10		10	10	10	10
Pellet plant	Scale	MT/year	120,000			120,000	120,000	120,000
	Operating hours	h/year	7,000			7,000	7,000	7,000
	Electricity price	€ /MWh	121.9		49.6	73.4	14.5	60.0
	Labour	€ /h	8.1		0.5	1.1	1.8	25.0
	Heat source		Biomass	Biomass	Biomass	Biomass	Biomass	Biomass
	Pelletizing cost	€/t	58.9	50	55.9	79.4	58.9	107.9
Transport	Distance to pellet plant	km	50		110	55	[b]	i
	Transport cost (truck)	€ /km/t	0.09	0.08	0.16	0.42	[b]	0.071[c]
	Truck loading			1.50				
	Transport cost (train)	€ /km/t			0.16		[b]	0.03
	Harbor cost	€ /t	7.26	21.50	1.46	0.37	[b]	[b]
	Ocean cost			15 / 20				
	Profit	%	10%		10	10	10%	10%
Agri residues	Field processing	€ /t field site	12.1	21.25/32.3[d]	2.04	3.36	12.1	
Forest residues	Field processing	€ /t field site	20.0		2.04		20.0	[e]
Energy crops	Field processing	€ /t field site	12.1				12.1	

[a]Due to data limitations it was not possible to use country-specific factors for Columbia to calculate the pellet production cost; instead total pelletizing costs were assumed
[b]For these two countries, it was possible to calculate the transport cost in more detail by making use of the existing BIT-UU model 30. In the case of Ukraine, transport cost from any point in the Ukraine until the Port of Rotterdam could be calculated. In the case of the US, the BIT-UU model included transport cost from several export ports to the Port of Rotterdam. ArcGIS was used to calculate the transport distance from each included spatially explicit location until the export ports. Combining the least cost combination resulted in the total cost.
[c]Calculated based on 122, with time cost and variable cost taken from data about trucks in the EU.
[d]Biomass cost, including cleaning of trash.
[e]Cost are taken from the Billion Ton Update 74. This study reports increasing production costs with increased mobilization of biomass, and represents the cost of mobilization. This is considered more realistic in a well-developed market such as the US, instead of using delivery cost.

Appendix E. States included in the Brazil case study

Appendix F. National electricity emission coefficients

Country	Electricity emission coefficient gCO2-eq/MJ123
United States	180
Ukraine	167
Colombia	45
Brazil	31
Indonesia	296
Kenya	81

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Appendix G. Other emissions factors

Nutrient substitution - emission factor chemicals[33]

Fertilizer		CO_2	CH_4	N_2O	CO_2-eq.
N	kg/t	2,670.87	6.94	2.10	0
P_2O_5	kg/t	1,459.04	3.73	0.00	0
K_2O	kg/t	409.20	0.17	0.00	0
Pesticides	kg/t	6,650.33	10.03	1.68	7,402.33

Pre-treatment[33]

		CO_2	CH_4	N_2O	CO_2-eq.
Cultivation	g/MJ wood pellets	0.842	0.0000088	0.0000368	0.85
Chipping	g/MJ wood pellets	0.248	0.0000026	0.0000109	0.25
Drying	g/MJ wood pellets	0.070	0.0000007	0.0000031	0.07
Pellet Mill	g/MJ wood pellets	0.146	0.0000015	0.0000064	0.15
Pellet Mill	MJ/MJ wood pellets	0.050			

Appendix H. Impacting factors to total supply chain costs (in €/GJ)

Country	Impacting factor	50%	75%	90%	100%	110%	125%	150%
Brazil	Electricity			12.7	12.9	13.1		
	Transport		11.8	12.4	12.9	13.3	14.0	
	Pre-processing		11.8	12.5	12.9	13.3	13.9	
	Capital	12.0	12.4	12.7	12.9	13.1	13.3	13.8
	Labour		12.9	12.9	12.9	12.9	12.9	
Indonesia	Electricity			13.5	13.6	13.6		
	Transport		12.0	13.0	13.6	14.2	15.1	
	Pre-processing		12.5	13.1	13.6	14.0	14.6	
	Capital	12.5	13.0	13.3	13.6	13.8	14.1	14.6
	Labour		13.5	13.6	13.6	13.6	13.6	
Kenya	Electricity			11.9	12.0	12.1		
	Transport		10.0	11.2	12.0	12.8	14.0	
	Pre-processing		11.8	11.9	12.0	12.1	12.3	
	Capital	11.1	11.6	11.8	12.0	12.2	12.4	12.9
	Labour		12.0	12.0	12.0	12.0	12.0	
Ukraine	Electricity			8.8	8.8	8.8		
	Transport		8.3	8.6	8.8	9.0	9.3	
	Pre-processing		7.8	8.4	8.8	9.2	9.8	
	Capital	7.9	8.3	8.6	8.8	9.0	9.2	9.7
	Labour		8.8	8.8	8.8	8.8	8.8	
The US	Electricity			11.6	11.7	11.8		
	Transport		11.0	11.4	11.7	12.0	12.4	
	Pre-processing		10.7	11.3	11.7	12.1	12.7	
	Capital	11.0	11.4	11.6	11.7	11.8	12.0	12.4
	Labour		11.6	11.7	11.7	11.7	11.8	

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Appendix I. Impacting factors to total GHG emissions (kg CO_2/GJ)

Country	Impacting factor	Low range	Base case	High range
Brazil	Nutrient substitution	12.4	12.9	13.7
	Local Transport	12.1	12.9	14.0
	Electricity	13.0	12.9	13.1
Colombia	Nutrient substitution	10.3	11.1	12.3
	Local Transport	11.1	11.1	11.5
	Electricity	11.2	11.1	11.4
Indonesia	Nutrient substitution	13.5	14.8	16.1
	Local Transport	14.6	14.8	15.0
	Electricity	14.7	14.8	14.9
Kenya	Nutrient substitution	12.7	13.3	13.8
	Local Transport	12.7	13.3	13.9
	Electricity	13.2	13.3	13.4
Ukraine	Nutrient substitution	6.5	7.3	8.1
	Local Transport	7.3	7.3	7.3
	Electricity	7.1	7.3	7.5
The US	Nutrient substitution	8.6	8.7	8.7
	Local Transport	8.3	8.7	9.0
	Electricity	8.5	8.7	8.8

© 2018 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.