Securing sustainable resource availability of biomass for energy applications in Europe; review of recent literature.

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I. The role of biomass for energy and materials for GHG mitigation from a global and European perspective.

Global

This paper provides an overview of state-of-the-art information on future biomass resource availability in Europe for energy and material applications and the preconditions under which those resources can be mobilized in a sustainable way.

Biomass is seen as one of the key renewable energy options to displace fossil fuels and contribute to mitigation of GHG emissions on a large scale (Woods et al., 2015). Many scenario's that describe how a low carbon future in 2050 can be achieved, project substantial shares of biomass in the future global energy supply, ranging between 10% to over a third, adding up to a contribution of 300 EJ (7200 Mtoe) in many scenarios in the second half of this century [IPCC, 2014] versus a projected total global energy use between 800 EJ (19200 Mtoe) to over 1500 EJ (35900 Mtoe). Among the reasons why biomass is so important in many mitigation scenarios is its versatility. It can deliver dispatchable power, high temperature heat, liquid and gaseous (transportation) fuels and renewable feedstock for material (chemicals, construction materials). Furthermore, many biomass conversion pathways are commercially attractive today (e.g. combined heat and power generation from biomass, organic waste conversion to e.g. biogas, ethanol production from sugar beet, etc, while biorefinery concepts and further advancements in value chains can make advanced biofuels (e.g produced from lignocellulosic material) and platform chemical in a competitive range in the medium term. Another key point is that state-of-the-art mitigation scenarios point out that Bioenergy combined with Carbon Capture and Storage (BECCS) can and should deliver negative emissions (carbon taken up during plant growth is released as CO_2 during conversion and subsequently captured for geological storage) which is required to meet the 1.5°C GMT target agreed in Paris. Negative emission on the desired scale can only be achieved by using (sustainable) biomass.

Global biomass energy potentials are found to range between 100 EJ (2390 Mtoe) to over 500 EJ/yr (12000 Mtoe) in 2050 (compared to a total global primary energy use of about 570EJ [13600 Mtoe] today), with increasing preconditions to realize the higher values of this range, e.g. with respect to improvements in agricultural efficiency and sustainability standards [Creutzig et al. 2014]. Crucial in these figures is that water limitations, biodiversity protection, and food demand are taken into consideration. Improvements of agricultural efficiency and crop choice (especially perennial cropping systems offer the best perspectives) are essential preconditions to reach the higher end of the range. Figure 1 summarizes these insights on global scale, based on a large number of studies and including estimates of global potential availability of biomass residues from agriculture and forestry.

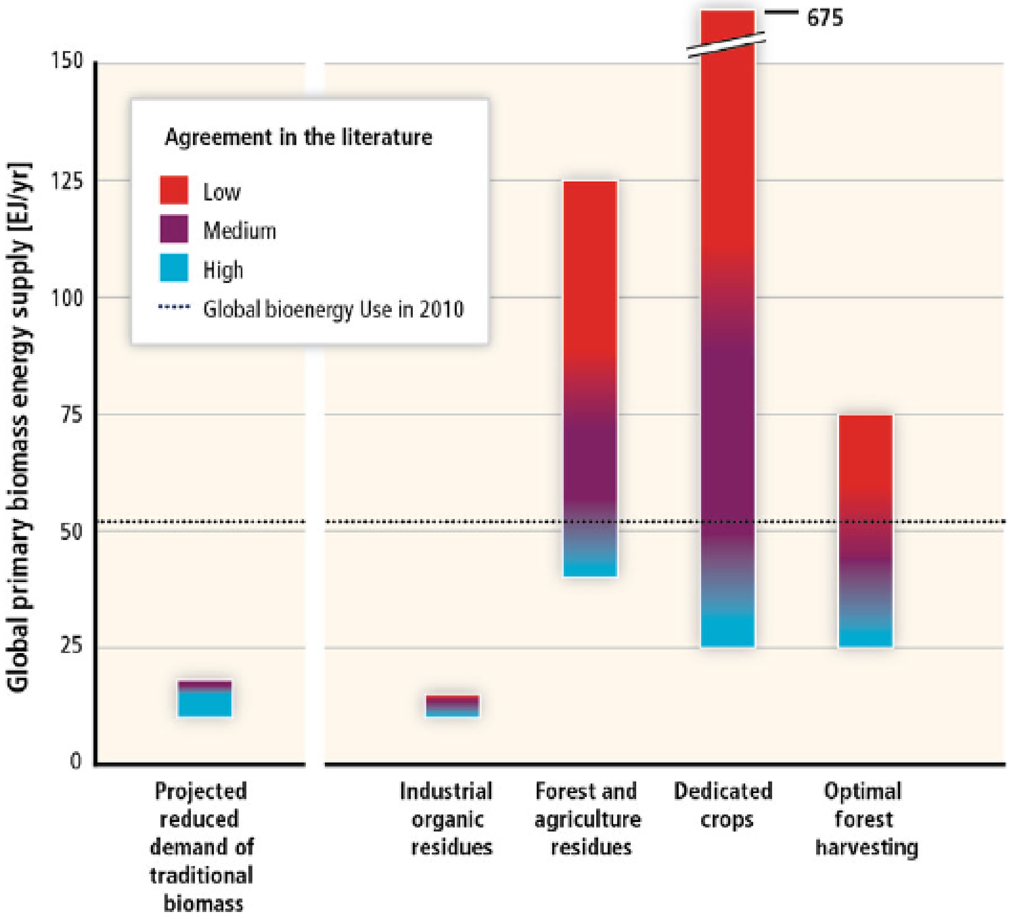

Figure 1: Global technical primary biomass potential for bioenergy by main resource category for the year 2050. The figure shows the ranges in the estimates by major resource category of the global technical primary biomass potential for bioenergy. The color grading is intended to show qualitatively the degree of agreement in the estimates, from blue (all researchers agree that this level can be attained) to purple (medium agreement) to red (few researchers agree that this level can be attained). [Creutzig et al., 2014]

Very recent work on global biomass resource potentials from [Daioglou et al., 2016] including all major parameters on overall land use change, carbon stock impacts, net availability of residual biomass, etc. and analysed for different future scenarios concerning developments in land use and agricultural management (SSP1 – SSP3; the different so –called socio-economic pathways as defined by the IPCC)[1], concludes the following:

*Biomass has an important role to play in future energy supply, irrespective of technological development or climate goals***.** Biomass accounts for at least 8%, and up to 35% of total primary energy supply by 2050 in all the baseline and mitigation scenarios presented, with its contribution increasing in mitigation scenarios. *In scenarios meeting ambitious "Paris style" climate targets, bioenergy makes up 26-35% of primary energy in 2050 and 32-50% in 2100, primarily used in the transport and power production sectors.* After 2050, bioenergy use is increasingly combined with CCS, providing so-called negative emissions which are very important when the strict emission constraints of ambitious climate targets are to be met.

High land requirements for energy production, together with other types of land use, run the risk of causing land-use change emissions per unit of energy above those of fossil fuels. Ensuring energy crop supply with low emission effects requires increases in productivity of both energy and food crops as well as livestock. These increases outpace the growth in food demand (including growing meat consumption). Optimizing land required for food

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[1] SSP1: low challenges for mitigation (resource efficiency) and adaptation (rapid development, also of key technologies and agricultural management improvements)
SSP3: high challenges for mitigation (regionalized energy / land policies) and adaptation (slow development)
SSP 2: in between SSP1 and SSP2.

production (especially pasture) would allow for the availability of large volumes of highly productive land for biomass production, at low LUC emissions. Improved crop yields would also increase the supply of residues while lowering their costs. The analysis highlights the favorable nature of the SSP1 implementation where strict land utilization constraints, improved crop yields and the reduction of extensive pastures may allow for low LUC/ILUC emissions of biomass production, as well as land-based mitigation, in contrast with the opposite SSP3, where substantial amounts of biomass are used, but with much reduced GHG mitigation impacts due to indirect emissions and impacts on carbon stocks.

Europe

The Paris agreement gives a clear and ambitious direction for investment in low carbon innovation. The implementation of the European Union's commitments towards the Paris agreement is now the priority and depends to a large extent on the successful transition to a clean energy system, as two thirds of Greenhouse Gas (GHG) emissions result from energy production and use. In 2015 the primary energy use in EU28 was 68.1 EJ (or 1628 Mtoe).

Recently, a new 2030 Climate and Energy Framework has been set at the EU political level to cover the period beyond 2020. For renewable energy, a 32% target has been agreed, which will contribute together with 32.5% energy savings (compared with the business as usual scenario) to a 45% cut in GHG emissions compared to 1990 levels. At COP24 (December 2018), the Commission will present a long-term scenario to decarbonise the whole EU economy by 2050 and thus meet the Paris commitment to keep global warming well below 2°C. Bioenergy, representing 60% of the renewable energy mix today, will be one of the main drivers to a European net-zero carbon economy.

However, the exact role of bioenergy is not fixed and will depend *inter alia* on the available biomass potential. *Estimates including all possible biomass categories from organic wastes, agricultural residues, forest biomass and cultivated biomass vary roughly between over 6 EJ (143 Mtoe) up to 30 EJ (717 Mtoe) in 2050.* Comparing those numbers to the current 68.1 EJ (or 1628 Mtoe) primary energy use in the EU shows that bioenergy can play an important role in decarbonising the EU economy together with other renewable energy sources and energy efficiency measures.

One key challenge in increasing the use of bioenergy in the future is to maintain a sustainable production. With the Renewable Energy Directive II, sustainability criteria have been adopted for all biomass fuels and cover now both agricultural and forest biomass. The sustainability criteria address environmental aspects such as soil quality, land use and biodiversity. Greenhouse gas emission saving criteria ensure that bioenergy achieves high emission savings compared to fossil fuels.

Much evidence has been collected on how biomass can be sourced sustainably and under what conditions, land can be used without causing undesired impacts. State of the art insights suggest that sustainable availability of biomass for energy materials especially depends on how those preconditions are met. This paper will go into those matters and provide an overview of the biomass potentials in Europe on the short and long term and what factors determine the development of those potentials in a sustainable way [Woods et al., 2015]. The document provides a compilation of recent literature on European biomass potentials and is not a scientific publication to allow for easy readability and reach a broad readership. Nevertheless, state-of-the-art scientific literature is used to underpin the information and data presented. The paper further focuses on the EU and the time horizons considered are 2030 and 2050. When appropriate, information on global biomass resources and relevant scenarios are referred to.

II. Biomass resource availability and potential studies on Europe

General characteristics of biomass resources potentials and key factors determining availability

Published estimates of the potential of bioenergy vary widely, mainly due to the heterogeneity of methodologies, assumptions and datasets employed. These discrepancies are confusing for policy and it is thus important to have scientific clarity on the basis of the assessment outcomes. Such clear insights can enable harmonization of the different assessments.

The type of biomass energy potential is a crucial criterion, because this determines to a large extent the approach and methodology employed in a study and thereby also the data requirements as summarized below. Different types of bioenergy potentials can be distinguished (following [Batidzirai et al., 2012]).

(i) Theoretical potential: The theoretical potential is defined as the maximum amount of terrestrial biomass which can be considered theoretically available for bioenergy production within fundamental bio-physical limits. In the case of biomass from crops and forests, this represents the maximum productivity under a theoretically optimal management of agriculture and forestry, taking into account limitations that result from temperature, solar radiation and rainfall. For residues and waste, the theoretical biomass potentials are the same as the total residue production.

(ii) Technical potential: The technical potential is defined as the fraction of the theoretical potential which is available under current technological possibilities, and taking into account spatial restrictions due to competition with other land uses (food, feed and fiber production) as well as other non-technical constraints.

(iii) Market (or economic) potential: The market potential refers to the share of the technical potential which meets economic criteria within given conditions (e.g. competition with fossil fuels or assumed carbon prices). This depends on both the cost of production and the price of the biomass feedstock.

(iv) Ecologically sustainable potential: When restrictions related to environmental criteria such as nature conservation and soil/water/biodiversity preservation are considered then this fraction of technical potential is referred to as the ecologically sustainable potential.

(v) Implementation potential: A variant of the economic potential that can be implemented within a certain time frame and under concrete socio-political framework conditions, including economic, institutional and social constraints and policy incentives is referred to as the implementation potential.

As shown in Figure 2 there is hierarchical reduction in potential from theoretical to implementation potential and an overlap between market potential and ecological potential. This overlap comes about, for example when biomass potential considered to be ecologically sustainable does not meet economic criteria and vice versa.

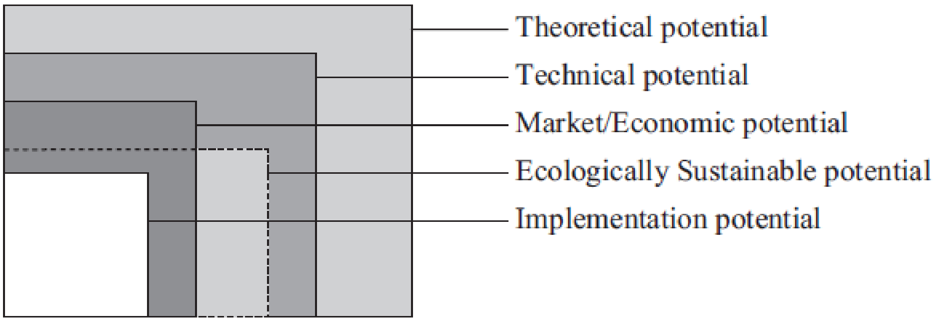

Figure 2: Categorization and overlap between theoretical, technical and market, ecological and implementation bioenergy potentials. [Batidzirai et al., 2012].

European biomass resources, potentials and analyses

An integral synthesis of biomass resource studies is very hard, because the methods, scenario definitions, geographic scope, time frame, biomass resources included, different type of potentials, (etc.) differ between the studies. This is confirmed by [Kluts et al. 2017], [Hänninen et al. 2018], [Creutzig et al., 2014] and [Batidzirai et al., 2012]. In simple words; the perfect biomass resource potential study does not (yet) exist. Key issues observed in recent studies are:

- Environmental impacts of intensification via different farming systems receive limited attention while these impacts should be accounted for if intensification is required to make land available for energy cropping.
- Future productivity developments of crops and livestock, and the associated land-use and environmental effects are currently limited to conventional intensification measures whereby the proportion between inputs and outputs is fixed. Sustainable intensification measures, which increase land productivity with similar or lower inputs, are ignored in the reviewed studies.
- Livestock productivity developments, livestock specific intensification measures and their environmental effects are poorly or not at all covered in the reviewed studies.
- Most studies neglect sustainability constraints other than GHG emissions in the selection of energy crops. This includes limitations to rainfed energy crop cultivation, a minimum number of crop species, the structural diversity within cropping areas and the integration of energy crops in existing or new crop rotations, while simultaneously considering the effects on subsequent crops. At the same time benefits that could be achieved by sustainable intensification and ecological benefits of more diverse land use and soil and biodiversity benefits of perennial crops are poorly covered as well.

These points suggest that the identification of sustainable pathways for European bioenergy production requires a more integrative approach combining land demand for food, feed and energy crop production, including different intensification pathways, and the consequent direct and indirect environmental impacts. A better inclusion of management practices into such approach will improve the assessment of intensification, its environmental consequences and the sustainable bioenergy potential from agricultural feedstocks. Many of these points apply to residue availability and forestry practices as well. Appendix II gives an overview of the main factors and parameters affecting biomass resource potentials and recommendations to reduce uncertainties.

Nevertheless, this paper compiles information from a range of studies and reviews to provide an overall picture and ranges for the European biomass resource potentials over time, including cultivated biomass (energy crops), agricultural residues, forest biomass and organic waste streams. Focus lays on the EU27, but in some cases other European countries are included as well, depending on the geographic scope of the original studies.

Biomass produced via energy crops

[Kluts et al. 2017], provided a very recent review of European land and bioenergy potential studies. Figure 3 shows the estimated arable and pastureland area available for energy crop cultivation according this assessment. The area ranges from 0 to 30 Mha currently, 7 to 42 Mha in 2020 and 7 to 52 Mha in 2030. This is the equivalent of 7–39% of arable land in 2012 in the EU-27 and 7–48% in 2030. In addition, [de Wit et al., 2010] and [Fischer et al., 2010] estimate the amount of pastureland available for the cultivation of woody and grassy energy crops at approximately 10 Mha in 2020 and 15 to 19 Mha in 2030, corresponding to a share of around 15% of pastureland in 2012 in the EU- 27 in 2020 and 23–28% in 2030.

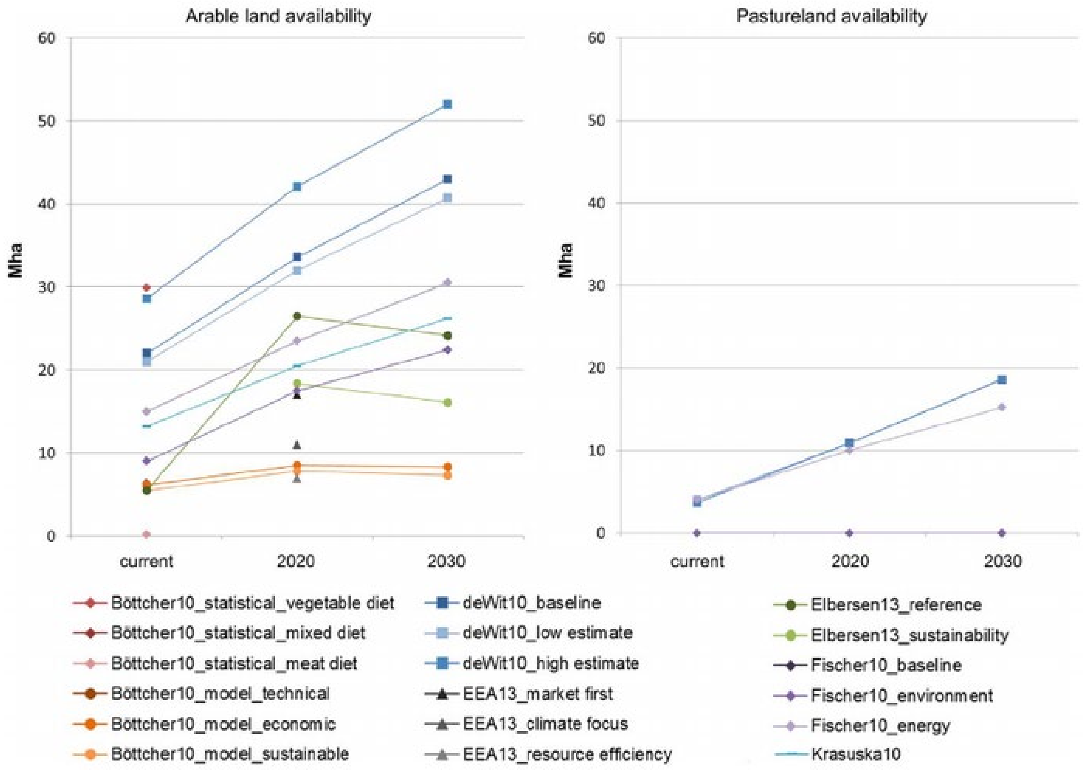

Figure 3: Land available for energy crop cultivation in Europe, estimated by a range of studies. For most studies, the EU 28 is covered, but for some, like [de Wit et al., 2010], some other countries are included like Ukraine.

The bioenergy potentials from energy crops as estimated by all reviewed studies [Böttcher et al., 2012] and [de Wit et al., 2010] estimate the technical potential of energy crops without any other sustainability constraints than food security and the exclusion of nature conservation areas.
As shown in figure 4, the range for the technical potential varies between 0.7 EJ (17 Mtoe) and 5.7 EJ (136 Mtoe) yr-1 now, to 2.7 (65 Mtoe) and 12.1 EJ (289 Mtoe) yr-1 in 2020 and 3.3 EJ (79 Mtoe) and 15.8 EJ (377 Mtoe) yr-1 in 2030, depending on the energy crop cultivated and which land is considered for production. The detailed results are included in appendix I. [Elbersen et al., 2013] estimate an ecologically sustainable potential varying between 2.2 EJ (53 Mtoe) and 3.2 EJ (76 Mtoe) yr-1 in 2020 and 1.5 EJ (36 Mtoe) and 2.7 EJ (65 Mtoe) yr-1 in 2030.

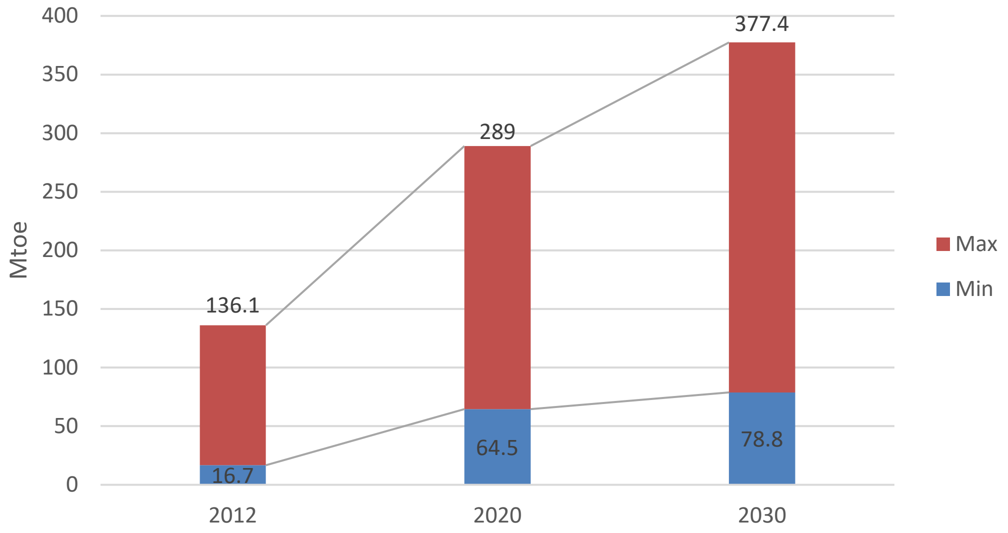

Figure 4: Range of technical potential for energy crop in Europe estimated by different studies [Kluts et al., 2017].

The high technical potentials found by [de Wit et al., 2010] are explained by the cultivation of all land with one specific crop group, and assumed high yield increases in Eastern European countries. Furthermore, de Wit includes Ukraine. De Wit's results show the importance of crop selection on the potential. The highest potential is from grassy crops, followed by woody crops. Grassy and woody crops reach high yields with relative extensive agriculture management practices. This lowers costs and GHG emissions.

The cultivation of only one crop type (e.g. only miscanthus, switchgrasss and reed canary grass or only poplar, willow and eucalyptus), is not desirable for biodiversity reasons. Woody and grassy crops are expected to play a key role in the future bioenergy potential, in particular in scenarios which apply stricter sustainability criteria. The estimated potential derived from arable crops is reduced to zero in the scenarios considering stricter sustainability criteria in [Böttcher et al., 2013], [EEA, 2013] and [Elbersen et al., 2013], due to the avoidance of bioenergy production with high ILUC impacts in these scenarios.

The Joint Research Centre has relatively recently inventoried results from analysis on future biomass resource potentials (partially using the same knowledge base as included in the review of [Kluts et al., 2017]), and also distinguished between low and high estimates [Ruiz et al., 2015]. The ranges found coincide largely with the figures mentioned here.

The work of De Wit et al is important in this context, because it did not only produce different land use scenarios for the EU (with different biomass resource potentials as a consequence of these scenarios), but also included analysis of yield gaps in European agriculture and livestock management [Wit et al., 2011], as well as implications for total GHG emissions and impact on carbon stocks, both for biomass production and agriculture [Wit et al., 2014]. Furthermore, these scenario results include both optimistic and more conservative pessimistic yield developments for agriculture and livestock, in line with the conditions explained in recent global scenarios.

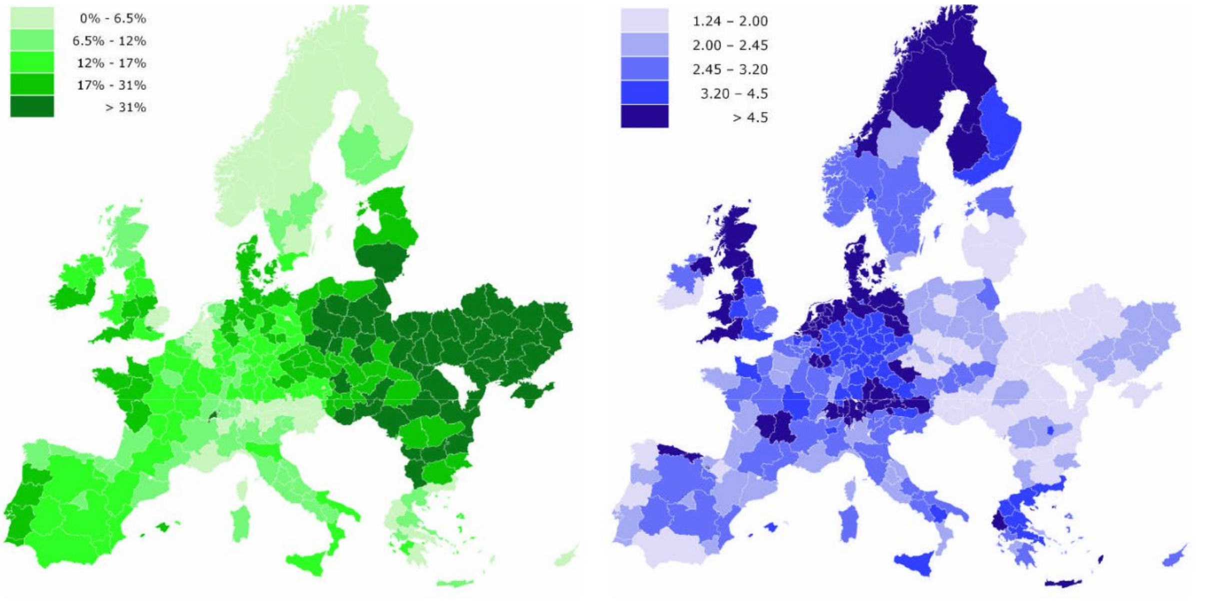

Figure 5: The 'surplus' land potentially available for the production of biomass by 2030 (left, green shades indicate the amount of surplus land as a percentage of the total land) and the production costs for woody crops in 2005 (right, blue shades indicate the production costs of woody crops) together indicate favorable locations for the production of biomass; in particular Eastern Europe and to a lesser extent South-West Europe are promising [de Wit et al., 2010].

The main results of this work are presented in figures 5 and 6. The latter figure presents cost–supply curves for five considered crop groups, with the crude assumption that all surplus land following from the land use scenarios would be used for one crop group (which is sub-optimal). The curve shows a large initial supply potential (w60% of total supply) to relatively low cost, under 2.5 Euro/GJ, which is mostly concentrated in Central and Eastern Europe, dominated by willow cultivation, and some low-cost production areas in Southern Europe, dominated by eucalyptus cultivation. In addition to the low cost large supply regions some moderate regions supply (w30% of total supply) to moderate costs between 2.5 Euro/GJ and 4.0 Euro/GJ. At production costs higher than 4.0 Euro/GJ only a marginal supply (w10% of total supply) is available, characterized by regions with high input costs or low productivity, and most often a combination of both. An overall learning-induced production costs' reduction of 20% (between 2005 and 2030) is applied.

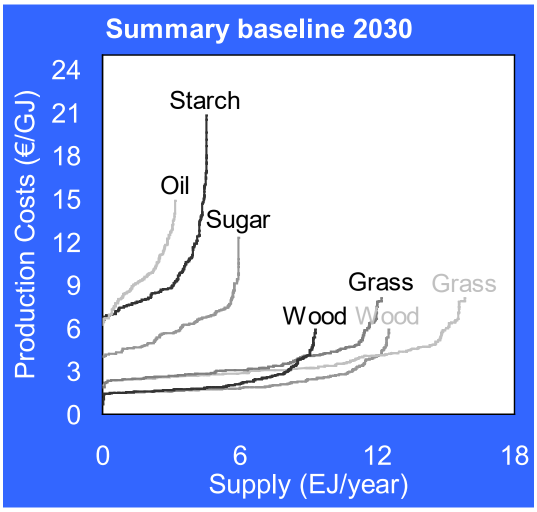

Figure 6: Cost–supply curves for five assessed crop groups. The figure depicts cost–supply for all crop groups for the 2030 curves for the baseline scenario. Each curve assumes all calculated surplus land would be used for one crop type (which is sub-optimal). [Wit et al., 2010]

Agricultural residues

Primary agricultural residues are also expected to play a key role in the future bioenergy potential. In [Kluts et al., 2017] reviewed a wide numbers of studies on the subject. The annual ecologically sustainable energy potential from these residues ranges from 0.7 EJ (17 Mtoe) to 3.6 EJ (86 Mtoe) currently, 1.9 EJ (45 Mtoe) to 3.1 EJ (74 Mtoe) in 2020 and 1.9 (45 Mtoe) to 2.8 EJ (67 Mtoe) in 2030 (based on a lower heating value of 17.0 MJ/kg dry matter) (see figure 7). [de Wit et al., 2010] and [Fischer et al., 2010] do not account for competitive uses in their residue potential while the other studies do. When non-EU Member States are included, the annual ecologically sustainable potential is estimated to be 3.5 EJ (84 Mtoe) currently, 3.7 EJ (88 Mtoe) in 2020 and 3.9 EJ (93 Mtoe) in 2030 (based on a lower heating value of 17.0 MJ/kg dry matter). However, large temporal variation in residue availability is caused by weather influences. [Scarlat et al., 2010], for example, estimated this yearly variation to be in the range of +23% to −28% compared to average residue availability.

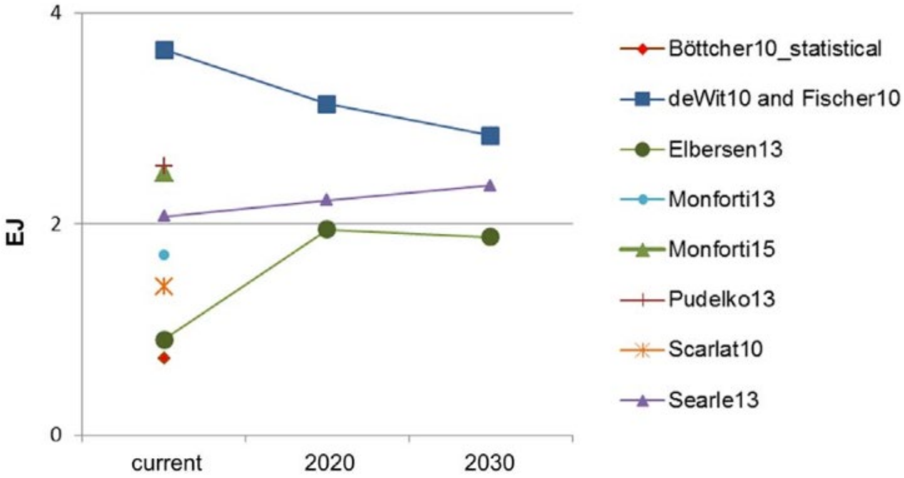

Figure 7: Ecologically sustainable potentials from straw in the EU-27 as estimated by different studies. [Kluts et al., 2017]

Most studies included in this review only estimate potentials from straw and maize stover, while some others also include cuttings and pruning residues. The annual amount of straw and stover that is available in the EU-27 and that includes environmental constraints, is estimated to range from 45 to 215 Mt dry matter currently, 115 to 185 Mt dry matter in 2020 and 110 to 165 Mt dry matter in 2030. The current total contribution of straw to primary agricultural residues is estimated to be 93%. Overall, wheat straw contributes most to these primary agricultural residues (35% of the total agricultural residues), followed by barley and maize (both 15% of the total), while the remaining straw is contributed by a larger array of other crops.

An increase in crop yield likely leads to a decrease in the residue to product ratio of crops as the share of the harvestable component of the crop has been increased through crop breeding over the last decades. [DeWit et al., 2010] and [Fischer et al., 2010] consequently project a decrease of approximately 9–14% per decade in agricultural residue availability (Figure 7). However, Bentsen et al.,2014], [Daioglou et al., 2016] and [Monforti et al., 2015] estimate more residue availability with increased yields because the use of crop residues for soil protection is proportional to the amount of land used. [Bentsen et al., 2014] estimates a 12% increase in agricultural residues which are theoretically available through agricultural intensification in Western, Northern and Southern Europe (from 204 to 229 Mt dry matter yr−1). This increase in crop residues through agricultural intensification is relatively low in these regions, since high input agriculture is already commonplace here.

[De Wit et al., 2010] also specifically zoomed in on the possible cost supply curves for agricultural residues (see figure 8). As confirmed in [Ruiz et al, 2015] the bulk of the potential could be available below 5 Euro/GJ.

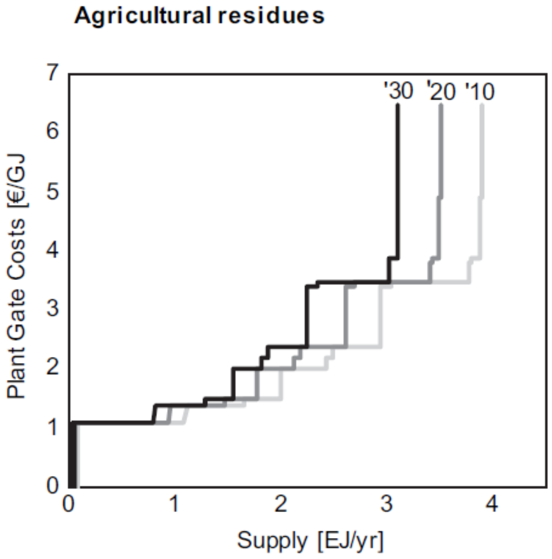

Figure 8: Cost supply curves for agricultural residues as presented in [de Wit et al., 2010], for 2010, 2020 and 2030 (presenting roadside costs).

Biomass resources from forestry

A recent review of literature on Future Forest Bioenergy Markets and potentials from [Hänninen et al., 2018] confirms the insights in the variability of biomass availability from forests, depending largely on the type of forest management deployed and targets set.

Energy wood demand projections (for producing heat, electricity and biofuels) are estimated (based on different scenarios) to increase by 57 – 200% between 2010 and 2030. Different available studies differ in their assessments whether this will lead to shortages in energy wood availability or not.

According to [Verkerk et al., 2015] forests in the EU could potentially supply 620 – 891 million cubic metres per year in 2030. In comparison, the overall use of wood was 485 million tons in the EU28 in 2013, of which about half was primarily used in the wood products and paper and pulp industries and half for production of heat and power (including industrial residues). It should be noted that the availability of forest and wood processing residues depends on the demand and consumption of wood use for products, paper, etc. When talking about forest bioenergy, it is important to take into account the close relation between the industrial use of wood and wood for energy. Indeed, one cubic meter of wood use for industrial purposes can generate up to 50% of by-products such as bark, saw dust, back liquor, etc… Each of which can be use either for material purposes or energy. Moreover, higher volumes of wood harvested for industrial purposes lead to higher volumes of forest residues available, as those are closely linked together.

The forest biomass supply potential in the EU in 2030 has been estimated to be 23 – 573 Mm^3/a, versus a possible demand of forest biomass in 2030 between 151 – 752 Mm^3/a. Estimates for the use of energy wood vary from 114 – 150 Mm^3/a. The share of wood used by biorefineries producing liquid biofuels is estimated to range from 10-15% in 2030. Various studies indicate that the growing bioenergy demand in the EU is mainly to be covered by agro-biomass, imports and increased use of forest residues.

Table 1: Overview European forest biomass supply assessments

Region and study	**Time frame**	**Estimate (EJ/yr)**	**Estimate (Mtoe/yr)**	**Estimate (Mm^3/yr)**	**Type of estimate**
EU27 [Mantau et al., 2010]	2010	3.9	93	450	Sum different potentials
	2020	4.5	108	514	Sum different potentials
	2030	5.0	119	573	Sum different potentials
EU27[Moiseyev et al., 2011]	2020	0.2-4.4	5 -105	23-505	Maximum potential study
	2030	0.2-3.1	5 -74	23-356	Sum different potentials
East & West Europe; [Smeets & Faaij, 2007]	2050	7.4	177	638	Theoretical potential
	2050	7.3	174	629	Technical potential
	2050	5.9	141	509	Economic potential
	2050	4.7	112	405	Economic-ecological potential

Defining forest biomass is not straightforward, as it includes logging residues as well as industrial by-products of wood processing. The latter includes residues from logging, bark and chips from sawmilling and black liquor from the pulp industry. Three main categories are often distinguished: primary forest residues (such as thinnings, but also plantation wood), secondary forest residues (bark, sawdust, etc.) and tertiary residues including consumer waste and recycled building materials. The definitions of different potentials as highlighted by figure 2 apply most certainly to forest biomass as well and because of the different definitions and related preconditions, the estimates of (future) potentials differ significantly as well. A study by [Smeets & Faaij, 2007] on forest biomass resources highlighted this. The economic – ecological potential for Europe was estimated to amount 405 Mm^3 under ecological criteria that were more stringent than considered in other potential categories [Smeets & Faaij, 2007]. [Rettenmaier et al., 2010] also employed different definitions and criteria to European forest biomass potentials in 2050, resulting in estimates of 638 Mm^3 theoretical, 629 Mm^3 technical, 509 Mm^3 economic and 405 Mm3 sustainable implementation potential. The table 1 above and figure 9 below (summarized from [Hänninen et al., 2018]) present the overview obtained by the most recent available assessment.

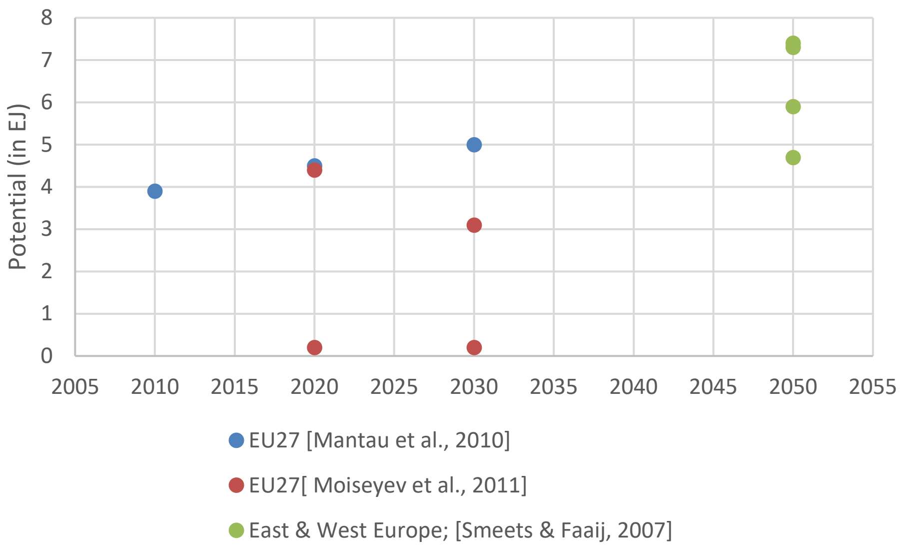

Figure 9: Overview European forest biomass supply assessments

Clearly, forest biomass potential cannot be expressed in a single figure. The range obtained from this review lies between 0.2 EJ (5 Mtoe) -7.3 EJ (174 Mtoe) (on longer term). The low estimate assumes criteria that basically all residue material is left in the forest. Most studies however agree that a supply of some 4 EJ (96 Mtoe) could be mobilized around 2030 and depending on actions taken on forest management and criteria applied, with a growth potential of up to 6 EJ (143 Mtoe) or 7 EJ (167 Mtoe). This is confirmed in turn by the review of [Ruiz et al., 2015] who presents figures on the combination of wood products, forest residue potentials and wood processing residues in 2050 between 1.3 EJ (31 Mtoe) and over 11 EJ (263 Mtoe). It should be noted that wood products account for over 3 EJ (72 Mtoe) in the maximum estimate. This can be compared to the reported use in 2013 of 485 Mm^3 (or about 4.2 EJ [100 Mtoe]) wood out of which some 50% (about 2.1 EJ [50 Mtoe]) was for energy in the EU. The higher potentials on longer term are explained by expected higher demand for forest products in the underlying economic scenarios.

[De Wit et al., 2010] also specifically zoomed in on the possible cost supply curves for forestry residues (see figure 10). As confirmed in [Ruiz et al, 2015] the bulk of the potential could be available below 5 Euro/GJ.

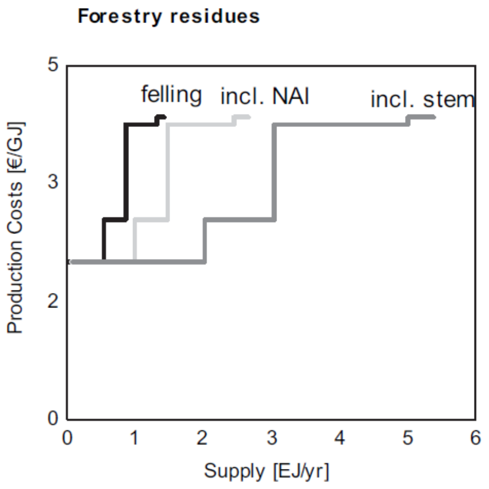

Figure 10: Cost supply curves (representing roadside costs) for forestry residues as presented in [de Wit et al., 2010], for 2010, 2020 and 2030.

Biomass waste streams

Biomass is also available as waste streams, e.g. the organic fraction of municipal solid wastes is in various countries contributing to production of heat and electricity via incineration facilities with energy recovery. Also, organic waste streams released in various industries (e.g. food processing) add to the potential, while other industries as well as waste water treatment facilities deliver sludges that, via digestion, can deliver biogas or, although less common, energy carriers via other conversion technologies. Biogas production is also done via digestion of manure, which may or may not be called a waste stream, but it represents an energy potential as well. The supply of such streams is directly related to the economic activity in the respective sectors, as well as markets for various waste streams (that can fluctuate over time). The potential of such streams is therefore constrained, but is nevertheless not negligible. Table 2 presents the results for the 2050 projections (taken from [Ruiz et al., 2015]). This overview also includes the estimates for waste biomass, which includes biogas production potential (e.g. produced from manure and very wet organic waste streams). Biogas is presented separately, as the energy content of manure is hard to present in heating value given the high moisture content. The other categories are suitable for e.g. combustion, including municipal solid wastes and industrial waste-sludge production. The range of those combined categories lies between 1.7 EJ (41 Mtoe) up to 5 EJ (119 Mtoe) (with 3 EJ (72 Mtoe) as the reference).

Table 2:.Estimates for biomass waste stream availability (including biogas production potential) in 2050 in the EU for a pessimistic (low), optimistic (high estimate) and reference conditions (in EJ/yr) [Ruiz et al., 2015].

Potential	High	Reference	Low
Biogas Production	1.87	1.25	0.62
Agricultural waste potential	2.14	1.03	0.61
Municipal Waste Production	0.92	0.74	0.44
Industrial Waste-Sludge Production	0.07	0.052	0.03
Total	**5.0**	**3.1**	**1.7**

Overall estimates of biomass resources in Europe

Primary data from the large amount of original studies are sometimes difficult to harmonize due to variable definitions of potentials, difference in geographic scope and of course methodologies use, nevertheless, an effort is made with table 3 to compile results with respect to energy potentials, Mtonnes of biomass and millions of hectares available land for crop production. Please keep in mind that these figures are indicative and do not follow from one integrated analysis. The timeframe at which (part of) those potentials may be mobilized is variable. The studies used cover the 2020 – 2050 timeframe. The speed at which agricultural management may be improved can highly vary and is strongly dependent on policies. The same is true of management and logistics required to mobilize both agricultural and forestry residues. The figures in table 3 depict the overall improvement potential.

On the other hand, the ranges do provide a reasonably good overview of the lower and higher estimates of the different resource category (figure 11), as follows from analyses available to date. The overall range of a minimum of 6 EJ (143 Mtoe) -7 EJ (167 Mtoe) and a high end biomass resource availability of over 30 EJ (716 Mtoe) (based on highest estimates of technical potentials and all resource categories combined) is a solid result. Also note that much lower supplies are possible if various measures to mobilize and grow additional biomass are not implemented. Again, the key factors here are further productivity increases of agriculture and further improvements in forest management (such as thinnings, replanting, fertilization, etc.).

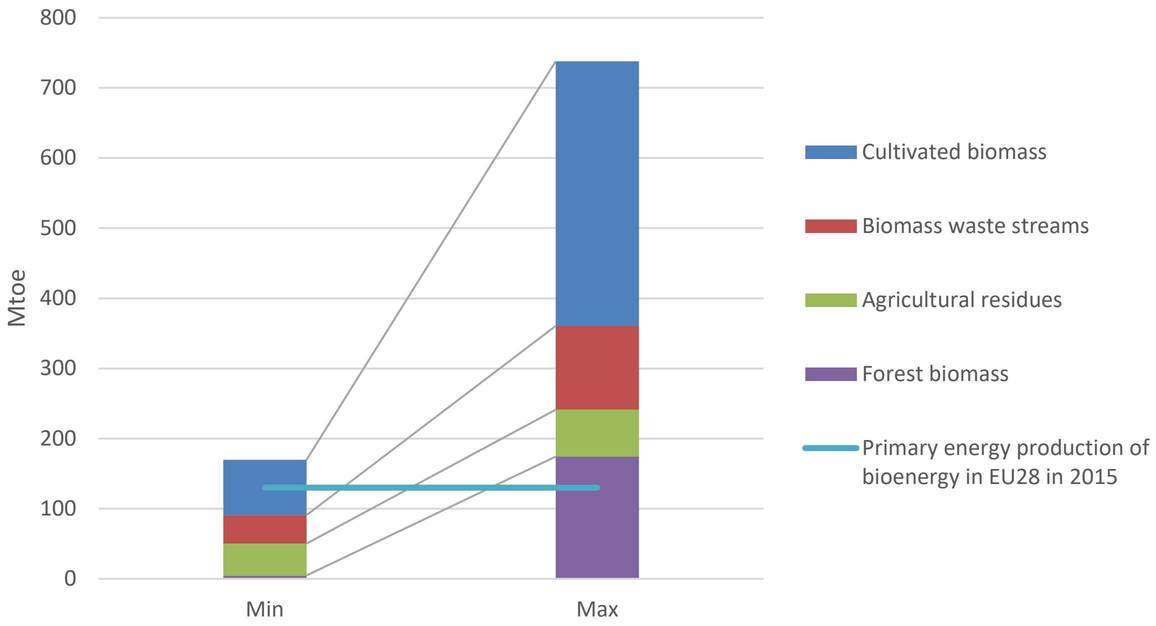

Figure 11: shows the contribution of the main categories to biomass potential for the presented minimum and maximum biomass supply potential. The potential is quite evenly distributed across several categories for the low estimate, but the largest development potential on medium to longer term lies in cultivated biomass and improved forest management, which is also confirmed by the review of [Ruiz et al., 2015].

Compared to roughly 68.1 EJ (or 1628 Mtoe) of primary energy use in the EU today, which is likely to stay stable over the coming decades according to various GHG mitigation scenarios, it seems feasible that the combination of biomass resources available or that could be mobilized over time can cover minimally some 10% and, considering various constraints on the technical potential, 25% (17 EJ [406 Mtoe] or about half of the technical potential, excluding the most expensive biomass categories and considering ''medium'' scenarios for agricultural productivity improvements). Such a contribution would be in the same order as mineral oil contributes today to the EU energy mix.

Concerning costs, the previous sections reported cost supply curves included in different studies. [Ruiz et al., 2015] presents a crude supply curve for all biomass supplies included in that review. Almost 86 % of the biomass has a cost below 5 €/GJ. However, the two most expensive categories are the ones that could be used for 1st generation biofuels and have no competition for other uses (starch and rapeseed). It should also be noted that the land used for such annual agricultural crops may also be used for producing perennial crops (as is included in the analyses of de Wit et al., 2010, see figure 5) that illustrates that total energy yields for perennial crops are higher than for annual crops).

Table 3: Crude synthesis on European Biomass potentials. The time frame covers the period 2030-2050 (relevant for RED directive and for 2050 full decarbonization). The relevant geographical zone for the potential is EU28, including analyses that cover the Ukraine and some other European countries that are not part of the EU28.

Biomass category	**Mha's**	**EJ**	**Mtoe**
Cultivated biomass	7-52 Mha arable land 10-19 Mha pasture land	3.3 - 15.8	79 - 377
Agricultural residues	N.A.	1.9 – 2.8	45 - 67
Forest biomass	N.A.	0.2 – 7.3	5 - 174
Biomass waste streams	N.A.	1.7 - 5	40 -119
Totals		**7.1 – 30.7**	**169-737**

1 EJ = 23.9 Mtoe (1000 Mtoe = 41.9 EJ, 1 Mtoe = 41.9 PJ, 1 toe = 41.9 GJ,)

III. Preconditions to secure future biomass resources and implications for agriculture, livestock, land use; implications for land use, environmental performance and GHG mitigation potential

The previous sections highlighted that the substantial biomass resource potentials in Europe can be developed, but at the same time a considerable number of sustainability criteria need to be fulfilled. The key risk to tackle is the displacement of land use (indirect land use changes), but also in markets, because if biomass resources are taken away from existing markets, supplies need to be produced elsewhere as well. (iWUC; indirect wood use change in forestry). Improvements in productivity of agriculture, livestock and forest management, as well as using marginal and degraded lands can avoid this risk. Furthermore, net residue availability can improve this way. However, with changes in agricultural and forest management towards more productive systems, negative impacts with respect to emissions of fertilizers, agrochemical use, biodiversity, water and soil quality are to be avoided. These criteria have been well covered by state-of-the-art sustainability frameworks and criteria. Appendix III gives a selection of important frameworks to date (for biofuels, forest biomass or biobased value chains in general) based on a recent review.

State-of-the-art insights show that the way in which productivity is increased, e.g. via ''simple'' increased input levels of fertilizers and use of agrochemicals versus precision farming techniques that achieve far lower emissions (less Greenhouse gas emissions, as well as reduced leaching and use of fertilizers and agrochemicals) with higher yields, have a major positive influence on the overall environmental performance (see e.g. [Gerssen-Gondelach et al., 2016] for a detailed analysis of different management schemes in Western Poland) and similar results for Rumania and Hungary as analyzed by [Brinkman et al., 2018].

The same is true for forest management, which plays a critical role in whether forests are effective carbon sinks and stable carbon pools. Both forest operations (e.g. replanting, thinning) as well as safeguarding the entire forest area (e.g. in a country) and carbon stocks are important in this respect. [Creutzig at al., 2014] highlight that for forest biomass, carbon payback time is another concern. In large managed forest estates, management activities in one stand are coordinated with activities elsewhere in the landscape with the purpose to provide a steady flow of harvested wood. While carbon stock decreases in stands that are harvested, carbon stock increases in other stands resulting in landscape-level carbon stock that fluctuates around a trend line that can be increasing or decreasing, or remain roughly stable. Changes in the management of forests to provide biomass for energy can result in both losses and gains in forest carbon stocks, which are determined by the dynamics of management operations and natural biotic and abiotic forces.

Carbon accounting at the stand level that start the accounting when biomass is harvested for bioenergy naturally finds upfront carbon losses that is found to delay net GHG savings up to several decades (carbon debt). Assessments over larger landscapes report both forest carbon gains and losses delaying the GHG reduction benefit, as well as reductions in forest sink strength (foregone carbon sequestration) reducing or even outweighing for some period of time the GHG emissions savings from displacing fossil fuels. In short, biomass that would otherwise be burned without energy recovery, rapidly decomposing residues and organic wastes can produce close to immediate GHG savings when used for bioenergy, similarly to increasing the biomass outtake from forests affected by high mortality rates. When slowly decomposing residues are used and when changes in forest management to provide biomass for energy cause reductions in forest carbon stocks or carbon sink strength, the GHG mitigation benefits are delayed, sometimes by many decades. Conversely, when management changes in response to bioenergy demand so as to enhance the sink strength in the forest landscape, this improves the GHG mitigation benefit.

Appendix IV (taken from [Creutzig et al, 2014]) provides a rich overview of the variability of impacts that biomass production and use for energy (and materials) can have depending on how this is done. On basically any relevant sustainability criteria (whether these cover environmental or socio-economic impacts) the implications can be positive or negative depending on crop choice, management of land, organization of the supply chain, etc. Furthermore, the notion that optimal solutions will differ from place to place is important. There is not one optimal biomass resource and the combination of agricultural and land management with crop choices and cultivation methods determines the overall performance and range of impacts. At the same time, this basic notion also makes it clear that in many cases tailor made solutions can be identified and implemented. Well established sustainability frameworks and criteria as developed under the RSB, GBEP or other key frameworks (see appendix III) give clear guidelines on how this can be done on local and regional level, including minimizing displacement risks.

Combining agricultural efficiency improvements with increasing biomass production in Europe and the combined impacts on GHG emissions from both biomass production and use as well as the emissions of agricultural production has been analyzed by [de Wit et al., 2014]; see figure 12, which is directly based on the land use and biomass resource potential analysis discussed in section 2. This figure illustrates the cumulative GHG impacts by lowering the yield gaps in European agriculture that can not only facilitate biomass production without displacement, but also lower GHG emissions of agriculture itself, while simultaneously having a positive impact on carbon stocks on (former) agricultural land, especially when perennial crops are used. The same point is made on a global scale by recent analyses with Integrated Assessment Modelling by [Daioglou et al., 2018] for SSP1 conditions.

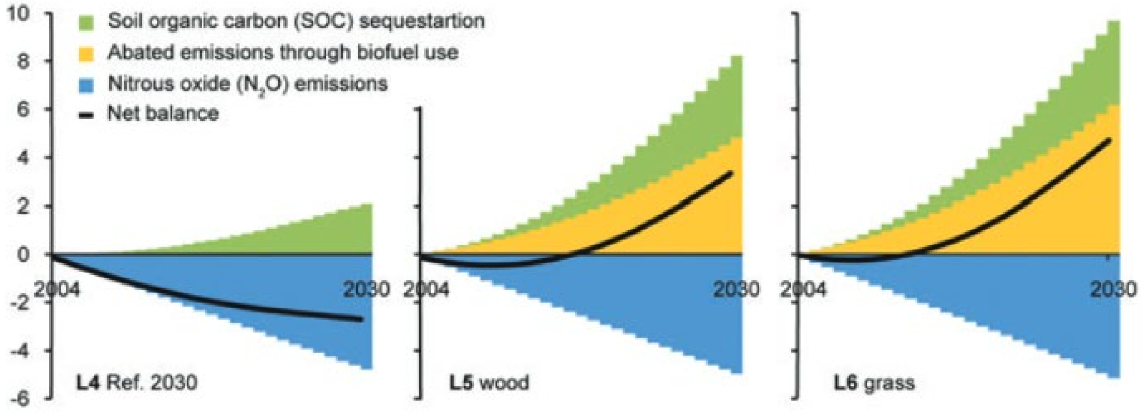

Figure 12: Partitioning of the cumulative mitigation balance of greenhouse gas emission in European agriculture from 2004 to 2030 that consider substantial agricultural yield improvements and gradually increasing surplus land. This land is a assumed to be used in different land-use variants (where land use variant L5 depicts use of surplus land for wood production and L6 perennial grasses), considering N_2O emissions (blue), net soil organic carbon sequestration (green), abated emissions of avoided oil use due to biofuel deployment (yellow) and the net balance (black line). Negative values indicate emissions; positive values indicate GHG mitigation. The avoided emissions due to displacement of fossil fuel are complemented by increased carbon storage in soils and by lowering agricultural emissions compared to the baseline scenario. L4 depicts surplus land gradually converted to forest (that is not harvested). This will increase carbon stocks (to comparable levels al L5 and L6) but does not result in net biomass supplies that can replace fossil fuels over time. [Wit et al., 2014]

IV. Possible future for biomass use for energy and materials in Europe, possibilities, implications, preconditions and priorities for policy.

Bioenergy is currently the largest renewable source in the European Union and is likely to remain one of the largest RE sources for the first half of this century. Biomass is of increasing importance to deliver carbon neutral feedstock for chemical and other materials, as for liquid and gaseous fuels for key sectors like aviation, shipping and long distance truck transport. There is considerable growth potential to make more biomass resources available in a sustainable basis, but it requires active development. These main conclusions and recommendations follow previous conclusions from Chum et al., 2011 from the IPCC.

- Assessments in the recent literature as summarized in this paper show that the resource potential of biomass for energy in the European Union may be reach well over 20 EJ/yr (478 Mtoe) by 2050. However, uncertainty exists about important factors such as market and policy conditions that affect this potential.
- State-of-the-art energy and GHG mitigation scenarios suggest that whatever biomass resources are available, they will be used for various mentioned markets. An additional driver for biomass deployment is the possibility to deliver negative emissions when the conversion of biomass is combined with carbon capture and storage. Many recent scenario analyses point out that such options are necessary to achieve the 1.5 – 2 ºC GMT change target as set in the Paris agreement. Realizing this potential represents a major challenge but would make a substantial contribution to the EU’s primary energy demand in 2050 of one third or even higher.

- Bioenergy has significant potential to mitigate greenhouse gas (GHG) emissions if resources are sustainably developed and efficient technologies are applied. Certain current systems and key future options, including perennial crops, forest products and biomass residues and wastes, and advanced conversion technologies, can deliver significant GHG mitigation performance - an 80 to 90% reduction compared to the fossil energy baseline. To achieve such impact and performance, land use conversion and forest management should be so that losses of carbon stocks and indirect land-use change (ILUC) are avoided. Recent insights show that this is feasible.
- In order to achieve the high potential deployment levels of biomass for energy, increases in competing food and fibre demand must be moderate, land must be properly managed and agricultural and forestry yields must increase substantially, e.g. by improving forest management practices. Expansion of bioenergy in the absence of monitoring and good governance of land use carries the risk of significant conflicts with respect to food supplies, water resources and biodiversity, as well as a risk of low greenhouse gas (GHG) benefits. Conversely, an implementation that follows effective sustainability frameworks could mitigate such conflicts and allow for the realization of positive outcomes, for example, in rural development, cleaner and more sustainable agriculture, land amelioration and climate change mitigation, including opportunities to combine adaptation measures.
- The impacts and performance of biomass production and use are region- and site-specific. Therefore, as part of good governance of land use and rural development, bioenergy policies need to consider regional conditions and priorities along with the agricultural (crops and livestock) and forestry sectors.

The key conditions for mobilizing sustainable resource potentials require ‘’smart’’ agriculture practices, including precision farming techniques, integrated concepts with nutrient recycling (e.g. with digestion of manure from livestock management) allowing for combining higher yields and reducing land use per unit of food with lowering GHG and other emissions, improving soil quality with increased carbon storage and better economic performance. Especially when biomass is produced via perennial crops on lesser quality land, ecological benefits can be achieved. Increased sustainable residue availability from agriculture can also be improved this way. For forest residues, good forest management is the key to mobilizing biomass resources in a sustainable way and with good carbon payback times.

This key interlinkage between biobased economy and optimizing agricultural production (in terms of efficiency and environmental performance) represents a major opportunity for the EU. At the moment the Common Agricultural Policy (CAP), the renewable energy policy (with a focus on renewables and biobased options) and rural development are aligned, biobased production schemes can contribute in a major way to GHG mitigation and displacing fossil fuels, make the agricultural and forestry sectors more diverse and competitive and contribute to a more sustainable agricultural production at large.

The lessons learned from the previous biofuel support schemes, which combined targets with subsidies, is that such policies should be integrated with supporting measures to avoid competition for land and other natural resources. Innovation in biomass sourcing interlinked with better management of forest, land and agriculture should be at the heart of such policies. Furthermore, any future target should be dependent on the rate of improvement that can be achieved in agricultural and forest management.

If achieved, this strategy can deliver new and sustainable economic activity to Europe’s rural regions, contribute to a new generation of agro- and forest industries, contribute considerably to energy security, deliver major savings on fossil fuel imports and improve the trade balance of the EU and, last but not least, improve agricultural and forest management practices with the possibility to save considerably on agricultural subsidies.

All in all, this opportunity is too important to discard for the EU.

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Appendix I: Bioenergy potentials in Europe according the review of [Kluts et al., 2017]

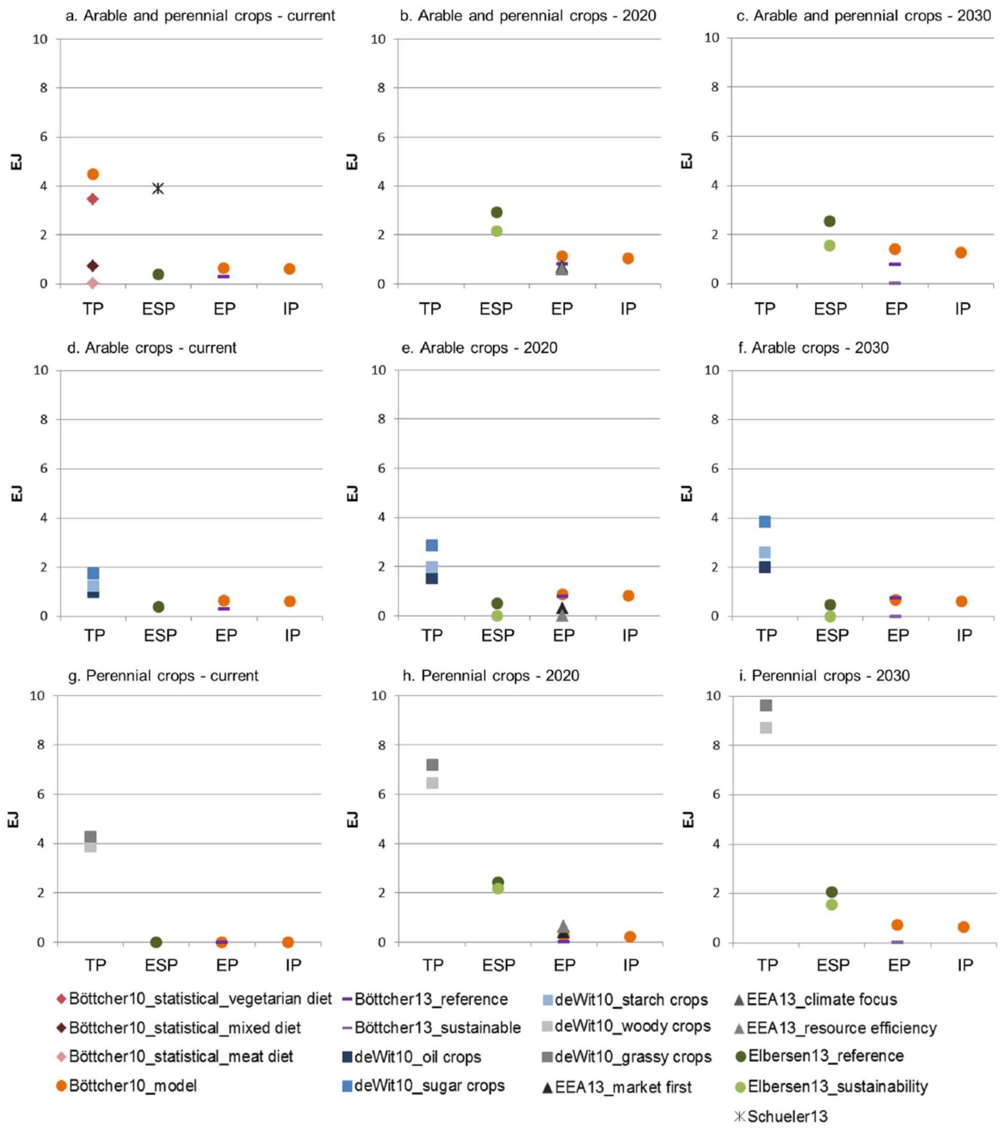


Fig. 2. : Bioenergy potential from energy crops as estimated by different studies. TP: Technical potential; ESP: Ecologically sustainable potential; EP: Economic potential; IP: Implementation potential. Potentials from deWit10 are estimations of the whole land area cropped with one specific crop type. EEA13 calculated the economic potentials with the following feedstock prices: EEA13_market focus < 3 €/GJ; EEA13_climate focus and EEA13_resource efficiency < 6 €/GJ. Böttcher10_modelling approach and Böttcher13 did not state the feedstock prices.

Appendix II: overview of main parameters and their impact on biomass resource potentials and recommended activities to reduce uncertainties and achieve better results, avoid negative or achieve positive impacts (reworked from [Dornburg et al., 2010])

Issue/effect	Importance	Recommended activities to reduce uncertainties and achieve better results, avoid negative or achieve positive impacts

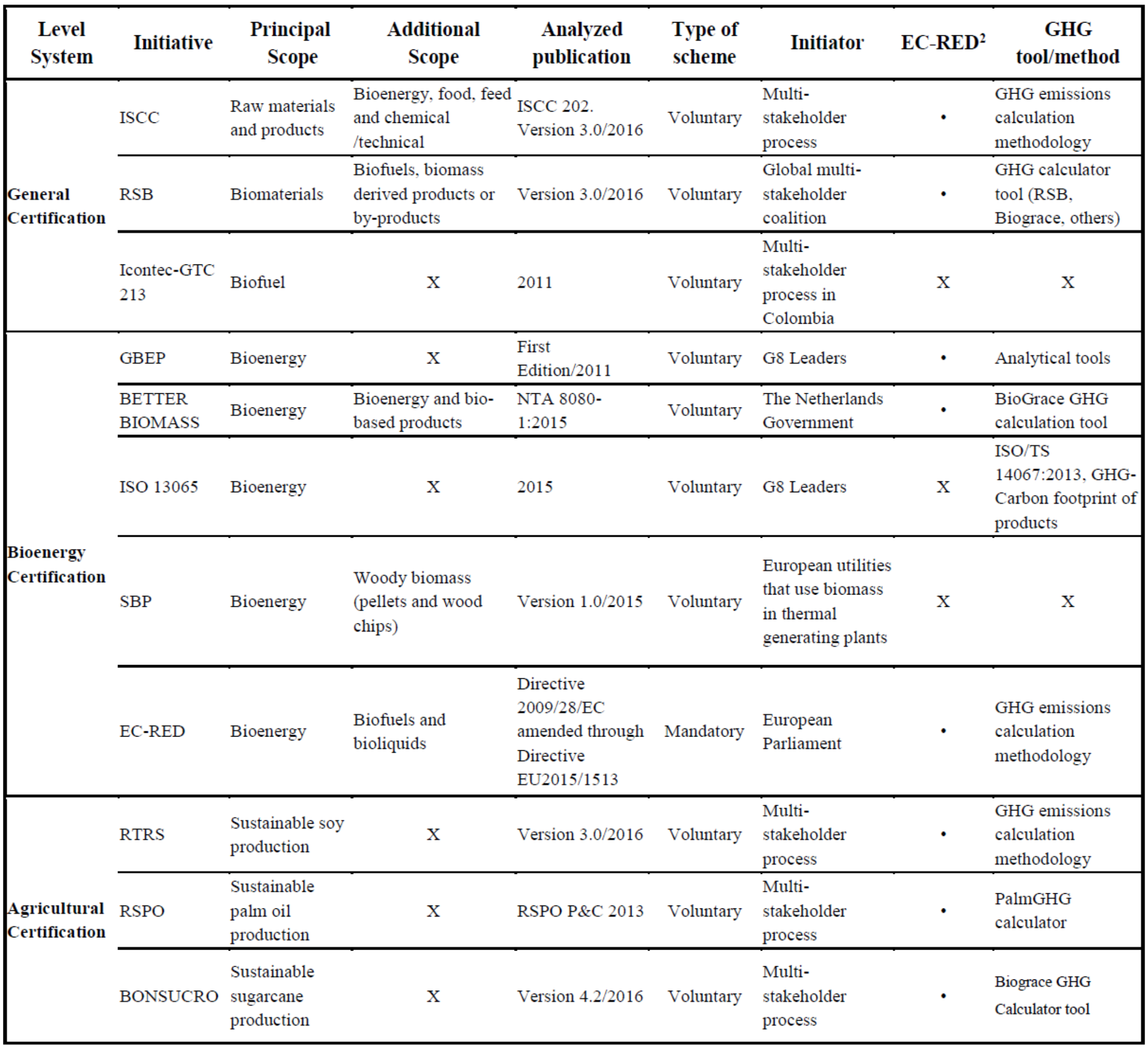
Improvement agricultural management	***	Better understand how crop yields and efficiency of livestock management can be increased in a sustainable manner and for different settings. Insight in development pathways and feasible rates of improvement.. Improved insights in preconditions for improvements can provide a basis for targeted policies
Choice of crops	***	There are clear recommendations on the importance of lignocellulosic biomass production systems for different settings. Under certain conditions, agricultural and annual crops can achieve good performance as well. Much more market experience with such production systems needed in different settings, including degraded and marginal lands, intercropping schemes (e.g., agroforestry), and management of grasslands. The latter is an important land-use category on which current understanding and experience needs improvement.
Food demand and efficiency of use	***	Increases in food demand beyond the base scenarios will strongly affect possibilities for bioenergy. Vice versa, limited population growth and limiting (currently sizeable) losses in food supply chains will mean the opposite
Use of degraded land	***	Represents a significant share of possible biomass resource supplies. Experiences with recultivation and knowledge on these lands (that represent a wide diversity of settings) are limited so far. More research is required to assess the cause of marginality and degradation and the perspectives for taking the land into cultivation. Research and demonstration activities required to understand the economic and practical feasibility of using degraded/marginal land is needed.
Competition for water	***	Increased water demand for conventional agriculture, domestic, and industrial use is a concern in various world regions, with agriculture being by far the most important sector in this respect. Constraints in water supplies and sustainable management need ultimately to be studied at water basins scale, in interaction with local scales. Furthermore, better crop management and reforestation can improve water use efficiency and retention functions.
Use of agricultural/forestry by-products	**	Residues are an important resource category. The net availability for energy purposes is constrained by competing applications (e.g. fodder) and ecological reasons (maintaining soil fertility). Their net availability can be improved by better infrastructure and logistics.
Protected area expansion	**	Increased ambition levels for nature reserves impacts net land availability for biomass production. Furthermore, more insights are desired in how land-use planning including new bioenergy crops can maximize biodiversity benefits. Evaluating biodiversity impacts on regional level is still a field under scientific development and more fundamental work is needed in this arena
Water use efficiency	**	An important factor in the equation is improvement of water use efficiency in both current agriculture (that could be achieved through efficient management adapted to the local production situation, increasing resource use efficiency) and in biomass production itself. Technical improvement potentials are considerable compared to current average practice. This suggests that for various areas water management is a prime design parameter for sustainable biomass production and land-use management.

Climate change	**	The impact of climate change on agricultural production and productivity of lands could be significant, but exact effects are also uncertain. Varying reported effects of climate change on natural systems and their biodiversity deserve further attention. Furthermore, although agriculture may face serious barriers due to climate change, this may also enhance the need for alternative adaptation measures to avoid soil losses and maintain vegetation covers. Biomass production (again especially via perennial systems) may then play a role as adaptation measure. Such strategies (under different climate change scenarios) are so far poorly studied.
Alternative protein chains	**	Possible but uncertain reversal of current diet trends, i.e., introduction of more novel plant protein products (as alternative for meat) could on the longer term strongly reduce land and water demand for food. Such options and the feasibility in terms of implementation are, however, insufficiently studied.
Demand for biomaterials	*	Demand for biomass to produce biomaterials (both conventional as building material as new ones as bulk bio-based chemicals and plastics) can be a significant factor, but is limited due to market size (compared to demand for energy carriers). Furthermore, biomaterials will also end up as (organic) waste material later in their lifecycle, indirectly adding to increased availability of organic wastes. In many cases this "cascaded use" of biomass increases the net mitigation effect of biomass use.
GHG balances of biomass chains	*	The net GHG performance of biomass production systems is not identified as a limiting factor for the potential, provided perennial cropping systems are considered. Also, striving for biomass production that is similar or better than previous land use (e.g., grasslands that remain grasslands or trees that replace annual crops) generally improves the overall carbon balance. This can also be true for replanting of degraded lands. The key factor in the net carbon balance is leakage. Avoiding leakage is directly related to increased efficiency in agriculture and livestock and net carbon impacts of biomass production should include this dimension.

Importance of the issues on the range of estimated biomass potentials: *** - large, ** - medium, * - small

Appendix III: selection of important sustainability frameworks to date (for biofuels, forest biomass or biobased value chains in general) based on a recent review [Ramirez & Faaij, 2018].

Table 1. General characteristics of certification systems included in this overview. • = Included; X= not included.



Level System	Initiative	Principal Scope	Additional Scope	Analyzed publication	Type of scheme	Initiator	EC-RED[2]	GHG tool/method
General Certification	ISCC	Raw materials and products	Bioenergy, food, feed and chemical /technical	ISCC 202. Version 3.0/2016	Voluntary	Multi-stakeholder process	•	GHG emissions calculation methodology
	RSB	Biomaterials	Biofuels, biomass derived products or by-products	Version 3.0/2016	Voluntary	Global multi-stakeholder coalition	•	GHG calculator tool (RSB, Biograce, others)
	Icontec-GTC 213	Biofuel	X	2011	Voluntary	Multi-stakeholder process in Colombia	X	X
Bioenergy Certification	GBEP	Bioenergy	X	First Edition/2011	Voluntary	G8 Leaders	•	Analytical tools
	BETTER BIOMASS	Bioenergy	Bioenergy and bio-based products	NTA 8080-1:2015	Voluntary	The Netherlands Government	•	BioGrace GHG calculation tool
	ISO 13065	Bioenergy	X	2015	Voluntary	G8 Leaders	X	ISO/TS 14067:2013, GHG-Carbon footprint of products
	SBP	Bioenergy	Woody biomass (pellets and wood chips)	Version 1.0/2015	Voluntary	European utilities that use biomass in thermal generating plants	X	X
	EC-RED	Bioenergy	Biofuels and bioliquids	Directive 2009/28/EC amended through Directive EU2015/1513	Mandatory	European Parliament	•	GHG emissions calculation methodology
Agricultural Certification	RTRS	Sustainable soy production	X	Version 3.0/2016	Voluntary	Multi-stakeholder process	•	GHG emissions calculation methodology
	RSPO	Sustainable palm oil production	X	RSPO P&C 2013	Voluntary	Multi-stakeholder process	•	PalmGHG calculator
	BONSUCRO	Sustainable sugarcane production	X	Version 4.2/2016	Voluntary	Multi-stakeholder process	•	Biograce GHG Calculator tool

Appendix IV, taken from [Creutzig et al, 2014], provides an overview of the variability of impacts that biomass production and use for energy (and materials) can have depending on how this is done

Table 1 Potential institutional, social, environmental, economic, and technological implications of bioenergy options at local to global scale

	Scale	
Institutional issues and Governance systems		
May contribute to energy independence (+), especially at the local level (reduce dependency on fossil fuels) (2, 20, 32, 39, 50)	+	Local to national
Can improve (+) or decrease (–) land tenure and use rights for local stakeholders (2, 17, 38, 50)	+/–	Local
Cross-sectoral coordination (+) or conflicts (–) between forestry, agriculture, energy and/or mining (2, 13, 26, 31, 59)	+/–	Local to national
Impacts on labor rights among the value chain (2, 6, 17)	+/–	Local to national
Promoting of participative mechanisms for small-scale producers (14, 15)	+	Local to national
Social		
Competition with food security including food availability (through reduced food production at the local level), food access (due to price volatility) use usage (as food crops can be diverted toward biofuel production) and consequently to food stability. Bioenergy derived from residues, wastes or by-products is an exception (1,2, 7, 9, 12, 18, 23)	–	Local to global
Integrated systems (including agroforestry) can improve food production at the local level creating a positive impact toward food security (51, 52, 53, 66, 70, 71, 72). Further, biomass production combined with improved agricultural management can avoid such competition and bring investment in agricultural production systems with overall improvements of management as a result (as observed in Brazil) (59, 62, 67, 68)	+	Local
Increasing (+) or decreasing (–) existing conflicts or social tension (9, 14, 19, 26)	+/–	Local to national
Impacts on traditional practices: using local knowledge in production and treatment of bioenergy crops (+) or discouraging local knowledge and practices (–) (2, 50)	+/–	Local
Displacement of small-scale farmers (14, 15, 19). Bioenergy alternatives can also empower local farmers by creating local income opportunities	+/–	Local
Promote capacity building and new skills (3, 15, 50)	+	Local
Gender impacts (2, 4, 14, 15, 27)	+/–	Local to national
Efficient biomass techniques for cooking (e.g., biomass cookstoves) can have positive impacts on health specially for women and children in developing countries (42, 43, 44)	+	Local to national
Environmental		
Biofuel plantations can promote deforestation and/or forest degradation, under weak or no regulation (1, 8, 22)	–	Local to global
When used on degraded lands, perennial crops offer large-scale potential to improve soil carbon and structure, abate erosion and salinity problems. Agroforestry schemes can have multiple benefits including increased overall biomass production, increase biodiversity and higher resilience to climate changes (58, 63, 64, 66, 71)	+	Local to global
Some large-scale bioenergy crops can have negative impacts on soil quality, water pollution and biodiversity. Similarly potential adverse side effects can be a consequence of increments in use of fertilizers for increasing productivity (7, 12, 26, 30). Experience with sugarcane plantations has shown that they can maintain soil structure (56) and application of pesticides can be substituted by the use of natural predators and parasitoids (68)	–/+	Local to transboundary
Can displace activities or other land uses (8, 26)	–	Local to global
Smart modernization and intensification can lead to lower environmental impacts and more efficient land use (73, 74)	+	Local to transboundary
Creating bioenergy plantations on degraded land can have positive impacts on soil and biodiversity (12)	+	Local to transboundary
There can be trade-offs between different land uses, reducing land availability for local stakeholders (45, 46, 47, 48, 49). Multicropping system provide bioenergy while better maintaining ecological diversity and reducing land use competition (57)	–/+	Local to national
Ethanol utilization leads to the phase-out of lead additives and MBTE and reduces sulfur, particulate matter and carbon monoxide emissions (55)	+	Local to global
Economic		
Increase in economic activity, income generation and income diversification (1, 2, 3, 12, 20, 21, 27, 54)	+	Local
Increase (+) or decrease (–) market opportunities (16, 27, 31)	+/–	Local to national
Contribute to the changes in prices of feedstock (2, 3, 5, 21)	+/–	Local to global

Table 1 (continued)

	Scale	
May promote concentration of income and/or increase poverty if sustainability criteria and strong governance is not in place (2, 16, 26)	–	Local to regional
Using waste and residues may create socio-economic benefits with little environmental risks (2, 41, 36)	+	Local to regional
Uncertainty about mid- and long term revenues (6, 30)	–	National
Employment creation (3, 14, 15)	+	Local to regional
Technological		
Can promote technology development and/or facilitate technology transfer (2, 27, 31)	+	Local to global
Increasing infrastructure coverage (+). However if access to infrastructure and/or technology is reduced to few social groups it can increase marginalization (–) (27, 28, 29)	+/–	Local
Bioenergy options for generating local power or to use residues may increase labor demand, creating new job opportunities. Participatory technology development also increases acceptance and appropriation (6, 8, 10, 37, 40)	+	Local
Technology might reduce labor demand (–). High dependent of tech. transfer and/or acceptance	–	Local

(1) (Finco & Doppler, 2010); (2) (Amigun *et al.*, 2011); (3) (Arndt *et al.*, 2012); (4) (Arndt *et al.*, 2011a); (5) (Arndt *et al.*, 2011a,b); (6) (Awudu & Zhang, 2012); (7) (Beringer *et al.*, 2011); (8) (Borzoni, 2011); (9) (Bringezu *et al.*, 2012); (10) (Cacciatore *et al.*, 2012); (11) (Cançado *et al.*, 2006); (12) (Danielsen *et al.*, 2009);(13) (Diaz-Chavez, 2011); (14) (Duvenage *et al.*, 2013); (15) (Ewing & Msangi, 2009); (16) (Gasparatos *et al.*, 2011); (17) (German & Schoneveld, 2012); (18) (Haberl *et al.*, 2011); (19) (Hall *et al.*, 2009); (20) (Hanff *et al.*, 2011); (21) (Huang *et al.*, 2012); (22) (Koh & Wilcove, 2008); (23) (Koizumi, 2013); (24) (Kyu *et al.*, 2010); (25) (Madlener *et al.*, 2006); (26) (Martinelli & Filoso, 2008); (27) (Mwakaje, 2012); (28) (Oberling *et al.*, 2012); (29) (Schut *et al.*, 2010); (30) (Selfa *et al.*, 2011); (31) (Steenblik, 2007); (32) (Stromberg & Gasparatos, 2012); (33) (Searchinger *et al.*, 2009); (34) (Searchinger *et al.*, 2008); (35) (Smith & Searchinger, 2012); (36) (Tilman *et al.*, 2009); (37) (Van de Velde *et al.*, 2009); (38) (Von Maltitz & Setzkorn, 2013); (39) (Wu & Lin, 2009); (40) (Zhang *et al.*, 2011); (41) (Fargione *et al.*, 2008); (42) (Jerneck & Olsson, 2013); (43) (Gurung & Oh, 2013); (44) (O'Shaughnessy *et al.*, 2013); (45) (German *et al.*, 2013); (46) (Cotula, 2012); (47) (Mwakaje, 2012); (48) (Scheidel & Sorman, 2012); (49) (Haberl *et al.*, 2013b); (50) (Muys *et al.*, 2014); (51) (Egeskog *et al.*, 2011); (52) (Diaz-Chavez, 2012); (53) (Ewing & Msangi, 2009); (54) (De Moraes *et al.*, 2010); (55) (Goldemberg, 2007); (56) (Walter *et al.*, 2008); (57) (Langeveld *et al.*, 2013); (58) (Van Dam *et al.*, 2009a,b); (59) (Van Dam *et al.*, 2010); (60) (Van Eijck *et al.*, 2012); (61) (van Eijck *et al.*, 2013, 2014); (62) (Martínez *et al.*, 2013); (63) (Van der Hilst *et al.*, 2010); (64) (Van der Hilst *et al.*, 2012a,b,c); (65) (Hoefnagels *et al.*, 2013); (66) (Immerzeel *et al.*, 2014); (67) (Lynd *et al.*, 2011); (68) (Smeets *et al.*, 2008); (69) (Smeets & Faaij, 2010); (70) (Wicke *et al.*, 2011a); (71) (Wicke *et al.*, 2013); (72) (Wiskerke *et al.*, 2010); (73) (De Wit *et al.*, 2011); (74) (De Wit *et al.*, 2013).