Institute for European Environmental Policy

THE GHG EMISSIONS INTENSITY OF BIOENERGY

Does bioenergy have a role to play in reducing Europe's GHG emissions?

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EXECUTIVE SUMMARY

The scope of the report

The aim of this report is to provide a rapid review of current knowledge of the degree to which greenhouse gas (GHG) emission savings can be achieved through bioenergy use in the heating, cooling and power sectors. It is based on an expanding literature, some of it relatively recent, with particular reference to Europe. The primary focus is on solid bioenergy sources, principally from forests, rather than biofuels. It is hoped that the review and accompanying commentary from a climate perspective might contribute to the debate on Europe's future bioenergy footprint, in which several areas of contention are evident.

Bioenergy use in Europe is growing, a trend which is expected to continue, not least because it is being promoted as a renewable source of heat and power as well as transport fuel, under the EU Renewable Energy Directive (RED). According to Eurostat data, primary energy production from wood and wood waste grew by 38 per cent between 2003 and 2010, while for biogas it was 225 per cent. According to some forecasts, the use of wood for energy is predicted to more than double from 360 million m^3 in 2010 to 750 million m^3 in 2030 (UNECE/FAO, 2011). Much of the rationale for promoting renewables, including bioenergy, rests on the assumption that the greenhouse gas emissions associated with their use are low, and significantly lower than from fossil fuels.

The particularities of bioenergy

Biomass based energy systems are fundamentally different from other renewable energy technologies, not least in relationship to the management of land, a resource in limited supply. The presumption of 'carbon neutrality' for bioenergy has become conceptually the norm in many circles. In this context, carbon neutrality assumes that end of pipe emissions are offset instantly through regrowth of biomass that would not have happened in the absence of bioenergy production. However, this characterisation of bioenergy is problematic both in terms of misrepresenting its heterogeneity and generalising the GHG emission intensity of its use, often in a misleading way.

The literature identifies several key characteristics of bioenergy as distinctive in climate terms, amongst which:

- Bioenergy is not a single entity, but encompasses a collection of very different feedstocks and conversion technologies which can be utilised to offset the use of different fossil fuels in various circumstances. Supply chains exhibit great variety in terms of climate impact.

- Unlike other renewable sources of energy, a new biomass combustion facility requires a continued supply of biomass resources to feed it over a period of years, not necessarily from the same source. Consequently, its climate impact is not static over time and may be subject to considerable variation; assumptions about future supply patterns need to be made when evaluating the merits of a new (or an existing) scheme.

- The overall pathway chosen to derive useful energy from bioenergy, including the origins of the feedstock used, determines the GHG emission intensity of the various forms of bioenergy. The final conversion technologies in the supply chain are only one component.

- Utilisation for energy represents only one potential use of diverse biomass materials within society and one means of achieving greenhouse gas emission reductions from the material. In a variety of situations other uses will be preferable purely in terms of climate impact, and irrespective of other considerations. Consequently, maximising the potential carbon benefit from the use of bioenergy will require an appropriately balanced and effective policy framework that is sensitive to the choices and trade-offs.

- 'Carbon intensity' is used as a shorthand for various purposes, often referring to the climate impact of an energy source. Here we refer principally to the 'greenhouse gas intensity' of an energy source which is a useful concept in this discussion (see Definition of Terms on page 11.

Estimating the GHG emissions intensity of bioenergy

For the reasons outlined above and the sheer variety of circumstances in which feedstocks of a broadly similar kind are produced, the GHG emission intensity of different bioenergy supply chains varies greatly and depends on many different factors, including assumptions about what would have occurred in the absence of bioenergy production (the counterfactual). It is difficult to speak meaningfully about the GHG emission intensity of bioenergy as a whole. In principle it is possible to estimate it for different supply pathways through techniques such as lifecycle analysis (LCA) and a number of studies set out to do this. Some do address the challenges in an appropriate way but many are based on unsatisfactory assumptions, creating weak foundations for policy formation.

At present, the metrics that have been used routinely for the comparison of GHG emissions intensity between different bioenergy pathways and between those pathways and fossil fuels (typically coal burning) increasingly are being recognised as flawed. This applies particularly to commonly used approaches to life cycle analysis (LCA) that presume 'carbon neutrality' of the bioenergy feedstock, unless land use change has occurred and been recognised and allowed for. The use of this simplistic approach stems primarily from the misapplication of the rules of the international reporting and accounting regime, which was developed to represent emissions and removals within national boundaries, to contexts where the purpose and system boundary is different. This has led to misrepresentation of the actual impacts of bioenergy use on emissions and to flawed LCAs.

Beyond this fundamental point, there remain significant empirical challenges in drawing up LCAs that capture impacts on emissions satisfactorily. There are marked divisions between authors and stakeholders about the appropriate methodology for addressing some key issues, particularly in the realm of forestry, with a significant disagreement on how GHG emission intensity should be analysed and accounted for in this sector. However, from the more recent literature, there appears to be a general appreciation that increasing the intensity of forestry management and increasing biomass extraction rates over time will lead to a 'carbon deficit'. This then needs to be 'repaid' before the exploitation of bioenergy from such resources can deliver emission savings compared to burning fossil fuels. This must also take account of the sequestration services provided by the forest in a realistic counterfactual scenario that might have occurred without the increased delivery of bioenergy. The net impacts on the global climate if bioenergy use continues expanding over time is another relevant question which has drawn relatively little attention so far.

Studies which do attempt more complete LCAs of forest based bioenergy supply chains vary considerably in their estimates of the 'payback time' for the intensified management that might be required to increase supplies. In many cases these are expected to stretch from between 35 and 50 years and, in some studies, up to two or three centuries, depending on the alternative scenario assumed (what would happen to the land/forest over the relevant period of time in the absence of bioenergy exploitation on the scale assumed). One respected estimate of the impact of increased forest management to boost bioenergy supply suggests a time lag of 16 years for the extraction of additional residues, and 38 years for whole standing trees, before emission savings are delivered, taking coal use as a comparator (McKechnie *et al*, 2011). As a consequence, over a 100 year period forest residue use delivered only 73 per cent of the savings that would be anticipated based on the 'carbon neutral' assumption. Standing wood delivered only 44 per cent of the anticipated savings over a 100 year period (McKechnie *et al*, 2011)[1]. This translates into the achievement of approximately 20 per cent of the anticipated savings after 50 years.

However, estimates of this time lag vary considerably given the great range of conditions to be taken into account, not least the nature of the management of the original feedstock and the extent to which this is altered over time by opting for an expansion in bioenergy supply.

Strengthening Emissions Accounting for Bioenergy

Estimating the full impact on emissions that will arise from exploiting bioenergy pathways means addressing some challenging issues. Five of these are summarised in the table below:

Some Key Issues for Correct Accounting
A credible counterfactual – What would have happened in a situation without the use of a specific source of biomass for energy (eg forest left unfelled) and what impact would this have had on the overall GHG emission intensity of the supply chain being considered? Where the comparator is another energy supply chain, normally based on fossil fuels, the question of the realistic counterfactual also arises. We cannot assume coal to be the most relevant comparator in all cases, and even if it is for now, it cannot remain so indefinitely.
***Providing a fair baseline for comparing the GHG emission intensity of the different biomass sources* in LCAs** – How should carbon emissions be accounted for, in particular from primary biomass and associated residues, when production and use may occur in different countries and when there are substantive disagreements as to the emissions associated with exploiting the resource?
Leakage effect – What are the consequences of promoting bioenergy in, say, Europe in terms of exporting global GHG emissions, whether because of changing land use management (such as changes indirectly caused by displacement of production of soya meal and cereals for feed through the increased production of biomass for energy) or displacement of industries which could have used the feedstock for alternative purposes?
The consequence of scale – The resource base for bioenergy is different from that of the major fossil fuels and includes a number of relatively localised and small scale feedstocks and larger forests that can be exploited only at a limited rate without a major change in management. Creating long term markets for bioenergy, eg through building major combustion plants that will need to be 'fed', for decades possibly, can lock the energy system into an expanding feedstock exploitation pathway. This in turn can have major implications for the resources required that do not apply at a small scale. How will the resource base evolve as pressure to increase usage of bioenergy mounts globally and what are the climate and other environmental consequences of this?
Controlling for the evolution of land use – Many assessments of the GHG emission intensity of bioenergy supply chains presume that there is no associated land use change or major vegetation management change arising from the exploitation of the feedstock. Often such changes do occur in practice, either at the site where the biomass has been harvested or elsewhere. It is not realistic or appropriate simply to assume no significant change either in primary land use or key management parameters over the periods under discussion, such as 60 year forestry rotations. How can such critical uncertainties, including forest fires and unplanned events, be addressed in credible LCAs?

[1] It should be noted that McKechnie *et al* (2011) also analysed the use of standing forestry and forestry residues for use as ethanol ie advanced biofuels. Within the analysis, standing forestry did not reach the point at which it reduces emissions at any point over a 100 year horizon, with forest residues only doing so after approximately 75 years.

Analysing the complete net effects on the climate of exploiting bioenergy from land based sources requires a capacity to take account of the full dynamics of the terrestrial sinks affected, with counterfactuals being a key consideration. To extract useful energy from biomass also implies, in most cases, its combustion. This process will release carbon dioxide emissions equivalent to the carbon the material contains. As a consequence, there is an excess of GHG emissions from the burning of a source of bioenergy over that from the fossil fuel reference energy source and therefore there will be a time delay before the emissions from exploiting bioenergy systems will have been reduced through absorption by plant or tree re-growth to a breakeven point relative to the fossil fuel systems. Achieving this balance may take decades or even centuries in the case of forest biomass and greenhouse gases will therefore reside in the atmosphere for a long time. Furthermore, the net effects on the climate, ie the full global warming impact, may range from better to substantially worse.

There are two important reasons why the net impact is often negative. One concerns the significant delay that is likely to occur in the onset of carbon sequestration on a scale additional to the payback of emissions comparable to those from the replaced fossil fuel system. This time period depends on the composition and history of the forest affected and the rate of acceleration of absorption of carbon from the atmosphere through re-growth compared to that in an unharvested forest. The second reason is that it is not sufficient to assume that consumption of bioenergy at time X is simply followed by an immediate period of regrowth until a GHG balance has been attained, as it is often assumed in life cycle assessments relying on a more schematic approach. In reality, successive episodes of bioenergy exploitation may well occur and keep creating a GHG emission debt so that the additive effects keep pushing the date for the eventual balance in GHG emissions further and further into the future. To grasp this through the metrics of an LCA would need more complex assessment frameworks which consider both GHG from energy use and forest management than the frameworks currently used considering both GHG from energy use and forestry management.

Hence the importance of counterfactual scenarios about land use and biomass management in the absence of its exploitation for energy purposes. The management currently taking place on the land is only half of the story. The counterfactual needed to estimate the net effect on the atmosphere should utilise a realistic scenario of the land dynamics at the particular point in time in the given location, under the same general pressures on land. This cannot be equated simply with the earlier land use. A weakness of current bioenergy policies is that they rely too much on top-down and end-product oriented approaches which lack this holistic dimension. More prudent might be to use a more resource oriented approach, based on assessing the resources available at regional and local scales (eg by utilising more wood in clearly undermanaged forests) and focussing on pathways genuinely additional to the existing uses of the resource.

Given the acknowledged length of the carbon debt arising from most enhanced forest exploitation options in particular and the uncertainties summarised in the table above, a question then arises about the compatibility of the timelines for forestry management and for climate action. Can shifts in forestry management to increase output be used to deliver carbon savings over the timelines now confronting us for climate mitigation? The period to 2050 is particularly critical in climate terms but implies an upper bounding on carbon debt of little more than twenty five years at least; many options do not achieve this.

Towards more robust evidence and policy for bioenergy

The evidence base for making informed decisions about bioenergy in relation to climate change needs to be strengthened considerably as a matter of urgency and some interim judgements made to give policy a stronger and more transparent foundation. Amongst the most important steps to take are the following:

- Intensified investment is required in developing more satisfactory LCAs for bioenergy supply chains, covering GHG emission accounting methodologies, comparative metrics, counterfactual scenarios and supporting databases. This is a priority both for publicly funded research and for working methodologies used to support policy decisions, nationally and at the EU level. This involves a continuing dialogue around the most appropriate approaches to GHG emission accounting for bioenergy and development of a clear metric to enable comparison between the different bioenergy resources as well as alternative energy sources. This should build on analysis of appropriate counterfactuals and will need to take into account temporal factors. Almost certainly these will be interim approaches to be revised in the light of more refined estimates based on more sophisticated models and better data in the future.

- There is an urgent need to address the question of the representation within LCAs of forestry biomass in particular. It needs to be appreciated that most conventional LCAs do not take into account the non-linearity of carbon sinks associated with land use activities, arising not only from outright land use change but also from long rotation forestry in particular[2], nor do they normally account for shifts in management that increasingly are identified as reducing carbon storage potential.

- Policies based on misleading LCAs need to be revisited and revised as appropriate.

- Research is needed to develop more robust integrated assessments of the carbon leakage consequences of increasing bioenergy use in a European context. Key issues include the nature, origin and use of imports, the land use consequences of expanded demand (both in terms of changes in primary use and key management practices), and the implications for the evolution of other industries which are reliant on biomass. Feedback loops between bioenergy and other interim and end uses for biomaterials, such as wood, need to be better understood and the results fed into relevant sectoral policies.

- An intensified policy debate is needed to attain greater agreement on an acceptable timeline for carbon payback, marrying climate and forestry timelines. While this remains a matter of judgement in many respects, it needs serious attention both in climate policy and related domains, eg energy and forestry policies. As a stimulant, it would be helpful in the near future to bring together key experts from the energy, climate, forestry and land management disciplines to advance the debate on payback times and define what is acceptable in terms of climate impact and what is achievable in terms of carbon management within forestry systems.

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[2] Non-linearity of carbon sinks means that any intervention in terrestrial carbon stocks, eg by planting of forests or drainage of peatland for agricultural use, carries a time signature. The associated carbon sinks (eg the increased absorption of atmospheric CO_2 by new tree growth or the loss of carbon and reduction of absorption of atmospheric CO_2 by peatland after drainage) have an initial pulse followed by a long tail. This non-linear development of sinks is very important in determining the net GHG impacts of land use activities.

- Both researchers and policy makers need to focus more on situating bioenergy decisions within the broader question of a sustainable bioeconomy and a resource efficient Europe. This involves both more sophisticated assessments (eg of what can be derived from the land base and the full impacts of sectoral incentives) and more engagement with key actors, for example to determine the carbon consequences of pursuing an energy driven agenda. Bioenergy decisions need to be located more firmly within the broader resource efficiency agenda and based on a clearer understanding of the synergies and the consequences of different strategies for the utilisation of the bioenergy resource base. The concept of cascading biomass use, whereby material use of wood, eg in construction, precedes energy recovery at the end of its life, is a demonstrated way of improving the GHG profile of bioenergy pathways and could inform a more holistic policy framework.

- A more sophisticated EU framework is needed to incorporate the GHG emission intensity dimension of bioenergy pathways in energy and climate policies. This needs to take account of the inherent variability of bioenergy feedstocks and supply pathways and incorporate reasoned judgements concerning the relative merits of different feedstocks. A robust mechanism for monitoring bioenergy usage and feedstock supply patterns and their evolution is needed

- The consequences of EU demand and the associated GHG emission intensity impact, both in space and time.

At the same time, more investment is needed in identifying the medium and long-term impacts on overall GHG emission balances (including positive and negative impacts) from bioenergy exploitation, and deepening understanding of the real level of GHG savings to be expected from bioenergy use up to 2020. The National Renewable Energy Action Plans (NREAPs) prepared by Member States, and modifications to them, will be a key signpost to future bioenergy deployment. Given the current accounting processes and LCA metrics in place, it is not possible to define the emissions profile and savings associated with Europe's expanded use of biomass for energy at all precisely for different feedstocks.

This means that there is no policy process currently in place to secure the choice of truly low-carbon bioenergy pathways. As a consequence, at present we have considerable knowledge of the science and principles involved in extracting bioenergy from agricultural and forestry, and a commitment to much greater bioenergy use up to 2020, but no associated guarantee of emission reductions.

DEFINITION OF TERMS

The term 'carbon intensity' is frequently used in contemporary debates and life cycle frameworks concerned with the potential of bioenergy and its impacts. In some respects it is journalistic shorthand for communicating a relatively complex technical issue in a simplified way. Part of the task of this report is to disentangle some of the key issues usually being addressed when this term is employed. The definitions used in this study are as follows:

Greenhouse gas (GHG) emission intensity: the GHG emissions emitted as a result of combustion per unit of energy use at a point in time. This concept is frequently referred to as the GHG emission intensity of energy use as a form of shorthand. It is important to note, however, that the greenhouse gas emissions associated with land use activities for the production of bioenergy feedstocks include not only carbon dioxide (CO_2) but also other gases such as reactive compounds of nitrogen, methane, aerosol particles, eg black carbon, etc.[3] Its value will depend on many bio-physical, environmental, climatic and agronomic or silvicultural factors affecting the nature of carbon stocks in the particular forest or agricultural ecosystem at a particular place and point in time when the biomass in question is harvested. We recognise that this term is not based on a scientific definition underpinned by an IPCC global assessment, but we use it in this report because it is commonly utilised in the life cycle assessments developed in the energy sector, typically at national level.

GHG emissions balance: the overall atmospheric balance of life cycle greenhouse gases over a stated period of time for a given level of energy use. It is determined by the balance between emissions (from human activities and natural systems) and removals of gases from the atmosphere (by conversion to a different chemical compound) (IPCC, 2007). The long term EU targets are expressed as a reduction of the overall GHG emission balance by 80 to 95 per cent by 2050 in comparison with 1990.

Global warming impact: the net global warming impact over a stated period of time for a given level of energy use.

(Terrestrial) carbon stock: pools of carbon, ie the overall carbon content accumulated in ecosystems. These pools include carbon in living biomass (above and below ground), dead organic matter (eg deadwood and litter) and soil organic carbon (UNFCCC, 1992). Carbon is accumulated by a forest only up to a point when a steady state is reached so the carbon stock of a given forest stand is finite.

Carbon sink (sequestration service): any process, activity or mechanism which removes a greenhouse gas (or an aerosol) from the atmosphere (UNFCCC, 1992). The sink function of a forest can best be described in terms of change in the growing forest carbon stock.This occurs for example when a forest is growing (quite naturally or in response to arrangement) and reverses in the case of dieback, decay and fire. The sink function of a newly created woodland is typically high because the stock is in a steep growth curve and the rate of carbon absorption from the atmosphere through photosynthesis is high, whilst the sink function of a mature forest is approaching zero. The accumulation of carbon by terrestrial

[3] Aerosols may have either a cooling effect on the climate by reflecting incoming solar radiation or a warming effect, by directly absorbing heat radiation and indirectly by changing surface albedo (eg, black carbon soot from biomass combustion) (IPCC, 2007; IPCC, 2011).

biomass is reversible since greenhouse gas emissions can be returned to the atmosphere through natural disturbances or premature harvest. Carbon sinks are sometimes mistakenly equated with carbon stocks under the assumption that eg mature forest holds more carbon from the atmosphere than a newly created woodland. Such misapplication of the term can significantly distort life cycle assessments of the impacts of biomass use.

Carbon leakage: in one sense the term refers to emissions from biomass produced within one geopolitical/national unit which have been displaced beyond the boundaries of this area (geographical understanding). In another sense, the term refers to a concealed breach of the boundaries of the accounting framework, as in the case of indirect land use change (climate policy understanding). Another example of the latter aspect is 'leakage' defined in the principles of the Clean Development Mechanism as the prohibited displacement of emissions beyond the project boundaries. A 'project' in this policy context is not a geographic realisation of a mitigation activity but an accounting framework for such an activity. Both aspects of the term are of relevance in understanding the effects of bioenergy use

Carbon debt: the excess of GHG emissions from the burning of a source of bioenergy over that from the reference energy source, usually fossil fuel (net emissions over fossil). There is a time delay before the emissions from exploiting bioenergy systems will have reached a breakeven point relative to the fossil fuel systems. We recognise that this definition simplifies the GHG debt incurred by the burning of bioenergy (eg by neglecting the effect of black carbon and aerosol particles). An alternative definition of 'carbon debt' refers to all the CO_2 released from the combustion of biomass (absolute emissions). However, this definition is less frequently adopted and it is therefore not used in this report.

Payback time: the time it takes to 'pay off' the carbon debt, ie the time it takes for biomass to grow and absorb CO_2 so that the excess emissions that resulted from the combustion of the biomass over the comparable use of fossil fuel are sequestered. Achieving this balance may take decades or even centuries in the case of forest biomass and greenhouse gases will therefore reside in the atmosphere for a long time.

Relative GHG savings: the reduction of emissions relative to the fossil fuel alternative for a specific biomass use. As an indicator, it does not distinguish between different bioenergy pathways and biomass uses.

1 INTRODUCTION

The aim of this report is to provide a rapid review of current knowledge of the degree to which greenhouse gas (GHG) emission savings can be achieved through bioenergy use in the heating, cooling and power sectors. It is based on an expanding literature, some of it relatively recent, with particular reference to Europe. The primary focus is on solid bioenergy sources, particularly from forests, rather than biofuels[4]. It is hoped that the review and accompanying commentary from a climate perspective might contribute to the debate on Europe's future bioenergy footprint, in which several areas of contention are evident.

This report considers the potential use of bioenergy in the EU context and specifically the implications for greenhouse gas (GHG) emissions and the GHG balance. Whilst these climate impacts are clearly critical it must also be emphasised that forests and several other sources of living biomass provide significant ecosystem services. The exploitation of bioenergy on any significant scale has important consequences for biodiversity and other environmental media such as water and soil which need to be taken into account. However these are outside the scope of the present study, which is concerned solely with the climate dimension of bioenergy use.

1.1 Bioenergy and GHG Emissions

Climate impacts are important because biomass is being exploited for energy purposes on a growing scale, in Europe and elsewhere. In Europe this is being driven to a large degree by policy measures promoting renewable energy, one of the prime goals of which is to contribute to the mitigation of climate change. The key driver is the EU Renewable Energy Directive (RED). Many of the core strategies examining ways to deliver a decarbonised Europe up to 2050[5], rely extensively on the expansion of bioenergy and it is seen as a crucial element of the renewables mix in many countries. Clearly, well founded mitigation actions and low-carbon investment decisions are needed now in order to avoid lock in to carbon-intensive technologies and to achieve sufficiently deep emissions reduction to allow the 2°C target set out in the EU climate policy to be met (EU Climate Change Expert Group, 2008). Appropriate renewables are needed on a large scale to contribute to the mitigation effort over the next three decades, particularly in the power and heat sectors.

Member States are assessing the ways in which they can meet the RED target by 2020 and some may prioritise bioenergy over other renewables even more than previously planned, as certain feedstocks, such as wood pellets, are readily available. In some cases this could be driven by cost arguments. For example estimates for the UK in the Government's recent Bioenergy Strategy suggest that if biomass was to be excluded from the energy mix it would significantly increase the cost of reducing the use of fossil fuels in the energy system, representing an estimated increase of £44 billion (HM Government, 2012)[6]. In the Netherlands, where it appears unlikely that the Government can meet its 2020 target of 14 per cent of energy supply delivered from renewables, a recent study by the national environmental assessment agency (PBL) and energy research institute (ECN) proposes remedial options such as a 20 per cent biomass mandate for coal fired power stations (ECN, 2012).

[4] It is noted that the report does not comment on the Commission's proposal (COM(2012) 595 final) on how to address indirect land use change from biofuel use issued on 17 October 2012.

[5] For example those prepared by organisations such as the European Climate Foundation and WWF Europe.

[6] Using an exchange rate of 1.239 from 21 June 2012 (http://www.oanda.com/currency/converter/), this converts into €54.5 billion.

Given these forces to escalate bioenergy use it is all the more important to be clear about the contribution that it is likely to make to climate mitigation. Since there are serious doubts on this issue, robust assessments of specific initiatives using credible LCAs are essential. Here there is much progress to be made. Despite the anticipated scaling up in Europe's bioenergy use, there are currently no EU rules to ensure that biomass for heat and power is collectively sourced in a sustainable way or utilised to deliver energy efficiently[7]. Biomass has the potential to deliver emissions savings compared to fossil fuel but the extent of these savings is variable[8] depending upon the precise feedstocks use; and a range of considerations discussed in this paper relating to the feedstock source and its characteristics, counterfactual land management and processing and conversion efficiency. The IPCC provides one example:

'Bioenergy has significant potential to mitigate GHGs 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. However, land conversion and forest management that lead to a large loss of carbon stocks and ILUC effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts'. IPCC, SRREN, 2011

However, to extract useful energy from biomass implies, in most cases, its combustion. This process will release carbon dioxide emissions equivalent to the carbon the material contains. Box 1 demonstrates that this issue has been consistently highlighted in the treatment of bioenergy emissions by the United Nations Framework Convention for Climate change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). However, a number of issues arise.

Box 1: UNFCCC and IPCC treatment of emissions from the consumption of bioenergy

- An overview of the elements of **physical science provided in The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)** identifies the key role of land use, crop production, conversion of grasslands to croplands and biomass burning in the increase in atmospheric CO_2 concentrations (IPCC AR4, Chapter 7.3). The report identifies land use activities and biomass burning as key factors contributing to global warming alongside the burning of fossil fuels and deforestation.

- Emissions from the consumption of energy are identified as one of the anthropogenic sources of greenhouse gases that drive global warming in the **United Nations Framework Convention for Climate Change** (UNFCCC, 1992). The Convention requires **annual reporting** by all parties, including Annex I and non-Annex I countries (IPCC, 1996; IPCC, 2006). One requirement is that all parties have to draw up national inventories of GHG emissions and must count biomass emissions either within the energy sector or, alternatively, within the Land Use and Land Use Change and Forestry (LULUCF) sector. Land use emissions are described by reporting changes in the carbon stocks of agricultural or forest ecosystems, including those that supply biomass feedstock for energy facilities. The Convention thus provides the only framework which is applied at both the global and national levels and which includes all emissions relating to bioenergy production;

[7] It should be noted that the European Commission (2012b) has stated that in the context of expanding bioenergy use it will 'produce reports and proposals to further develop the EU's sustainability framework. It will also investigate the most appropriate use of bioenergy after 2020 in a way that is consistent with the EU energy and climate ambition to 2030 while fully taking into account environmental, social and economic considerations'. However, the means through which this may be achieved are as yet uncertain.

[8] There is a widespread assumption in Europe that, given the proportional nature of the EU 2020 target for renewables, bioenergy use will be displacing fossil fuel rather than simply providing additional supply capacity.

- **The accounting framework for LULUCF** under the first commitment period of the **Kyoto Protocol** has to be interpreted against the backdrop of its objective which is to ensure that overall GHG emissions do not exceed the emission limitations and reduction commitments assigned per signatory country ('caps') with a view to reducing overall GHG emissions by at least 5 per cent below 1990 levels in the commitment period 2008–2012 (Article 3). It allows for bioenergy emissions being ignored within the energy sector on the condition that they are counted within the LULUCF sector (in another country in some cases) in the same framework. The accounting framework is correct in its intent, although the consequence, which is a shift of the reporting of GHG emissions from bioenergy combustion into the LULUCF sector is to some degree inconsistent with the structure of the national inventories under the UNFCCC reporting process. More importantly, the implementation of the LULUCF requirements by governments party to the Protocol is very incomplete at this point, with the result that emissions from bioenergy consumption are not accounted systematically anywhere in the progress toward the Kyoto targets.

- A good example of the more systematic treatment of biomass emissions is provided under the **Clean Development Mechanism** (CDM), established within the Kyoto Protocol (Article 12). It aims to provide a degree of flexibility to Annex I countries in their efforts towards fulfilling the overall objective of the Convention and complying with the quantified emission limitation and reduction commitments ('caps') under the Kyoto Protocol. To meet part of their caps Annex I countries can use Certified Emission Reductions from projects, including bioenergy and biomass projects, in developing countries. Such projects are subject to rigorous rules and control intended to ensure that they deliver real, measurable, and long-term benefits for the mitigation of climate change and that the emission reductions are 'additional' to any other GHG reductions that would occur without the certified project. A 'project' in this context is therefore defined as the accounting framework for the activity, not the activity itself. Any displacement of the emissions associated with the activity entailed in the project beyond the project boundary (ie the boundary of the accounting framework, not the geographical boundary) is disallowed. Projects focussing on the creation of forest sinks are particularly strictly regulated, the main reason being fears that such projects cannot guarantee permanent storage of carbon and that the methods of accounting for carbon storage in biomass are complex and still under development.

Despite the science and quite some policy debate in this area, much of the literature on biomass use for heat and power makes the central assumption that bioenergy resources are 'carbon neutral'. The assumption is typically based on a form of common wisdom that the biomass regrows after harvest and while doing so absorbs CO_2 through photosynthesis. The main reason for this misapprehension is perhaps the incomplete implementation of international accounting rules and the misapplied use of the accounting frameworks and life cycle metrics for greenhouse gas emissions from bioenergy which typically address only a part of the actual emissions that occur in the physical world.

The assumption of 'carbon neutrality' is misleading because it conceals the fact that often the absorption of carbon by plants would occur (fully or partly) even in the absence of bioenergy production. It is only the difference in the overall level of carbon absorption (arising from the deliberate use of bioenergy) that can be reasonably credited to offset the emissions arising from diverting biomass into energy supply. This is a much more demanding test of the contribution of bioenergy use to climate change than assuming that carbon neutrality is inherent.

Furthermore, there is a second important factor to take into account. The emission and absorption of carbon by living organisms do not occur in the same time period. Consequently, any claim of carbon neutrality may in effect borrow from, and presume, future emission savings from future growth of plants that has yet to occur and may not take place as envisaged. In effect, an implicit claim is being made on the land where the future absorption is supposed to happen.

1.2 Carbon neutrality and carbon debt

In this context a terminological discussion is helpful. 'Carbon neutrality' is a shorthand term that is frequently used in assuming that CO_2 emitted during the combustion of biomass to generate useful energy will be sequestered again during regrowth of an equivalent mass of biomass. Alternatively, there is the assumption that biomass is carbon neutral because CO_2 emitted through combustion previously had been absorbed from the atmosphere. At a more sophisticated level the International Energy Agency (IEA) standard methodological framework for comparing bioenergy and fossil energy systems in lifecycle analysis presumes stable atmospheric carbon for bioenergy systems and increasing atmospheric carbon for fossil reference systems. It states that the atmosphere and biosphere represent a single carbon pool, with fluxes between the two spheres, and therefore stable atmospheric carbon can be assumed for bioenergy systems (IEA, 2011)[9].

The EU Renewable Energy Directive does not make an explicit claim about the carbon neutrality of bioenergy but treats the emissions from the burning of biomass as effectively neutral by excluding them from the methodology that Member States should follow for the counting of greenhouse gas emission savings from biofuel use (Annex V). The IPCC and UNFCCC treatment of bioenergy emissions referred to in Box 1 may help to explain this unsatisfactory arrangement within EU legislation.

Consequently, carbon debt and 'payback time' are often used as fairly simple short term indicators of the relative merits and de-merits of different bioenergy feedstocks. They intend to measure the excess of GHG emissions from the burning of different bioenergy feedstocks over a reference source of energy, generally fossil fuels, yielding a 'carbon debt' and then to determine the time delay before the emissions from these bioenergy systems will have reached a breakeven point compared with the fossil fuel systems ('payback time').

It is important to note that for bioenergy systems based on agricultural feedstocks from annual crops, carbon debt typically will be low, but it needs to take account of the releases of emissions from soil and any direct or indirect land use change and so will vary between cases. Annual crops that do not involve any major releases give rise to a very low carbon debt, but depending on soil types and management factors, there would be very high debts in some cases, eg for biofuel crops produced on drained peatland[10]. The carbon debt accrued through the burning of harvested biomass always will be significantly higher than the debt associated with feedstocks from annual cropping systems, not least because trees take a much longer time to grow to maturity (typically from 60 to 150 years in Europe).

[9] The IEA, Task 38 (IEA, 2011).

[10] EU sustainability criteria for biofuels do not allow biofuels coming from feedstocks from drained peatland to be counted toward national bioenergy targets. Given the 2008 baseline specified in the criteria, biomass feedstocks for biofuels from the peatlands that were drained prior to 2008 are compliant. For the purposes of this report, the physical dimension is as important as the policy dimension, ie drainage leads to peat oxidation and causes CO_2 emissions that reside in the atmosphere over decades (Schils *et al*, 2008). Net emissions can be several times higher than the displaced emissions of the comparator fossil fuel system (Edwards *et al*, 2008 cited in IPCC, 2011). The effects of drainage are reflected also in the GHG profile of crops and woody biomass from the extended areas of peatlands that are currently under agricultural and forestry land use in Northern Europe. Since these areas were first drained and converted to current uses in the past, potential biomass feedstocks originating from these systems are compliant with the EU sustainability criteria.

Beside the simple arithmetic measurements involved in these two indicators, the physical and geophysical dimension of the temporal issue has to be properly considered too. The carbon debt associated with the consumption of biomass refers to a given point in time, at a particular place where the biomass was harvested. There follows from harvest a period of time during which the excess emissions over the fossil fuel referent will reside in the atmosphere, potentially over many decades, with adverse impacts on the net GHG balance and global warming. It is uncertain whether such impacts in the interim risk overstepping planetary boundaries (Rockström, 2009). Since the metrics of the carbon debt and payback time are limited by the referent comparator (fossil fuel emissions in typical current assessments), basic carbon debt calculations allow only for representing relatively short term and simplified impacts on the atmosphere to be represented. They do not represent the long term effects of the delay in the provision of carbon sequestration services into the future and the accumulation of atmospheric CO_2 in the interim. A simple carbon debt calculation accounts merely for the compensation for the sink function of the forest harvested which is brought about by re-growth which is assumed eventually to absorb the emissions of the bioenergy (assumed to be replacing fossil fuel). However, the level of future sequestration services is uncertain while the results of combustion are relatively certain. So, relying on a one to one substitution between the present and future level of carbon sequestration is a problematic assumption in both of these indicators.

This time differential is of particular importance given the commitment to limit global warming to 2 degrees; according to IPCC scenarios this would require GHG emissions to peak by 2016 and fall by between 80 and 50 per cent by 2050 (IPCC, 2007). Increasingly, it is therefore important both to question whether it is appropriate to treat all forms of bioenergy equally, and to critically review the assumption of ‘carbon neutrality’.

Given the envisaged extent of reliance on bioenergy to deliver Europe’s central climate goals, a much stronger common understanding is required of these critical aspects of bioenergy use and the accompanying uncertainty while moving towards policy approaches that can resolve them. Appropriate forms and quantities of bioenergy then can be used to contribute towards reducing Europe’s GHG emissions. Without progress in this direction there is a marked danger of investing in inappropriate technologies.

2 ACCOUNTING FOR DIVERSITY – POTENTIAL PATHWAYS FOR BIOMASS

Bioenergy represents a highly heterogeneous resource in terms of the type of feedstocks that can be drawn upon, the way in which these are produced and processed and the end uses to which they are put, both within and outside the energy sector. Moreover, use of bioenergy for climate mitigation purposes (more than other renewable energy sources such as wind, solar or wave power) implies the continued use of a key resource such as land, in a particular way over a period of time stretching into the future. Actual GHG savings arising from any bioenergy source will be revealed only over time and will depend on changes in supply conditions, the scale and intensity of production and so on.

This section is intended to provide an introduction to the nature of bioenergy, its heterogeneity, both in terms of feedstock and use, and the associated implications for the net GHG balance. It does not attempt to provide a full account of potential life cycle emissions from bioenergy but focuses on two questions: what feedstocks might be utilised; and to what end use are they being put? These represent areas of uncertainty for practical bioenergy projects. The focus of the report is on feedstocks rather than the subsequent processing and transportation, the next links in the bioenergy supply chain, understanding of which is relatively well established. It is the GHG attributes of the use of feedstocks that have been insufficiently considered in GHG accounting and need scrutiny. The question of capturing a complete and meaningful representation of the actual impacts of GHG emissions in a life cycle assessment (LCA) framework will be discussed in Section 3.

2.1 Potential feedstocks

Which biomass materials are used for energy production? Fundamentally there are two subsets: primary raw materials, some of which are cultivated specifically to meet the growing need for biomass[11]; and wastes and residues. The carbon characteristics of the former are linked to questions of land management, cultivation and harvest. The latter class relies on the ability to capture waste and residue streams from a variety of sectors such as forestry, agriculture, wood pulp, paper, food, construction and furniture industries and the efficient processing and reuse of the materials.

Table 1 below sets out some categories that can be used to subdivide the bioenergy resource and summarises the nature of the resource available in each category. The volume of certain residues available for bioenergy is clearly linked to the dynamics of the main production activity (for example the availability of cereal straw depends on the area of cereal cropping)[12], in particular in the case of primary and secondary forestry and agricultural residues. Each type of resource will have its own characteristics that determine how it might be used to deliver bioenergy.

[11] It should be noted that at the time of harvest/cultivation it may not be known whether the materials will ultimately be used for bioenergy. At present, end usage is often determined by fluctuating commodity prices; often it would be decided at an intermediate stage how a resource will be used in the end (Böttcher *et al*, 2012)

[12] 'Production' is understood in this report in the socio-economic sense, in terms of the provisioning services provided by land and the material outputs removed from it. The term is not applied in the physical sense of the biomass produced on land and available for harvest (ie 'net primary production', NPP). The latter concept is usefully reviewed by IPCC SRREN (2011) demonstrating that the total terrestrial aboveground NPP is larger than the global energy demand of society currently, but to mobilise it for bioenergy would require diversion of a significant part of the global terrestrial NPP into agricultural and forestry production systems that provide bioenergy feedstocks.

There are many studies that explore potential sourcing of bioenergy feedstocks in Europe and its Member States (eg the Biomass Futures bioenergy atlas, see Elbersen *et al*, 2012a/b) or strategies for mobilising bioenergy resources. In contrast, analysis of how this resource will be translated into energy production is often incomplete. For example many studies only consider EU supply profiles, failing to analyse how resource use might evolve over time, or not considering how resource availability will determine the location and appropriateness of different bioenergy technologies. What is clear, however, is that the characteristics of different resources will have an impact on how they are able to replace or interact with fossil fuel use and the consequent impact on net GHG emissions.

Table 1: The bioenergy resource

Class of bioenergy resource	General Description
Wastes and Residues	
Wastes	Grass cuttings, residues from food processing, biodegradable municipal waste, sludges, used fats and oils and used paper and board
Agricultural residues and by-products	Manure, straw, other residues including prunings and cuttings from permanent crops
Landscape care wood	Residues such as cuttings from landscaping and management activities
Primary forestry residues	Logging residues, early thinnings and extracted stumps
Secondary forestry residues	Residues from the wood processing industry ie black liquor, sawmills and other industrial residues
Tertiary forestry residues	Post-consumer wood waste ie from households, building sites
Primary production	
Rotational crops	Crops grown to meet bioenergy needs such as maize for biogas and crops used as bioliquid feedstocks such as oilseed rape
Perennial crops	Dedicated energy crops providing ligno-cellulosic material eg short rotation coppice
Roundwood production	Stem wood from forests reaching maturity[13]
Additional harvestable roundwood	Additional potential for the harvesting of stem wood within sustainable limits[14]

Source: Biomass Futures (Elbersen *et al*, 2012a) building on the approach set out in the EU wood project (Mantau *et al*, 2010), see also Elbersen *et al* (2012b, p43) for additional information

Bioenergy use is inherently linked to land; in effect a given unit of land can deliver a certain energy potential depending on the biomass material produced on it. The literature suggests a range of values, with ligno-cellulosic feedstocks such as short rotation coppice delivering between 80 and 415 GJ/ha/year and residues between 2 and 155 GJ/ha/year depending on the crop / residue type

[13] It is assumed in Elbersen *et al* (2012a) that roundwood and additional harvestable roundwood come from forests that are sustainably managed and where harvests take place at the point of forest maturity. For the purposes of this report, it is notable that forests need to be managed in a sustainable way in future if current estimates of GHG emissions savings from bioenergy exploitation are to remain valid. This is not a trivial consideration.) , Land use systems dedicated to the production of biomass for energy can exacerbate soil and vegetation degradation associated with overexploitation of forests, excessively intensive crop and forest residue removal, and water overuse, similarly to conventional agriculture and forestry (IPCC SRREN, 2011). Equally important, the assumption of forests being harvested at the age of maturity implies that there is no shortening of rotation periods over time, which may not be compatible with increased demand for feedstocks, not least to meet bioenergy targets. If changes in the rotation length occur, they are likely to adversely affect sequestration services in the future compared to the level of carbon sequestration provided by the same forest if harvesting for bioenergy had not taken place. Such adverse effects are not captured by the carbon intensity indicator nor the 'payback time' indicator.

[14] Ibid.

and the geographic origin (IPCC, 2011). GHG emissions from bioenergy will not only be related to the nature and efficiency of the biomass feedstock used but also the land use, its intensity and land management practices employed to deliver that biomass. Both the efficiency of feedstock usage and the efficiency of land use for energy production need to be considered.

The characteristics of biomass as an energy source differ from those of fossil fuels. Table 2 provides an example of the energy values estimated for different bioenergy resources in comparison to standard coal and gas values. While there are major variations, all forms of bioenergy listed deliver lower levels of energy per weight and volume compared to fossil fuels, ie a tonne of biomass will not replace a tonne of coal. As a consequence, the end of pipe emissions of CO_2 per unit of energy associated with bioenergy also differ from fossil fuels. Sources suggest that emissions from burning dry wood pellets are approximately double that for natural gas and greater than for coal (IPCC, 2006; PFPI, 2012). Therefore, bioenergy does not reduce overall end of pipe emissions from a given power plant per se, rather it may contribute to ultimate global emission reductions only on the basis that the excess carbon emitted following combustion ('carbon debt') will be reabsorbed when plants regrow which does not occur with fossil fuels. As explained in Section 1, it cannot be assumed that a positive contribution will occur; the net impact may be negative in many cases.

Table 2: Examples of typical characteristics of biomass fuels compared to fuel oil and coal

	GJ/t	toe/t	Volume oil equivalent (m³)
Fossil fuel oil	41.9	1.00	1.0
Coal	25.0	0.60	1.6
Pellets (8% moist)	17.5	0.42	3.5
Pile wood (stacked, 50%)	9.5	0.23	7.0
Industrial softwood chips 50% moist	9.5	0.23	13.1
Industrial softwood chips 20% moist	15.2	0.36	12.5
Forest softwood chips 30% moist	13.3	0.32	12.0
Forest hardwood chips 30% moist	13.3	0.32	9.3
Straw chopped 15% moist	14.5	0.35	45.9
Straw big bales 15% moist	14.5	0.35	19.7

Source: EUBIA (2012). Note: The data here represent averages collated by EUBIA, from what is sometimes a wide range. For coal, the range stretches from 20-30 GJ/tonne. Volume oil equivalent (m³) in the last column denotes 'Volume (m³) required to substitute one cubic meter of oil by some other fuels'.

2.2 From biomass to energy

Bioenergy is being promoted as an alternative to the use of fossil fuels. As a consequence the GHG emission intensity of a particularly bioenergy pathway is both inherent to specific supply chains (stretching from the original feedstock to the combustion technology) and also relative to the emissions from the fossil fuel that its use offsets. In the case of waste, it is equal to the comparators with the GHG emissions avoided during degradation and disposal of the material concerned (see section 3.1). The type of end use will clearly influence both the efficiency of energy production and the nature of the fossil fuel it replaces.

Given that the supply of bioenergy feedstocks is constrained by the finite availability of land, arguably it is particularly vital to ensure that it is utilised efficiently (IEEP, 2011). The efficiency of use of a feedstock will depend on the way in which the biomass is converted to energy (ie to deliver power, heat or combined outputs) and also the efficiency of the plant. For example, the Environment Agency for England and Wales has recommended tightening the efficiency standards for biomass boilers (Environment Agency, 2009a) which are set for small and medium sized boilers by European standards. There are substantial benefits from the use of bioenergy for combined heat and power (CHP) rather than simply to provide power alone, as is the case for fossil CHP as well. For CHP the efficiency of material use is 60 per cent compared to an average of 36 per cent in dedicated biomass plants for power alone (CCC, 2011c).

A given quantity of biomass delivers the highest level of GHG emission savings compared to fossil fuel use when it offsets coal consumption, given coal's relatively higher emissions profile. However, it should not be automatically assumed that bioenergy use will offset coal combustion of which is declining in many countries. The UK Climate Change Committee recently stated in its review of bioenergy that it considered co-firing or conversion of existing coal plants (within efficiency constraints) to be preferable to the establishment of new, large scale dedicated plants for power from bioenergy (CCC, 2011a). This is because the former should offset coal use (with a 'carbon intensity' of 900-1,000 gCO_2/kWh), assuming that incentives are correctly focused to avoid increased production overall from such plants, while the latter would often displace new gas fired capacity (with a 'carbon intensity' of 380-430 gCO_2/kWh) (CCC, 2011c).

Bioenergy of course is not the only renewable energy source which can displace fossil fuels, there are other low carbon alternatives, which may deliver greater emission savings than bioenergy. Indeed, these will be needed on a large scale in order to stabilise the concentration of GHGs in the atmosphere over the coming decades. Lifecycle emissions from other renewables are normally below 50 gCO_2e/kWh[15] and falling for many technologies given improvements in production processes (Parliamentary Office for Science and Technology, 2011). Therefore, coal cannot be assumed to remain the relevant comparator for long into the future. Future emissions from bioenergy will have to be compared to other energy sources of a lower GHG profile, thus significantly reducing apparent savings and pushing out the 'payback period'.

The end use to which biomass is to be put can also determine the nature of the feedstocks that are appropriate and the processing methods needed. For example, co-firing of biomass in coal plants or its use in converted coal plants usually requires high-grade 'clean' wood pellets, with a high energy density (eg 16-18 GJ/tonne). While pellets can be produced from a variety of feedstocks (such as some agricultural residues or energy crops), generators are anticipated to require pellets from timber feedstock with a high core wood content (CCC, 2012c).

Similarly, analysis by the Biomass Energy Resource Center (2012) reviewing production in seven of the US southern states noted that pellet production in the region (primarily envisaged for export to Europe) requires high quality roundwood rather than residues (or 'slash'). They conclude that pellet mills and small-scale dedicated biomass power plants in the region are complementary and symbiotic in terms of their procurement needs; the former using the main wood harvest and the latter the residues. How far such complementary resources can be relied on for domestic or imported supplies is a different question.

2.3 Alternative uses for biomass

Fundamentally, biomass is a multipurpose resource with bioenergy only one of the potential uses to which it might be put. Very few bioenergy feedstocks can be used only in this sector and there

[15] Solar PV can be up to 116 gCO_2eq/kWh depending on operating conditions and final disposal (Parliamentary Office for Science and Technology, 2011)

are other potential uses for the materials. The literature suggests that generally bioenergy has represented the primary or sole commercial use of materials in the following cases: genuinely residual waste such as sewage sludge, livestock residues and slurries, food waste (taking into account ongoing efforts to prevent waste) and waste that is not recyclable (IEEP, 2011), as well as landscape care wood (Searchinger, 2012). With the advent of the bioeconomy, however, other sectors such as the chemicals and plastics sectors can be expected increasingly to claim a share of these resources, using technologies such as gasification.

Other residues, in particular those from forestry, are available for bioenergy production but are often already being utilised in other industries, such as the wood panel industry (chips, sawdust) or chemicals (crude tall oil from the recovery of black liquor produced in the pulp and paper industry). They may also be relied upon to maintain the carbon stores in areas of managed forest. Similarly, residues from agriculture may be in use in other ways, for example as bedding or as a soil improver (Kretschmer *et al*, 2012).

For primary materials from both forestry and agriculture there are likely to be alternative uses, exposing other sectors to competition with the energy system for resources and to changes in global and local environmental and economic conditions. For example the level of supply of agricultural crops is sensitive to competition from food markets, to changeable subsidy levels and real constraints on the global availability of suitable arable land. The availability of forestry materials will be determined by the evolution of forest management but also by environmental factors such as large scale forest die back in recent years, or economic conditions, such as demand for other wood based commodities like paper, pulp or timber for construction. Moreover, multi-purpose land use is common in Europe and may become more so. Therefore forested land may simultaneously be in use to supply wood resources, deliver a carbon sink (usually by default), provide habitat for key species, offer space for recreation and potentially deliver other ecosystem services such as the protection of water resources (Lambin and Meyfroidt, 2011).

Since there are multiple competing uses for most biomass, with deployment influenced by both policy and market forces, it is not always simple to predict supply availability or volumes. Factors affecting the nature of supply will include:

- Energy prices, bringing investment into the bioenergy sector when prices are high and potentially mobilising more expensive sources of biomass for energy use;
- Renewable energy policy, some of which is directed at specific elements of the bioenergy sector eg incentives for biogas plants in Germany, Denmark and elsewhere;
- Commodity prices for wood, food crops, straw and other materials, the primary use of which is not bioenergy;
- The location, scale and performance of various industries producing waste with energy potential and regulations which can influence their investment in waste management;
- New technologies making energy recovery more cost effective; and
- Consumer habits and waste policies, which influence the level of waste generated and the way it is managed.

In parallel to the proposed expansion of biomass for energy, there is an ongoing debate in Europe with the intent of moving towards more sophisticated natural resource management. In the majority of cases use for bioenergy, unlike many other approaches to using biomass, represents the last use to which that material can be put[16]. There is, therefore, a growing body of literature that considers that in only a limited number of cases should bioenergy be the primary use of a material, ie when it cannot be used economically elsewhere in society or used initially only for co-products and then for final disposal following reuse and recycling efforts (Forest Research, 2012).

Prior to use for energy production biomass should be prioritised for socially preferable products such as construction materials and other services. This is the concept of the cascading use of biomass (see also Keegan *et al*, forthcoming). For example, wood might be deployed first in buildings and combusted only at the end of its useful life. If this is adopted in policy it will have a considerable influence on the scale of bioenergy production possible, the nature of the likely bioenergy technologies up to 2020 and the GHG emission intensity of production. For example, analysis by the Committee on Climate Change (2011) looked at potential long-term abatement scenarios for the UK and the ability of different options to limit carbon emissions. One of the key routes identified was the use of wood in construction to replace steel. This was anticipated to abate 250 per cent of the carbon in the wood feedstock due to the fact that use in construction sequesters carbon, and, most importantly, reduces industrial emissions.

2.4 Possible future patterns of bioenergy sourcing and use

Estimates of biomass availability and use for bioenergy vary greatly. The majority of published estimates focus on the kind and volume of biomass resources that may be available and do not investigate the impact of the use of all the resources identified on the overall GHG balance or on global warming. According to the International Energy Agency (IEA), scenarios looking at the penetration of different low carbon energy sources, future global energy demand could be up to 250 EJ/year[17] (IEA, 2009). According to the National Renewable Energy Action Plans (NREAPs) submitted to the Commission in 2010, EU Member States estimate they will require 13.3 Mtoe of electricity and 81 Mtoe of heat from solid biomass alongside 5.5 Mtoe for power and 5.1 Mtoe for heat from biogas by 2020 (Beurskens *et al*, 2011), equating to a total bioenergy use from solid and gaseous sources of 4.4 EJ in 2020[18]. According to IPCC SRREN (2011), global bioenergy potential may be as high as 500 EJ/year[19].

A recent literature review by the UK Energy Research Centre suggested that the projections of available global biomass for energy can be considered to fall into two categories: those projections that test the boundaries of what might be physically possible to source from agricultural and forestry systems and those that challenge the boundaries of what might be socially acceptable or environmentally responsible. The analysis banded assessments of the globally available resource from 'low' (less than 100 EJ) to 'high' (over 600 EJ). However, it must be emphasised that even the 'low' estimates under the categorisation proposed by Slade *et al* (2011) amount to up to 20 per

[16] Excluding for example anaerobic digestion of manure and other sludge wastes where outputs can then be used as a nutrient enhancer.

[17] Equivalent to approximately 69,444 TWh based on one TWh being equivalent to 0.00359999999712 EJ

[18] Based on a conversion factor of 1 Mtoe = 0.041868 EJ

[19] To put the figures here in context: Total global world primary energy demand in 2050 is expected to be in between 600 to 1000 EJ, compared to about 500 EJ in 2008 (IEA, 2009), highlighting the large size of the bioenergy estimate of potential put forward by IPCC SRREN (2011).

cent of current global energy use, whilst the 'high' estimates exceed current global energy use by a factor of around 1.5. In this context, the emphasis by Slade *et al* (2011) on the various preconditions that would have to be met if such estimates were to be realised is worth noting. For example the 'low' band of estimates, would rely on a combination of the use of residues, wastes and energy crops. Moving from 'low' to 'medium' ranges in this exercise entails a dominant role for energy crops and significant assumptions concerning changes to agricultural systems. Moving to 'high' ranges (over 300 EJ) assumes substantial and radical constraints on population, diet or extensive deforestation/conversion to managed forest. Ambitious scenarios of this kind need to be approached with great caution given that they would have very serious consequences for both ecosystems and the global climate. Other commentators point out that 100 EJ may be a more plausible upper limit than 300, but even this requires an exceedingly ambitious land management framework and unsustainable outcomes are likely to occur. Different assumptions are required to bring climate factors into such exercises in a meaningful way, leading to estimates that are likely to be much lower.

Whatever the overall supply level, usage patterns will vary substantially between sources and localities. Some feedstocks, such as wet wastes and certain residues from agriculture and forestry or from local landscape management, are generally considered most appropriate for local use, given the challenges of transportation. Bioenergy feedstocks considered as tradable are predominantly woody-based ie forest biomass, energy crops and some agricultural wastes normally in the form of pellets or chips (CCC, 2011b). Due to variations in agricultural production and the tradability of agricultural residues in particular, the profile of the resources available for bioenergy will vary significantly both spatially and temporally across Europe. Scarlat *et al* (2010) highlight that yearly variations in crop residues can range from +23 per cent to -28 per cent compared to average data sets; this presents significant logistical challenges and potential changes in feedstock use patterns on an annual basis.

Recently, research has been undertaken on the usage patterns for European spruced biomass. For example, the analysis by ECN within the 'Biomass Futures' project models anticipated biomass usage patterns for energy. This suggests that cheaper European domestic feedstocks such as wood residues, black liquor and post-consumer wood will be fully utilised up to 2020. However, domestic production of other feedstocks for bioenergy will apparently remain underutilised; this is the case for some roundwood production, additional harvestable roundwood, straw, grassy perennials and dry manure. This is either because of logistical reasons or due to the cost of the material. European roundwood, whether currently harvested or additionally harvested roundwood, generally is considered too expensive compared to imported wood pellets. Hence it is not likely to be utilised on a significant scale. This is envisaged to remain the case in 2030, the outer bound for the analysis (Uslu *et al*, 2012).

The ECN analysis suggests that at least 15 per cent of biomass for energy in Europe will be imported in 2020. This would most likely be in the form of wood pellets. Of the 16 Mt of wood pellets consumed in 2010 globally, 13 Mt were consumed in Europe. According to the analysis by the CCC (CCC, 2011c) meeting European demand for power alone in 2020 from bioenergy could consume up to 90 Mt of wood pellets, estimated to be 45 per cent of the total global demand. Given the reliance of pellet production on high-grade wood materials, this has significant implications for forestry production in third countries up to 2020 and for the global GHG impact of EU bioenergy use.

3 ASSESSING THE GHG INTENSITY OF BIOENERGY

The data on the GHG emission intensity of bioenergy that are found in the literature, and some of which are represented below for illustration purposes, are mostly based on flawed life cycle metrics. Perhaps the greatest weaknesses reside in the assumptions underlying the life cycle calculations of end of pipe emissions within much of the literature, which largely have been carried over into EU bioenergy policy. These are assumptions that:

- bioenergy is 'carbon neutral', ie that emissions associated with the combustion of bioenergy are offset, based on the logic that biomass material will regrow and hence absorb the carbon emitted (see previous section);
- good practice occurs in both the production and conversion of feedstocks;
- direct land use change, carbon leakage associated with indirect land use change (ILUC) and displacement of alternative uses of biomass materials are controlled for; and
- typical attributional LCA methodologies for assessing bioenergy developments are an adequate tool for capturing the full GHG impacts from a future stream of bioenergy consumption. This is despite the point that they are confined to attributing environmental effects to the particular industrial production processes occurring within the finite system boundaries of the specific bioenergy pathway (see Box 2 for details).

Where these assumptions are made they lead to inflated estimates of the potential emission reductions associated with use of biomass for heat and power compared to fossil fuels. While the precise assumptions chosen vary between studies, it is not uncommon to report that bioenergy can deliver up to a 97 per cent saving in terms of GHG emissions compared to coal (Environment Agency, 2009a), or between an 80 and 90 per cent saving in comparison to coal (IPCC SRREN,2011). For example in one study, the emissions from the burning of chips from forestry residues are reported as 22 kg CO_2e per MWh, taking into account transportation, production inputs and processing energy (Environment Agency 2009a), based on the assumptions that no land use change has occurred, that good practice is adopted and that the CO_2 emissions from combustion of the carbon stored in the product are offset.

However, it is likely that these savings will not materialise or be far less positive for the climate than this, relative to a counterfactual without the bioenergy production. One reason for this is because of variable practice in feedstock management. For example analysis by the Environment Agency (2009b) estimates that the worst management practices could cause GHG savings to drop by between 15 and 50 per cent compared to best practice. Further, the consequence of the residency time of CO_2 in the atmosphere on a decadal time scale should be noted as an area of concern for future climate change (Matthews and Caldeira, 2008; Allen *et al*, 2009). Bioenergy consumption potentially contributes to accumulated atmospheric CO_2 emissions over decades from:

- the burning of forest biomass (IPCC, 2006; IPCC AR4, 2007);
- direct and indirect land use change that is likely to be associated with a significant share of biomass production (IPCC SRREN, 2011; IEA, 2011; Laborde *et al*, 2011; Haberl *et al*, 2012); and

- accelerated emissions from drained peatland under agricultural or forestry systems used as new sources of biomass and ploughed carbon rich grasslands, all examples of land use impacts with particularly significant climate impacts (Edwards *et al*, 2008; Schils *et al*, 2008).

Methodological issues merit attention too. It is apparent that the choices made in constructing an LCA are critical for the environmental outcome. Although a standardised LCA methodology has been developed for forest biomass in energy supply (IEA, 2011), it takes a long-term perspective on a forestry system and assumes that forest carbon stores are stable. This neglects the long term impact on sequestration time of those emissions from the combustion of harvested biomass that occur over and above those from the fossil fuel referent. There are many aspects relating to land use emissions and sequestration services need to be taken into account adequately. However, methods for this are not standardised and uniformly applied. Issues include defining the correct system boundaries, functional units, the reference scenario and the ways of accounting for energy and emission flows across the relevant boundaries. Some commentators therefore emphasise the limits of the quantitative LCA approaches undertaken, particularly for forest based energy (Box 2). Understanding these limits is important in appreciating the nature and relevance of bioenergy LCAs carried out at national or project level for bioenergy and climate policies. Box 2 provides an overview of some of the most significant issues.

Box 2: Issues arising in life cycle frameworks for bioenergy

To differentiate between the GHG intensities of different bioenergy pathways, 'attributional' LCAs typically are employed. These approaches analyse the impacts of industrial production processes within certain finite system boundaries drawn around the key inputs into these particular processes (IPCC SRREN, 2011). Such metrics initially were developed for industrial products to capture the impacts of manufacturing, processing, transporting, etc on water, air, and other environmental media, not for assessing energy pathways or climate related impacts over time. The standard LCA metrics for such products were refined by IEA (2011) to address the GHG emission intensity of bioenergy by extending the system boundary by adding a comparison of the GHG performance of the aggregate inputs utilised in a specific bioenergy pathway with the fossil fuel referent on the assumption of 'carbon neutrality'.

An analysis by McKechnie *et al* (2011) acknowledges that the 'attributional' approach to the life cycle assessment of bioenergy needs to be improved to understand the relative merits and de-merits of using forest biomass compared to other pathways. Improved assessment has to take account of CO_2 fluxes between forest and atmosphere, assess the forest response following harvest and the fate of the biomass source if it is not harvested for bioenergy, whilst considering site-specific conditions for the forests in question. On this basis, it is suggested that two different assessment tools need to be integrated in order to adequately assess the relationship between forest carbon stocks and the use of harvested biomass for energy, given its complexity. Using one tool is insufficient and the typical life cycle inventory of inputs into a biomass energy pathway, has to be converted to the time frame relevant for the other tool, ie the assessment of fluxes of forest CO_2. The time frame is suggested to be around 100 years. The application of such improved assessments have demonstrated that simplified LCA tools based on the 'carbon neutrality' principle overstate the GHG mitigation performance of forest bioenergy and fail to report the length of time required to achieve overall emission reductions (McKechnie et al, 2011). The consequences for the key long term climate indicators, such as global GHG balance, have not been investigated.

To capture the long term effects of bioenergy use on climate change more adequately, the LCA would need to go beyond the assessment of GHG emissions intensity based on finite inputs into the specified bioenergy production processes and instead apply a 'consequential' LCA approach. This has a much wider system boundary (IPCC SRREN, 2011). This type of LCA requires support from, for example, economic equilibrium models to investigate systemic responses to bioenergy expansion (eg changes in land use patterns influenced by diversion of crops and forest biomass from other markets such as food and timber to bioenergy production, potentially lower demand for fossil fuel and lower fossil fuel prices).However, some recent commentaries emphasise that the both 'attributional' and 'consequential' LCAs have significant limitations, albeit of different kinds, which cannot readily be overcome in the short term (eg DeLucchi, 2008). The boundaries of the former approach are too narrow, therefore limiting consideration to predominantly short term impacts on climate, whilst the latter casts system boundaries at the global level and has to rely on complex models which are costly and have inherent uncertainties. This seems to indicate the need to consider alternatives to LCA metrics for informing policies and projects, eg by using resource efficiency oriented approaches.

In addition to the broader considerations outlined above, the mix of materials that make up the bioenergy resource mean that it is not possible to specify a single value of GHG emission intensity for bioenergy. Emission intensities associated with the different feedstocks vary because of their characteristics and the conversion pathways through which they can be utilised. Some recent estimates for a range of feedstocks based on UK conditions circa 2009 are set out in Table 3. These are based on a study with a broadly attributional approach to life cycle assessment. A single value is given for the GHG emission intensity of a specific feedstock based on woody biomass; usually this is understood as a proxy for a wide variety of different intensities depending on where and when the biomass was sourced and on other locally specific conditions. A similar caveat applies to estimates of the generic GHG emission intensity of feedstocks based on agricultural crops. There are potentially large variations, ranging from the very high GHG profile of biomass coming from farming or plantation systems on drained peatland to high for biomass from converted semi-natural grasslands, to potentially much lower for biomass from annual cropping systems on some carbon poor soils.

Table 3: Estimated emissions of a range of bioenergy feedstocks assuming good practice approaches to management and combustion

	Feedstock	Emissions ($kgCO_2e$ per MWh)	Percentage saving compared to coal	Percentage saving compared to gas
Chips	UK forestry residues	10	97%	95%
	Imported forestry residues	22	94%	90%
	Waste wood	7	98%	97%
	Short rotation coppice	17	96%	93%
	Miscanthus	18	95%	92%
Pellets	UK forestry residues	38	90%	83%
	Imported forestry residues	50	87%	78%
	Waste wood	51	87%	77%
	Imported waste wood	66	83%	71%
	Short rotation coppice	100	74%	56%
	Miscanthus	65	83%	71%
Other	Olive cake	9	98%	96%
	Palm kernel expeller	82	79%	64%
	Medium density fibreboard	5	99%	98%
	Straw	73	81%	68%
	Glycerine from oil seed rape	94	76%	58%
	Glycerine from used cooking oil	28	93%	87%

Source: Environment Agency, 2009a

The assumption of 'carbon neutrality' and its application across the whole range of potential bioenergy feedstocks and pathways increasingly is being questioned in the literature. Haberl *et al* (2012) and the EEA Scientific Committee (2011) highlighted that for some elements of the bioenergy supply chain this may lead to a substantial risk of underestimating emissions associated with bioenergy (Table 4). As suggested in Searchinger (2012), 'bioenergy can only reduce greenhouse gas emissions to the extent real emissions of carbon from biomass burning can be legitimately ignored'[20]. For some elements of the bioenergy resource there is substantive risk associated with current approaches to calculating emissions.

'Several European Union energy Directives encourage a switch from fossil fuels to renewable energy derived from plant biomass based on the premise that biomass combustion, regardless of source of the biomass, would not result in carbon accumulation in the atmosphere. This mistaken assumption results in a serious accounting error.' EEA Scientific Committee, 2011

The risk of overestimating emission reductions is considered to be highest for woody-based biomass and lowest for certain wastes. For this reason McKechnie *et al* (2011) call for the current approaches to LCA to be amended and integrated with a forest carbon assessment dimension to provide a more accurate picture of true life cycle emissions. Others emphasise that any type of LCA analysis will run into limits that cannot be overcome in the short term because it is a tool suited to end-of-life products and much less so to whole energy pathways (eg DeLucchi, 2008). The level of risk that emissions will be underestimated varies considerably according to the feedstock used. An overview of variations between feedstocks is provided in Table 4.

Many of the commentators that draw attention to the accounting error that informs a number of bioenergy policies go on to call for the correction of international and EU policy frameworks. UNFCCC reporting guidelines provide an accurate and perhaps the most complete blueprint for understanding the overall emissions relating to bioenergy systems that currently exist (see Box 1). It would be useful if this UNFCCC blueprint is acknowledged in the more pragmatic assessments made of the potential of specific bioenergy feedstocks at national or project levels and in the potential revisions of the Directive.

Forests and agricultural crops are not the only feedstocks available for bioenergy use; certain wastes and residues can be used for bioenergy purposes at varying scales. However, with the increasing awareness of the misapplied accounting frameworks, there is an emerging divide in the literature over whether woody biomass in particular can be considered a viable renewable energy source that can be relied upon to deliver emission savings (including some primary forestry residues). The case of wastes and residues on the one hand and primary biomass for energy (ie from forestry and agriculture) on the other hand are discussed in the subsequent sections.

[20] The same argument is put forward by Smith and Searchinger (2012) in the context of crop-based biofuels, hence recommending that biofuels should be drawn from additional biomass grown on currently unproductive land or wastes, so ILUC effects don't arise.

Table 4: Risk of underestimating emissions in accounting exercises for different sources of biomass where carbon neutrality is presumed

Source of biomass	Degree of likely accounting error	Form of error
Converting forests currently sequestering carbon to agricultural bioenergy crops	Very high	Ignoring both immediate release of carbon and often continuing carbon sequestration of the forest if unharvested
Harvesting forests for bioenergy and allowing to regrow	High	As above
Diverting crops or growing bioenergy crops on otherwise high yielding agricultural land	High	Likely release of carbon in replacing the crops, with alternative food crops, reduced crop consumption, potential indirect effects, including ILUC
Using crop residues	Variable	Risk of underestimating/ignoring alternative uses, need to replace nutrients, or potential effects on soil productivity and soil carbon stocks
Planting high-yielding energy crops on grasslands	Variable	Carbon rich grasslands (eg many moorlands and semi-natural grasslands) are likely to be net sinks and their sequestration services will be lost under intensive management ('high error'). Intensive temporary grasslands are likely to have low carbon content but the conversion to energy crops would displace the associated food production ('low error'). Grasslands on drained peat are likely sources of emissions at present but the management impacts on peat mineralisation may still be significant ('high to medium error').
Using post-harvest timber slash	Little or none	May ignore or underestimate temporal dimension of decomposition or existing uses. (only if the slash were otherwise oxidised immediately, like site preparation through burning)
Using organic wastes otherwise deposited in landfill	Little or none	May underestimate savings since capturing and destroying methane from solid waste disposal sites would save emissions even without energy recovery.

Source: adapted from Haberl *et al*, 2012 and Schils *et al* (2008).

3.1 Utilising wastes and residues

A range of wastes, residues and by-products can be utilised for bioenergy. These tend to be heterogeneous; some may be contaminated or mixed with soil. Nearly all are less dense than most primary products. As a consequence, long distance transport is undesirable and uneconomic for many wastes and residues and they tend to be more suited to smaller, local applications rather than central installations such as large power plants.

When considering the GHG emission intensity of waste and residues one key question is whether these are genuine residual materials. These can be defined as wastes that cannot easily be avoided or managed in a way to deliver additional resources to society before being ultimately disposed of through combustion, and that are not already in use to deliver other benefits. For example, for some primary forestry residues and agricultural residues it may be better to keep them *in situ*, helping to maintain soil carbon stocks (IEEP, 2011).

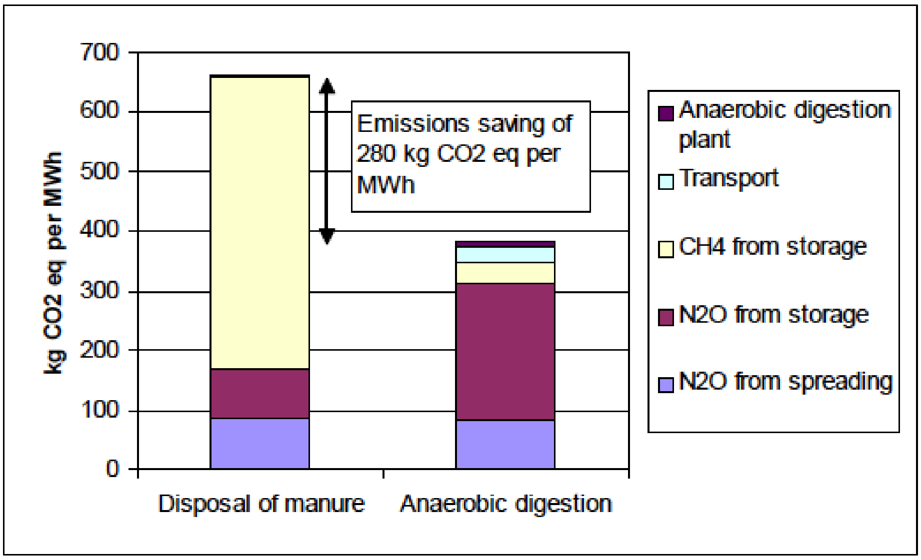
Final disposal of genuinely residual waste often implies the emission of carbon dioxide or methane in the process of breaking down that waste. Using an appropriate bioenergy route to capture and replace alternative disposal options will result in GHG emissions, for example from combustion, but these emissions potentially may be lower than if the waste management process involved no energy capture. This is either the consequence of a reduction in the global warming potential of the associated emissions or the utilisation of waste to generate energy in the final disposal stage hence offsetting other energy sources (Forest Research, 2012).

In the former case, for example, CO_2 emissions from combustion might replace methane emissions leading to a lower overall global warming potential. An example of this is the anaerobic digestion of manure, sewage sludge or biological wastes that otherwise would have decomposed without methane capture, with the resulting biogas burned for heat or power – see Figure 1 for anticipated savings. A well-managed digester should produce a sterile soil improver, so that the fertilisation effect of manure application for example is not entirely lost and nutrients like nitrogen can be recycled into the soil and not have to be offset by the use of artificial nitrogen based fertilisers, which could lead to additional GHG emissions. In this example the technology (anaerobic digestion with gasification and combustion) is merely the tool that is used. It is the pathway leading to bioenergy production combined with the alternative use scenarios, ie the counterfactual, which delivers the low carbon emission profile. Nonetheless, some pathways for the anaerobic digestion of non-waste biomass or non-residual waste can be inappropriate. For example in Germany large amounts of maize are being diverted into digesters, in some cases grown on land which previously may have been permanent grassland (see Elbersen *et al* in preparation, IEEP 2011, and vTI for examples of this discussion).

It can be challenging to identify the circumstances in which the displacement of waste disposal processes without energy recovery by a bioenergy pathway offers an overall carbon benefit, particularly when it is not clear whether the waste is truly residual. The baseline for the classification of 'waste' is changing, in particular in light of the European debate on resource efficiency and the development of the Resource Efficiency Roadmap (European Commission, 2011a). In May 2012, the European Parliament adopted its opinion on the Roadmap calling for both a ban on the landfill and the phasing out of incineration of recyclable and compostable waste by 2020. In tandem the Commission has also developed a Strategy and Action Plan for the bioeconomy (European Commission, 2012a).

There is increasing concern among the waste policy community that efforts in the bioenergy sector could 'lock in' waste production, hampering prevention, reuse and recycling efforts which should take priority over incineration for energy recovery (IEEP *et al*, 2010). Bioenergy policy needs to sit within this broader debate on how to manage resources, biomaterials and waste products in Europe rather than be dealt with separately. This debate may need to rely more on regional bottom-up assessments of the land resources that can be mobilised efficiently in practice rather than on top-down life cycle modelling approaches. This is necessary not only to avoid concerns over competing material uses and agendas, but also to maximise Europe's ability to deliver emission reductions (Watkins *et al*, 2012, Keegan *et al*, forthcoming, and Forest Research, 2012).

Figure 1: Comparison of emissions from the disposal of dairy manure and its utilisation for biogas to produce electricity



Source: Environment Agency, 2009a

3.2 Forest biomass

In many assessments woody biomass is projected to be the critical source of global bioenergy feedstocks, at least in the short to medium term, given its ability to be utilised more easily for co-firing and its tradability (see section 2.4). The importance of the temporal question is much greater for forest biomass than for the waste sector. Increasingly it is being addressed, with many papers challenging the assumption of carbon neutrality in particular for woody biomass which takes years to regrow[21].

Biomass production in forests, crops and in other vegetation occurs within living systems. These are part of dynamic ecosystems that continually change because of natural conditions and human intervention. The intensity of GHG emissions from wood, therefore, cannot be taken as a static measure. As a consequence any approach to assessing climate impacts will need to consider it in a relevant timeframe. Taking account of what would happen to a resource in the absence of bioenergy use, ie the counterfactual, is not simple; the principles involved and methods to be employed are the source of extensive debate and disagreement amongst those within the bioenergy community and beyond. Despite fundamental differences over the counterfactual there is, however, substantial agreement within the literature over key issues and their importance for establishing the climate impacts of utilising forestry materials for bioenergy:

- Changes in standing biomass in forests must be taken into account when woody biomass is the feedstock. This is not only a matter of associated land use change, but also of any changes in the

[21] It should be noted that in a limited number of reports, including IEA (2011), other arguments are put forward. That report considers the atmosphere and biosphere to be a continuum in terms of a global carbon pool and hence fluxes are considered of less importance compared to the additional carbon added permanently by fossil fuel combustion. It also highlights the permanence of the stock of carbon in the biosphere, hence the justification of treating the atmosphere and biosphere as being in flux. However, the 'in-flux' argument seems not to take account of the fact that carbon in the biosphere is not gaseous and therefore not contributing to global warming, whereas carbon in the atmosphere is.

intensity of forest management, particularly where revised above the optimum harvest yields; this variable is not captured in assessments of absolute land use change.

- The approach to management practices in the forest will have a significant influence on the eventual intensity of GHG emissions from the ultimate bioenergy application; hence the emerging debate around the development of sustainability standards for solid biomass and the end use processes within which they are used (Environment Agency, 2009; Fritsche, 2012).

- Land use change, either directly caused by growth of materials for bioenergy or indirectly from the displacement of land uses to other locations in the world, will in most cases leave a carbon debt that will be difficult to repay in any reasonable timescale in order to deliver emission reductions (ECF *et al*, 2010; CCC, 2011b).

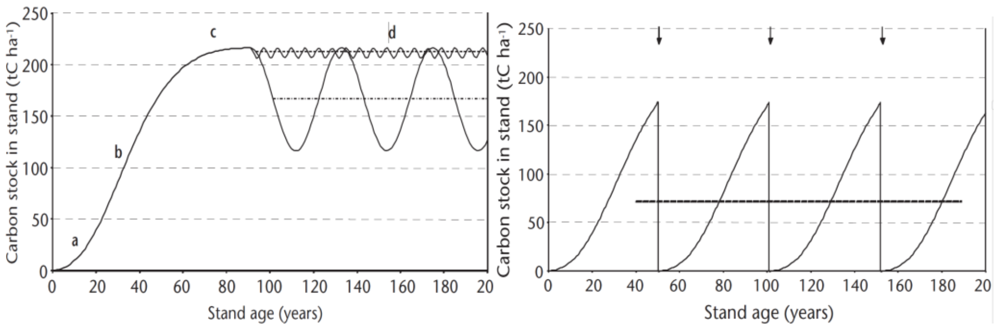
The IPCC guidelines are helpful in referring to the fluxes in the carbon stocks in forestry ecosystems (emissions and removals). In principle, measurements of the fluxes should take account of the basic elements of forestry ecology and the associated CO_2 cycling between forest and atmosphere. Box 3 provides an overview of the basic elements to consider.

Box 3: Growth, carbon stocks, carbon sinks: some basic dynamics in forest ecosystems

- Forestry rotations in managed forests are typically faster than naturally occurring disturbances, the average age of harvest in the stands that make up a managed forest are typically significantly younger than in under-managed or non-managed forests.
- Forests go through a number of growth phases, initially slow in newly established forests, a phase of vigorous growth and finally a plateau as forests reach maturity (Figure 2a).
- Carbon stocks, ie the mass of carbon accumulated in forest, are directly proportional to the phase of growth, low in the initial phase and high in the final phase. In high-yielding forestry for commercial purposes, the whole cycle recurs. The biomass harvest decreases forest carbon stock and, if burnt for energy, it releases a corresponding amount of CO_2 into the atmosphere (Figure 2b).
- Carbon sinks, which represent a rate of incremental change in forest carbon stocks, are higher in the younger forests than in forests at the point of maturity, and finally reach zero change compared to the baseline sink. Therefore, harvesting of mature forest commonly increases carbon sinks, albeit temporarily, and accelerates the rate of absorption of atmospheric CO_2 by forests.

Source: IPCC, 2006; Forest Research, 2012

Figure 2: comparison of carbon stock of (a) newly created forest and (b) commercial forest



2a – Carbon stock of a forest under non-commercial management
a, b, c – phases of initial growth, vigorous growth and steady state
d – natural disturbances in the steady state

2b – Carbon stock in a high-yielding commercial forest. An example of the carbon stocks associated with above-ground biomass of an even-aged stand of trees, harvested and replanted on a 50-year rotation in order to maintain a high growth rate in the stand. However, the optimum rotation period in the majority of EU forests under commercial management is between 65 and 100 years

Source: Forestry Commission, 2003

Two factors require particular attention:

- the changes in forest carbon stocks that are attributable to bioenergy production;
- the extent of carbon debt associated with the increase in atmospheric CO_2 from burnt biomass compared to fossil fuel alternative in the interim.

The IPCC guidelines recommend that measurements of carbon sinks, ie changes in living biomass, dead organic matter and soil organic carbon of forests, are consistently related to the changes in stocks that would have occurred under the baseline management (the ‘counterfactual’), ie forest grown and harvested without the expansion of bioenergy production. The types of change from the baseline forest management which could affect carbon sinks and could be relevant include:

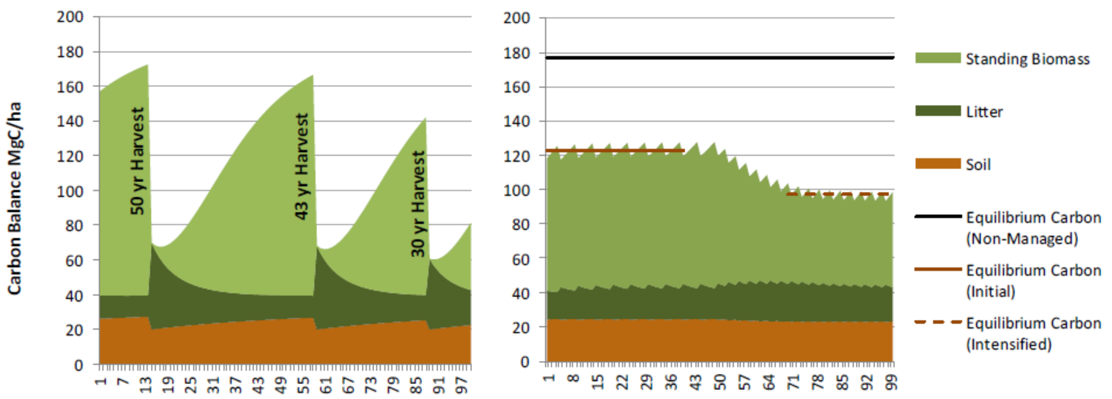
- harvesting of under-managed or unmanaged forest;
- changes in forest species composition;
- continuing and/or intensifying forest management etc; and
- establishing new forest on unused or previously agricultural land.

Some of the basic effects of forest management changes on carbon stocks and carbon sinks are reviewed in Box 4.

Box 4: The effect of forest management changes on carbon stocks and carbon sinks

- Forest management that is consistent over several rotation cycles will result in a relatively stable overall level of carbon stocks and carbon sinks compared to the baseline management. However this long term equilibrium does not override the fact that a temporary release of CO_2 emissions in biomass combustion will have to be absorbed by present or future carbon sinks.
- Younger forests hold less carbon, ie overall carbon stocks within the forest are lower compared to those under the baseline management.
- Any additional harvest (necessarily resulting in a lower carbon stocks in the forest) may result in the same or a bigger carbon sink at present than that of the forest under the baseline management. A bigger sink would result from eg fertilisation, irrigation, the use of fast-growing species or changes in thinning practices which involve faster re-growth than would occur without such changes in management practice.
- Any additional harvest produces imbalances in carbon cycling ('carbon debt' over the fossil fuel referent) for another rotation period until the stock reaches a new, lower, steady state. (Figure 3). Therefore, the intensified harvest may have negative impacts on future carbon sinks unless the temporary excess of atmospheric CO_2 is mitigated by other means.
- If harvesting ceases, there would be a rise in the carbon stock until the natural equilibrium level is reached.

Figure 3: Changes in carbon stocks per hectare in a managed forest with an intensified harvest regime and gradually shortened rotation, first on a plot scale and second on a landscape scale

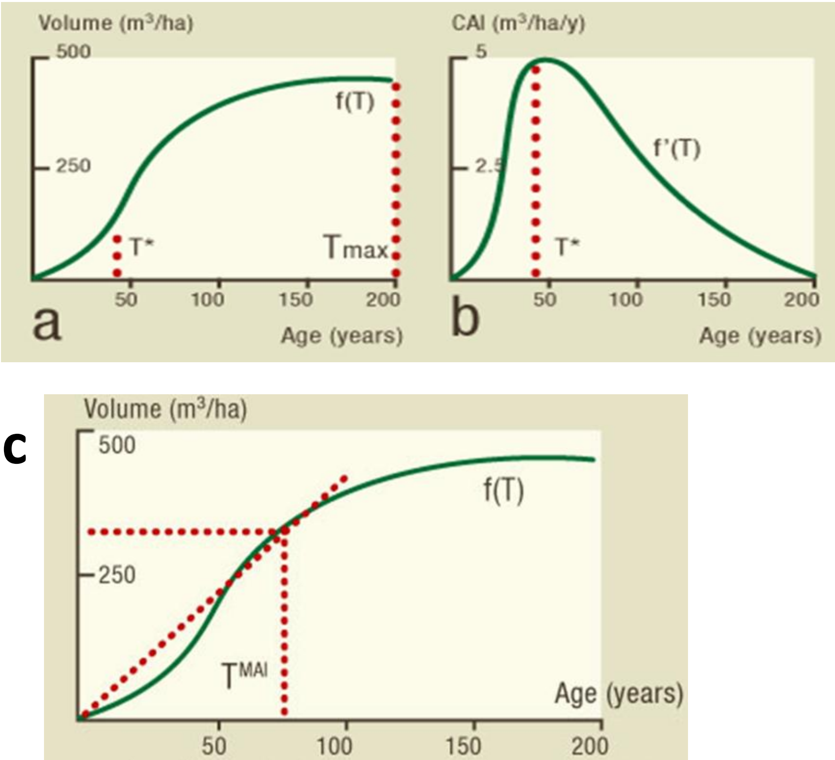


Note: The figure represents commercial forest management in a fairly high yielding forest of the type found in some countries outside the EU. For EU forests, rotation periods are more usually 65 to 100 years (ignoring coppicing), therefore a 50-year length would imply a highly intensive management regime which usually would not be feasible to sustain in the long term.

Source: IPCC, 2006; Fisher *et al*, 2012 (figure)

The interaction between harvest intensity, carbon stocks and incremental changes in stocks (carbon sinks) has an economic dimension which will be important in influencing management decisions. In short, the typical growth curve described above points to an optimum harvest intensity or rotation age that coincides with the culmination of the mean annual increment ('maximum sustained yield').

Figure 4: A schematic view of forest growth and yield increment as a function of forest age: (a) cumulative growth; (b) current annual increment; and (c) the optimum rotation age, T^{MAI}, maximising mean annual increment. The slope of the red (straight) line depicts the mean annual increment at age T^{MAI}. It is equal to the slope of the green curve, which depicts current annual increment at age T^{MAI}.



Source: United Nations University, Japan, and the University of Joensuu, Finland, http://foper.unu.edu/course/?page_id=116

There are two possible departures in direction from the near optimum management of the forest, both relevant to GHG emissions intensity of woody biomass, albeit in different ways:

- *The forest is less intensively managed (longer rotation, higher average carbon stock) than the optimum management*. In such forests, intensification of management will reduce the stock, as already pointed out, and also increase yield. The latter allows the loss in carbon stock to be compensated over time. Time would show whether this compensation is sufficient to pay back the 'carbon debt' over the referent fossil fuel emissions in a policy relevant time frame (eg until 2020) and if it produces any additional emission savings.

- *Forests are harvested more intensively than the optimum for a period*. Further intensification will again reduce stocks, but will also reduce yields over time and the loss in carbon stock will never be compensated. Post-war Europe is an example of a period when harvests had to be reduced until stocks could recover to optimum levels.

In sum, if the forest is managed at the usual management optimum, there is little reserve in the system; any change will reduce mean annual increments (sustained yield) (Hyytiäinen and Tahvonen, 2003; Viitala, 2006; Möhring, 2001). The majority of significant EU forests are managed near the optimum, although many are less intensive and some more intensive. Therefore, the reserve for increasing biomass yields and compensating for losses in European stocks on a decadal scale relevant for climate policy is relatively small. In this light, a balanced forest system (managed near the optimum harvest) cannot increase biomass output to any significant degree unless it reduces associated carbon stocks and/or yields and/or quality (Hyytiäinen and Tahvonen, 2003; Viitala, 2006; Möhring, 2001). A forest system therefore should not be considered 'sustainable' and 'carbon neutral' in and of itself; sustainable management is generally understood as producing biomass at or below a fairly sustained yield (mean annual increment). In these circumstances more rapid extraction of biomass for the purposes of satisfying new, additional demand and which is undertaken for the purpose of reducing emissions will come only at the expense of other uses or at the expense of the forest (neither would be carbon neutral).

As a consequence, the combustion of biomass in the EU will result in 'carbon debt' over the fossil fuel referent over a significant number of years in the great majority of circumstances. In addition, not all regrowth can be counted towards reducing the 'carbon debt', only growth over and beyond what would occur otherwise (Fisher *et al*, 2012; EEA SC, 2011; Haberl *et al,* 2012; McKechnie *et al*, 2011; EEA Scientific Committee, 2011). Therefore, the debt can be repaid only in cases where harvesting increases growth. Depending on the site specific conditions and management practices applied in comparison with the baseline forest management (the 'counterfactual'), the debt might be relatively small (in feedstocks sourced from initially less intensive forestry systems which undergo intensified harvesting) or much higher (in feedstocks sourced from systems above optimum harvest levels which are further intensified). Some authors point out that intensification of forest management in underutilised forests can shorten but not eliminate the period during which net emissions increase through the consumption of woody biomass (McKechnie *et al*, 2011). Nonetheless it is important to remember that increased harvest rates push out the 'payback time' into the future, due to the overall decrease in the steady state level of carbon stocks, and the difficulty in sustaining higher yields over a period relevant to climate policy.

However, both issues tend to be side-lined in some of the most prominent assessments of GHG emission intensity of woody biomass, in favour of an emphasis on the eventual offsetting of the debt at a future point in time (eg Forest Research, 2011; IEA, 2011). These employ two complementary strands of thinking to propose the neutrality of energy use in the case of woody biomass. The first approach emphasises the eventual regrowth of an equivalent amount of biomass to compensate for removals, and the second points to the role of managing the use of primary biomass in such a way that incremental regrowth in a given year 'offsets' the emissions associated with the loss of the material taken for energy. For example a recent IEA study (2011) makes the assumption that the forest remains *in situ* in the long term allowing the stands to undergo a full carbon cycle and full regrowth, which maintains the balance of carbon fluxes. Alternatively work published by Forest Research (2012) states that the carbon neutrality of woody biomass is determined by the fact that forest is managed in a way that ensures a balance being kept between the carbon flux of extraction and of growth. This is assumed to be an essential characteristic of forests managed at the same intensity over several rotation periods (Forest Research, 2012). Nonetheless, there is an acknowledgement in several such studies that a lack of consensus remains as to how best to consider bioenergy's GHG emission intensity and that the modalities for attributing forest carbon fluxes to increased deployment for bioenergy are uncertain (Forest Research, 2012).

If forest is managed for 'maximum sustained yield' (near optimum harvest intensity), the scope for net reductions in GHG emissions by the combustion of biomass is rather constrained. The key missing element is that for a steady-state system (eg balanced age, class and harvest rate), the output will also be steady state (ie generally the same as in the past). Such systems therefore can be expected to deliver only as much bioenergy as has been achieved over the last century or so, unless there is a change in approach so as to:

- manage the forest for low density wood (with quality lower than demanded for most wood products);
- employ new varieties of traditional species or different species adapted to the site;
- use more nutrients while ensuring careful management of the water and soil resource;
- collect brush wood in undermanaged forests; or
- displace existing uses by diverting wood or other materials to energy.

Changes in the management of a forest cannot necessarily be introduced at will; they may be constrained by the stage in the production cycle. Some changes could be introduced only after a major harvest and would raise yields only after several decades.

Given that demand for bioenergy is set to rise, and the economic appeal of using woody biomass in particular for power generation, it is anticipated that there will be pressure to increase woody biomass production. Analysis by the Climate Change Committee (2011b) highlighted that relevant standards and legislation in many countries are anticipated to discourage deforestation; hence the most immediate risk is that higher biomass demand could result in the harvesting of forests already under management being intensified or encourage the expansion of harvesting to areas previously not subject to continuous management and into previously unmanaged forests (eg some boreal forests) where carbon stocks are higher compared to managed forests[22]. The combined life cycle and carbon impacts resulting from the exploitation of both standing trees and forestry residues for co-firing in the form of pellets has been investigated in recent analysis by McKechnie *et al* (2011); similar results are reported in Zanchi *et al* (forthcoming). The analysis models a forestry system whereby further exploitation shifts the forests' overall carbon store equilibrium. For residues, assuming continued harvesting and offsetting of coal, there was an initial period of 16 years when loss of forest carbon resulted in additional emissions. For whole standing trees this breakeven point was after 38 years of continuous production and displacement. This means that the use of standing wood would significantly increase emissions even 25 years from now. As a consequence, over a 100 year period, forest residue use delivered only 73 per cent of the savings that would be anticipated based on the 'carbon neutral' assumption. Standing wood delivered only 44 per cent of the

[22] ACCC notes that bioenergy demand is also anticipated to drive the development of short rotation forestry in South America and South East Asia, where favourable climatic conditions result in faster growing plantations than in Europe. The main concern related to this production switch relates to land use change emissions if plantations result in the clearing of secondary tropical forest.

anticipated savings over a 100 year period (McKechnie *et al*, 2011).[23] This translates into the achievement of approximately 20 per cent of the anticipated savings after 50 years.

More recent analysis (Biomass Energy Resource Center, 2012) has included a case example of the Southeastern forests of the US, looking to expand the use of bioenergy into electric power generation. It is noted that it took between 35 and 50 years before the additional forestry biomass yielded a carbon benefit compared to fossil fuel (the range of estimates is based on the different coal based technologies that would be replaced).

In conclusion, an anticipated increase in the intensity of management of forests is expected to deliver increased levels of emissions in the short to medium term. Moreover, current approaches to assessment are insufficient to capture these shifts. GHG savings from the use of woody biomass in most cases might be generated only after extended time periods, with the length of payback time linked to the increase in intensity of use. The question of time is, however, vitally important as noted earlier.

[23] It should be noted that McKechnie *et al* (2011) also analysed the use of standing forestry and forestry residues for use as ethanol ie advanced biofuels. Within the analysis, standing forestry did not reach the point at which it reduces emissions at any point over a 100 year horizon, with forest residues only doing so after approximately 75 years.

4 SOURCES OF VARIATION AND UNCERTAINTY AND MEANS OF ADDRESSING THEM

Given the characteristics of bioenergy there always will be variation in the GHG emission intensity of the different feedstocks and production pathways. This inherent variability needs to be taken into account within any system that promotes its use. The large number of circumstances in which feedstocks are produced, the element of unpredictability in land use dynamics and the sheer number of production pathways mean that a stable and uniform level of net GHG emission intensity may not be possible to identify for most bioenergy supply chains. In this sense, biomass based systems are fundamentally different from other renewable energy technologies and policy mechanisms need to be developed to manage these realities. Comparison is needed with other energy sources on an equitable basis. Data is also required to inform policy choices which might include for example the control of certain practices to set limits on acceptable levels of GHG emission intensity.

In addition to the inherent variability associated with biomass use for energy, some areas of bioenergy science and understanding remain either genuinely uncertain or the source of significant contention. For example, there are limitations in the extent of research into the GHG impacts of bioenergy use, and divisions among experts as to the appropriate approaches to account for carbon at project level and compare bioenergy use to other alternatives. These need to be addressed on several fronts before a full picture of the GHG emission intensity of this range of technologies can be defined. Nonetheless certain judgements can be made on the appropriateness of large scale bioenergy use on the basis of existing analysis.

Table 5 attempts to summarise the core sources of variation and uncertainty that need to be addressed to complement efforts to define the most appropriate role for bioenergy, with subsequent sections exploring these further and discussing the linkage with more effective policy making.

Table 5: Some sources of inherent variations and key issues to be addressed for correct accounting

<table>
<tr><th colspan="2">Sources of inherent variation</th></tr>
<tr><td>Heterogeneous feedstocks – there is no one source but a multiplicity of biomass materials that in many cases can be used interchangeably</td><td rowspan="4">There are various ways of seeking to address the density of feedstocks and conditions and the related incentives. Most are still being developed but they include:
• Debates around the utility and content of sustainability standards for bioenergy (for example Fritsche, 2012). In May 2012, ISCC (2012)[24] consulted on extending its sustainable certification system for biofuel feedstocks to food, feed, technical/chemical (eg bioplastics) and other bioenergy (eg solid biomass)
• Emerging proposals in the UK to limit maximum life cycle emissions from bioenergy (CCC, 2011a)
• Proposals to develop more restrictive efficiency standards (EA, 2009a)
• Efforts to develop data resources to better understand bioenergy sourcing</td></tr>
<tr><td>Variation in management practices and local circumstances relevant during biomass production and processing</td></tr>
<tr><td>Different potential end uses of biomass material in the energy system and the consequent differences in efficiency and the offsetting of fossil fuel emissions</td></tr>
<tr><td>Unpredictability of specific future sources of feedstock for a particularly bioenergy facility over its lifetime. Feedstock characteristics will vary over time.</td></tr>
</table>

[24] International Sustainability and Carbon Certification, one of the sustainability schemes recognised by the Commission for demonstrating compliance with the Renewable Energy Directive's criteria for biofuels.

Key Issues for Correct Accounting
A credible counterfactual – What would have happened in a situation without the use of a specific source of biomass for energy (eg forest left unfelled) and what impact would this have had on the overall GHG emission intensity of the supply chain being considered? Where the comparator is another energy supply chain, normally based on fossil fuels, the question of the realistic counterfactual also arises. We cannot assume coal to be the most relevant comparator in all cases, and even if it is for now, it cannot remain so indefinitely.
Providing a fair baseline for comparing the GHG emission intensity of the different biomass sources in LCAs – How should GHG emissions be accounted for, in particular from primary biomass and associated residues, when production and use may occur in different countries and when there are substantive disagreements as to the emissions associated with exploiting the resource?
Leakage effect – What are the consequences of promoting bioenergy in, say, Europe in terms of exporting global GHG emissions, whether because of changing land use management (such as changes indirectly caused by displacement of production of soya meal and cereals for feed through the increased production of biomass for energy) or displacement of industries which could have used the feedstock for alternative purposes?
The consequence of scale – The resource base for bioenergy is different from that of the major fossil fuels and includes a number of relatively localised and small scale feedstocks and larger forests that can be exploited only at a limited rate without a major change in management. Creating long term markets for bioenergy, eg through building major combustion plants that will need to be 'fed', for decades possibly, can lock the energy system into an expanding feedstock exploitation pathway that could have major implications for the resources required that do not apply at small scale. How will the resource base evolve as pressure to increase usage of bioenergy mounts globally and what are the climate and other environmental consequences of this?
Controlling for the evolution of land use – Many assessments of the GHG emission intensity of bioenergy supply chains presume that there is no associated land use change or major vegetation management change arising from the exploitation of the feedstock. Often such changes do occur in practice, either at the site where the biomass has been harvested or elsewhere. It is not realistic or appropriate simply to assume no significant change either in primary land use or key management parameters over the periods under discussion, such as 60 year forestry rotations. How can such critical uncertainties be addressed in credible LCAs?
Short term losses vs long term gain – how can carbon emissions that are increasingly identified as a consequence of intensifying forestry production be balanced against the pressing need to reduce GHG emissions globally? For example, many are looking to the power sector to decarbonise by 2050 in order to deliver on long term climate ambitions. What are acceptable levels of carbon debt?
Maximising carbon benefits from biomass – What is bioenergy's role in terms of using biomass to deliver emission reductions more generally? Does the GHG emission intensity of bioenergy, and the saving compared to fossil fuel use, justify usage in the power sector of primary materials?

4.1 Some sources of uncertainty, potential solutions and analytical questions

4.1.1 The counterfactual

As noted earlier, the counterfactual has been source of considerable debate, specifically in relation to the extent to which forestry biomass would have acted as a source or a sink of carbon under business as usual conditions (Searchinger, 2009, and Haberl *et al*, 2012, contrasted with IEA, 2009). The EEA Scientific Committee (2011), recently followed for example by McKechnie *et al* (2011) and Fisher *et al* (2012), argues that current thinking on carbon neutrality fails to take into account the production and use of biomass that land would generate if it were not used for bioenergy.

This is not only a question for the bioenergy sector; determining the counterfactual for biomass and land use is notoriously complex. To some extent efforts to take account of the counterfactual have been made in the agriculture sector, often to aid decisions regarding support policies, under the CAP for example. Analysis, such as that reviewing GHG impacts associated with subsidising rice production, has demonstrated the complexities of trying to define the counterfactual conditions in a satisfactory way. It underlies the importance of understanding global and local land use drivers in order to make informed decisions. Even with this knowledge, evaluation of the impact on climate involves expert judgement and qualitative analysis rather than being a purely quantitative exercise computing trade-offs (COGEA, 2009).

A variety of issues need to be considered in constructing a credible counterfactual. These are likely to include:

- The existence of realistic alternatives to the harvest of trees, roots and residues (was it originally envisaged that there would be lower harvesting levels or no harvesting at all?);
- The most likely future use of the material harvested, which may be different from the previous uses;
- The alternative uses of wood/wood products;
- How the wood products would be disposed of if not used for bioenergy;
- The future trajectory of the forest as it would evolve in the absence of a bioenergy motivated harvest, including the outlook for maturation and risks of fire, disease, etc;
- Are there second order effects of higher extraction rates, particularly if these are maintained over time?
- The energy displaced and its emissions profile. It should be kept in mind that the current energy mix cannot be assumed to remain unchanged for decades into the future, as fossil fuels are playing a reduced role and ultimately need to be phased out under climate change mitigation scenarios and be replaced by other (lower emitting) energy sources, consequently the comparator to bioenergy will continue to change, in practice lowering any projected emissions savings.

It is worth noting that where a specific project or initiative is being assessed certain local considerations will carry weight. By contrast, when a broader policy initiative is being assessed, where trade impacts might be significant for example, the suite of relevant variables would not be identical. Appropriate methodologies are required for each case.

While there are divisions in view over the appropriate baseline for assessing forestry biomass scenarios in particular and it is not easy to do, there is at least an ongoing debate. For other elements of the counterfactual there has been more limited research undertaken to enable realistic comparison between different bioenergy sources. It would be helpful to define a consistent approach to the consideration of counterfactuals for the bioenergy sector so as to enable the development of appropriate systems for comparing and understanding the GHG emission consequences of current and projected supply patterns. Variants of the approach will be required depending on whether the subject is a project or a policy and at what level, eg national or European.

4.1.2 System boundaries

System boundaries need to be understood and respected in accounting exercises to assess the potential GHG emissions associated with bioenergy. It is not uncommon for key indicators to be understood and treated in different ways. Misinterpretations arising from the complex system boundaries of different accounting frameworks do arise in the literature. In some cases emissions are not accounted for correctly as a result.

Emissions from the utilisation of biomass for energy in Europe need to be accounted for in Europe, whatever the origin of the material and should include Europe's overall emissions relative to the counterfactual. If wood pellets for example are imported into the EU for combustion in a power plant then the emissions from combustion need to be accounted for in the EU, rather than being categorised as 'carbon neutral', as can occur. Any emissions arising from the production of the pellets, including harvesting, transporting and processing of wood, need to be accounted for in the country of origin along with less obvious emissions, such as from soil disturbance. Following harvest the carbon sink may increase in the region concerned and would be accounted for there. This approach to accounting is not always followed however.

A second category of emissions that may remain unaccounted for arises from activities that occur because a particular biomass resource, which was utilised previously for other purposes, has now been directed to energy use. Particularly significant can be direct or indirect land use change, whether taking place inside or outside Europe. An example would be where a food crop such as maize is directed into bioethanol production rather than the food chain and land elsewhere is then ploughed to grow maize to meet continued food demand.

Modelling work (for example by CCC, 2011) suggests a significant global footprint associated with the direct use of biomass. As noted above, there is a danger of these emissions not being accounted for correctly, particularly if a credit is taken within the EU for displacing fossil fuel emissions by using a bioenergy source instead without accounting anywhere for the emissions from the combustion of this material. Under-accounting can be compounded by failure to take account of indirect effects. Analyses by Forest Research (2012) and McKechnie *et al* (2011) anticipate an increase in the scale and intensity of production of some forms of biomass eg from forests associated with increasing bioenergy demand. The consequences have yet to be fully assessed in an integrated way, either in terms of potential land use change (indirect and direct) or the overall GHG impacts of intensifying land use to secure higher yields. Moreover, as noted earlier, the use of wood and certain residues for energy could lead to the displacement of other economic activities that made use of these materials previously or at least increase the price of certain commodities. IPCC SRREN (2011) highlights that many residues and other potential feedstocks are already in use to some extent. Given the carbon storage potential of utilising wood in more durable products it is important to understand any trade-offs associated with the expansion in the bioenergy sector so as to provide a clearer picture of the consequences for GHG emission intensity.

Generally, the GHG emission intensity of the use of forest residues is anticipated to be lower than that of the main roundwood harvest (eg McKechnie *et al*, 2011). However, the production of residues is closely linked to the success, expansion and location of the wider wood based economy (Biomass Energy Resource Center, 2012) as well as more local considerations and purely technical factors. It is therefore important to understand the interactions between the key drivers of supply of different biomass feedstocks. These reflect patterns of demand in sometimes quite different markets, eg for timber for house construction. The interplay between these drivers and different bioenergy pathways will in turn have consequences on the emissions profile of the feedstocks and their eventual applications.

While extensive work has been completed on the global impact of increased use of biofuels, in particular the land use consequences (for example Laborde, 2011), this has not been the case more generally for bioenergy. There is a need for an integrated analysis of the cumulative GHG effects associated with bioenergy both within and across the system boundaries of different accounting frameworks, including land use change and management intensity impacts and broader questions regarding the consequences for the wood based industry.

4.1.3 Providing a clear comparative baseline for decision making

There are now significant numbers of experts (EEA SC, 2011; Searchinger *et al*, 2009 and Searchinger, 2012; Haberl *et al*, 2012; CCC, 2011) calling for a change in the basis on which GHG emission accounting for biomass is undertaken, for example under the UNFCCC. They maintain that the current accounting approach fails appropriately to take into account the full consequences of GHG emissions associated with bioenergy production. Others are calling for and suggesting new approaches to the provision of a metric that can be used to compare the multiplicity of bioenergy resources in a fair, consistent and transparent way. For example, McKechnie *et al* (2011) suggest the combining of current LCA approaches with forest carbon calculations, while Joanneum Research (2011) has developed what they term a Carbon Neutrality Factor.

In the US there has been intensive debate on how to account for end of pipe carbon dioxide emissions from bioenergy use, with the EPA 'revisiting the premise that burning biomass for energy is carbon neutral in the context of the natural carbon cycle' (EPA, 2011). This exercise requires consideration of what is the appropriate accounting baseline for carbon emissions, and debate has focused on whether a simple growth and removals calculation is sufficient. This approach has been criticised for oversimplifying forestry systems in particular, hence overlooking changes in carbon stocks and not portraying the tonnes of new carbon sequestration foregone accurately. The alternative, a comparative approach to assessment, seeks to estimate both the carbon consequences of harvest and the sequestration foregone (Biomass Energy Resource Center, 2012).

At present there is no agreed approach to comparing the GHG emission intensity of bioenergy supply chains with each other and with other energy sources (both costs and benefits), nor a consistent approach to deal with the temporal factor in the calculation. Both these elements need to be addressed before it is possible to make better informed judgements on the benefits of bioenergy and the appropriate scale of its use. In the absence of a clear framework there is a risk of perverse incentives being introduced for measures which do not achieve the desired objectives (Searchinger, 2009).

4.1.4 The consequence of scale

If, as anticipated, demand for bioenergy rises over time, the pattern of feedstocks being exploited will change in the light of different resource profiles. Some feedstocks have scope for expansion, either soon or in the longer term; others, including several waste streams, are in limited supply. For some resources, the quantity available will fall over time, for example in industries which become more efficient and produce fewer wastes. There is a relationship between the scale of demand, the pattern of feedstocks being drawn in by what may be an inelastic demand once bioenergy plants have been built and the GHG profiles of these feedstocks. This relationship will not be linear. Scaling up demand will have consequences for the climate impacts of the bioenergy sector.

One example would be the exhausting of easily accessible agricultural residues, causing a shift to forestry residues or a switch to a biomass feedstock produced primarily for energy (McKechnie *et al*, 2011, EEA, 2009a). Shifts would also occur within certain feedstock groupings. For example, as demand exhausts the woody material available from existing forests based on current management regimes, this is likely to drive more intensive forest management or incentivise higher extraction rates because of the inelastic nature of demand.(Forest Research, 2012). This is likely to adversely affect future sinks (sequestration services) provided by living forest biomass, deadwood and soil organic carbon.

Over the lifetime of a bioenergy plant it is often not possible to predict in advance the feedstock that will be utilised. In some cases this could vary annually depending on availability and market conditions (IEEP, 2011). Moreover, the expansion in bioenergy comes at a time when some other industries utilising biomaterials are also expanding. It is important to recognise that as bioenergy use expands there will be consequences for the GHG emission intensity of the power or heat supplied.

Assessments of the usage patterns for bioenergy feedstocks are only beginning to emerge (eg ECN, 2012) and they do not currently model how usage might evolve within a complex set of systems over time. It would be helpful to understand more about where tipping points might exist, for example the conditions in which resources with a higher GHG emission intensity might be triggered.

Several studies have attempted to develop hierarchies to guide the future selection of feedstock usage for bioenergy, ie proposing a preferred order of use in relation to broader social goals, such as mitigating climate change (eg IEEP, 2011). If these were adopted in policy they would generate different outcomes from a more market led approach. These too would need continuous refinement in order to inform policy decisions on how to manage the evolution of the bioenergy system so as to bring about the greatest overall impact on climate change mitigation. Nonetheless, in principle, establishing hierarchies would be a helpful way to try to identify the most resource efficient pathways for utilising limited stocks, since market prices alone will not produce this outcome.

4.1.5 Considering future land use

One issue around which there is agreement regarding the use of forestry biomass is that the material harvested must be replaced by new growth in order to compensate for emissions. Given that forestry rotations can be long, there is a question over whether further land use and management practices can be relied upon to ensure the biomass has the necessary time and conditions to regenerate. The extent to which further land use and management practices, both within Europe and beyond, can be predicated or influenced by public authorities needs to be considered. This is particularly relevant within the EU given that Europe already relies on imports for 25 per cent of its biomass requirement (EEA, 2010). This proportion could rise considerably.

In Europe the extent of change in the broad patterns of land use over past decades has been relatively limited. Between 1990 and 2000 the rate of change in broad categories of land cover in Europe was estimated to be 0.2 per cent annually; this fell to 0.1 per cent annually between 2000 and 2006 (EEA, 2010). The 2010 State of the Environment Report (EEA, 2010) noted that in Europe the area of forest increased by 0.1 per cent per year between 2000 and 2006. While forestry in some parts of Europe is not particularly profitable, there have been incentives for establishing new forest or woodland in many Member States for more than two decades. Since the 1990s under the

CAP, farmers can receive support for the afforestation of agricultural land. This measure has been taken upon hugely varying scales in different Member States and there is scarce evidence for the intended environmental outcomes of the schemes that have been supported. In many regions, natural regeneration has occurred on a larger scale than policy driven (subsidised) deliberate establishment of forests. This trend is not necessarily envisaged to continue and may even be reversed given pressure to make use of agricultural land in Europe as global food demand increases and agricultural commodity prices rise.

Rates of land use change in the third countries can be more extensive. Lambin and Meyfroidt (2011) noted that between 1980 and 2000 more than half of new agricultural land across the tropics came at the expense of intact forest, and another 28 per cent from disturbed forest. Lambin and Meyfroidt estimate that by 2030 an additional 285 to 792 Mha of land for agriculture and other economic uses will be needed; essentially representing a doubling of demand between 2000 and 2030 (based on both low and high level estimates)[25].

In Europe the debate on land use is gathering pace. Under the auspices of the Resource Efficiency Roadmap the Commission will 'further develop the scientific knowledge-base on biotic material, land-use effects and trends, and spatial planning, including impacts at global level and effects on trading partners, and highlight best practices in the Member States, leading to a Communication on land use in 2014'. New approaches to engage with the debate on future land use and to better understand and account for likely land use carbon fluxes within the lifetime of biomass regrowth would be helpful. This could inform tools used to assess the GHG emission intensity of bioenergy. Better data and modelling of land use change dynamics and scenarios would contribute to better bioenergy decisions.

4.1.6 Short-term losses versus long-term gains – appropriate timescales for emission reduction

There are two dimensions to the question of timescales: 1) What is the cycle time for the carbon between the atmosphere and the biosphere, ie how fast is the CO_2 emitted during combustion re-absorbed through plant growth? This determines the length of the residency period of CO_2 that is from bioenergy combustion in the atmosphere and thus its global warming potential; and 2) What is the relevant policy timeframe over which the assessment of increased atmospheric CO_2 and associated global warming impact should be carried out? Does bioenergy use contribute to global warming or cooling over this timeframe?

The climate policy timeframe is given by efforts to stabilise the concentration of GHG in the atmosphere to contain climate change. The EU has committed itself to reducing GHG emissions to at least 80 per cent below 1990 levels by 2050. To achieve this will in essence require the power sector to be completely decarbonised by 2050 (European Commission, 2011b). This gives a timeline of less than 38 years from the present to deliver appropriate emission reductions.

Analysis in the literature suggests that the moment at which bioenergy use starts to generate overall emission reductions may be much further in the future than 38 years, depending on the biomass feedstock in question. Most recent assessments of the consequences of intensifying forest production to produce additional supplies suggest payback times from 35 to over 100 years, depending on the assessment approach applied and the fossil fuel to be offset. Estimated

[25] These figures take into account additional demands from croplands, biofuel crops, grazing land, urban expansion, industrial forestry, protected areas and land degradation.

breakeven points for roundwood include: 35-50 years (Biomass Energy Resource Center, 2012); 16 years for forest residues and 38 years for whole standing trees (McKechnie *et al*, 2011); 20 years for forest residues and up to 2-3 centuries for additional fellings (Joanneum Research, 2011).

Manomet (2010) expresses the cumulated carbon savings from using forest biomass for energy against different fossil fuels as a percentage against a final base year (see Table 6). Their work clearly demonstrates the importance of timeline, the efficiency of end use technology and the nature of the fossil fuel offset when considering whether a biomass resource is appropriate as a low carbon energy resource. Table 6 shows the total net change in atmospheric carbon in 2050 and 2010 due to 40 years of biomass use (over 2010-2050) compared to using fossil fuels over the same period. It indicates that up to 2050 the accumulated emissions from using forest biomass, net of forest carbon sequestration, are lower compared to accumulated emissions from fossil fuel use only in the case of oil-fired thermal/CHP applications. This is one of four comparators considered. Emissions from using biomass are higher in all other cases, ie the carbon debt is not paid off and no emission reductions are achieved within the timeframe. This changes when looking at 2100 (though gas-fired electricity generation is still more favourable then). However, looking so far ahead does raise a multiplicity of questions including whether any significant quantity of fossil fuels will still be used in the latter part of the 21st century given the outlook for supply and costs.

Table 6: **Cumulative dividends from biomass replacing fossil fuel based on use of forest biomass**

Biomass: Cumulative % Reduction in Carbon Emissions (Net of Forest Carbon Sequestration)				
Year	**Oil (#6) Thermal/CHP**	**Coal, Electric**	**Gas, Thermal**	**Gas, Electric**
2050	25%	-3%	-13%	-110%
2100	42%	19%	12%	-63%

Source: Manomet, 2010, p7 (reformatted from original to ensure legible text)

Management practices are central to determining overall payback times as highlighted by Forest Research (2012) and others. Determining the appropriate cut off in terms of payback timeline and how this should best be calculated is an important area where further work is needed. Crucially this should bring experts, evidence and approaches together to determine a coherent approach and an informed decision. Such an approach would need to improve the research base on payback times, but also provide a mechanism for choosing the best bioenergy options in light of the data available.

Some would argue that forest management practices can be changed in a way that biomass harvest is increased while baseline carbon sinks (sequestration services by forest and forest soils) are maintained in the long term. However, several studies suggest that current approaches to 'sustainable forestry' are not sufficient to ensure this (eg CCC, 2011). As noted above, the timelines associated with forest management mean that initiating change often takes effect only after an extended period, so that it is likely that within the timeframes relevant to climate policy, incremental increases in harvest usually are achievable only when previous management was below optimum harvest.

There is a growing body of literature that considers how forestry management might evolve to maintain baseline carbon sinks over the long term while improving yield, including some analysis that incorporates carbon sink development alongside harvesting (Asante, 2011; Forest Research and North Energy, 2012; Böttcher *et al*, 2008). However, an increasing rotation length is recommended by Böttcher *et al* (2008), which again is not necessarily compatible with delivering short-term carbon emissions savings or a higher intensity of material for an expanding bioenergy industry. Moreover many of these exercises are modelled and at present theoretical. It remains unclear from the literature whether in practice forestry management is taking long-term carbon storage into account when defining rotation and harvesting regimes.

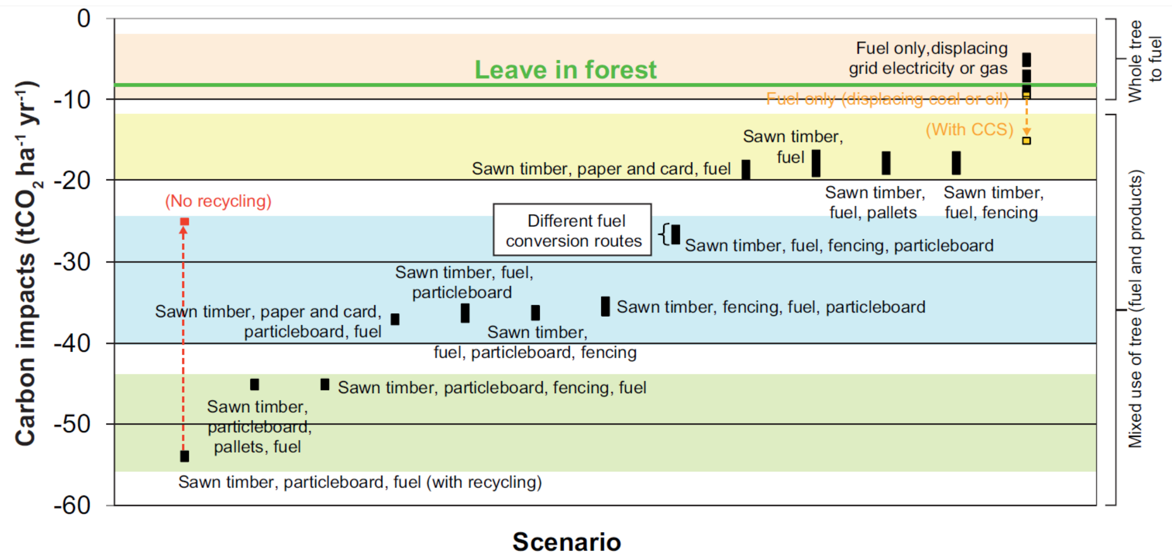
Further analysis is needed on the question of appropriate forest management and the ability to evolve existing practices to a timeline appropriate for combatting climate change. This would improve understanding of the consequences of current infield forest management practices for climate change, including the bioenergy dimension. Beyond this a more focussed debate is needed on the implications of realistic emissions negotiations and payback times for bioenergy as a means of contributing to climate mitigation goals over the next three decades. More consensus would be helpful on the methodology for calculating payback times and the extent to which bioenergy projects can be justified when payback times exceed a certain threshold, which could be short given mitigation targets for 2020 and 2050. This represents a very considerable hurdle for new bioenergy projects to surmount.

4.1.7 Maximising carbon benefits from biomass

A common theme in the literature is that the bioenergy industry is not operating in isolation; it is integrally linked to other biomass based industries, both established and novel. Unlike other energy solutions the biomass resource represents a store of atmospheric carbon. Wood products often have low embodied energy, unlike metals, concrete or plastics, which means there is an important carbon benefit when wood is used to substitute other materials. While this varies by use and by product, Malmsheimer (2011) estimates that on average every tonne of wood used as a building material removes 2.1 tonnes of carbon from the atmosphere.

Forest Research (2012) assessed the use of biomass for energy, compared to cascading approaches to biomass use whereby the original material is used, reused and recycled before finally being 'used' again as a feedstock for bioenergy. Figure 5, extracted from their analysis, shows that utilising biomass directly for bioenergy can deliver limited emission savings compared to maintaining forests for sequestration over a 100 year timeline. In the same period savings can be over six times greater when a more integrated approach to the management of biomass resources is pursued, including bioenergy being deployed selectively when it contributes most to the overall goal of mitigating climate change.

Figure 5: The carbon impact of the use of whole trees solely for fuel compared to their use within combined material and fuel pathways



Notes: Based on 100 year timeline for UK woodland:

- Green band – savings when harvested wood is converted to a range of products including sawn timber, particle board, pallets and fencing with some associated production of bioenergy;
- Blue band – savings based on mixed use of harvested wood but with lower production levels of particle board (impact associated with lower levels of recycling given that particle board is a key product from recycled wood material;
- Yellow band – savings when utilising only sawn timber and fuel;
- Orange band – use of all harvested wood for bioenergy, saving levels are similar to those arising if material were allowed to remain in forest and carbon stocks allowed to accumulate – green line.

Source: UK Bioenergy Strategy, 2012 based on analysis in Forest Research (2012).

As noted in Bringezu *et al* (2007), policy making still tends to treat the energy and other raw material spheres separately. Accordingly there is a lack of integrated assessment to provide a sound foundation to compare competing options and synergies. Moreover, key models used to assess energy potentials, such as POLES and RESolve, do not take into account the alternative uses of biomass, but optimise savings purely within the energy system. There is increasingly a desire from the wider biomass using industries to engage with the bioenergy and carbon agenda, as demonstrated by the recent 2050 Roadmap towards a low carbon bioeconomy produced by the European Paper Industry (CEPI, 2011). This underlines the value of investing in more integrated approaches, both in the form of models and studies and direct engagement with stakeholders. More linkages between the European bioeconomy, resource efficiency and bioenergy policies are required, informed by a strong analysis of the climate consequences of different options. The GHG profile of using biomass should be assessed for different pathways.

4.2 Priority actions – providing a basis for informed policy making

The evidence base for making informed decisions about bioenergy in relation to climate change needs to be strengthened considerably as a matter of urgency and some interim judgements made to give policy a stronger foundation. Some of the most important steps to take are the following:

- Resolve the question of comparative metrics and GHG emission accounting and urgently address the question of misleading life cycle studies (LCA). European authorities should take the lead in establishing a dialogue around the most appropriate approaches to GHG emission accounting for bioenergy and develop a clear metric to enable comparison between the different bioenergy resources. This should build on analysis of appropriate counterfactuals and will need to take into account temporal factors. These may be interim approaches in the absence of definitive data.It should be made clear that most conventional LCAs do not take into account land use change, nor do they normally account for shifts in forest management that are increasingly identified as reducing carbon storage potential. This has implications for their relevance to climate policy.

- Research is needed to develop more robust integrated assessments of the carbon leakage consequences of bioenergy use in a European context. These should include the use of imports, land use consequences of expanded demand, both in terms of change in primary use and change key management practices, and consequences for the evolution of other industries reliant on biomass. The latter should include consideration of the feedback loops between bioenergy and other industries, eg in terms of the impact of expanded demand from bioenergy on the ability of other industries to operate and utilise wood.

- An intensified policy debate is needed to attain greater agreement on an acceptable timeline for carbon payback marrying climate and forestry timelines. While this remains a matter of judgement, it would be helpful to bring together key experts from the energy, climate, forestry and land management disciplines to advance the debate on payback times and define what is acceptable in terms of climate impact and what is achievable in terms of carbon management within forestry systems.

- Both researchers and policy makers need to focus more on situating bioenergy decisions within the broader question of a sustainable bioeconomy and a resource efficient Europe. This involves assessing and engaging with key actors, for example to determine the carbon consequences of pursuing an energy driven agenda. Bioenergy decisions need to be located more firmly within the resource efficiency agenda and based on a clearer understanding of synergies and consequences for the bioenergy resource base. This includes considering the concept of cascading biomass use, whereby material use of wood eg in construction precedes energy recovery, which is a demonstrated way of improving the GHG profile of bioenergy pathways.

- A more sophisticated EU framework is needed to incorporate the GHG emission intensity dimension of bioenergy pathways in energy and climate policies. These need to take account of the inherent variability of bioenergy and reasoned judgements concerning the relative merits of different feedstocks. This should include a robust mechanism for monitoring bioenergy usage and feedstock supply patterns and their evolution to make more transparent and explicit the consequences of EU demand and the associated GHG emission intensity impact both in space and time.

5 CONCLUSIONS – THE GHG EMISSION INTENSITY OF BIOENERGY

At present, the multiplicity of bioenergy supply chains is often treated as one sector, for which the presumption of carbon neutrality has been conceptually the norm in most circles. Carbon neutrality, in this context, is an assumption that end of pipe emissions are offset through regrowth of biomass. However, this characterisation of bioenergy is problematic both in terms of misrepresenting its heterogeneity and generalising the GHG emission intensity of use, often in a misleading way, tending to over-estimate its contribution to climate mitigation goals, sometimes very significantly.

Policies based on this misapprehension need to be reviewed. Maximising the potential carbon benefit from the use of bioenergy will require integrating energy and material based uses of biomass more effectively.

In terms of its impact on the climate, bioenergy is distinctive from other renewables in several respects due to complex linkages with land management issues, the variety of feedstocks and energy supply pathways. These factors need to be taken into account when assessing the likely contribution to climate mitigation, along with alternative uses for the biomass in question.

For these reasons, and the sheer variety of circumstances in which feedstocks of a broadly similar kind are produced, no single GHG emission intensity for bioenergy as a whole can be proposed. At present, the metrics used routinely for the comparison of GHG emission intensity between different bioenergy pathways and between them and fossil fuels increasingly are recognised as flawed. Standard and commonly used approaches to life cycle analysis (LCA) presume carbon neutrality of the feedstock, unless land use change has occurred and been recognised. However, this approach constitutes a very significant risk in terms of misrepresenting the emissions profile, in particular, of woody based biomass. Moreover, there is no clear understanding from the literature on what the profile of biomass use for energy will be in 2020.

In terms of maximising reductions in GHG emissions and mitigating climate change, the literature suggests a hierarchy of preferences in the use of broad categories of feedstock. An indicative hierarchy would be:

- Genuinely residual waste and residues, including sewage sludge, livestock residues and slurries, food waste and landscape care wood;
- Agricultural wastes;
- Forestry residues; and
- Primary biomass, ie agriculture commodities, energy crops or whole trees from forestry.

Scale effects need to be considered as several of these feedstocks are in limited supply and the impact of increased demand for bioenergy over time may be to increase the share of feedstocks at the bottom of the hierarchy in the supply mix. However, the likely patterns of biomass use in future do not tally with such a hierarchy as far as can be judged from the limited evidence. Analysis suggests the use of significant and growing quantities of woody biomass in Europe, particularly in the form of pellets, given the ease with which such commodities can be traded and transported.

It is in particular in the realm of forestry, where marked divisions prevail between certain authors and stakeholders about the appropriate methodology for addressing some key issues. There is significant disagreement on how GHG emission intensity should be analysed and accounted for in this sector. However, drilling down into the literature, there appears to be a general appreciation that increasing the intensity of forestry management and increasing biomass extraction rates over time will lead to a carbon deficit. This then needs to be repaid before the bioenergy demand from such resources can deliver emission savings compared to burning fossil fuels, while allowing for the sequestration services provided by the forest in the realistic counterfactual scenario without the bioenergy expansion. What happens to feedstocks and land use patterns if bioenergy use continues to expand is another relevant question that has drawn insignificant attention so far.

The range of payback times estimated in studies which do attempt more complete LCAs of forest based bioenergy supply chains varies considerably, in many cases stretching from between 35 and 50 years and in some studies up to 2 to 3 centuries, depending on the type of trees felled. The length of this time lag will depend on several factors, including the nature of the management of the original feedstock and the extent to which this is altered over time.

At present there is no basis for presuming that EU bioenergy use to 2020 will deliver emission savings, and a significant risk that it may result in additional emissions. This is based on:

- The lack of a clear comparative metric and an agreed basis for estimating emissions from bioenergy;
- The uncertainty over supply patterns over time and the divergence between apparent current components of supply and the mix of feedstocks that would be deployed if the maximum benefit for the climate were being pursued;
- A common lack of understanding in GHG emission accounting practices about the trade-offs in terms of emissions associated with biomass use for energy (ie the counterfactual) and the carbon leakage impact associated with the adoption of bioenergy in Europe;
- The segregation of bioenergy from the broader resource use agenda, meaning that opportunities for the use of residues and wastes and from cascading may not be captured;
- A lack of a European policy infrastructure that differentiates between bioenergy sources and pathways in an appropriate fashion.

This leads to a situation where it is not currently possible to define the emissions profile and savings associated with Europe's expanding use of biomass for energy, nor is there any policy process currently in place to secure this. As a consequence, at present there is only the certainty of commitment to bioenergy use up to 2020, but no associated guarantee of emission reduction.

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