Sustainability of biomass for cofiring

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Abstract

There are many items to include when considering the sustainability of biomass for cofiring, and some of them are hard to quantify. The focus of this report is on the greenhouse gas emission aspects of sustainability. The reduction of greenhouse gas emissions achieved by substituting biomass for coal depends on a number of factors such as the nature of the fossil fuel reference system, the source of the biomass, and how it is produced. Relevant issues in biomass production include the energy balance, the greenhouse gas balance, land use change, non-CO_2 greenhouse gas emission from soils, changes to soil organic carbon, and the timing of emissions and removal of CO_2 which relates to the scale of biomass production. Certification of sustainable biomass is slow to emerge at the national and international level, so various organisations are developing and using their own standards for sustainable production. The EU does not yet have sustainability standards for solid biomass, but the UK and Belgium have developed their own.

Acronyms and abbreviations

BCAP	Biomass Crop Assistance Program (USA)
CEEC	central and eastern European countries
CEN	European Committee for Standardisation
CH_4	methane
CHP	combined heat and power (cogeneration)
CO	carbon monoxide
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
CoC	chain of custody
CSBP	Council on Sustainable Biomass Production
DLUC	direct land use change
dt	dry tonne
EC	European Commission
EEA	European Environment Agency
EIA	Energy Information Administration (USA)
EISA	Energy Independence and Security Act (USA)
EJ	exajoule, 10^{18} joule
EPA	Environmental Protection Agency (USA)
ETS	Emissions Trading System (EU)
FAO	Food and Agriculture Organisation (UN)
FSC	Forest Stewardship Council
GATT	General Agreement on Tariffs and Trade
GBEP	Global Bioenergy Partnership
GGL	Green Gold Label
GHG	greenhouse gas
Gt	gigatonne, 10^9 tonne
Gtoe	gigatonnes oil equivalent
GWP	global warming potential
IBEP	International Bioenergy Platform
ILUC	indirect land use change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
ITC	Investment Tax Credit
kWh	kilowatt hour
LCA	life cycle assessment
Mdt	million dry tonnes
MEA	multilateral environmental agreement
Mha	million hectares
MS	member states (of EU)
Mt	megatonne, 10^6 tonne
Mtoe	million tonnes of oil equivalent
MW	megawatt
N_2O	nitrous oxide
NOx	nitrogen oxide and nitrogen dioxide
PAH	polycyclic aromatic hydrocarbons
PCC	pulverised coal combustion
PEFC	Programme for the Endorsement of Forest Certification Schemes
PPM	production process and production methods
PTC	Production Tax Credit
REC	Renewable Energy Credits

RED	Renewable Energy Directive (EU)
RES	renewable energy sources
RFS	Renewable Fuel Standard (US)
RO	Renewables Obligation (UK)
RTFO	Renewable Transport Fuels Obligation (UK)
SOC	soil organic carbon
TBT	Technical Barriers to Trade
TPP	Timber Procurement Policy (UK)
TPES	total primary energy supply
UNFCCC	United Nations Framework Convention on Climate Change
US DOE	Department of Energy (USA)
WEC	Western European Countries
WTO	World Trade Organisation

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1 Introduction

There is a growing interest in bioenergy at a national and global level, as shown by recent policy documents approved by the US congress (such as the American Clean Energy and Security Act, the Waxman-Markey Bill) and by the European Parliament (Directive 2009/28/EC on the promotion of the use of energy from renewable sources). EU policy requires 20% of energy to be supplied by renewable sources by 2020. As a result of this and other policies the use of renewables such as wind, solar and biomass is increasing. Multiple drivers are emerging for bioenergy systems and their deployment in sustainable directions. Examples include rapidly changing policy contexts, recent market-based activities, the increasing support for biomass options and, in particular, the development of sustainability criteria and frameworks. Sustained cost reductions of key technologies in biomass production and conversion, supply infrastructure development, and integrated systems research can lead to the implementation of strategies that facilitate sustainable land and water use and gain public and political acceptance (IPCC, 2011).

There are high expectations for biomass as a resource for sustainable energy. Many industrialised countries have adopted ambitious policy targets and have introduced financial measures to stimulate the production or use of bioenergy. Diverse reasons are typically given for why bioenergy should be promoted: it is 'carbon-neutral', it is made from renewable resources, it stimulates the agricultural sector, it does not suffer the intermittency problems of wind and solar power, and it may be produced domestically in many countries, thus encouraging energy independence. However, questions exist about the sustainability of bioenergy pathways. There are side-effects and perceived associated risks which range from a less favourable energy balance to unforeseen land use change, and could include competition with food production (Guinée and others, 2009). In addition, indirect effects like land use change may contribute to complicate the overall picture.

A reduction in greenhouse gas (GHG) emissions is often attributed to the use of energy from biomass. According to the Intergovernmental Panel on Climate Change (IPCC), certain current systems and key future options including the use of biomass residues and wastes are able to deliver 80–90% emission reductions compared to the fossil energy baseline. At the state, national, and international level, policies encouraging the development of forest biomass energy have generally adopted a view of biomass as a carbon neutral energy source because the carbon emissions were considered part of a natural cycle in which growing forests over time would re-capture the carbon emitted by wood-burning energy facilities. One significant environmental advantage of biomass is that the CO_2 released on combustion was relatively recently fixed from the atmosphere via photosynthesis, so that there is *theoretically* no net increase in the atmospheric CO_2 burden when biomass from a sustainably managed source is combusted.

Beginning in the 1990s, however, researchers began conducting studies that reflect a more complex understanding of the carbon cycle implications of biomass combustion. Bioenergy is different from the other renewable energy technologies as it is a part of the terrestrial carbon cycle. Burning biomass increases the amount of CO_2 in the air, just like burning coal, oil and gas, if harvesting the biomass decreases the amount of carbon stored in plants and soils, or reduces ongoing carbon sequestration (EEA, 2011). Two important factors that determine whether bioenergy reduces carbon in the atmosphere compared to fossil fuels are where and how the biomass is produced and harvested. The CO_2 emitted due to bioenergy use and that subsequently sequestered again if the bioenergy system is managed sustainably, may not necessarily be in temporal balance with each other (for example due to long rotation periods of forest stands). Any imbalance can be an important issue. In addition to changes in atmospheric carbon, bioenergy use may cause changes in terrestrial carbon stocks (IPCC, 2011). According to the EEA (2011), it is possible that legislation that encourages substitution of fossil fuels by bioenergy, irrespective of the biomass source, may result in increased carbon emissions. Also, when the overall life cycle is assessed, some activities such as the use of machinery to grow and harvest the biomass and ships and trains to transport it to power plants negate a fraction of the GHG savings (Thornley, 2006).

The focus of this report is on solid biomass as it is frequently used together with coal in coal-fired power plants. It can be cofired at rates of up to 10% (thermal), or even higher, with minimal impact on the workings of the power plant. Cofiring is a relatively efficient way to use solid biomass compared to direct combustion (IPCC, 2011). Biomass cofiring benefits from the infrastructure that is in place for large-scale coal combustion. Some individual coal-fired power units have been converted to 100% biomass combustion, and even whole power plants may be converted to run on biomass. If biomass is sustainably sourced and is 'carbon neutral' then cofiring biomass with coal, or conversion to biomass can have a significant impact on GHG emissions.

This report considers the sustainable sourcing of solid biomass and its carbon neutrality. It defines biomass, sustainability, and the various factors that contribute to the sustainable production of biomass. The focus is on the GHG aspects of sustainability, and not the socio-economic ones. There is particular emphasis on carbon neutrality, as this term is widely used in support of biomass combustion. Sustainability policies are introduced and described.

2 Biomass, cofiring and sustainability

Biomass is defined in this chapter and the process of biomass combustion is explained. The concept of sustainability is described.

2.1 What is biomass?

Biomass material for cofiring in coal-fired power plants can be broadly classified into the following groups based on a general assessment of the source (Williams and others, 2012):

- woody, such as pine chips and willow chips;
- herbaceous, including *Miscanthus* and switchgrass;
- agricultural residues, such as straw, rice husks, palm kernel expeller, bagasse (residue from sugar cane crushing), olive residue or olive cake (the waste from olive oil mills).

This means that solid biomass fuels are available in a variety of physical forms, such as traditional logs and straw bales, as well as processed products such as chips and pellets. Most biomass for cofiring is received at the power plant in pellet form. Much traded biomass conforms to standards. In Table 1 the fuel properties of various forms of biomass are compared with coal. For example, standard (CEN/TS 14961:2005 (E)) can be applied to wood chips and pellets with respect to the dimensions, moisture content, ash and nitrogen content. Pellets are small particles (about 5 mm) of biomass which have been compressed while steam heated. Lignin present in the biomass acts as a binding agent, or a binder may be added. Pellets are an accepted form of fuel for many units and are used widely and internationally traded. Power stations require a fuel pulverised to a size similar to that of pulverised coal in order to achieve a high combustion intensity, which partly explains the demand for pelletised biomass (Williams and others, 2012).

Table 1 Biomass fuel properties compared to coal (Kleinschmidt, 2011)

	Wood	Wood pellets	Torrefaction pellets	Charcoal	Coal
Moisture content, %wt	30–45	7–10	1–5	1–5	10–15
Calorific value, MJ/kg	9–12	15–16	20–24	30–32	23–28
Volatiles, % db	70–75	70–75	55–65	10–12	15–30
Fixed carbon, % db	20–25	20–25	28–35	85–87	50–55
Bulk density, kg/l	0.2–0.25	0.55–0.75	0.75–0.85	~0.20	0.8–0.85
Volumetric energy density, GJ/m^3	2.0-3.0	7.5–10.4	15.0–18.7	6–6.4	18.4–23.8
Dust	Average	Limited	Limited	High	Limited
Hydroscopic properties	Hydrophilic	Hydrophilic	Hydrophobic	Hydrophobic	Hydrophobic
Biological degradation	Yes	Yes	No	No	No
Milling requirements	Special	Special	Classic	Classic	Classic
Handling properties	Special	Easy	Easy	Easy	Easy
Product consistency	Limited	High	High	High	High
Transport cost	High	Average	Low	Average	Low

Until recently, solid biomass fuels were not traded on a large scale commercially, apart from specialist applications of industrial waste. The development in the last decade of biomass on a large industrial scale has prompted the use of standard test methods, and in the case of solid fuels, the methods developed for coal coking and combustion were used in the first instance (Williams and others, 2012).

The tremendous diversity of biomass feedstock means that there is a need for a comprehensive classification system which covers both physical and chemical specifications and can allow the user to predict the behaviour of a biomass feedstock. Some properties which it might be useful to predict include: storage potential; self-heating potential; milling behaviour; pyrolysis behaviour; tar yield; volatile composition; yield and composition of the char and its reactivity towards oxygen; and impact of inorganic composition (which is more variable for biomass than coal) on ash behaviour (Williams and others, 2012).

2.2 Cofiring and combustion of biomass

Biomass combustion consists of the following steps: heating up; drying; devolatilisation to produce char and volatiles, where the volatiles consist of tars and gases; combustion of the volatiles; and combustion of the char (Williams and others, 2012):

Wet biomass → heating up/drying → dry biomass

Biomass → volatiles (tars and gases) + char

Volatiles + air → CO + CO_2 (+ PAH + unburned hydrocarbons + soot + inorganic aerosols)

Char + air → CO + CO_2

Volatiles (N, S, K and others) → N, S, K based pollutants

Char (N, S, K and others) → N, S, K based pollutants

(PAH = polycyclic aromatic hydrocarbons)

Pollutants are formed alongside the main combustion reactions from the N, S, Cl, K as well as other trace elements contained in the volatiles and char. Carbon monoxide (CO), PAH, soot and others, are released if the combustion is incomplete. The nitrogen compounds are partially released with the volatiles, while some form a C–N matrix in the char and are then released during the char combustion stage forming nitrogen oxides (NOx) and the NOx precursors, HCN and HNCO. Sulphur is released as sulphur dioxide (SO_2) during both volatile and char combustion. Potassium chloride (KCl), potassium hydroxide (KOH) and other metal containing compounds together with the sulphur compounds form a range of gas phase species, which can be released as aerosols, but importantly, also deposit in combustion chambers (Williams and others, 2012).

Biomass moisture content plays a significant role in the combustion process. The moisture content of wood is still at least 20% even after considerable ambient drying. For combustion of small particles, such as cofiring with pulverised coal, the particles are assumed to heat up virtually instantly, but there is an efficiency loss due to the latent energy of water evaporation from the biomass. As a result of this, a drying process is usually carried out separately. However, in the large scale utilisation of biomass the drying process is energy intensive and there is growing interest in using dried processed fuels which have been either pelletised or torrefied to optimise the use of energy (Williams and others, 2012).

The use of biomass in direct combustion processes results in the release of gaseous and particulate pollutants to the atmosphere which can have significant effects if the pollutants emitted are not controlled. Due to the move towards the use of solid biomass as a renewable energy source in many countries the future environmental impact has to be considered with care. One advantage of using biomass in large scale cofiring is the high generation cycle efficiency, extensive emission control equipment and therefore reduced emissions per unit of electricity. Sustainability issues are also better handled with large plant, both from a supply aspect and that of recycling ash (Williams and others, 2012).

In the case of large combustion units, the combustor size permits a longer residence time and more complete burnout of the soot, but the fine particles still remain a problem. Catalytic emission control units are helpful, as is the use of particle reduction equipment. The choice of pretreated fuels is also important, in that a reduction in potassium and nitrogen contents reduces emissions, and the use of wood chips results in a fuel that burns more uniformly with a reduced formation of char fragments compared with lump wood. Large plant has the opportunity to reduce all forms of the pollutants and thus is the preferred method of biomass combustion, although the control of ultra-fine particles remains a problem (Williams and others, 2012).

More than 150 power plants worldwide have experience of cofiring biomass or waste fuels, at least on a trial basis. There are approximately 40 pulverised coal combustion (PCC) plants that cofire biomass on a commercial basis with an average of 3% energy input from biomass. Although many coal-fired power plants have cofired low percentages of biomass, only about a dozen have cofired high percentages over extended periods. Circulating fluidised bed combustion (CFBC) is often more suitable for cofiring biomass than PCC. In Fernando's (2012) report for the IEA Clean Coal Centre, a high cofiring ratio is taken to mean about 15% biomass by weight or 10% by energy output. Cofiring can be direct, where the biomass and the coal are fired in the same boiler or indirect, where the combustion or gasification of the biomass occurs in a separate unit. Direct cofiring is the simplest and most widely applied technology for cofiring biomass. In this process, as all the components of the biomass enter the coal boiler, several technical issues arise which need to be considered. If the proportion of biomass is high, the fuel volume increases considerably and can adversely affect combined grinding and feeding; separate mills may be needed. The lower melting point of the resulting ash can increase the likelihood of slagging and fouling. Some biofuels, such as straw, contain high chlorine levels which can cause high temperature corrosion. The constituents of the ash change during cofiring and this affects ash utilisation and disposal options. These technical issues do not arise during indirect cofiring as the biomass ash and the coal ash are kept separate. However, indirect cofiring is more costly than direct cofiring. Thus, although there have been a considerable number of coal-fired plant which have directly cofired biomass, only a handful have incorporated indirect cofiring. Indirect cofiring may be a suitable option for cofiring high ratios (Fernando, 2012).

2.3 What is sustainability?

The definition of sustainability, or sustainable development, is by no means agreed and is subject to value judgements. The most well-known definition is that of the World Commission on Environment and Development from 1987:

'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs'.

It has been suggested that achieving sustainable policy relies on reconciling divergent views of communities on intra-generational and inter-generational distribution, and ecosystem maintenance. Furthermore, there are different forms of sustainability, both weak and strong. Strong sustainability has been defined as a condition whereby some natural capital (called critical natural capital) provides functions that are not substitutable by man-made capital; the stock of natural capital handed down to future generations must not be smaller than that enjoyed by the current generation. Weak sustainability, on the other hand, reflects a view whereby natural and man-made capital together comprise total capital. Natural capital is considered to be substitutable for man-made capital and weak sustainability occurs when the level of total capital passed onto future generations does not decrease (the inference being that man-made capital has replaced natural capital to maintain total capital). The definition of what constitutes critical natural capital is itself value based, often relying on the views of ecologists as to what might be 'critical' (Bond and others, 2011).

Both the definition of sustainability, including what might constitute critical natural capital, and the expectations for the role of sustainability appraisal are value based. A pluralistic stewardship approach to achieving sustainability has been suggested, using different values systems termed ecocentric, biocentric or anthropocentric. These 'centrisms' are not unrelated to the three pillars of sustainability: social, economic and environmental which have a tension between them. As understanding of environmental systems is incomplete it is possible that a pluralistic stewardship approach will restrict decision-makers choices to those which are most acceptable to multiple value systems (Bond and others, 2011).

The actors involved in environmental decision-making are not neutral and the decisions taken are embedded in institutional frames. For sustainability appraisal, the framework itself is similarly subject to institutional framing, and this can affect the extent to which sustainable outcomes are achieved where 'good governance' seems apparent. It has been suggested that appraisal processes are subjected to a tension between sustainability and good governance considerations. A factor that leads to this conclusion is the evidence that people and communities tend to emphasise socio-economic values over environmental values (Bond and others, 2011).

The use of sustainability appraisal is problematic because of the value-laden nature of interpretations of sustainability; the multitude of framings associated with the effectiveness of decision-making tools attempting to make decision-making more sustainable; and the tensions between achieving good governance at the same time as sustainable outcomes (Bond and others, 2011).

There are other methods for valuing environmental components in a sustainability context. Recent moves have acknowledged the value of the ecological, economic, and socio-cultural services that ecosystems provide and aim to provide information on the value of the services of ecosystems in order to enhance decision-making for their (strong) sustainable use (Bond and others, 2011).

Sustainability is not an absolute concept; the definition will vary, depending on scale and situation. While universal 'sustainability principles' can be identified, the measures by which sustainability is assessed need to be adapted to the local context, recognising the objectives and priorities of local communities (Cowie and others, 2011).

2.3.1 Biomass sustainability

Relevant sustainability criteria for biomass and bioenergy can be classified in three categories:

1. Environmental criteria, such as GHG emission saving, carbon stocks conservation, environment quality preservation;
2. Socio-economic criteria, such as food security, respect of workers' rights, respect of land property rights; and
3. Cross-cutting issues, mainly related to direct land use changes (DLUC) or indirect land use change (ILUC), which can have negative impacts on GHG emissions, biodiversity, and socio-economic outcomes (Van Stappen and others, 2011).

As a component of the much larger agriculture and forestry systems of the world, biomass affects social and environmental issues ranging from health and poverty to biodiversity and water quality. Land and water resources need to be properly managed in concert with each specific region's economic development situation and suitable types of bioenergy. Bioenergy has the opportunity to contribute positively to climate change mitigation, secure energy supply and diversity goals, and economic development in developed and developing countries alike. However, the effects of bioenergy on environmental sustainability may also be negative depending upon local conditions, how criteria are defined, and how actual projects are designed and implemented, among many other factors (IPCC, 2011). These issues are discussed in depth in Chapters 3 and 4.

3 The biomass resource

Many estimates have been made of the possible contribution of biomass to future energy supply, especially in the next 30–50 y. Biomass energy annual usage currently represents about 8–14% of the world final energy consumption as detailed in Table 2. The data in Table 2 come from a variety of sources. Current and future estimates of biomass utilisation are subject to uncertainty and global values can vary by a factor of 5, but well-resourced information is available for major countries, such as Brazil, China, Europe India, Russia, and the USA. The upper estimate of biomass annual availability is about 4500 EJ (exajoule, 10^{18} joule)(220 Gt mass, 108 Gtoe) and is almost 10 times the current world energy requirement. Resources vary from country to country and are dependent mainly on geographic location, the climate, the population density, and the degree of industrialisation of the country (Williams and others, 2012).

Table 2 Annual global energy consumption, Gtoe 2010 (Williams and others, 2012)

Fossil fuels	10.45
Oil	4.03
Coal	3.56
Natural gas	2.86
Nuclear	0.63
Renewables	0.94
Hydro	0.78
Wind, commercial biomass, solar	0.16
Estimated biomass (traditional)	1–2
Total global energy consumption	12.00*
Gtoe including all biomass	13.0–14.0

* commercial energy
† including all biomass

Biomass provides about 10% (50.3 EJ in 2008) of the annual global primary energy supply. As presented in Table 3, about 60% (IEA accounted) to 70% (including unaccounted informal sector) of this biomass is used in rural areas and refers to charcoal, wood, agricultural residues and manure used for cooking, lighting and space heating, generally by the poorer part of the population in developing countries (IPCC, 2011).

Modern biomass use (for electricity and CHP for the power sector; modern residential, commercial, and public buildings heating; or transport fuels) provided a significant

Table 3 Examples of traditional and select modern biomass energy flows in 2008 (IPCC, 2011)

Type	Approximate primary energy, EJ/y	Approximate average efficiency, %	Approximate secondary energy, EJ/y
Traditional biomass			
Accounted for in IEA energy statistics	30.7	10–20	3–6
Estimated for informal sectors (such as charcoal)	6–12		0.6–2.4
Total traditional Biomass	37–43		3.6–8.4
Modern bioenergy			
Electricity and CHP from biomass, MSW, and biogas	4.0	32	1.3
Heat in residential, public/commercial buildings from solid biomass and biogas	4.2	80	3.4
Road transport fuels (ethanol and biodiesel)	3.1	60	1.9
Total modern bioenergy	11.3	58	6.6

contribution of about 11.3 EJ of the 2008 total primary energy supply (TPES) from biomass of 50.3 EJ. This was an increase from 9.6 EJ17 in 2004 (IPCC, 2007), and a rough estimate of 8 EJ in 2000. From 1990 to 2008, the average annual growth rate of solid biomass use for bioenergy was 1.5% (IEA, 2010; IEA Bioenergy, 2007; IPCC, 2011). Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008, representing 1% of the world's electricity and a doubling since 1990 (from 131 TWh, 0.47 EJ) (IPCC, 2011).

Global bioenergy use has grown steadily worldwide in absolute terms in the last 40 years, with large differences among countries. In 2006, China led all countries and used 9 EJ of biomass for energy, followed by India (6 EJ), the USA (2.3 EJ) and Brazil (2 EJ) (GBEP, 2008). In the same year bioenergy provided 5–27% of TPES in the largest emerging countries (China, India, Mexico, Brazil and South Africa), mainly through the use of traditional forms, and it provided more than 80% of TPES in the poorest countries. The bioenergy share in India, China and Mexico is decreasing, mostly as traditional biomass is substituted by kerosene and liquefied petroleum gas within large cities. However, consumption in absolute terms continues to grow. This trend is also true for most African countries, where demand has been driven by a steady increase in wood fuels, particularly in the use of charcoal in booming urban areas (GBEP, 2008; IPCC, 2011).

Bioenergy provides a relatively small but growing share of TPES (1–4 % in 2006) in the G8 countries (Canada, France, Germany, Italy, Japan, Russia, UK and USA). The use of solid biomass for electricity production is particularly important in pulp and paper plants and in sugar mills. Bioenergy's share in total energy consumption is generally increasing in the G8 countries through the use of modern biomass forms (such as cofiring for electricity generation, space heating with pellets) especially in Germany, Italy and the UK (IPCC, 2011).

3.1 Global future potential of biomass

The inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterise. Different types of resource potentials are assessed but the following are commonly referred to (IPCC, 2011):

- Theoretical potential refers to the biomass supply as limited only by biophysical constraints;
- Technical potential considers the limitations of the biomass production practices assumed to be employed and also takes into account concurrent demand for food, fodder, fibre, forest products and area requirements for human infrastructure. Restrictions connected to nature conservation and soil/water/biodiversity preservation can also be considered. In such cases, the term sustainable potential is sometimes used;
- Market potential refers to the part of the technical potential that can be produced given a specified requirement for the level of economic profit in production. This depends not only on the cost of production but also on the price of the biomass feedstock, which is determined by a range of factors such as the characteristics of biomass conversion technologies, the price of competing energy technologies and the prevailing policy regime.

Three principal categories are considered in assessments of biomass resource potentials:

1 Primary products which are plants produced for energy supply, including conventional food/fodder/industrial crops, surplus roundwood forestry products, and new agricultural, forestry or aquatic plants.
2 Primary residues from conventional food and fibre production in agriculture and forestry, such as cereal straw and logging residues;
3 Secondary and tertiary residues in the form of food/forest industry by-products and retail/post-consumer waste.

Literature studies range from zero (no biomass potential available as energy) to around 1500 EJ, the theoretical potential for terrestrial biomass based on modelling studies exploring the widest potential ranges of favourable conditions. The IPCC (2011) consider that potential deployment levels of biomass for energy by 2050 could be in the range of 100–300 EJ. There are a number of important uncertainties which account for this wide range, including:

- population and economic/technology development; food, fodder and fibre demand (including diets and dietary changes) and developments in agriculture and forestry;
- climate change impacts on future land use and its ability to adapt;
- extent of land degradation, water scarcity, and biodiversity and nature conservation requirements;
- residue flows in agriculture and forestry and unused agricultural land are important sources for the expansion of biomass production for energy, both in the near and longer term. Biodiversity-induced limits and the need to ensure maintenance of healthy ecosystems and avoid soil degradation will restrict residue extraction in agriculture and forestry;
- the cultivation of suitable (especially perennial) crops and woody species can lead to a higher technical potential for biomass. These crops can produce bioenergy on lands less suited for agriculture. Multifunctional land use systems with bioenergy production integrated into agriculture and forestry systems could contribute to biodiversity conservation and help restore/maintain soil productivity and healthy ecosystems;
- regions experiencing water scarcity may have limited production. The possibility that conversion of lands to biomass plantations may reduce downstream water availability needs to be considered. Assessments of biomass resource potentials need to consider constraints and opportunities carefully in relation to water availability and competing uses.

Other large uncertainties in this potential include market and policy conditions. The rate of improvement in the production of food and fodder as well as wood and pulp products is also important. The upper bound of the technical potential of biomass for energy may be as large as 500 EJ/y by 2050 (IPCC, 2011).

Reaching a substantial fraction of the technical potential will require sophisticated land and water management, large worldwide plant productivity increases, land optimisation and other measures. Realising this potential will be a major challenge, but biomass could make a substantial contribution to the world's primary energy supply by 2050. For comparison, the equivalent heat content of the total biomass harvested worldwide for food, fodder and fibre is about 219 EJ/y today (IPCC, 2011).

Major policy efforts would be required to reach the upper range of the deployment level of 300 EJ/y, especially targeting improvements and efficiency increases in the agricultural sector and good governance (IPCC, 2011).

There have been several attempts to quantify the potential of biomass available for energy supply with varying degrees of sustainability constraints. Estimates can differ within a large range, depending on factors such as whether the study takes a holistic view of land management and the stringency of the applied sustainability criteria. Not many of these studies look at the end uses for this biomass potential in detail. Other studies postulate the use of biomass to fill a demand need, but do not always specify in detail where this biomass would come from (Cornelissen and others, 2012).

Due to the competition for land between bioenergy crops and food production, and because of the sustainability requirement, integrated processes may have advantages. These are where the primary value products, foodstuffs and oils are produced, and the agricultural residues and biomass wastes are used for energy applications (Williams and others, 2012).

Success in implementing sustainability and policy frameworks that ensure good governance of land use and improvements in forestry, agricultural and livestock management will influence biomass potentials. However, biomass supplies may remain limited to approximately 100 EJ/y in 2050 if such policy frameworks and enforcing mechanisms are not introduced and if there is strong competition for biomaterials from other sectors. These issues are discussed later in the report.

Cornelissen and others (2012) analysed the supply potential and use of biomass in the context of a transition to a fully renewable global energy system by 2050. They investigated bioenergy potential within a framework of technological choices and sustainability criteria, including criteria for land use and food security, agricultural and processing inputs, complementary felling, residues and waste. They found that the potential for sustainable bioenergy from residues and waste, complementary felling, energy crops and algal oil in 2050 to be 340 EJ/y of primary energy. This potential was then compared to the demand for biomass-based energy in the demand scenario, the Ecofys Energy Scenario. This scenario, after applying energy efficiency and non-bioenergy renewable options, requires a significant contribution of bioenergy to meet the remaining energy demand: 185 EJ/y of the 340 EJ/y from potential supply. For land use for energy crops, they found a maximum of 2,500,000 km^2 was needed of a 6,730,000 km^2 sustainable potential. For GHG emissions from bioenergy, a 75–85% reduction could be achieved compared to fossil references. Cornelissen and others (2012) concluded that bioenergy can meet residual demand in the Ecofys Energy Scenario sustainably with low associated GHG emissions.

They did not include the following land for bioenergy cropping:
- land used for supplying food, feed and fibre, taking into account future population growth and a diet change scenario;
- land used for protection of biodiversity and high carbon stock forest ecosystems;
- land used for human development by expanding the built environment;
- land not or marginally suitable for rain-fed cultivation of energy crops.

This resulted in a 6,730,000 km^2 (673 million hectares (Mha)) potential for energy crops.

In their modelling approach Cornelissen and others (2012) acknowledged that:
- bioenergy requires a thorough analytical framework to analyse sustainability, as cultivation, harvesting and processing of biomass and use of bioenergy have a large range of associated sustainability issues;
- bioenergy encompasses energy supply for a number of energy carrier types, such as heat, electricity and transport fuels, using a multitude of different energy sources. Therefore, a detailed framework of conversion routes is needed.

The potential for sustainable additional forest growth was primarily based on a study by Smeets (2008) and reviewed by Cornelissen and others (2012). According to the study, the global technical potential for additional forest growth would be about 64 EJ of woody biomass in 2050. However, the ecologically constrained potential was found to be about 8 EJ. The difference is due to the exclusion of all protected, inaccessible and undisturbed areas. Thus, only areas of forest classified as 'disturbed and currently available for wood supply' are included. A further sustainability safeguard is the use of only commercial species in the gross annual increment, rather than all available species (Cornelissen and others, 2012).

The land available for bioenergy cropping in the work of Cornelissen and others (2012) is influenced by the assumptions made in the food analysis. Their results are sensitive to developments in food demand and supply and the balance between them.

The technical potential in residues from forestry is estimated at 12–74 EJ/y, that from agriculture at 15–70 EJ/y and that from waste at 13 EJ/y. These biomass resource categories are largely available before 2030, but are also partly uncertain. The uncertainty comes from possible competing uses (such as increased use of biomaterials from forest residues and the use of agricultural residues for fodder and fertiliser) and differing assumptions about sustainability criteria deployed with respect to forest management and agricultural intensity (IPCC, 2011).

The carbon mitigation potential for electricity generation from biomass reaches 1220 $MtCO_2eq$ for the year 2030, a substantial fraction of it at costs lower than US$2005 19.5/$tCO_2$. From a top-down assessment, the economic mitigation potential of biomass energy supplied from agriculture is estimated to range from 70–1260 $MtCO_2eq$/y at costs of up to US$2005 19.5/$tCO_2eq$ and from 560–2320 $MtCO_2eq$/y at costs of up to US$2005 48.5/$tCO_2eq$. The overall mitigation from biomass energy coming from the forest sector is estimated to reach 400 $MtCO_2$/y up to 2030 (IPCC, 2011).

3.2 Uncertainties in biomass potential

Obtaining insights into the consequences of large-scale bioenergy use is complex because of the number of factors involved. Bottom-up estimates have been used to assess potential bioenergy available. These studies result in bioenergy estimates of several hundred EJ/y in the second half of the century, but often do not take into account issues such as land degradation and water scarcity. Sensitivity analyses were carried out by Van Vuuren and others (2009) to determine whether these issues could influence estimates of bioenergy potential. Their calculations focused on dedicated bioenergy crops. Van Vuuren and others (2009) found the potential for bioenergy to be around 150 EJ under a business-as-usual scenario (the default scenario of the OECD Environmental Outlook). This does not take into account limitations of land degradation, water scarcity, or expansion of nature reserves. Alternative land-use scenarios and/or different yield assumptions lead to results ranging from 120–300 EJ/y. Yield assumptions especially represent a crucial uncertainty. The numbers are low compared to previous studies which had medium estimates of 300–800 EJ. However, more restrictive land-use criteria were used and agricultural residues were not included.

The potential reported is almost exclusively based on woody biomass such as willow and switch grass. Competition between bioenergy and food could be somewhat less for woody biomass than for bioenergy from food crops due to potentially higher energy yields and production in areas of low yields for food crops. Yet, large-scale application of woody bioenergy could lead to competition for land. Van Vuuren and others (2009) focused on the potential for bioenergy on abandoned agricultural land and natural grassland, thus excluding any form of competition. When land degradation, water scarcity and expansion of nature reserves were included, the minimum estimate was 65 EJ, and more modest corrections would limit potential to about 115 EJ. Thus, wider consideration of potential impacts of bioenergy may have consequences for availability estimates.

Van Vuuren and others (2009) concluded that in the period 2000-50, in terms of penetration, bioenergy will be limited by its marginal costs not by its total potential. This is because other options can be more competitive in terms of specific mitigation costs, especially for power generation.

3.3 Factors influencing biomass resource potentials

As mentioned in the previous section there are a number of factors that influence the potential size of the biomass resource for energy use.

3.3.1 Residue supply in agriculture and forestry

Soil conservation and biodiversity requirements influence the technical potential for both agriculture and forestry residues. However, modelling studies indicate that the potential loss of soil productivity may restrict the removal of biomass residues to much less than the quantity of biomass physically available in forestry (IPCC, 2011).

3.3.2 Dedicated biomass production in agriculture and forestry

There may be a significant potential to intensify conventional long-rotation forestry by increasing forest growth and total biomass output, for example, by fertilising selected stands and using shorter rotations. This could work well in regions of the world with large forest areas that currently practise extensive forest management. However, the prospects for intensifying conventional long-rotation forestry are often not thoroughly investigated in studies of biomass resource potentials. Besides tree plantations, short-rotation coppicing plants such as willow and perennial grasses such as switchgrass and *Miscanthus* are considered candidate bioenergy plants to become established on these lands (IPCC, 2011).

It is commonly assumed that biomass plantations are established on surplus agricultural land. Intensification in agriculture is therefore a key aspect in essentially all of the assessed studies because it influences both land availability for biomass plantations (indirectly by determining the land requirements in the food sector) and the biomass yield levels obtained (IPCC, 2011).

3.3.3 Use of marginal lands

Biomass resource potential studies also point to marginal/degraded lands, where productive capacity has declined temporarily or permanently, as areas that can be used for biomass production. Some studies show a significant technical potential for marginal/degraded land, but it is uncertain how much of this technical potential can be realised. The main challenges in relation to the use of marginal/degraded land for bioenergy include (1) the large efforts and long time periods required for the reclamation and maintenance of more degraded land; (2) the low productivity levels of these soils; and (3) ensuring that the needs of local populations that use degraded lands for their subsistence are carefully addressed (IPCC, 2011).

Scarcity of water and land are potential factors limiting bioenergy production. In evaluating land scarcity, consideration needs to be given to whether abandoned agricultural land becomes available; whether degraded lands can be used for bioenergy production; and whether natural areas can be used. Proponents of bioenergy often point to the opportunity to use degraded areas or set-aside land for bioenergy production for the following reasons: it would not lead to competition with crop production; it would not lead to biodiversity loss; and it could help improve soil quality. As such, the relationship between land degradation and bioenergy potential is important. However, Van Vuuren and others (2009) reasoned that severely degraded areas should be excluded for potential estimates as it may not be possible to reclaim these degraded soils for production or for natural vegetation. On less severely degraded areas, soil recovery might be enhanced in combination with bioenergy production.

3.3.4 Water scarcity

Local water scarcity may be an important factor in large-scale bioenergy production. The question remains, whether water use efficiency can be increased in agriculture and so increase biomass potential (Van Vuuren and others, 2009).

3.3.5 Biodiversity protection

Biodiversity considerations can limit residue extraction as well as the intensification and expansion of agricultural land area. Expansion of agricultural land for bioenergy production will lead to biodiversity loss, but the potential contribution of bioenergy to mitigating climate change may limit biodiversity loss. Both factors are uncertain. Given higher yields and the potential option of combining production and protection objectives, perennial lignocellulosic crops have lower impacts on biodiversity than food crops, but many questions remain to be answered (Van Vuuren and others, 2009).

3.3.6 Dietary change

Van Vuuren and others (2009) do not include the impact of dietary changes. Less meat-intensive diets could substantially reduce demand for pasture and crop land worldwide, and thus increase the area potentially available to grow bioenergy crops.

3.4 Potential in the EU

The EU27 biomass supply was reviewed by Panoutsou and others (2009) in terms of feedstock types, available quantities, quality characteristics, supply costs and future potentials for 2010, 2020 and 2030 based on individual sector analysis for agriculture, forestry and wastes. Biomass resource assessments are determined by various definitions for availability as well as the reliability of homogeneous datasets across regions. The accuracy of the predictions is further restricted by the expanding set of assumptions on which the availability is based, from land uses and resource yielding potentials to conflict with other markets and future demand. Large quantities of residues are traded informally, such as domestic firewood, straw for animal feed and bedding, but the respective trade records are heterogeneous and not comparable.

According to Panoutsou and others (2009), the total availability of biomass fuels in the western European countries (WEC), and central and eastern European countries (CEEC) in their study was 135 Mtoe/y (million tonnes of oil equivalent per year) for 2000, increasing to 186 Mtoe/y in 2020. The availability of agricultural residues was almost 60 Mtoe for 2020 with field agricultural residues accounting for two thirds of the total and wet manure for 17 Mtoe. Forest biomass has a slightly lower potential with 51 Mtoe for 2020, in which refined wood fuels have a major share (30 Mtoe). The growth in the availability of organic wastes is the most striking, but can be attributed to measures in the Landfill Directive.

Biomass availability in the examined Member States totals about 159 Mtoe/y for 2010; the agricultural biomass share is 54 Mtoe, forestry 46 Mtoe and waste derived biomass 30 Mtoe. The remaining 29 Mtoe derive from industrial biomass such as solid industrial residues, black liquor and sewage sludges. The CEEC present significant biomass potentials and in most cases supply costs are relatively lower than the WEC. However, this is expected to change gradually, and within the next few years supply costs in the CEEC will rise due to the increase in labour and land purchase/rent costs. However, some of the data remain unverified. Some key observations for biomass potentials in the various sectors are as follows (Panoutsou and others, 2009):

- Member States with a large agricultural area (France, Denmark, Poland, Bulgaria and Romania) have higher potentials for field residues.
- Potentials from eastern EU Member States (such as Poland, Hungary, Bulgaria and Romania) are expected to rise up to three-fold due to improved yields and management practices for example, but their respective cost is also expected to rise as a result of factors such as improved salaries, higher economic standards, and increasing land prices.
- Scandinavia and northern Member States have higher potentials and well developed forest industries due to landscape and climate.
- Southern Member States face more forest fires which combined with a less-developed infrastructure restricts forest potential.
- Untapped potential exists but much needs to be done in the areas of pre-conditioning and pre-sorting.

3.5 Potential in the USA

The US Department of Energy (US DOE) commissioned a report, 'US Billion-Ton Update: biomass supply for a bioenergy and bioproducts industry' (Perlack and Stokes, 2011). The 2011 report was an update of one produced in 2005 which was an estimate of potential biomass within the contiguous US based on numerous assumptions about current and future inventory and production capacity, availability and technology. In the 2005 study, a strategic analysis was undertaken to determine if US agriculture and forest resources have the potential capability to produce at least one billion dry tons of biomass annually, in a sustainable manner; enough to displace approximately 30% of the country's present petroleum consumption. So the study considered biomass for biofuel production, rather than cofiring for power generation, but it is still of interest. The study used conservative assumptions to ensure reasonable confidence in the study results. However, for both agriculture and forestry, the resource potential was not restricted by price. That is, all identified biomass was potentially available, even though some potential feedstock would probably be too expensive to be economically available (Perlack and Stokes, 2011). The 2011 report provides estimates of biomass to roadside or the farmgate. The estimates given do not represent the total cost or the actual available tonnage to the biorefinery. There are additional costs to pre-process, handle and transport the biomass. There may be storage costs for specific feedstocks. The estimates include losses to roadside, but do not include losses due to continued handling, additional processing, storage, material degradation, and quality separation. Two scenarios are evaluated: baseline and high-yield. The baseline scenario is derived from the US Department of Agriculture ten year forecast. The average annual corn yield increase is assumed to be slightly more than 1% over the 20 y simulation period. Energy crop yields assume an annual increase of 1%. Under the high-yield scenario the projected increase in corn yield averages almost 2%/y over the 20-year simulation period. Energy crop productivity is modelled at three levels, 2%, 3% and 4% annually. All feedstock quantities and their composite total are shown at price of 60 US$/dry tonne (dt) as it includes most of the available tonnage from all of the feedstocks.

Using the baseline assumptions, Perlack and Stokes (2011) found that over a price range of 20–80 US$/dt the quantity of forest resources varied from 33–119 million dry tonnes (Mdt) in 2010 to about 35–125 Mdt in 2030. Primary forest biomass, that is logging, fuel treatment operations and land clearing, is the single largest source of forest-based feedstock. The resource potential does not increase much over time given the standing inventory nature of the resource and how it is managed. Results also show that little conventional pulpwood is available for bioenergy at process below 60 US$/dt.

In sum, Perlack and Stokes (2011) found that potential supplies at a forest roadside or farmgate price of 60 $/dt range from 602–1009 Mdt by 2022 and from about 767–1305 Mdt by 2030, depending on the assumptions about energy crop productivity (1–4% annual increase over current yields). The estimate does not include resources that are currently being used, such as corn grain and forest products industry residues. If currently used resources are included the total biomass estimate increases to over one billion dry tonnes. Table 4 summarises current and potential biomass use in the USA.

The study does not evaluate a whole suite of sustainability criteria nor assess changes in the indicators as a function of production scenarios. Perlack and Stokes (2011) stressed that bioenergy markets do not currently exist for the resource potential identified. The analysis and results are based on limited data so require that numerous assumptions are made.

3.6 Summary

Narrowing down the technical potential of the biomass resource to precise numbers is not possible. It is expected that between less than 50 and several hundred EJ per year can be provided for energy in the future, the latter strongly conditional on favourable developments. The IPCC (2011) consider that deployment levels of biomass for energy could reach a range of 100–300 EJ/y around 2050. This can be compared with the present biomass use for energy of about 50 EJ/y. While recent assessments employing improved data and modelling capacity have not succeeded in providing narrow, distinct estimates of the biomass resource potential, they have advanced the understanding of how influential various factors are on the resource potential and that both positive and negative effects may follow

Table 4 Summary of currently used and potential forest and agricultural biomass at 60 US$/dt or less, under baseline and high-yield scenario assumptions (Perlack and Stokes, 2011)

Feedstock, Mdt	2012	2017	2022	2030
Baseline scenario				
Forest resources currently used	129	182	210	226
Forest biomass and waste resource potential	97	98	100	102
Agricultural resources currently used	85	103	103	103
Agricultural biomass and waste resource potential	162	192	221	265
Energy crops*	0	101	282	400
Total currently used	214	284	312	328
Total potential resources	258	392	602	767
Total – baseline	473	676	914	1094
High-yield scenario, 2–4%				
Agricultural biomass and waste resource potential†	244	310	346	404
Energy crops	0	139–180	410–564	540–799
Total potential resources	340	547–588	855–1009	1046–1305
Total high-yield, 2–4%	555	831–872	1168–1322	1374–1633

Under the high-yield scenario, energy crops are shown for 2–4% annual increase in yield. Numbers may not add up due to rounding.

* Energy crops are planned starting in 2014

† Agricultural residues are generated under a high-yield traditional crop scenario with high no-till adoption. Energy crop yield follows a baseline growth pattern of 1% annually

from increased biomass use for energy. One important conclusion is that the effects of land use change (LUC) associated with bioenergy expansion can considerably influence the climate benefit of bioenergy.

Biomass availability remains a critical issue for successful bioenergy deployment and the recent increased interest in the bioenergy sector may restrict current and future planning and investment opportunities (Panoutsou and others, 2009).

In policy terms, the debate on the consequences of large-scale bioenergy use has led to an interest by policy-makers in sustainability criteria. For example, current EU legislation sets criteria with respect to biodiversity impacts: ‘not be made.... from land with recognised high biodiversity value’ and the GHG balance. An important issue is how much bioenergy potential remains if such criteria are met (Van Vuuren and others, 2009). Thus the following chapters investigate the issues of sustainability of biomass in more depth.

4 Life cycle assessment of biomass for sustainability

Life cycle assessment (LCA) methodology, or a life-cycle approach is often used to estimate the environmental impacts of biomass energy uses. This chapter considers the relevant factors in the life cycle assessment (LCA) of biomass for fuel that influence its assumed carbon neutrality. Much of this scientific literature has been reviewed by Cherubini and Strømman (2011). Various aspects of LCA are described in this chapter, followed by an introduction to the main factors that influence the GHG balance of biomass production.

4.1 Life cycle assessment

Life cycle assessment (LCA) is a powerful tool that may be used to quantify the environmental impacts of products and services. It includes all processes, from cradle-to-grave along the supply chain of the product. Prompted perhaps by the variety of processes for converting biomass resources to bioenergy for heat, electricity or transport purposes, and the vigorous discussion of the 'net benefit' of bioenergy, many studies have been undertaken worldwide using LCA methodology to analyse the GHG and energy balance of various bioenergy systems (Bird and others, 2011). The International Standards Organisation (ISO) has also published a series of standards for LCA (ISO 14040, 14044).

The life cycle emissions of a bioenergy system are compared with the emissions of a reference energy system when using LCA to determine the climate change mitigation benefits of bioenergy. The selection of the reference energy system can strongly affect the outcome. The type of technology, scale of plant, and co-products in both the bioenergy and reference energy system can influence the GHG mitigation benefits of the bioenergy system. The reference energy system chosen should be one that is realistically likely to be displaced by the bioenergy system. If this reference system is not certain, then one option is to use the average fossil energy for that region as the reference energy system. Another option is to make a conservative evaluation by comparing the bioenergy system with the best available fossil energy technology (Bird and others, 2011).

Comparing the two systems requires some metric for the comparison. In LCA terminology, this is called the functional unit. It provides a reference to which the input and output process data are normalised. The results of the comparison are expressed in terms of the same functional unit, to ensure that the comparison of different systems is based on the delivery of the same service (Bird and others, 2011).

4.1.1 Functional unit

Four types of functional units can be identified in LCA of bioenergy systems which makes it difficult to compare LCA results. The four are:

1 Input unit related: the functional unit is the unit of input biomass, either in mass or energy unit. Results are independent from conversion processes and type of end-products with this type of functional unit. This unit is selected for studies which aim to compare the best uses for a given biomass feedstock (Cherubini and Strømman, 2011). Using input-related functional units answers the following questions (Bird and others, 2011):
   - What amount of GHG emissions and fossil energy might be saved by using one biomass input unit (that is kgCO_2eq saved/kg biomass)?
   - What amount of GHG emissions and fossil fuels can be saved per hectare by cultivating energy crops on agricultural land or harvesting forests for wood fuel (that is kgCO_2eq saved/ha)?

2 Output unit related: the functional unit is the unit of output, such as unit of heat or power produced. This type of functional unit is usually selected by studies which aim to compare the provision of a given service from different feedstocks. Output-related functional units answer the question (Bird and others, 2011):
   - What amount of GHG emissions and fossil energy might be saved by providing the same energy service from bioenergy?
     Output-related functional units depend on the type of energy service provided by the bioenergy system. For example a typical functional unit for heat is gCO_2eq saved/kWh_{heat} and for electricity it is gCO_2eq saved/$kWh_{electricity}$.
3 Unit of agricultural land: the functional unit refers to the hectare of agricultural land needed to produce the biomass feedstock. This unit should be the first parameter to take into account when biomass is produced from dedicated energy crops. The question of relative land use efficiency for different biofuel pathways is often not addressed in LCA.
4 Year: results of the assessment may even be reported on an annual basis. This type of functional unit is used in studies characterised by multiple final products, since it avoids allocating the emissions between the various products.

The output unit related functional unit is used the most frequently, while results per unit of agricultural land is used the least often even if they are based on biomass derived from dedicated crops. This is an important parameter since biomass could compete with food, feed or fibre production under land-availability constraints (Cherubini and Strømman, 2011).

4.1.2 Reference system

The reference system should always refer to the scope and geographical context of the study. In general, the bioenergy system is compared with a fossil fuel reference system producing the same amount of products and services. It should be noted that when production of feedstock for bioenergy uses land previously dedicated to other purposes or when the same feedstock is used for another task, the reference system should include an alternative land use or an alternative biomass use, respectively. This requirement increases the uncertainty of the assessment, making the adoption of consequential LCA questionable. Similarly, when the bioenergy pathway delivers some co-products able to replace existing products, the reference substituted products should be defined in the fossil reference system and the emissions for their production accounted for (Cherubini and Strømman, 2011).

The definition of the reference system may also play a key role in the estimation of the environmental impact savings of the bioenergy chain. According to the assumptions made, results can differ widely. In fact, fossil fuel-derived electricity can be assumed to be produced from oil, natural gas, coal or other sources, all of which have different GHG emission factors. Clearly, savings are larger if coal derived electricity is displaced rather than natural gas derived electricity. The definition of a fossil fuel reference system is used in legislation, which usually set specific GHG emission savings targets which bioenergy systems must achieve (see for instance the EU directive and the US Energy Independence and Security Act) (Cherubini and Strømman, 2011).

The basic format for calculating the GHG reduction when comparing a particular biomass production chain with a reference fossil fuel chain is (Guinée and others, 2009):

$$GHG_{reduction}\ (\%) = GHG_{emission,\ fossil\ chain} - GHG_{emission,\ biochain}\ x\ 100\ GHG_{emission,\ fossil\ chain}$$

Problems that show up persistently in LCA of bioenergy and products from agriculture and forestry in general include:
- the handling of biogenic carbon balances;
- the treatment of co-products and recycling.

4.1.3 System boundary

The scope of the analysis (the system boundary) should include all processes along the value chain that have significant GHG emissions including, where relevant, upstream processes of extraction or biomass production, and end-of-life processes. The system boundary should be defined so that the bioenergy and reference fossil systems provide equivalent products and services. If it is not possible to achieve this through expansion of the system boundary then the GHG can be allocated amongst energy and non-energy co-products of the bioenergy system (such as biodiesel and rapeseed cake, from processing of rapeseed oil), based on their share of physical (for example energy) or financial contributions (Bird and others, 2011). Changes in carbon stocks in biomass, soil, and landfill can cause GHG emissions (or removals). These can be important and so should be included in the analysis.

As it has been suggested by policy makers that the GHG indicator may constitute the basis for granting subsidies to stimulate the use of bioenergy, for example, it is important that the indicator results are robust. According to Guinée and others (2009), most guidebooks on LCA do not contain discussions on how to handle biogenic carbon balances, and nor do they include guidelines for how to handle sequestering 'negative emissions' of CO_2. Common practice in energy LCA is that no explicit biogenic carbon balances are made, but that CO_2 fixation during crop growth for bioenergy is set to zero, and the CO_2 emission of combustion of the biofuel is also set to zero. In some cases, the part of CO_2 fixated but released as CH_4 may have been manually corrected by taking the full amount of biogenic CH_4 into account (Guinée and others, 2009).

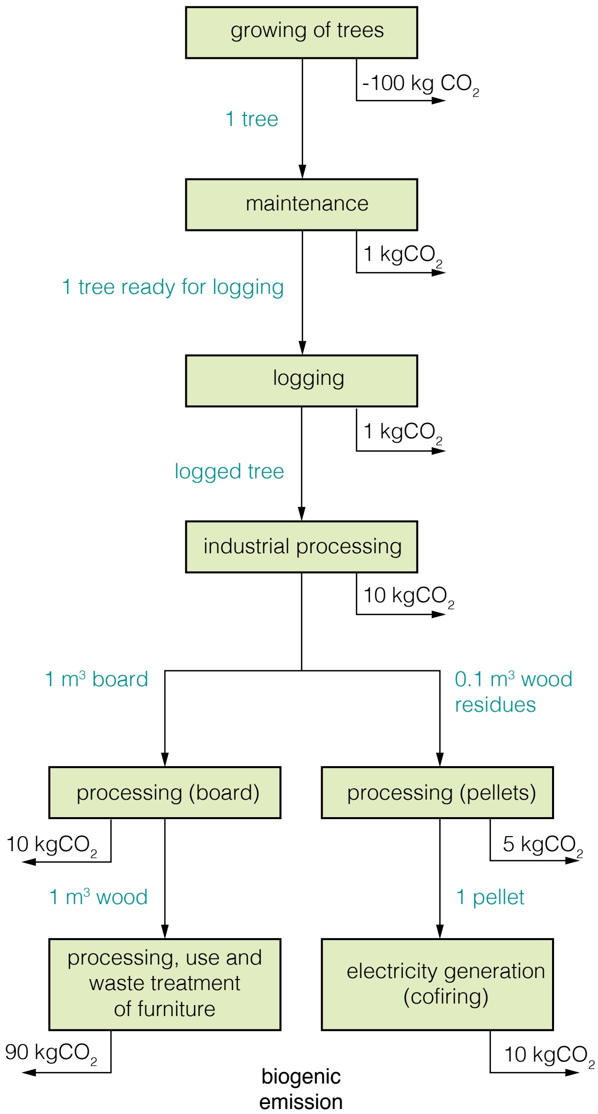

Figure 1 Production system for wood pellets for cofiring (Guinée and others, 2009)

4.1.4 Allocation

Allocation in LCA is carried out to attribute shares of the total environmental impact to the different products of a system. This concept is important for bioenergy systems, which are usually characterised by multiple products. For example, wood residues from timber production are used to generate electricity, and so is manure from poultry farming. Incorporating co-products in the modelling framework is therefore a critical issue (Guinée and others, 2009). The publicly available methodological standards try to overcome such a divergence on allocation methods, by proposing specific procedures. However, they all recommend different approaches (Cherubini and Strømman, 2011).

As illustration, the production of wood pellets for cofiring in a coal-fired power plant has been used as a hypothetical biofuel system for analysis of the sensitivity of the GHG indicator. The functional unit is 1 kW of electricity (Guinée and others, 2009). Figure 1 is a flow diagram of the production system of wood pellets that are cofired in a coal-fired power plant. The example is limited to CO_2

only, and therefore units are $kgCO_2$, and the values for CO_2 emissions are fictitious and rounded figures.

The EU directive suggests allocation of GHG emissions according to the energy content of co-products (EU, 2009).

4.2 Factors in LCA of biomass

Some of the relevant factors in an LCA of biomass include:
- co-products of biomass production;
- agricultural and forestry techniques;
- land use change and indirect land use change.

However, there are other environmental impacts that need to be considered besides the GHG balance, when considering the sustainability of a biomass enterprise. These include emissions from additional vehicle movements and the plant itself, environmental effects of agricultural chemical use, any

Table 5 Possible benefits and consequences of different aspects of bioenergy development (Thornley, 2006)

Factor	Benefits	Consequences
Environmental	Increased biodiversity	Impacts on particular native species
	Reduced GHG emissions	Loss of existing natural habitats
	Possible improved soil fertility	Visual impact of crop growth and conversion plant
	Uptake/removal of heavy metals from soil	Associated traffic noise and pollution
	Generally reduced use of agricultural chemicals compared to conventional arable farming	Environmental emissions associated with thermal conversion plant
		Uptake of significant amounts of water from below ground
		Potential soil erosion with poor management practices
Social	Diversification of rural economies	Actual and perceived impact of conversion plant on quality of life
	Opportunities for farm labourers in winter months	Potential impacts on tourism and leisure opportunities
	Local employment at conversion plant and associated activities	
	Potential for low cost heat supply	
	Potentially improved security of supply	
Economic	Potential income stream for farmers	Requirement for financial/policy support in addition to existing Renewable Obligation (RO) (UK)
	Local economic activity related to employment opportunities	
	Development of manufacturing and export potential	
	Competitive/expensive cost per tonne of CO_2 saved?	

changes in soil fertility, mineral and carbon balance, ecological impacts on natural and semi-natural habitats and the biodiversity supported. There are socio-economic impacts that are also factors in sustainability that could be expected from modifying existing land-use patterns to accommodate energy crops. These factors include changes in agricultural labour patterns, and positive contributions to rural economic diversification. There may be potentially negative implications for the preservation of sub-soil archaeological remains given the extent and invasiveness of root spread from some biomass crops. The thermal conversion plant itself may also have social impacts. For example, new biomass capacity may result in an adverse reaction from sections of the local community. Table 5 illustrates some of the possible impacts arising from bioenergy development (Thornley, 2006). However, the focus of this chapter is on the GHG balance of biomass, as the social and economic sustainability issues are beyond the scope of this report.

4.3 Greenhouse gas emissions

The most important GHG in energy systems are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). CO_2 is the main product of the combustion of fossil fuel and biomass. The amount of CO_2 emitted per energy unit depends, among other things, on the carbon content and heating value of the fuel. In the biosphere, CO_2 is removed from the atmosphere by growing plants, through photosynthetic production of carbon compounds and their subsequent accumulation in plant biomass. CO_2 is also produced by the aerobic degradation (decay) of biomass. Carbon stock changes that occur because of land use changes are converted to CO_2 by multiplying by the ratio of the molecular weights of CO_2 to C.

Methane (CH_4) is the main component of natural gas, but it is also a product of incomplete combustion processes. In the biosphere, the anaerobic degradation of biomass produces CH_4. This occurs mostly from the management of animal and human excrement, the landfilling of organic waste and rice production.

Nitrous oxide (N_2O) is formed in combustion processes under certain conditions. N_2O is also emitted as a consequence of nitrification and de-nitrification processes controlling the fate of nitrogen applied as chemical fertiliser, manure or through fixation by legumes.

Global Warming Potential (GWP) is used to express the contribution of different GHG to global warming. The impacts of the non-CO_2 GHG are expressed in terms of the equivalent amount of CO_2 (CO_2eq). The equivalency factors of the different gases are dependent on the time period over which the equivalency is calculated since different gases have different residence times in the atmosphere. Usually 100 year GWP factors are used. For example, 1 gCH_4 has the equivalent global warming impact of 25 gCO_2 when a 100 year time horizon is used. Using the same time horizon, 1 gN_2O has the equivalent global warming impact of 298 gCO_2.

4.3.1 GHG balance

LCA studies of bioenergy systems report results with different indices and indicators, often based on different functional units, and use different reference systems to estimate GHG emission savings. This means that outcomes are often not immediately comparable and can be hard to interpret. Moreover, there is a wide variation of methodologies used to estimate GHG emissions, mainly due to the selection of system boundaries, allocation procedures, inclusion of land-use change effects and others. As a consequence, this indicator has a higher degree of divergence across studies than energy analysis which is why regulatory agencies and organisations have proposed methodological standards for calculating the carbon footprint of products (EU, 2009; ISO, 2013; PAS2050, 2011) (Cherubini and Strømman, 2011).

Bioenergy systems generally ensure GHG emission savings when compared to conventional fossil reference systems. For example, net GHG emissions from generation of a unit of electricity from biomass are usually 5–10% of those from fossil fuel-based electricity generation (Cherubini and others, 2009; Varun and others, 2009). The ratio will be more favourable (lower), if biomass is produced with low energy input (or derived from residue streams), transported short distances or by fuel-efficient means of transport, converted efficiently (ideally in cogeneration applications) and if the fossil fuel reference use is inefficient and based on a carbon-intensive fuel such as coal. However, the inclusion in the GHG balance of indirect effects is important, given their potentially large influence on final results. Another issue is the allocation of GHG between co-products (Johnson, 2009; Searchinger and others, 2008; Cherubini and Strømman, 2011).

Choice of biomass feedstock plays an important role in the GHG emissions of the bioenergy system. In general, the use of industrial and domestic residues for bioenergy has the lowest GHG emissions from the procurement stage. Energy crops grown specifically for bioenergy have the highest emissions, due to the energy and material input, from the use of tractors and fertilisers for example. Bioenergy systems based on in-field crop and forestry residues generally have intermediate emissions. However, the use of the non-energy co-products of energy crops (such as soy meal for animal feed) and the reference use of the residues must be taken into account, as these factors can enhance or counteract the GHG savings from use of bioenergy (Bird and others, 2011).

4.4 Energy balance

Many bioenergy LCA studies include primary energy analysis in their assessment, in order to quantify the possible non-renewable energy savings of the bioenergy system. The energy analysis approach usually evaluates all the energy inputs along the full chain, from agricultural cultivation, transport, processing and final distribution. The resulting cumulative primary energy demand is sometimes used to calculate the Energy Return on Investment (EROI) index. This index is the ratio between energy out (that is the energy content of the biofuel) and the non-renewable energy that is required along the full life cycle. The cumulative energy demand can even be divided into fossil and renewable. Ranges on biomass for heat and power production are available (Cherubini and others, 2009; Cherubini and Strømman, 2011).

In general, bioenergy systems have lower conversion efficiency than fossil fuel ones which mean that their primary energy demand is greater to achieve the same level of energy output as fossil fuel energy systems. Thus, although more fuel is required, it is mainly the renewable energy fraction of the feedstock that is increased, and the fossil fuel energy consumption is significantly smaller (Cherubini and Jungmeier, 2010; Cherubini and Ulgiati, 2010). In bioenergy systems, the fossil fuel energy demand is predominantly affected by fossil fuel energy inputs during cultivation or processing (Cherubini and Strømman, 2011).

4.5 Land use change

Generally, organic carbon is stored in five different pools: above ground vegetation, below ground vegetation, dead wood, litter and soil. When changing land utilisation, these storage pools change until a new equilibrium is reached. This is an important aspect because of the large sizes of these storage pools, especially soil organic carbon (SOC). This stock of carbon is so large that even relatively small changes in its size can have relevance to the GHG balance. Land use changes (LUC) are therefore deemed especially important, and their effects can consistently reduce GHG savings of bioenergy systems based on dedicated crops or agricultural and forest residues, depending on the nature of the changes and the period of time assumed. There is no widely accepted methodology for including land use impacts in LCA. A distinction is generally made between direct and indirect LUC (Cherubini and Strømman, 2011).

4.5.1 Direct land use change (DLUC)

DLUC occurs when new agricultural land taken into production and feedstock for biofuel purposes displaces a prior land use (for example conversion of forest land to sugarcane plantations), thereby generating possible changes to the carbon stock of that land (Cherubini and Ulgiati, 2010; Cherubini and Strømman, 2011).

Depending on the earlier use of the land and the crop to be established, LUC can be a benefit or a disadvantage. When a forest is converted to agricultural land for biofuel production a loss of carbon stocks and a decrease in biodiversity is expected; this loss of carbon affects the whole GHG balance and may even make the bioenergy system worse than its respective fossil fuel reference. When set-aside land is taken into production, or perennial herbaceous crops replace annual row crops, the carbon stock may increase; this means that atmospheric CO_2 is sequestered from the atmosphere and stored in SOC, with a positive effect on the GHG balance of the bioenergy system (Cherubini and Jungmeier, 2010). The changes of carbon in soil and other pools are site-specific and highly dependent on former and current agronomic practices, climate, and soil characteristics. The approach generally used to estimate LUC effects is to quantify the increase or decrease of a carbon pool (both above and below ground) for a certain period of time, and then include this carbon loss as CO_2 emissions in accordance with the selected functional unit. This means that LUC effects are amortised over an assumed time horizon, spreading out an emission that mainly occurs in a short period of time over a longer time frame. This approach underestimates the true climate change effects of LUC, since the effect of a GHG increases with the time it remains in the atmosphere. Efforts to overcome this inconsistency can be recognised both in the literature (Kendall and others 2009; O'Hare and others, 2009) and methodological standards (ISO, 2009; ISO 2013).

Changes in carbon pools are usually estimated by means of literature references or software tools able to model soil carbon dynamics. In addition, the IPCC provides default values by which it is possible to estimate the annual effect of direct LUC (IPCC, 2006). The use of IPCC default values is recommended by most of the methodological standards, which suggest the use of annualised emissions over an arbitrary time frame, usually 20 years (EU, 2009; PAS2050, 2008). In particular, PAS2050 provides tables for conversion of forest land and grassland to agricultural land, disregarding SOC changes for agricultural soils, while the ISO GHG protocol stresses the importance of defining proper time boundaries for the assessment, in order to include future emissions (ISO, 2009). The EU directive has a specific land use section, which provides guidelines to estimate GHG emissions induced by LUC, which are straight-line amortised over 20 years (EU, 2009; Cherubini and Strømman, 2011).

4.5.2 Indirect land use change (ILUC)

Indirect land use change (ILUC), or leakage, occurs when land currently used for feed or food crops is changed into bioenergy feedstock production and the demand for the previous land use (that is feed or food) remains; the displaced agricultural production will move to other places (for instance, expansion of agricultural land after deforestation). If Farmer A converts his land from growing wheat to growing switchgrass, that is an example of DLUC. However, this DLUC may result in ILUC if for example, the reduced wheat availability drives up the wheat price, and so increases wheat production elsewhere. Thus if Farmer B converts his pasture to wheat cropping as a consequence of the action of Farmer A, CO_2 emissions may occur due to the ploughing of pasture land inducing SOC oxidation. This loss of SOC stock is an ILUC emission as it occurs at a site not directly affected by the biomass production, outside the control of Farmer A, and therefore outside the system boundary of the bioenergy system.

Quantifying emissions due to ILUC is difficult because, as there is no direct link, it is not possible to identify which land use change is a result of a specific bioenergy system, nor which land use change is due to other causes, such as increased demand for food by the growing global population, or urban expansion. Complex inter- and intra-sector interactions and trends need to be considered to determine emissions due to ILUC. These include regional and global deforestation, diets and their responsiveness to food prices, cropland expansion and trade of food, feed, fibre and bioenergy, and then ILUC can be calculated on a regional or sectoral basis.

Measures can be taken to minimise ILUC associated with bioenergy, for example, by using biomass that is considered waste, or land that is not under agricultural production. Specific measures include:
- lowering biomass demand through options such as stringent bioenergy efficiency requirements and efficient biomass-to-energy conversion;
- using wastes and residues as biomass sources for bioenergy;
- increasing biomass yield per hectare;
- increasing the intensity of production on other land remaining under agricultural use;
- using co-products as animal feed;
- using unproductive land (set-aside, fallow, degraded or otherwise marginal land) for energy production;
- integrating biomass production with agricultural land uses, such as through agroforestry.

Some of these measures are general requirements for optimising bioenergy systems but they may also mitigate food sector impacts resulting from the introduction of a bioenergy system. However, the consequences for land use change and the food sector will depend on the overall context, including existing policies. For instance, requirements for efficient biomass-to-energy conversion lower the biomass use per unit energy service provided, but also make biomass more valuable as bioenergy feedstock and this might instead increase the land pressure (and land price, and therefore food price) as biomass demand increases. If targets are set for specific bioenergy contributions then bioenergy efficiency requirements lower the volume of biomass needed to reach the target. If instead CO_2 targets or general renewable energy targets are used, and if more cost competitive bioenergy options become available, then more bioenergy will be used. In such a scenario, the GHG mitigation costs will be lower, but land use competition and pressures on valuable natural ecosystems may increase. In the absence of instruments discouraging conversion of carbon-rich land, the net effect may even be that land use change emissions increase.

It will be important that increased intensity of production (the third and fourth measures listed above) do not result in unsustainable land use practises, or perverse outcomes such as increased net GHG emissions due to higher N_2O emissions from additional nitrogen fertiliser inputs intended to increase biomass yields.

ILUC can be an issue with forestry as well as with agricultural biomass. For example, the diversion of forest biomass from household heating to electricity production may cause ILUC to supply biomass for household heating, as the household will need to replace their fuel wood with another source.

Land use change may be the most important factor that affects the GHG balances of bioenergy systems. According to Bird and others (2011), in extreme cases, the total emissions caused by land use change in order to create the bioenergy system may be more than 100 times greater than the annual GHG savings obtained from displacing fossil fuel consumption. Even if no methodological standards exist, GHG emissions from ILUC have been deemed by some to be even more important than emissions from DLUC (Cherubini and Strømman, 2011).

4.6 Non-CO_2 GHG emissions from soils

The contribution to net GHG emissions of N_2O, which evolves from nitrogen fertiliser application and organic matter decomposition in soil, is an important variable in LCA studies. Emissions from fields vary depending on soil type, climate, crop, tillage method, and fertiliser and manure application rates. The uncertainties in actual emissions are magnified by the high global warming potential of N_2O, which is 298 times greater than CO_2 over 100 y. The impacts of N_2O emissions are especially significant for annual biofuel crops, since they receive more fertiliser than perennial energy crops. Crops grown in high rainfall environments or under flood irrigation have the highest N_2O emissions, as denitrification is favoured under moist soil conditions where oxygen availability is low. N_2O emissions are generally quantified as a fraction of fertiliser nitrogen content and are based on literature references such as IPCC default emission factors (IPCC, 2006). Use of these factors is also recommended by PAS2050, while other methodological standards, including the EU directive, do not explicitly mention N-based soil emissions. IPCC data estimate that about 1.0–1.5% of N in synthetic fertiliser is emitted as N in N_2O in temperate regions. Crutzen and others (2007) used a different procedure for estimating this emission and proposed a value of 3–5%. In contrast, other studies claim that Crutzen and others (2007) apply an uncertain approach, questionable assumptions and inappropriate, selective comparisons to reach their conclusions (RFA, 2008). The application of fertilisers has other environmental impacts besides GHG emissions, such as contributing to acidification and eutrophication. However, it should be remembered that most biomass for cofiring originates as forest residues, and nitrogenous fertilisers are not widely applied in forestry.

Conversion of land use from cropland or pasture to woody energy crops may reduce emissions of CH_4. Within an LCA study, soil CH_4 fluxes usually make a relatively small contribution to the total life cycle GHG emissions of the bioenergy chain (Bird and others, 2011).

4.7 Environmental impact of residue removal

There is an ongoing debate about the desirability of utilising crop harvest residues from agricultural cropping systems for bioenergy production. Currently, there are generally two uses for these harvest residues: (i) removal for use as fodder or bedding for animals; or (ii) soil management where the harvest residues are either left on the surface as a mulch, or ploughed into the soil. In the first case, the straw is a valuable co-product that needs to be replaced if the straw is used for bioenergy. For example, an alternative source of animal feed should be provided in the bioenergy system and included in the analysis. If the residue is instead used for soil management in the reference system, the removal of crop residues could increase soil erosion, and reduce soil organic carbon (SOC) and nutrient content, potentially leading to soil productivity losses and lower crop yields. The effects are strongly influenced by local conditions such as climate, soil type and crop management (Bird and others, 2011). Direct GHG effects of this removal are a decline in SOC, and possibly changes in N_2O and CH_4 emissions from soil. In addition, if the soil fertility decreases, countervailing measures such as increased application of fertilisers to maintain yield levels or expansion of cropland to compensate for the yield losses, will likely result in additional GHG emissions. The system boundaries of the bioenergy system can be expanded to include this additional crop production elsewhere to consider such consequences (Bird and others, 2011).

4.8 Soil organic carbon

The change in SOC due to change in land use or land management is an important variable. The amount of SOC is site-specific and dependent on former and current agronomic practices, climate, and soil characteristics. At any one time, the amount of SOC reflects the balance between the inputs from plant residues and other organic matter, and losses due to decomposition, erosion and leaching. Intensive cultivation leads to loss of SOC, partly through the physical disturbance caused by tillage, which can stimulate decomposition. However, changed management to increase the biomass output from forests, such as forest fertilisation, can result in increased SOC (Bird and others, 2011).

Measuring changes in SOC is difficult as SOC depletion and build-up are relatively slow processes and SOC stocks are spatially variable. However, studies indicate that short rotation perennial bioenergy crops can increase SOC compared with intensive cropping. On the other hand, increasing intensity of harvest from existing agricultural and forest systems, and replacing pastures with short rotation energy crops may reduce SOC (Bird and others, 2011).

4.9 Timing of GHG emissions and removals

LCA is usually concerned with total environmental impacts over the entire lifetime of a process or service. Therefore, in conventional LCA it is commonly assumed that timing of emissions and removals is not important: the same weight is given to emissions that occur in the past, present and future. Thus, in LCA the total emissions from a process, including the establishment phase, are often amortised over the lifetime of the process. However, when operating a bioenergy system, there may be GHG emissions that occur primarily in the early stages (such as from combustion of biomass, as compared to natural decay due to utilisation of harvest and wood processing residues), even when the land is being sustainably managed in the long run (Bird and others, 2011).

Compensation for these emissions through carbon removals from the atmosphere may take some time; a new dynamic equilibrium will be reached, governed by dynamic ecosystem processes associated with the next rotation (for example forest growth and SOC dynamics) and the energy and bio-based products that are harvested (that is the fate of products and wastes). During the transition to a new equilibrium carbon balance, there will either be a net emission of CO_2 if carbon stocks are lower in the new land use, or there will be a net removal of CO_2 from the atmosphere if carbon stocks increase to a higher level under the new land use (Bird and others, 2011). However, there is agreement that over the long-term, bioenergy reduces GHG emissions when compared to fossil energy.

Example: Cofiring of plantation residues in existing 500 MW wood-fired generating station 360 km away from plantations (Bird and others, 2011)

In this example, the biomass is trucked 360 km and cofired in an existing 500 MW generation station. The facility is a pulverised coal fired plant in which biomass is cofired at a ratio of 5% by weight. The efficiency of the system is 29%, which is lower than the efficiency of coal combustion alone due to the higher moisture content of the biomass. In the reference system, electricity is generated from a 500 MW hard coal-fired power station. Forestry thinning residues decay on the forest floor, harvest residues are burned in the field and unused sawmill residues are burned at the mill.

Results: The results are shown in Table 6. Cofiring results in lower emissions per unit of biomass than the stand-alone system due to the greater efficiency of energy conversion in the cofired plant. (Note that the result for cofiring applies only to the electricity derived from biomass, not to the total

Table 6 GHG balance and energy input of 500 MW biomass cofired electricity generation (Bird and others, 2011)

Item	Reference system	Study system
Fossil energy input, kwh/kwh_{elec}		0.45
Emissions		
Land management change, gCO_2eq/kWh_{elec}	–235	–186
Cultivation and harvesting, gCO_2eq/kWh_{elec}	28	40
All other emissions, gCO_2eq/kWh_{elec}	981	88
Total, gCO_2eq/kWh_{elec}	774	-59
Emissions saved, gCO_2eq/kWh_{elec}	853	
tCO_2eq/t_{dry}	1.30	

electricity output of the plant). The long transport distances by truck increase the emissions for cofired bioelectricity. In comparison, the emissions for electricity production from the reference coal-fired power plant are 981 gCO_2eq/kWh. Overall, the GHG emission savings per tonne of biomass for the cofiring option are higher than the stand-alone option, due to the higher efficiency of the cofiring system, even though there are higher transport emissions due to the longer transport distance to coal-fired power stations.

While there seems general agreement that carbon emitted from biomass combustion was and will again be sequestered from the atmosphere given a sustainable biomass management system, and thus that bioenergy is a form of renewable energy, there is inherent concern that carbon release and sequestration rates may not be in temporal balance with each other. A temporal imbalance challenges whether an increase in bioenergy use may counteract current climate mitigation targets and requires a full accounting of bioenergy systems, incorporating life cycle with temporal carbon analyses against a reference of reduced bioenergy expansion. This is particularly the case for woody biomass-based systems that rely on longer rotation cycles. Biomass systems based on short rotation crops generally do not face this issue, and may even accrue initial carbon credits if established on land with low initial carbon stocks (Lamers and Junginger, 2013).

The temporal imbalance between the release and storage of carbon has raised a fundamental concern about the climate mitigation potential of forest biomass for energy. The potential carbon debt caused by harvest and the resulting time spans needed to reach pre-harvest carbon levels (payback) or those of a reference case (parity) have become important parameters for climate and bioenergy policy developments. The present range of analyses however varies in assumptions, regional scopes, and conclusions. Lamers and Junginger (2013) compared various modelling efforts and found that the results were largely affected by the same parameters. The size of the carbon debt is mostly determined by the type and amount of biomass harvested and whether land use change emissions need to be accounted for. Payback times are mainly determined by plant growth rates, that is the forest biome, tree species, site productivity and management. Parity times are primarily influenced by the choice and construction of the reference scenario and fossil carbon displacement efficiencies. Using small residual biomass (harvesting/processing), deadwood from highly insect-infected sites, or new plantations on highly productive or marginal land offers (almost) immediate net carbon benefits. However, their eventual climate mitigation potential is determined by the effectiveness of the fossil fuel displacement.

Current global wood pellet production is predominantly residue based. Production increases based on low-grade stemwood are expected in regions with a downturn in the local wood product sector, which highlights the importance of accounting for forest carbon trends.

While the study of single cut blocks may provide results that are easy to understand, for example on carbon effects of different harvesting choices, timber/woody biomass supply areas consist of several cut blocks, that is they have a time and space dynamic. Thus, Lamers and Junginger (2013) visualised an area consisting of *x* (80 for example) individual cut blocks following an *x* (80) year rotation cycle. One plot is harvested per year while the remaining *x-1* (79) (re-)grow. Harvesting choices can be randomised but they are typically organised sequentially, so that the first cut block is harvested again only after a regrowth period of *x* (80) years. The landscape carbon balance forms the total sum of all cut blocks. Harvesting regrown forest means that the net forest carbon emissions are zero, if no significant soil disturbance and soil carbon release has taken place.

Recent studies evaluating the carbon debt of bioenergy production from forest biomass vary in assumptions and methodologies, regional scopes, and ultimately conclusions. Policy makers are confronted with this portfolio while needing to address the temporal carbon aspect in current regulations. In order to define policies for our carbon constrained world, it is critical to understand better the dimensions and regional differences of these carbon cycles (Lamers and Junginger, 2013).

4.10 Recent trends and future challenges

This introduction to LCA for biomass shows that the determination of environmental performance is complex, and different combinations of feedstocks, conversion routes, fuels, end-use applications and methodological assumptions may lead to a wide range of results. In particular, different approaches are used to deal with the indirect effects which have a large influence on final figures, and the way by which they should be estimated is still under discussion. Even though valuable improvements have been achieved in determining the direct GHG emissions of bioenergy, a standard methodology for the indirect effects is still at a preliminary phase, and further research is needed. It is therefore likely that future LCA studies will focus on reducing the uncertainties of these current key open issues, such as the inclusion in the assessment of ILUC effects and their amortisation over time (Cherubini and Strømman, 2011). However, it is generally accepted that ILUC is not a major issue for biomass sourced from forestry.

Standardisation in GHG balance accounting (the carbon footprint) of products is perceived as urgent by policy makers, and so standards are being developed to try to address this need. A variety of policy objectives have motivated various governments around the world to promote bioenergy, on condition that a certain amount of GHG emission savings is achieved. Thus legislation requires a standardised GHG accounting procedure to encompass the inclusion of indirect emissions in the life cycle of bioenergy, even if this topic is still in its scientific infancy. In most of the proposed standards, the guidelines tend to simplify or overlook concepts such as ILUC effects and carbon storage in products. In addition, methodological standards usually restrict the assessment to a limited number of indices and indicators. On one hand, these simplifications can make the overall assessment and interpretation of final results easier, but on the other hand approximation and fixed approaches may have the drawback of misleading and inaccurate conclusions. Finding a compromise is challenging, because a certain degree of simplicity and standardisation in sustainability assessment of bioenergy systems is desirable (Cherubini and Strømman, 2011).

Standardisation of the inclusion of indirect effects in LCA may also give the possibility to establish LUC policies aimed at mitigating climate change. In fact, while deforestation and decrease of SOC are detrimental for climate change, suitable land use policies may even have the opposite effect, given the large potential of GHG mitigation provided by CO_2 sequestration in terrestrial and vegetation carbon pools (UN-REDD, 2008; UNFCCC,2005).

4.11 Summary

LCA is a powerful tool used to quantify the environmental impacts of products and services. It includes all processes from cradle-to-grave along the supply chain of the product or service. LCA can be used to quantify the GHG emission savings of bioenergy, by comparing the bioenergy system with a reference fossil energy system. However, large ranges of GHG emissions and emissions saved per functional unit are given from LCA studies of similar bioenergy systems. The differences occur for a multitude of reasons. For example, the studies may use different technologies, different system boundaries, different reference systems or different methods of allocation or system expansion. Furthermore, some studies are inconsistent in that the bioenergy system and reference system provide different services. Others may not include some sources of emissions such as land use change. Bird and others (2011) conclude that LCA is the tool of choice for quantifying the GHG emissions from, and emissions saved by, bioenergy systems. However, to ensure that reliable comparisons are drawn, LCA should be conducted following standard procedures.

LCA analyses require significant effort. Thus, it would be sensible to direct the effort towards confirming the accuracy of the more significant emission sources (Adams and others, 2013). The overall yield and any land use change are often crucial parameters, while emissions associated with ILUC are complex and limited with regards to forestry residues for biomass cofiring.

One disadvantage of LCA is that it is a static tool that does not take account of the timing of emissions, which is a serious limitation in its adequacy for assessing bioenergy systems.

5 Certification of sustainability

Setting standards and establishing certification schemes are possible strategies that can help ensure that biomass is produced in a sustainable manner. Various efforts have been made towards the certification of imported biomass.

5.1 Factors generally included in sustainability standards

The factors itemised in this section are generally included in biomass sustainability standards.

5.1.1 Greenhouse gas emissions

One of the widely claimed benefits of bioenergy use, and the focus of this report, is the reduced GHG emissions in comparison to fossil fuel combustion. In order to compare bioenergy chains with their fossil equivalents to assess the accuracy of the claims, GHG emissions need to be assessed through a transparent and comprehensive methodology. The most consensual carbon-related sustainability criterion therefore considers a GHG emission reduction potential of bioenergy, in comparison with a fossil fuel equivalent. GHG emission saving is determined by comparing all steps of a bioenergy chain with a fossil fuel reference, measured as CO_2 equivalent based on global warming potential as g/MJ of final fuel (Van Stappen and others, 2011).

Methodologies for GHG balance calculation are proposed in almost all developing sustainability initiatives. However, the methodology proposed by the EC for biofuels and bioliquids in the Renewable Energy Directive (EC-RED) will most likely also be used by Member States for assessing solid biomass. Thus Member States will adapt their existing regulatory frameworks to align their calculation method to that of the EC. Yet, this methodology still needs clarification regarding open issues such as ILUC (Van Stappen and others, 2011).

Various initiatives have developed principles that require levels of GHG reductions based on a life cycle assessment (LCA) of production processes. Some of these principles require process improvements over time, while others require a specific target to be achieved (Van Dam and others, 2010). For example, the EC, Netherlands, UK, Roundtable on Sustainable Biomaterials, British Standards Institution and other initiatives propose or are developing methodologies and default values to calculate the GHG emission (reduction) for bioenergy chains. These ongoing developments are complementary to already existing GHG tools, such as CO2Fix model and TimberCam databases including SimaPro and Ecoinvent and international protocols as developed within the framework of UNFCCC. In addition, there are several initiatives such as the Greenhouse Gas Protocol Initiative, GBEP and BioGrace to promote the harmonisation of methodologies to calculate GHG emission reductions (Van Dam and others, 2010).

5.1.2 Land use change

Discussions on how to calculate and prevent emissions from direct and indirect land use change are ongoing. Various initiatives, for example EC-RED, US Renewable Fuel Standard (US-RFS) and NTA8080 (Netherlands Technical Agreement) attempt to safeguard GHG gains by barring bioenergy on some newly converted lands with high carbon stock levels. US-RFS contains tougher criteria than the EC-RED. However, EC-RED has created a disincentive by accounting for emissions from DLUC amortised over 20 years, with specific emissions specified for different potential types of land conversion (Van Dam and others, 2010). The role of bioenergy production on ILUC is still uncertain and current initiatives have rarely captured impacts from ILUC in their standards. Addressing unwanted LUC requires first of all sustainable land use production and good governance, regardless of the end-use of the product (Van Dam and others, 2010). Carbon emissions from LUC are site specific, although they are often calculated with default values.

Various initiatives have included prevention measures to avoid the negative impacts of ILUC. One of the proposed solutions is to include additional GHG emissions in an LCA with the use of the ILUC factor. Both US-RFS and the Low Carbon Fuel Standard programme (LCFS, California, USA) have included an ILUC-factor in their policies. The US Energy Independence and Security Act (EISA) states that ILUC must be included in GHG emission reduction calculations. The US Environmental Protection Agency (EPA) is developing ILUC-values for several feedstocks in the US-RFS (Van Dam and others, 2010).

5.1.3 Maintenance of biodiversity

Biodiversity is generally recognised as a key principle to include in a sustainability standard for bioenergy. It is relevant on various spatial scales and for both short and long-term effects. However, standards differ strongly in their proposed criteria and indicators. Some standards assume that feedstock production may harm biodiversity. So, this is prevented by the exclusion of lands with a certain level of biodiversity. Other standards assume that feedstock production may enhance the biodiversity of a region, under certain conditions. In this situation feedstock production must be organised so as to promote or restore biodiversity.

5.1.4 Soil and water conservation

The need for soil and water conservation is recognised by most standards, although the principles and criteria developed show a variation in priorities between standards, partly explained by their different objectives (Van Dam and others, 2010).

5.1.5 Socio-economic factors

Most voluntary standards in the field of bioenergy, forestry and agriculture have included principles to safeguard the socio-economic well-being of their employees, land owners and the wider community. In the Netherlands, meeting the socio-economic principles laid down in NTA 8080 is a condition for obtaining a subsidy for bioenergy for heat and power. However, implementation is voluntary (Van Dam and others, 2010). One of the main reasons for choosing this pathway is compliance with the World Trade Organisation (WTO). The WTO is discussed in Section 5.12.

5.2 International organisations developing bioenergy policies and standardisation

At the international level, activities to develop a biomass certification system are initiated by international organisations, networks and roundtables in which various stakeholders participate. Various international bodies have recognised the need for biomass sustainability criteria including the Global Bioenergy Partnership (GBEP from the G8+5) and the OECD Roundtable on Sustainable Development. Within the UN, UN-Energy is the principal interagency mechanism in the field of energy. The International Bioenergy Platform (IBEP), established by the Food and Agriculture Organisation (FAO) is focused on knowledge management and transfer. IBEP provides expertise and advice for governments and private operators to formulate bioenergy policies and strategies. The FAO Forestry Department is working on biomass certification, in co-operation with IEA Bioenergy Task 31 to evaluate principles, criteria and indicators for biomass from forest used for energy as well as for wood fuel and charcoal production systems. IEA Bioenergy Task 40 on International Sustainable Bioenergy Trade aims to investigate what is needed to create a commodity market for bioenergy. Key priorities of the task include sustainability criteria, standardisation and terminology for biomass trade (Van Dam and others, 2008; IPCC, 2011).

Standardisation organisations such as the European Committee for Standardisation (CEN) and the International Organisation for Standardisation (ISO) are also involved (IPCC, 2011). The ISO intends to develop a standard specifically designed for the sustainability of bioenergy. Recommendations in 2009 to the Technical Management Board included the formal establishment of a new project committee with the scope of ‘standardisation in the field of sustainability criteria for production, supply chain and application of bioenergy’. This committee has to address an inventory of initiatives, terminology, greenhouse gases, environmental and socio-economic aspects, verification and auditing and indirect effects (Van Dam and others, 2010).

A new standard, ISO/TS 14067:2013, specifies principles, requirements and guidelines for the quantification and communication of the carbon footprint of a product, based on International Standards on life cycle assessment (ISO 14040 and ISO 14044) for quantification and on environmental labels and declarations (ISO 14020, ISO 14024 and ISO 14025) for communication. Communication tools of claim, label and declaration used by ISO to date are complemented by an external communication report and a carbon footprint performance report. The reports will provide consumers with rapid, traceable and, hence, reliable information that depends less on quantification. The standard also provides for the development of carbon footprint product category rules. It addresses only one impact category, that of climate change, and offsetting is outside its scope (ISO, 2013).

The Publicly Available Specification, PAS2050:2011, offers organisations a method to deliver improved understanding of the GHG emissions arising from their supply chains, but the primary objective of this PAS is to provide a common basis for GHG emission quantification that will inform and enable meaningful GHG emission reduction programmes. PAS2050 supports the assessment of life cycle GHG emissions of goods and services in a manner that can be disclosed later. For this reason, great emphasis is given to proper recording of processes and outcomes (PAS2050, 2011).

PAS 2050 builds on existing life cycle assessment methods established through BS EN ISO 14040 and BS EN ISO 14044 by giving requirements specifically for the assessment of GHG emissions within the life cycle of goods and services. These requirements further clarify the implementation of these standards in relation to the assessment of GHG emissions of goods and services, and establish particular principles and techniques, including:

- cradle-to-gate and cradle-to-grave GHG emissions assessment data as part of the life cycle GHG emissions assessment of goods and services;
- scope of greenhouse gases to be included;
- criteria for global warming potential (GWP) data;
- treatment of emissions and removals from land use change and biogenic and fossil carbon sources;
- treatment of the impact of carbon storage in products and offsetting;
- requirements for the treatment of GHG emissions arising from specific processes;
- data requirements and accounting for emissions from renewable energy generation.

Within Europe, CEN has established a technical committee (CEN TC 383) on ‘sustainably produced biomass for energy applications’ to promote standardisation in the field of sustainably produced biomass. Various working groups have been established. In 2009 it was decided that CEN/TC 383 would focus on the principles that are also included in the EC Renewable Energy Directive in the first instance (Van Dam and others, 2010).

5.3 Biomass standards

A proliferation of standards exists, which differ from one country or region to another. This creates a risk of 'shopping' between standards, market distortion and a decrease in credibility. It can be argued that further coherence in biomass certification systems, possibly through the promotion of international agreements and standardisation is needed. Coherence in systems is limited partly because of differences in priority between systems: energy security and combating climate change by reducing greenhouse gas emissions have been the main drivers to develop sustainability principles and standards for bioenergy. In contrast, other standards have been developed primarily for health and safety purposes. Due to these differences in priority, the sustainability principles in agricultural and forestry standards cannot all be used to replace the sustainability issues that are stipulated by bioenergy standards under development (Van Dam and others, 2010).

Van Dam and others (2010) studied 67 ongoing certification initiatives to safeguard the sustainability of bioenergy. Their key recommendations for an efficient certification system include the need for further harmonisation, availability of reliable data and linking indicators on micro, meso and macro levels. The IPCC (2011) considers that certification should be combined with additional measurements and tools at regional, national and international levels. Thus, initiatives and debates are ongoing on the further development of principles, criteria and verifiable indicators to safeguard the sustainability of biomass and bioenergy.

Different certification schemes already exist for the forestry and agricultural sector to ensure environmentally benign or sustainable production methods. Various initiatives to guarantee the sustainability of bioenergy, such as NTA8080, make use of a meta-standard approach. This is because there is already a variety of existing standards covering agriculture, forestry and social conditions so a meta-standard serves as the benchmark standard. This means that compliance with the meta-standard is achieved through the existing standards. These need to prove that they guarantee sufficiently that there is compliance with (most of) the principles and criteria of the meta-standard. A consequence of using a meta-standard approach is that national and regional policies rely partly on voluntary certification standards for agriculture and forestry to meet project-scale sustainability initiatives (Van Dam and others, 2010). Thus a meta-standard approach, in combination with using international agreements, could partly solve the proliferation and priority differences of standards.

The differences in approaches between various initiatives show the difficulty in achieving a unified and internationally accepted methodology as well as default values.

5.4 Forestry certification

Precedents in the field of sustainability certification exist for a wide range of products. Certification schemes for forestry and agricultural products are relevant for the development of a biomass certification system. The Forest Stewardship Council (FSC) has led the introduction of forest certification. Since 1994, 150 million hectares (Mha) in more than 80 countries have been certified according to the FSC standard (www.ic.fsc.org). Two types of FSC certificates are available from certification bodies: the Forest Management certificate and the Chain of custody certificate. Chain of custody is the path taken by raw materials from the forest to the consumer, including all successive stages of processing, transformation, manufacturing and distribution. The FSC reviews its processes and criteria frequently (Van Dam and others, 2008).

The Programme for the Endorsement of Forest Certification Schemes (PEFC) is another major forest certification scheme. PEFC is a global umbrella organisation for the assessment and mutual recognition of national forest certification schemes. PEFC covers both forest management and chain of custody verification. About 245 Mha are managed in compliance with the PEFC standard. Currently around 8500 companies and organisations have achieved PEFC chain of custody certification. Thirty-five national members and 31 endorsed national certification systems have joined forces under the PEFC umbrella to promote sustainable forest management collaboratively (PEFC website, http://www.pefc.org/about-pefc/who-we-are/facts-a-figures, May 2012). The PEFC provides an assurance mechanism to purchasers of forest products that they are promoting the sustainable management of forests (Van Dam and others, 2008).

Another tool is the 'CEN/TS 15234-Solid biofuels, fuel quality assurance' in which the whole fuel supply chain has to be traced back to its origin. The fuel supplier documents the origin of the biomass and the fuel properties by quality declaration. The supplier or producer is advised to describe the fuel production process and state the critical control points where quality can change. This is a standard for fuel quality in terms of physical properties, but it could also be used for looking at other aspects in the entire production chain (Van Dam and others, 2008).

5.5 Green electricity labels

Demand for renewable energy sources (RES) is stimulated by obliging end-users to produce a share of their electricity from RES. In practice, this obligation is usually not imposed on the consumer but on electricity suppliers or distribution companies. It has led to market mechanisms and trade in sustainable energy production and has stimulated electricity suppliers in Europe who use biomass as feedstock to start initiatives to develop their own biomass certification systems (Van Dam and others, 2008).

There are a number of green electricity labels including EUGENE, Milieukeur, ok-power and Green Power, some of which include a definition for biomass. In general, two approaches to defining green electricity from biomass can be found:
- definition of the allowed feeding material and additional criteria defining the ecological quality of the biomass and the exclusion of certain technologies or types of biomass;
- specification of the technology (plant types) and assessment of the individual plant which applies for certification; criteria regarding the feeding material are applied additionally (Van Dam and others, 2008).

There are also other indicator and criteria systems to guarantee sustainability, such as that of the International Labour Organisation which has developed a set of criteria for sustainable labour conditions (Van Dam and others, 2008).

EUGENE is an independent network of environmental and consumer organisations and research institutes which promotes green electricity labelling as a market tool to facilitate production of renewable and energy efficient services. The EUGENE label can be applied to 'eligible sources' of biomass. Eligible sources for biomass include dedicated energy crops, and residual straw from agriculture (Van Dam and others, 2008).

Electrabel, a European energy company, has developed the Electrabel label as a certification procedure for imported biomass. Potential suppliers must conform with the Electrabel sustainability criteria before being accepted within the Belgian green certificate systems (Van Dam and others, 2008).

Essent, the largest Dutch user of biomass, and Control Union, a verification organisation, have developed Green Gold Label (GGL), a biomass certification system. It aims to be a traceability system for biomass from (by-)products from the power plant (and the green power it produces) back to the sustainable source. In this system mixing or contamination with non-intrinsic or environmentally harmful materials is prohibited. In every link of the chain written proof must be available that the GGL quality system is supported, sustained and maintained. The system consists of six different standards covering the complete biomass chain from production through to end-use. Among others, the standards define a chain of custody standard, criteria for forest management and criteria for agricultural products (Van Dam and others, 2008). GGL accepts existing certification systems, such as FSC standards, but has additional guidelines for pellet manufacturing and transport. A major criterion within GGL is the requirement for tracking custody of the biomass.

Laborelec, the research and competence centre of GDF Suez has developed sustainable criteria for biomass supply contracting. The sustainable certificate was developed in collaboration with SGS. The Laborelec criteria exclude wood from rain forests, biomass that is in competition with food production and wood that can still be recycled or reused. Fossil fuel consumption for handling and transport is taken into account. Respect for local legislation is also important. This includes the social aspect, environmentally sound cultivation, harvesting and collection of the biomass. The main choice of GDF Suez for its power plants in Belgium and the Netherlands is wood pellets as there are vast amounts available, for example in Canada, the Baltic states, Scandinavia and Russia. Long-term supply from these sources is guaranteed. The imported wood pellets meet the sustainability criteria. For Laborelec, another aspect of sustainability is the application of the by-products, mainly the bottom and fly ash. As long as limited quantities of biomass are cofired with coal, the ashes can still meet the requirements of the European standards for reuse in cement (EN197-1). The exact ratio depends on the characteristics of the coal and of the biomass or concrete (EN450-1) (Savat and others, 2012).

At 4000 MW Drax is the largest coal-fired power plant in the UK. It is currently converting three of its six units to run entirely on biomass. Drax has introduced its own sustainability policy, designed to ensure that it is possible to verify that the biomass consumed has been legally produced and is environmentally sustainable. As well as complying with sustainability requirements introduced by the UK Government, the aim of the procurement process is to ensure that the production and delivery of their biomass will:

- significantly reduce greenhouse gas emissions compared to coal-fired generation and give preference to biomass sources that maximise this benefit;
- not result in a net release of carbon from the vegetation and soil of either forests or agricultural lands;
- not endanger food supply or communities where the use of biomass is essential for subsistence (for example heat, medicines, building materials);
- not adversely affect protected or vulnerable biodiversity and, where possible, preference will be given to biomass production that strengthens biodiversity;
- deploy good practices to protect and/or improve soil, water and air quality;
- contribute to local prosperity in the area of supply chain management and biomass production;
- contribute to the social wellbeing of employees and the local population in the area of the biomass production.

These biomass sourcing principles are based on the developing regulatory and policy initiatives of the UK, European Union and other markets. Over time, Drax will seek to amend or improve them by working with accredited bodies to develop the use of internationally recognised standards and principles which will apply to all of their biomass procurement activities.

According to their website, Drax will:

- use purchase contracts to ensure that suppliers address these principles and provide Drax with the required information to demonstrate that these sustainability principles are being met;
- participate with applicable regulatory and policy initiatives to share experience, learn and help shape policy that will ensure sustainable biomass fuels throughout the UK and abroad;
- systematically review these principles and their application to develop sustainability policy;
- engage a qualified third party to implement a rigorous programme of audit and verification of biomass supply chains to ensure compliance against these principles (http://www.draxgroup.plc.uk/biomass/sustainability_policy/, 3 June 2013).

Other energy companies in Europe are considering or are developing their own biomass certification systems (Van Dam and others, 2008). The success of a biomass certification system depends on the involvement and support of the wide range of parties involved in the biomass production, trade and processing chain. Most stakeholders agree that a set of environmental, social and economic criteria should be included in a biomass certification system. The next chapter considers national sustainability certification schemes for solid biomass.

6 National sustainability certification schemes

Some countries have started to develop biomass certification schemes, including Belgium, the Netherlands, the UK and to some extent, Brazil, Germany, Canada and the USA. Many national policies relate to targets or incentives to stimulate the use of renewable energy sources. The Netherlands, UK, Belgium, Germany and EC have taken the initiative to start developing a policy framework to guarantee sustainable biomass. The systems in Belgium and the UK have the reduction of greenhouse gas emissions for sustainable biomass feedstock as the main criteria. The Netherlands and the UK have developed a wider set of principles including environmental, social and economic criteria (Van Dam and others, 2008). These schemes are described after the introduction of some relevant implementation and international issues.

6.1 Implementations issues for a sustainability standard

Procedures and solid documentation systems are needed to implement a reliable certification system. Also, compliance with criteria has to be controllable in practice, without incurring high additional costs. Certification of the primary product against a sustainability standard is needed to make it possible for a bioenergy user or supplier to declare compliance of the end product with sustainability requirements. In addition, a traceability system, also called Chain of Custody (CoC) needs to be established for the whole chain of production, processing and trade. Three different CoC models can be distinguished: mass balance, track and trace, (or identity preserved), physical segregation and book and claim (Van Dam and others, 2010).

Certification has the potential to influence the environmental and social impacts of direct bioenergy production with principles and criteria governing the particular lands and production processes used. Van Dam and others (2010) have made various recommendations to arrive at a harmonised, efficient certification system to guarantee the sustainability of biomass and bioenergy. They believe that further harmonisation and international agreement is needed on:
- definitions, such as biodiversity rich areas;
- methodologies, such as conditions to safeguard biodiversity on various spatial levels;
- performance indicators, such as required parameters for soil and water analysis;
- harmonisation of parameters and assumptions used in databases and models;
- verification and monitoring procedures.

Certification is one of the policy tools available to pursue the sustainability of biomass. But not everyone sees certification as a means to guarantee sustainable biomass production. Specific, quantifiable criteria for sustainability indicators need to be designed and adopted. Despite their specificity, they should be flexible enough to be adapted to the particular requirements of a region. Criteria have to be enforceable in practice, easily comprehended and controlled without generating high additional costs. The traceability of biomass needs to be guaranteed, which is still difficult and may make a transition period necessary. Experts should not unilaterally decide which sustainability criteria to include and how to prioritise them. The stakeholders should be alert to major concerns and provide methods for measuring, evaluating and monitoring the different aspects (Van Dam and others, 2008).

A biomass certification system needs to comply with international and national legislation and a proliferation of standards should be avoided. However, many organisations are developing their own sustainability standards, while national/international measures are slow to emerge.

Compliance with sustainability criteria has to be controllable in practice, without incurring high additional costs. There are costs associated with meeting sustainability criteria and with monitoring compliance and the physical traceability of the product. Costs for complying with (strict) sustainability criteria can be substantial; Van Dam and others (2008) found a range of 8–65% additional costs in the literature. Costs for the certification process itself and chain of custody are much lower in the case of large-scale operations – a range of 0.1–1.2% was found. Van Dam and others (2008) recommend linking with existing certification systems as far as possible to limit administrative burdens and costs.

Five main strategies have been identified for implementing a biomass certification system. The first is based on a government regulation for biomass minimum standards, possibly combined with incentives. The second is a bottom-up approach where a group of governments, companies, and other interested parties voluntarily adopt standards and certification schemes. For example, GGL and Electrabel are two voluntary certification schemes covering the complete biomass chain that have been implemented. As part of a voluntary certification scheme, a third approach would be to develop an eco-label for biomass-related products that meet standards higher than those mandated by law. A fourth approach comprises a voluntary bioenergy label combined with an international agreement. The final method would be to regulate sustainable biomass standards internationally in a legally binding form, through adoption of a multilateral environmental agreement (MEA) or by integrating the standards into existing international agreements or standards (Van Dam and others, 2008).

6.2 World Trade Organisation

Certification schemes and labelling programmes fall within a grey area of the World Trade Organisation (WTO). The Technical Barriers to Trade (TBT) agreement requires that regulations (mandatory) and standards (voluntary) should not create unnecessary obstacles. It prohibits discrimination between domestic and foreign products (the national treatment principle) and between products from different WTO members, called the ‘most favoured nation principle’ (Van Dam and others, 2008).

Environmental trade measures that distinguish between products based on their production process and production methods (PPM) that do not influence the physical characteristics of a product may violate the TBT obligations. This is important to consider, as criteria related to sustainable biomass certification are likely to be based on non-product related criteria. At present, the applicability of the TBT agreement that is based on non-product related PPM is unclear. Jurisprudence is not conclusive, and authors are divided on the subject. Several WTO members hold the position that standards and labels that refer to PPM are not among the measures covered by the TBT agreement. On the other hand, labelling programmes increasingly rely on life cycle analysis and indeed refer to PPM (Van Dam and others, 2008).

Sustainability standards can be linked to subsidies and tariffs. These may affect international trade and are therefore included in WTO rules. The classification of a product is important to define which tariff levels and which set of disciplines and domestic subsidies are applicable. A number of approaches allow countries to subsidise products. ‘Green boxes’ are permitted (in WTO terminology, ‘boxes’ identify subsidies). In order to qualify for the ‘green box’, a subsidy must not distort trade, or at least cause minimal distortion; they have to be government funded and must not involve price support (Van Dam and others, 2008).

Van Dam and others (2008) have summarised the WTO context for biomass certification:
- There are possibilities to design environmental measures and sustainability criteria for biomass in line with WTO principles, which distinguish ‘like products’.
- Subsidies should not have certain kinds of adverse trade effects or cause injury to a group and they should be non-specific and not directed at a limited group of particular products.
- There is an open market for certification systems with a risk of proliferation of systems.
- International consensus promotes acceptance of criteria and the Code of Good Practice can serve as a tool to promote transparency and stakeholder participation.

- WTO agreements are a result of negotiations between members and the outcome of these negotiations is unsure in advance.

There is concern that biomass certification could become an obstacle for international trade and trade restrictions could develop due to proposed sustainability criteria. The WTO gives a number of reasons why not to distinguish between products on the basis of how they are made:
- if one country sets rules such as requiring eco-labels, which deals with the way products are made in another country, then it is intervening in the producing country's rules;
- when products are identified only by what they are, not how they are made, countries can set their own standards as appropriate for their level of development and can then make their own trade-offs between their own needs (and values) for development and environmental protection;
- if countries do not impose their standards on each other, standards can be tailored to conditions, priorities and problems in different parts of the world.

No precedent exists within the WTO for biomass certification. Thus it is considered that a process to assess the WTO-compatibility of a biomass certification scheme is needed.

6.3 General Agreement on Tariffs and Trade

The General Agreement on Tariffs and Trade (GATT) has a few exceptions which may justify environment-related measures for products and the use of necessary measures to assure these standards are met, even though they violate the general principles of GATT. These exceptions are justified when:
- necessary to protect human, animal or plant life or health; or
- relating to conservation of exhaustible natural resources, if such measures are made effective in conjunction with restrictions on domestic production or consumption.

Air is considered as an exhaustible resource and the argument of adequate supply of (sustainable) biofuels within this context has plausibility as well (Van Dam and others, 2008).

6.4 European Union and Member States

The EU promotes the use of bioenergy to reduce emissions of GHG, increase decarbonisation, diversify fuel supply sources, develop long term replacements for fossil fuels and offer new opportunities for rural income. Introduced in 2007, the European energy policy sets a target of achieving at least a 20% reduction in GHG emissions and a 20% increase in renewable energy by 2020. Domestic energy security is another factor; at present 54% of the total energy consumed by the EU27 is imported, and the EC predicts that this dependency rate could increase to 70% if measures are not taken to increase domestic energy supplies (Magar and others, 2011).

For biomass produced within the EU, the current legal framework, notably related to agriculture and forest management, gives certain assurances for the sustainable management of forests and agriculture. The same is true for some third countries, but others lack such a framework. In its analysis of requirements for extending the EU sustainability scheme, the Commission has considered three principles which a European-wide policy on biomass sustainability has to meet (EC, 2010):
1 Effectiveness in dealing with problems of sustainable biomass use;
2 Cost-efficiency in meeting the objectives;
3 Consistency with existing policies.

The Renewable Energy Directive (Directive 2009/28/EC) published in June 2009 contained sustainability criteria for the use of biofuels for transport and bioliquids for heat and electricity generation and cooling, but did not address the use of solid and gaseous biomass sources together (biomass). This issue was considered separately by the EC, which reported its findings on sustainability requirements for solid biomass in a report published in 2010 (EC, 2010). Further guidance from the EC on sustainability requirements for solid biomass is expected in 2014.

The EU Renewable Energy Directive uses the following methods to account for the GHG emissions from bioenergy (EEA, 2011):

Total GHG emissions for the use of a fuel = Emissions from extraction or cultivation of raw materials + annualised emissions from carbon stock changes resulting from direct land-use change + emissions from processing + emissions from transport and distribution + emissions from the fuel in use – emission savings from carbon capture and geological storage – emission savings from carbon capture and replacement – emission savings from excess electricity from cogeneration (EEA, 2011).

The annualised emissions from carbon stock changes resulting from land-use change are calculated as follows:

$$\text{Annualised emissions} = (CSR - CSA) \times 3.664 \times 1/20 \times 1/P - eB$$

In this formula, CSR is the carbon stock of biota and soils under reference land-use, CSA the carbon stock of biota and soils under land-use with bioenergy production. 3.664 is a factor to convert carbon to CO_2. 1/20 means that the change in C stocks (CSR–CSA) is evenly distributed over 20 years. P is the energy yield of the energy crop, and eB is a bonus that is credited if the biofuel is obtained from restored degraded land. This formula accounts for carbon emissions resulting from land use change for energy crops as annualised stock change (20 y). However, according to the EEA (2011), it neglects some essential components: indirect land use change; the land's potential ongoing carbon sequestration; and the opportunity cost. If the land would not be required for food, feed, or fibre production, it could also be converted to another use to increase its carbon sequestration.

The current absence of EU regulation regarding biomass sustainability may risk individual Member States developing varied and potentially incompatible sustainability criteria at a national level. Such incompatibility could, in turn, create barriers to biomass trade between Member States, which may limit growth of the biomass sector and significantly affect its contribution towards the 2020 target of sourcing 20% of the EU's energy needs from renewable sources. The EC sustainability report therefore aims to identify recommendations for Member States to follow when developing and implementing biomass sustainability criteria to minimise the risk of policy incompatibility (EC, 2010; Fairley and Lord, 2010).

The report makes five main recommendations about biomass sustainability, which are in line with the mandatory criteria already in place for biofuels and bioliquids and are discussed below (EC, 2010; Fairley and Lord, 2010).

1 There should be a general prohibition on the use of biomass from land converted from forest, other high carbon stock areas and highly biodiverse areas. The EC-RED already prohibits conversion of continuously forested areas (30% canopy cover), and forest areas with 10–30% canopy cover unless GHG savings targets of 35% are met if the emissions of the carbon stock changes are included. It also prohibits conversion of primary forest, and protected areas and highly biodiverse grasslands. Individual Member States have implemented comprehensive forest management governance structures, which are linked to the Common Agricultural Policy, EU Forest Strategy and Ministerial Conference for the Protection of Forests in Europe. However, such governance structures are largely absent in developing countries, which export increasing amounts of biomass to the EU, heightening concerns that the unsustainable production of biomass is being encouraged. The recommended prohibition would encourage developing countries to implement certification schemes, and so encourage sustainable forest management.
2 A common greenhouse gas calculation methodology should be implemented to ensure that minimum greenhouse gas savings from biomass are at least 35% (rising to 50% in 2017 and 60%

in 2018 for new installations). The report recognises that there is an inconsistency with respect to the methodology applied to calculate the GHG performance of different forms of biomass, which hinders its accurate comparison with fossil fuel alternatives. The report suggests a methodology which is partly based on life cycle assessment methodologies.

3 EU Member States should seek to maximise the efficiency of energy consumption by introducing policies which incentivise the use of biomass installations with high energy conversion efficiencies.
4 EU Member States should retain a record of the amount and origin of primary biomass used in electricity, heating and cooling installations of 1 MW or above.
5 Sustainability criteria should not be applied to waste, which must already fulfil various rules and regulations imposed by national and EU legislation. The introduction of another set of criteria would just increase the complexity of the system (EC, 2010; Fairley and Lord, 2010).

The report encourages Member States to ensure that any national biomass sustainability policy integrates the recommendations given, to allow for the promotion of sustainable biomass production and use; and the development of a well-functioning internal market. Each Member State was required under the Directive to submit a national renewable action plan by June 2010, which the EC intends to use as a key tool for identifying the extent to which Member States are intending to exploit biomass as a renewable fuel source (EC, 2010; Fairley and Lord, 2010).

An efficient policy framework requires harmonisation among the various different bioenergy-related policies. This can be achieved through a number of processes, enhancing the application of policy instruments by integrating international methods for developing and administering standards. The objective of harmonisation is to replace the variety of different product standards and other regulatory policies adopted by nations with a coherent set of uniform standards. Uniform standards would underpin the confidence of fuel producers and consumers in the optimal, efficient and sustainable utilisation of bioenergy. European standards for bioenergy production, trade and consumption are emerging in the EU to help regulate trade and provide confidence for both energy producers as well as consumers with respect to protecting the environment and improving the efficiency of bioenergy. A robust certification system can ensure that biomass is produced in a sustainable way by chain of custody tracking, with reports on the sustainability of bioenergy throughout the supply chain (Magar and others, 2011).

The development of standards for selected bioenergy products was initiated in 2000. The CEN/TC is contributing to the development of European standards for bioenergy products. There are some initiatives that deal with solid biofuels, such as CEN/TC 338.

The development of a sustainable bioenergy trade in Europe is highly dependent on European standards. Along with standards, the need for bioenergy certification is another prominent issue related to system sustainability that must be addressed in the development of sustainable bioenergy trade. Certification and eco-labelling have been practised since the early 1990s in the forestry sector but have not yet been applied to bioenergy products. According to Magar and others (2011), the EU should apply best practices and approaches to certification such as those used in the forestry sector to the bioenergy industry. Standards and certification could not only address issues of environmental sustainability from biomass production to end use, but could also contribute to product differentiation and added value, ultimately enhancing a competitive bioenergy market.

Various individual European Member States (MS) are introducing sustainability standards at the national level, but, where applicable, individual MS are obliged to follow European legislation. However, with the exception of Belgium and the UK, no mandatory sustainability criteria for solid biomass (such as wood pellets) have been implemented – the European Commission reviewed this at the end of 2011 (EC, 2010). Sustainability criteria are expected to be introduced by the EC in 2014. The development of impact assessment frameworks and sustainability criteria involve significant challenges in relation to methodology, process development and harmonisation. Within the EU, a number of initiatives have started or have already set up certification schemes in order to guarantee a more sustainable cultivation of energy crops and production of energy carriers from modern biomass (including ISCC40; REDCert41 2010 in Germany; or the NTA8080/8081 (NEN42) in the Netherlands). Many initiatives focus on the sustainability of liquid biofuels, which are not included in this report (IPCC, 2011). Other European initiatives include the Dutch Cramer Commission, the UK Renewable Transport Fuels Obligation, the German Biofuels Sustainability Ordinance, the Roundtable on Sustainable Palm Oil and the Roundtable on Sustainable Biomaterials (Van Stappen and others, 2011). These regulatory and voluntary initiatives have fed the debate around the EU Renewable Energy Directive.

European Union policies promote the use of forest biomass energy, as embodied in the EU's 2006 Forest Action Plan. More than half of the EU's renewable energy already comes from biomass, 80% of which is wood biomass. Forestry can play an important role as a provider of biomass energy to offset fossil fuel emissions. There has recently been higher demand for wood from the energy sector in addition to rising demand from the established wood-processing industries. Many experts consider that significantly more wood could be mobilised from EU forests than is currently the case. However, the cost at which this can be done is a key factor (EU, 2009).

In European national sustainability initiatives, it is proposed that DLUC are assessed on the basis of guidelines developed by the IPCC. This methodology takes into account the above- and below-ground carbon stock balance between the new crop system and a reference system. Integrating crop productivity, this carbon difference is converted into CO_2 emissions according to C and CO_2 respective molecular weights and amortised over 20 years. This calculation expresses GHG intensity for direct land use conversion in g/MJCO_2eq. IPCC guidelines propose default emission factors (Tier 1) but always recommend using country-specific validated data (Tier 2 or 3) where they are available (Van Stappen and others, 2011).

Within the EU, Austria, Belgium, Denmark, France, Germany, Hungary, Italy, Lithuania, the Netherlands and the UK, are the main importers of biomass and bioenergy, whereas Bulgaria, Czech Republic, Estonia, Finland, Germany, Hungary, Latvia, Lithuania, Poland and Slovakia are the main exporters (Magar and others, 2011).

6.4.1 Belgium

Systems of green certificates have been developed in Belgium to make the level of the green support mechanism proportional to the energy efficiency of the whole supply chain. Within that frame Laborelec with SGS Belgium has developed a global biomass certification scheme in response to the wishes of the Belgian regional authorities.

At the request of GDF-SUEZ/Electrabel, SGS Belgium and Laborelec have jointly designed a verification scheme for biomass pellets fired in thermal power plants which has been in place since 2007 (Goh and others, 2012). The verification scheme includes the following procedures:

- Evaluation of energy consumption along the pellet supply chain (milling, drying, pelletising, transportation). If the raw material is a residue such as saw dust, the evaluation of energy use within the supply chain starts only from the point where the residue is generated, for example the sawmill.
- Full traceability of the resources used for manufacturing the biomass fuel and evidence that those resources are managed in a sustainable way.

In order for biomass to be accepted according to Laborelec's standards, it must be a byproduct from agriculture and forestry (preferably not a primary one so that additional certificates are not lost). The biomass must consist of organic material that comes from well-managed woods, (public) zones of vegetation or agricultural grounds. Energy consumption must be reasonable with respect to other references and heat for drying must be generated from renewable sources (biomass).

The granting of green certificates corresponds to the renewable electricity generated by firing wood pellets. It is focused on traceability of biomass from by-products (and its energy produced) back to the sustainable source. The authorities of both Flanders and Wallonia request at least an inspection report for each biomass fuel producing facility. Both regions have different legislation and different methodologies for calculating the number of certificates granted but Laborelec applies the same certification procedure (Goh and others, 2012).

SGS checks the source of the wood (hardwood, softwood, saw dust, shavings, coppice products) and the transport between the source and the pellet plant. If the biomass is not a secondary product but a primary one, then the entire energy consumption of planting, fertilising and harvesting for example must be taken into consideration and the energy used subtracted from the number of green certificates granted. SGS evaluates the energy consumption for making the pellets. Finally, SGS looks at the final transport to the harbour and checks the global traceability (Goh and others, 2012).

Each supplier undergoes an audit within six months of the first firing of biomass. The audit examines the sustainability of the raw material sourcing and details the energy balance of the whole supply chain. This includes the energy that is used for pelleting the wood and for transporting the final product to the site of the power plant. If the product appears to be in contradiction with the generic sustainability principle, the Walloon Energy Commission (CWaPE) has the right to cancel the granted green certificates. For each producer, the global supply chain is analysed by a local independent inspectorate, and approved by SGS Belgium. The latter is accepted as an independent body by Belgian authorities for the granting of green certificates.

There are five different Green Certificates mechanisms running in Belgium: two in Flanders (one Green, one Cogen), one in Wallonia, one in Brussels and one at the Federal level. This certification scheme applies to all of them (Goh and others, 2012).

6.4.2 The Netherlands

In the Netherlands, the Corbey Commission (CBD), established in 2009, advises the Dutch government on sustainability issues for biomass and bioenergy. Recent recommendations include advice on the implementation of the EC-RED reporting obligation, how to deal with ILUC and include sustainability criteria for solid biomass at the European level (Van Dam and others, 2010).

The Cramer Commission issued a report in 2007 which presented sustainability criteria and indicators formulated around six themes, three specific to biomass: GHG balance, competition with food, local energy supply, medicine and building materials; biodiversity; and three themes relating to the 'triple P' approach (people, planet, profit): environment, economic prosperity, and social well-being (Van Stappen and others, 2011).

In March 2009, the Cramer Criteria were made operational in a national standard, NTA 8080, which specifies the requirements for production of biomass for energy applications. This standard will be used by producers, conversion plant operators or traders willing to claim that they use sustainably produced, obtained and converted biomass. The standard also includes a GHG calculation methodology that will be adapted to the RED methodology and requirements for certification, for the chain of custody and logo use (Van Stappen and others, 2011). The successor to this standard, NTA8081, will include the European guidelines.

6.4.3 United Kingdom

The UK government uses a financial mechanism known as the Renewables Obligation (RO) to incentivise the deployment of large-scale renewable electricity generation. In August 2013 the UK

Government announced its decision to bring in sustainability controls for solid biomass and biogas that go beyond those currently recommended in the EU. The changes to the RO sustainability criteria set out in August 2013 will be brought in as a requirement to report against performance from April 2014 (DECC, 2013).

Following the publication of the EC report, expected in 2014, the UK intends to notify its RO sustainability criteria to the EU under the Technical Standards Directive (TSD) with the intention that the sustainability criteria for the use of solid biomass feedstocks under the Renewables Obligation will become mandatory from April 2015. This would mean that from this date generating stations would be required to demonstrate that solid biomass feedstocks meet the sustainability criteria in order to be eligible for support under the RO.

The UK Government has decided that biomass power, whether new or existing, with or without combined heat and power (CHP), dedicated, standard cofiring, enhanced cofiring, coal to biomass conversion, advanced conversion technologies or anaerobic digestion, will be placed on the same GHG emissions trajectory from 1 April 2020. Before this date existing biomass power generation will remain on the current target of a 60% GHG emissions saving compared to the EU fossil electricity average to give time for transition to the tighter target.

The GHG trajectories for generators using solid biomass will be:
(i) New-build dedicated biomass power (with or without CHP) that receives full accreditation on or after 1 April 2013
   - 240 kgCO_2eq per MWh from 1 April 2014 to 31 March 2020
   - 200 kgCO_2eq per MWh from 1 April 2020 to 31 March 2025
   - 180 kgCO_2eq per MWh from 1 April 2025 to 31 March 2030

(ii) All other biomass power (includes existing dedicated biomass power, with or without CHP, cofiring coal stations, coal stations converting to standard/enhanced cofiring or to 100% biomass conversion that accredit under the RO before its close in 2017):
   - 285 kgCO_2eq per MWh from 1 April 2014 to 31 March 2020
   - 200 kgCO_2eq per MWh from 1 April 2020 to 31 March 2025
   - 180 kgCO_2eq per MWh from 1 April 2025 to 31 March 2030

The targets represent an annual average.

The greenhouse gas lifecycle methodology is as set out under the 2009 EU-RED, reflecting the recommendations made in the European Commission's 2010 report on requirements for sustainability criteria for solid biomass and biogas. This methodology considers the emissions from the cultivation, harvesting, processing and transport of the biomass feedstocks. It also includes direct land use change where the land use has changed category since 2008. It does not include indirect impacts such as displacement effects. All biomass stations will be required to use a GHG tool, when reporting on their GHG lifecycle emissions from different feedstocks, such as the tool available from the Ofgem website or suitable alternatives.

The UK Government has decided that biomass power plant, using solid biomass feedstocks, whether a new or existing generating station or unit, with or without CHP, dedicated, cofiring or coal to biomass conversion will be subject to land criteria. The land criteria will be different for (i) virgin wood and (ii) all other non-waste biomass including energy crops. Land criteria will not apply to biomass waste or to feedstocks wholly derived from waste

Sustainable forest management criteria will be brought in for the use of feedstocks that are virgin wood or made from virgin wood from April 2014. The sustainable forest management criteria will be based on the UK Timber Procurement Policy (UK-TPP) principles for central Government. The UK TPP principles consider a range of social, economic and environmental issues relevant to forests, so for these feedstocks the land criteria will correspond to sustainable forest management criteria.

The proposed RO sustainability criteria do not currently directly address the preservation of land carbon stocks except where the reported use of the land changes. The government aims to include this issue in future reviews. The 2016-17 review will include consideration of the sustainability criteria that should apply to new biomass generation coming forward from April 2019.

The land criteria for all other solid biomass and biogas, including perennial energy crops, such as *Miscanthus* grass and short rotation coppice willow, and agricultural residues, such as straw, will correspond to the land criteria set out in the EU-RED for transport biofuels and bioliquids.

The government has also decided not to make further unilateral changes to the methodology underpinning the GHG targets or to other aspects of the RO sustainability criteria before 1 April 2027; the date when support for existing coal to biomass conversions under the Renewables Obligation is due to end. The UK Bioenergy Strategy identifies converting existing coal generation as a low-risk transitional pathway. However, if the EC makes relevant recommendations, then changes may follow in the UK.

Biomass power and CHP generating stations using solid biomass feedstocks will be required to provide an independent assessment/audit report for feedstocks used from 1 April 2014. For those using wastes, or feedstocks made wholly from waste, the independent assessment/audit report will cover the assessment of these feedstocks as waste, and hence they will be excluded from GHG and land criteria.

The Government requires additional information on land use and wood types for virgin wood feedstocks. The available information on forest management practices and region as well as country of origin will be required. If the reported data reveals significant use of high quality wood the Government will consider measures to mitigate adverse impacts, such as a voluntary code of practice for generators (DECC, 2013).

6.5 USA

US federal incentives for renewable energy (including forest biomass) have taken many forms over the past four decades. The focus of most of these programmes has been to encourage renewable electricity generation and, more recently, production of renewable transportation fuels, such as ethanol. The third area of energy use, thermal applications for heat, cooling and industrial process heat, has not been a focus of federal energy programmes until recently (Walker and others, 2010).

Federal policy initially encouraged renewable electricity generation by requiring utilities to purchase electricity from renewable energy generators at a fixed cost through the Public Utility Regulatory Policy Act (PURPA). More recently, federal policy has shifted towards encouraging renewable energy through tax incentives and direct grants, with the primary focus on renewable transportation fuels and renewable electricity generation (Walker and others, 2010).

Within the electric power sector biomass facilities are eligible for funding through four primary renewable electricity generation incentives (the Production Tax Credit (PTC), Investment Tax Credit, Modified Accelerated Cost Recovery System, and Clean Renewable Energy Bond programme). However they have received a relatively small share of the total funding. The US Energy Information Administration (EIA) estimates that in fiscal year 2007, open-loop biomass facilities received approximately US$4 million in tax credits under the production tax credit programme, compared to approximately US$600 million for wind facilities. Funding for combined heat and power or purely thermal facilities is also negligible compared to expenditure on other renewable resources (EIA, 2008). Many of the biomass-specific grant programmes have total annual allocations in the US$1–5 million range, with individual projects often capped in the $50,000–500,000 range (Walker and others, 2010). Within federal subsidies specific to biomass energy, there is an emphasis on transportation fuels, a limited focus on biomass power, and no historic public policy support for biomass thermal applications.

The primary federal subsidy or incentive to biomass electric power production is the Renewable Electricity Production Tax Credit which provides approximately 10 US$/MWh. While smaller in value than state Renewable Energy Credits (REC), which average 20–35 US$/MWh, the PTC does provide a significant and stable incentive for the development of biomass power over time. The federal renewable electricity production tax credit (PTC) is a per-kilowatt-hour tax credit for electricity generated by qualified energy resources and sold by the taxpayer to an unrelated person during the taxable year. The American Recovery and Reinvestment Act of 2009 allows taxpayers eligible for the PTC to take the federal business energy investment tax credit (ITC) or to receive a grant from the US Treasury Department instead of taking the PTC for new installations for up to 30% of capital costs following the beginning of commercial production. The new law also allows taxpayers eligible for the business ITC to receive a grant from the US Treasury instead of taking the business ITC for new installations. Grants are available to eligible properties placed in service in 2009 or 2010, or if completed by 2013 (Walker and others, 2010).

In addition to the federal PTC, the Biomass Crop Assistance Program (BCAP) has provided significant subsidies to the biomass supply sector. However, it is considered unlikely that the current high level of subsidies will continue. Created in the 2008 Farm Bill, BCAP (sec. 9011) is intended to support establishment and production of eligible crops for conversion to bioenergy, and to assist agricultural and forest landowners with collection, harvest, storage, and transport of these eligible materials to approved biomass conversion facilities (Walker and others, 2010).

6.5.1 Greenhouse gas reporting

The US Environmental Protection Agency (EPA) ruling on the mandatory reporting of greenhouse gases decided that electricity generation and thermal facilities are not required to count emissions associated with biomass combustion when determining whether they meet or exceed the threshold for reporting (emissions of 25,000 t/y for all aggregated sources at a facility). But if the threshold is exceeded, facilities are required to report emissions associated with the biomass combustion separately. Thus, facilities that rely primarily on biomass fuels are not required to report under the rule (EPA, 2009; Walker and others, 2010).

This approach is consistent with IPCC Guidelines for National Greenhouse Gas Inventories, which require the separate reporting of CO_2 emissions from biomass combustion, and the approach taken in the US Inventory of Greenhouse Gas Emissions and Sinks. Separate reporting of emissions from biomass combustion is also consistent with some state and regional GHG programmes, such as California's mandatory GHG reporting programme, the Western Climate Initiative, and the Climate Registry, all of which require reporting of biogenic emissions from stationary fuel combustion sources. While this reporting requirement does not imply whether emissions from combustion of biomass will or will not be regulated in the future, the data collected will improve the EPA's understanding of the extent of biomass combustion and the sectors of the economy where biomass fuels are used. It will also allow the EPA to improve methods for quantifying emissions through testing of biomass fuels (Walker and others, 2010).

This rule is based on the EPA's basic premise that burning biomass for energy is considered to be carbon-neutral when considered in the context of natural carbon cycling. Regarding consideration of life-cycle emissions, the EPA has stated that preparation of a complete life cycle analysis is beyond the scope of this rule (Walker and others, 2010):

'With respect to emissions and sequestration from agricultural sources and other land uses, the rule does not require reporting of emissions or sequestration associated with deforestation, carbon storage in living biomass or harvested wood products.' These categories were excluded because currently available, practical reporting methods to calculate facility-level emissions for these sources can be difficult to implement and can yield uncertain results. Currently, there are no direct GHG emission measurement methods available except for research methods that are 'very expensive and require sophisticated equipment' (EPA, 2009).

Pending federal climate and energy legislation continues to be in flux, with an uncertain future and significantly evolving content. Overall, the bills focus primarily on the production of renewable electricity and transportation fuels rather than production of thermal energy. In all of the various versions of these bills, energy produced from biomass is considered to be renewable and carbon neutral and generally excluded from proposed caps on carbon emissions and related proposals for carbon emission allowances. There is continuing debate about the definition of biomass from qualifying sources and various proposals to provide safeguards for natural resources on public and/or private lands (Walker and others, 2010).

This debate also includes consideration of sustainability requirements or guidelines for biomass to qualify as a renewable fuel. There is concern that aggressive targets for increasing the use of biomass for production of renewable electricity and transportation fuels from the current Renewable Fuels Standard, a proposed Renewable Electricity Standard and a limit on carbon emissions would outstrip the capacity of US forests to provide an economically and ecologically sustainable supply. To ensure sustainable harvesting levels and accurate accounting of carbon emissions and re-sequestration, there is discussion and debate about including emissions from renewable biomass energy under proposed carbon caps based on full lifecycle accounting. At this point, however, it is unclear what direction will emerge in this developing legislation (Walker and others, 2010).

6.5.2 The Council on Sustainable Biomass Production (CSBP)

The Council on Sustainable Biomass Production (CSBP) is a multi-stakeholder organisation established in 2007 and managed by the Meridian Institute in collaboration with Heissenbuttel Natural Resource Consulting. CSBP has generated broad, consensus guidelines for sustainability that it hopes will be the foundation for a certification programme for sustainable biomass and bioenergy production (Meridian Institute, 2013).

The CSBP submitted the final report of the Standard for Sustainable Production of Agricultural Biomass in March 2013. It can be downloaded at http://www.csbp.org/. The Standard was developed for agricultural biomass including interplanting and short rotation woody crops planted on agricultural land. It provides a means by which a biomass producer may voluntarily evaluate their operation based on the environmental, social and economic sustainability principles.

CSBP sought to develop a standard that would be cost effective and widely implemented, while assuring truly sustainable production of bioenergy. The standard was developed in two phases: first from field to energy production facility entry gate (biomass producer standard), the standard that was released in June 2012, and second for energy production facilities (biomass consumer standard).

During its work the CSBP found that the market for agricultural biomass has not developed as quickly as many expected five years ago for various reasons. In addition, although the market for forest biomass pellets is strong, achieving consensus on forestry issues with a multi-stakeholder group is not easy; so the CSBP has yet to agree on a forest biomass standard (Meridian Institute, 2013).

The following principles express the key elements of sustainable biomass production and serve as the framework for the criteria and indicators of the standard.

1 Biomass production is based on an integrated resource management plan that is completed, implemented, monitored, and updated to address the environmental risks associated with current and future production, appropriate to the scale and intensity of the operation.
2 Biomass production maintains or improves soil quality. Soil stability is vital, and soil fertility and organic matter are critical to the sustainable production of food, feed, fibre and fuel.

3 Biomass production contributes to the maintenance or enhancement of biological diversity, in particular native plants and wildlife.
4 Biomass and bioenergy production maintains or improves surface water, groundwater, and aquatic ecosystems. Biomass production should not contribute to the depletion of ground or surface water supplies.
5 GHG emissions are estimated via a consistent approach to life cycle assessment. Full LCA is used as the primary tool for ensuring substantive reduction in GHG emissions. Bioenergy facilities will be responsible for conducting GHG lifecycle analysis on the energy they seek to certify.
6 Biomass and bioenergy production takes place within a framework that sustainably distributes overall socio-economic opportunity for and among all stakeholders
7 Biomass production complies with applicable federal, state, and local laws, statutes, and regulations.
8 The process of certified biomass production is transparent, while protecting commercially sensitive information and maintaining intellectual property.
9 Biomass and bioenergy producers continuously improve practices and outcomes based on the best available science and appropriate grower development benchmarks.

The CSBP has developed a chain of custody standard to provide a structure and accountability for the sale of CSBP-certified biomass. The success of the standard is dependent on the market demand by biomass consumers for CSBP-certified material. Feedback and field testing of the Standard and chain of custody will determine the next steps forward for expanding the CSBP standards.

6.6 Canada

In Canada, a working group on renewable fuels has a sustainability subgroup that has drafted guiding principles for sustainable biofuels produced in Canada. In addition, Canadian provinces are reviewing their sustainable forest management requirements to see if they are adequate to allow for the increased removal of forest biomass for energy. Only one province, New Brunswick, has forest management guidelines for biomass removal for energy (Van Dam and others, 2010).

6.7 Japan

The Japanese government has established a voluntary label, called the ‘Biomass mark’ that can be obtained when a commodity originates totally or partly from biomass. However, this is not coupled to any sustainability requirement (Van Dam and others, 2010).

6.8 Discussion

A biomass certification system has to comply with international trade regulations. This requires coherence and co-ordination of the development of standards and policies from national to international level. However, using international environmental agreements has its limitations. Standards agreed upon are unlikely to be ambitious and international agreements and full implementation by contracting parties can take a long time. Also, MEAs are often inadequately implemented due to a combination of factors and problems, such as limited jurisprudence and soft commitments. With the need to secure the sustainability of biomass in a fast growing market, the initial development of a biomass certification system on a national/regional level, possibly expanded into an agreement on international standards on a longer term, seems to be more feasible.

A comprehensive, reliable and controllable biomass certification system is most efficient to secure the sustainability of biomass. This can best be achieved through a certain form of regulation and international coherence. However, achieving this requires a drawn-out process of negotiating towards an international treaty which can take a long time. Meanwhile organisations are developing their own sustainability criteria and certification schemes.

The need to secure the sustainability of biomass production and trade in a fast growing market is widely acknowledged by various stakeholder groups and setting standards and establishing certification schemes are recognised as possible strategies that help ensure sustainable biomass production and trade. Various stakeholder groups have undertaken a wide range of initiatives as steps towards the development of sustainability standards and biomass certification systems. Sustainability standards and criteria are developed by various organisations. Between them, there seems to be a general agreement that it is important to include economic, social and environmental criteria in the development of a biomass certification system. However, differences are also visible in the strictness, extent and level of detail of these criteria, due to various interests and priorities (Van Dam and others, 2008).

The development of a biomass certification system is impeded by a number of issues. Many uncertainties remain on the feasibility, implementation, costs and compliance with international trade law of international biomass certification systems. Also, the possible risk of proliferation of individual standards and systems causes loss of efficiency and credibility (Van Dam and others, 2008).

Certification is not the goal in itself, but the means to an end. It can be one of the policy tools that can be used to secure the sustainability of biomass. Setting up good practice codes and integrating sustainability safeguards in global business models may also be effective ways to ensure this.

7 Discussion

At the state, national, and international level, policies encouraging the development of forest biomass energy have generally adopted a view of biomass as a carbon neutral energy source because the carbon emissions were considered part of a natural cycle in which growing forests over time would re-capture the carbon emitted by wood-burning energy facilities. Beginning in the 1990s, however, researchers began conducting studies that reflect a more complex understanding of carbon cycle implications of biomass combustion.

It is widely assumed that biomass combustion is inherently 'carbon neutral' as it only releases carbon taken from the atmosphere during plant growth. However, this assumption results in a form of double-counting, as it ignores the fact that using land to produce plants for energy typically means that this land is not producing plants for other purposes, including carbon otherwise sequestered. A concern is that if bioenergy production replaces forests, reduces forest stocks or reduces forest growth, which would otherwise sequester more carbon, it can increase the atmospheric carbon concentration. If bioenergy crops displace food crops, this may have repercussions for food production, if crops are not replaced and may lead to emissions from land use change if they are.

The assumption that all biomass is carbon neutral results from a misapplication of the original guidance provided for national level counting under the UNFCCC. Under UNFCCC accounting, countries separately report their emissions from energy use and from land use change. For example, if a hectare of forest is cleared and the wood used for bioenergy, the carbon lost from the forest is counted as a land use emission. To avoid double-counting, the rules therefore allow countries to ignore the same carbon when it is released from a chimney. This accounting principle does not assume that biomass is carbon neutral, but rather that emissions can be reported in the land-use sector. This accounting system is complete and accurate because emissions are reported from both land and energy sectors worldwide.

These conditions do not apply to any treaties, such as the Kyoto Protocol, that seek to limit emissions from energy use but do not limit emissions from land use, or do so only weakly and do not apply worldwide. If the removal of trees from a forest does not count toward emissions limits on land use under a legal rule that also exempts CO_2 emitted by bioenergy, then carbon needs to be counted when it goes up a chimney because it would otherwise be legally ignored completely. A law that applies greenhouse limits only to the energy sector must therefore count CO_2 emissions from bioenergy combustion except emissions from burning 'additional biomass'. That is biomass whose production and harvest absorbs more carbon from the air than the land and its plant growth would otherwise absorb, or which reduces non-energy emissions. The accounting regime adopted for the Kyoto Protocol improperly maintained the exemption of carbon from burning biomass. This error was followed by two European directives or provisions:

- The EU ETS caps emissions from major factories and power plants, but ignores CO_2 emissions from biomass combustion.
- The Renewable Energy Directive, which requires that Member States increase their use of renewable energy to 20% by 2020, implicitly sets CO_2 emissions from biomass combustion to zero.

The net effects of using land to produce biomass for energy use vary over time, and any comprehensive accounting system needs to consider many different aspects of land and energy use.

Proper accounting needs to reflect not merely the loss of existing carbon stocks in the pursuit of biomass production for energy, but also any decline of carbon sequestration that would occur in the absence of bioenergy use. For example, forests worldwide, particularly in the Northern Hemisphere, are accumulating biomass and carbon for a variety of reasons, and this growth absorbs carbon from the atmosphere. Some estimates of bioenergy potential suggest that biomass reduces GHG emissions so long as it only harvests this net forest growth and leaves the carbon stocks of the forests stable. But merely keeping carbon stocks stable ignores the additional carbon sequestration that would occur in the absence of wood harvest for bioenergy (the counterfactual) and therefore does not make bioenergy carbon neutral. For this reason, sustainable forestry in the traditional sense does not necessarily mean that bioenergy produced from a forest is carbon neutral.

Eventually, if harvested forests are allowed to re-grow, they will achieve close to the same carbon storage levels as unharvested forests, as growth slows down as forests reach maturity. At that point, the use of the biomass would become carbon neutral. Achieving this parity may take some time. However, it is possible that forest management for biomass harvesting can promote carbon uptake.

In the light of the future expected competition for fertile land, it is becoming increasingly important for policy makers to understand the best uses of fertile land for climate change mitigation. One key question is: should an area of land be used to grow energy crops for bioenergy generation or be used to store atmospheric CO_2 in biomass carbon pools (such as forest)? Righelato and Spracklen (2007) argued that land used to store carbon in forest would sequester two to nine times more carbon over a 30-year period than the emissions avoided by the use of biofuel grown on the same land. They emphasise that only the conversion of woody biomass may be compatible with the retention of forest carbon stocks. Bird and others (2008) compared the relative benefits over 40 years of using land for bioenergy production with use of the same land for carbon sequestration. Results show that a combination of high yielding crop species and efficient fossil fuel substitution makes the bioenergy crop option preferable. By contrast, low efficiency of fossil fuel replacement, independent of growth rate, means that the land is better used for carbon sequestration. Bird and others (2008) concluded that bioenergy production should be preferred if biomass from high-yielding plantations is produced and converted efficiently, displaces GHG-intensive and low-efficiency fossil energy, and if a long-term view is taken.

Various studies project bioenergy as a potentially large and carbon-free replacement for fossil fuels. Policies that consider bioenergy as carbon neutral may have significant ramifications. Producing several hundred EJ/y of bioenergy would require a multifold increase in the human harvest of global plant production. Currently, the total global biomass harvest for food, feed, fibre, wood products and traditional wood use amount to about 12 Gt/y dry matter of plant material. This biomass has a chemical energy value of 230 EJ/y. Thus, with the competition for land and resources, there will be a limit on the potential of biomass for cofiring. But it can still have an important role, especially in areas where forest has traditionally been managed, possibly for the pulp and paper industry which is now in decline.

Estimates of land use change (LUC) effects require value judgments about the temporal scale of analysis, the land use under the assumed ‘no action’ scenario, the expected uses in the longer term, and the allocation of impacts among different uses over time. However, a system that ensures consistent and accurate inventory of and reporting on carbon stocks is considered an important first step towards LUC carbon accounting.

Emissions of pollutants such as SO_2 and NOx, are generally lower for biomass than for coal. Thus, bioenergy can reduce negative impacts on air quality. Bioenergy impacts on water resources can be positive or negative, depending on the particular feedstock, supply chain element and processing methodologies. Bioenergy systems similar to conventional food and feed crop systems can contribute to loss of habitat and biodiversity, but bioenergy plantations can be designed to provide filters for nutrient loss, to function as ecological corridors, to reduce pressure on natural forests and to restore degraded or abandoned land.

It is important that the most likely, that is, the most realistic, counterfactual to (no) bioenergy harvest is defined, which includes accounting for potential displacement effects. Bioenergy systems are typically connected to existing forestry industries. Thus bioenergy extraction takes place within existing demand-supply patterns for other woody biomass products (primarily timber and cellulose). From a nature conservancy viewpoint forest protection is a valid baseline case. However, it would have to be evaluated holistically, that is it should include carbon emissions from displacement effects, such as LUC in other regions, and socio-economic consequences.

The vast majority of wood pellets imported to Europe for cofiring are based on processing and harvesting residues with an increasing though still minor share from low-grade roundwood. Generally, the higher economic value for timber and cellulose products makes large-scale use of whole trees for energy purposes highly unlikely wherever there is regional competition for the fibre.

The debate of the carbon consequences of bioenergy has highlighted the importance of considering timescales when comparing alternative energy supply and GHG mitigation options. Forest bioenergy is a case in point as short-term renewable energy consumption targets, for example by the EU for 2020, may have climate effects beyond these timescales. A first step could be to decide whether bioenergy should contribute to short- or long-term emission savings. In general, there is a possibility to achieve emission reductions in the long term.

Further, there are a number of feedstock options that offer (almost) immediate net carbon benefits, provided they substitute GHG intensive fossil fuels. These include the use of:
- harvesting or processing residues;
- standing deadwood from highly insect-infected sites;
- new plantations on highly productive or marginal/previously unused (and carbon poor) land.

The continued import dependency of the EU regarding woody biomass for energy, in particular wood pellets for large-scale co- and mono-firing, makes the current debate on the temporal carbon balance of bioenergy particularly relevant for European policy makers. The discussion so far does not acknowledge that current wood pellet import streams are predominantly residue based while (low-grade) roundwood still plays a marginal role. Yet many temporal carbon analyses focused on whole-tree harvesting in subboreal regions. Future EU import streams will likely continue to be dominated by North America, especially from the south east USA where an increasing share is based on pulp-grade plantation roundwood from the temperate southern forest biome. The wood fibre demand increase for pellet production in this region however coincides with a steady downturn in the US forest products sector (since 2006) and regional oversupply of pulp-grade roundwood. Thus it is important to put temporal carbon balances into regional market perspectives when defining future policy measures.

Biomass for cofiring is not as clear cut carbon neutral as say wind or solar power, but it is reliable. It is not intermittent, and it takes advantage of the massive infrastructure that is in place for coal-fired power generation. Biomass for cofiring reduces emissions of NOx and SOx. Most biomass that is being used is from forestry residues and thinnings, so has a low environmental impact. It is important to consider biomass use from the landscape rather than from the stand perspective. Generally forests are managed on a rotation, so as one stand is felled the others are at various stages of regrowth, so if anything, the whole forest will be accumulating carbon. In the south east USA, one of the main sources of biomass for the EU, the total forest cover is increasing. Biomass for pellets is replacing the falling demand for pulp and paper. If the demand for biomass for cofiring increases, there may be an overall increase in forest cover to meet the supply, and hence an increase in carbon storage. It is unlikely to compete with land for food production, due to market economics.

There is a lack of standards for the sustainable production of biomass at the international level. The EU raised the issue of standards in 2010, but a policy has not been published. The FSC and PEFC have set widely-used and well-recognised standards on sustainable forestry but do not include an assessment of the GHG impacts of forestry. While industry awaits national and international guidance on sustainable biomass, many organisations are developing their own criteria and certification schemes. It may be that this is more appropriate, that standards should be developed for different types of biomass source and means of production, as there is such variety. It may mean that strong standards with more credibility emerge and become more widely-recognised. Such a process may take no longer than the emergence of an international agreement that may be unwieldy, and not appropriate for every situation.

Biomass can be sustainable, and can be carbon neutral, but there are many factors that must be considered, measured and certified, before it can be declared so.

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