

EU bioenergy potential from a resource-efficiency perspective

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resource efficiency perspective. Key ETC staff and other experts also contributed to the EEA report, in particular Berien Elbersen at Alterra and Uwe Fritzsche at IINAS.

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Executive summary

The bioenergy challenge

The European Union has set itself the ambitious target to increase the share of renewable sources in final energy consumption to 20 % by 2020 (EC, 2009). This is motivated by the widespread recognition that using fossil fuels to generate energy causes significant harm to the environment and human well-being. Renewable energy technologies offer a way to increase resource efficiency significantly — enabling society to meet its energy needs at much lower environmental costs.

In Europe, bioenergy plays a central role in national renewable energy action plans (NREAPs), accounting for more than half of projected renewable energy output in 2020. Yet while these targets offer potentially significant environmental benefits, it is clear that the extent of those benefits will vary hugely depending on how bioenergy is developed.

Whereas all renewable energy sources necessitate some use of natural resources, bioenergy differs in the extent and complexity of its impacts. While some bioenergy sources and technologies offer significant advantages over fossil fuel-based systems, others lead to environmental concerns. This is particularly the case where bioenergy involves using agricultural land to cultivate energy crops, since it often results in changes to land use, including expanding or intensifying agriculture at other locations. This can have significant implications for the natural environment, such as biodiversity and the water, nutrient and carbon cycles, affecting ecosystem functioning and resilience in diverse ways.

It is very important, therefore, to apply resource efficiency principles to developing EU bioenergy production. This means producing more with less while avoiding environmental impacts. There are numerous types and sources of biomass, conversion technologies and potential end uses. Some of these are a good fit with resource efficiency principles, others are not. Biomass from waste and residues from agriculture and forestry offer high resource efficiency whereas the environmental benefits from cultivating crops for bioenergy

('energy cropping') are often limited. Finding resource-efficient combinations of biomass sources, conversion technologies and energy end uses is the main challenge for the further development of EU bioenergy production in an environmental perspective.

Report background and aims

To support decision-making in this complex area, the European Environment Agency (EEA) has produced a series of reports estimating the European Union's bioenergy potential in an environmental perspective and analysing its most efficient use to support greenhouse gas (GHG) mitigation (EEA, 2006, 2007, 2008). Understanding of key issues has since advanced, particularly regarding the crucial role of indirect land use change (ILUC) in determining environmental impacts of bioenergy. The EEA European Topic Centre on Spatial Integration and Analysis (ETC/SIA) produced a report in 2013 re-evaluating Europe's bioenergy potential and providing further insights into:

- the potential GHG savings from different technological options to convert biomass to energy ('bioenergy pathways');
- how to bring a resource efficiency perspective into the design of bioenergy development;
- concerns about the GHG benefits of using forest biomass to produce energy ('carbon debt');
- the desirability of current bioenergy cropping trends from an environmental perspective.

This EEA report provides an analytical summary of the results of this ETC/SIA report, and includes additional qualitative analysis of the 'carbon debt' issue. It primarily addresses the agricultural sector as it is clearly the biomass source with greatest potential for growth and for adverse environmental impacts — often as a result of ILUC. However, the study also includes the estimated bioenergy potentials for the EU forest and waste sectors from

earlier EEA reports in order to provide a complete analysis of the most resource-efficient approach for reaching the EU 2020 bioenergy ambitions.

Methodology

The present study builds on previous work by the EEA in terms of the analytical approaches applied but combines them in a novel way and introduces ILUC effects in the analysis. Firstly, it updates the 2006 estimate of the agriculture bioenergy potential (while the forest and waste potentials remain as in 2006). In a second step, life cycle analysis and land use-environment models are combined to estimate the GHG emissions and energy yields from different bioenergy pathways. The third step involves the development of three alternative futures ('storylines') to explore the influence of different environmental, technological and policy factors on the resource efficiency of EU bioenergy production. Their main characteristics are (see also Box 1.3):

- The 'Market first' storyline leaves bioenergy development and the attainment of EU renewable energy targets largely to market forces. This means no new policy interventions to avoid environmental impacts or ILUC effects are expected.
- The second storyline 'Climate focus' assumes more policy intervention, including constraints on the areas that can be used for bioenergy cropping, exclusion of biofuel pathways that fail to reduce GHG emissions by at least 50 % compared to fossil fuels, and the introduction of a floor price for biomass feedstock.
- The third storyline, 'Resource efficiency', includes all of the conditions of the 'Climate focus' storyline, but applies the mitigation requirement of 50 % to all bioenergy pathways. Furthermore, it includes additional policy measures to prevent negative impacts on natural resources and biodiversity, and to enhance the efficiency of bioenergy production across sectors.

The fourth step involves combining different analytical outputs in an overall assessment. Applying the storyline assumptions enabled the different input data to be transformed into projections of land use change, biomass production, energy output and related GHG emissions. Via modelling the land use change anticipated in each storyline is translated into impacts on water, soil, air and biodiversity.

Taken together, these findings illustrate the potential environmental impacts of energy cropping, the most resource-efficient approaches to developing bioenergy, and the feasibility and implications of current bioenergy targets in NREAPs.

Key results

The storyline-based analysis clearly illustrates that the efficiency and environmental impacts of bioenergy development in the EU are likely to vary substantially, depending on the pathways chosen. Specifically, the analysis delivers the following main findings:

- **ILUC matters:** Comparing the bioenergy potential in the three storylines with the estimates of bioenergy potential in earlier EEA reports demonstrates the importance of incorporating indirect land use change into the analysis. Accounting for ILUC reduces the amount of bioenergy that can be produced, but more significantly it alters the bioenergy mix. In particular most first generation biofuel pathways are excluded as including ILUC renders their GHG balance negative.
- **The contrasting policy constraints deliver little variation in total bioenergy potential but larger difference in the energy crop mix:** Although the tighter environmental constraints in the 'Climate focus' and 'Resource efficiency' storylines reduce biomass potential, this is offset by price supports and more efficient bioenergy pathways, which are absent from the 'Market first' storyline. As a result, the overall bioenergy potential is similar in all three storylines. However, the storyline assumptions imply large differences in the crop mix and the energy conversion pathways. The 'Climate focus' and 'Resource efficiency' storylines result in a shift away from first generation biofuels and towards perennial crops and relatively more heat, electricity and biogas production.
- **The alternative bioenergy pathways vary significantly in their GHG efficiency:** The absence of environmental constraints in the 'Market first' storyline implies that the NREAP bioenergy targets would be achieved at the cost of producing 44 kg of CO₂-equivalent per GJ. That is 62 % less GHG emission than if the energy were generated using fossil fuels. In contrast, the strict environmental constraints in the 'Resource efficiency' storyline imply a substantially lower burden of

25 kg CO₂-equivalent per GJ, which represents an 80 % reduction compared to fossil fuels.

- **The bioenergy pathways also vary greatly in their ecosystem impacts:** The storylines differ significantly in impacts on water quantity, soil erosion and farmland bird diversity. The 'Market first' storyline leads to negative environmental impacts in these areas. The 'Climate focus' storyline shows that prioritising the reduction of GHG emissions can still lead to negative increases in water abstraction and loss of farmland bird diversity. The 'Resource efficiency' storyline comes closest to an environmentally beneficial approach as it performs better than the other two storylines on both the water abstraction and the farmland bird effects while still achieving current bioenergy targets across the EU.
- **Current energy cropping trends are not 'environmentally compatible':** Comparing current energy cropping trends with the 'environmentally compatible' cropping scenario developed by the EEA in 2006 reveals substantial differences. Whereas annual arable crops currently dominate and perennials account for a tiny proportion of the crop mix, the environmentally compatible energy crop mix proposed in 2006 foresaw a strong shift to perennial crops and grasses by 2020.

Conclusions

As the storyline-based analysis illustrates clearly, bioenergy's GHG efficiency and ecosystem impacts can vary significantly depending on the economic and policy constraints in place and the resulting bioenergy pathways. Where feedstock is sourced from waste or agricultural residues, it implies zero land use change and substantial advantages over fossil fuel energy in terms of both greenhouse gas efficiency and ecosystem impacts. Conversely, where biomass is derived from energy cropping, some bioenergy pathways lead to additional GHG emissions and other environmental impacts. Indirect land use change effects are particularly important

in this regard and need to be addressed by the EU bioenergy policy framework.

From a resource-efficiency perspective, the core message from this study is clear: bioenergy can play a valuable role in meeting society's energy needs while preserving our natural capital — but only if it focuses on the most resource-efficient use of biomass through the whole biomass-to-energy production chain.

The analysis illustrates that policies aimed at making upstream parts of the bioenergy chain (i.e. the sourcing of biomass) environmentally compatible need to be combined with measures that stimulate improvements in other parts of the chain. This concerns particularly the downstream conversion approach but also includes all logistics and final end-uses of bioenergy.

Potentially adverse environmental effects connected to direct land-use effects, including changes in land management, currently fall outside the EU bioenergy policy framework. Additional policy incentives and safeguards are needed to address such environmental impacts, particularly with respect to water resources and farmland biodiversity.

The use of waste biomass and residues from forestry and agriculture is very favourable in a resource efficiency perspective. However, the question of carbon debt associated with the use of forest biomass from trees presents an environmental concern. This issue clearly requires further investigation as it potentially negates the GHG mitigation gains from a substantial part of the currently estimated forest bioenergy potential.

This analysis has made further progress in understanding the potential environmental benefits and impacts of EU bioenergy production. Nevertheless, further analytical work would help to address additional policy questions and reduce uncertainties in assessment results. This will require additional progress in developing suitable modelling and assessment tools. Improving analytical certainty, however, also requires an adequate investment in monitoring trends in energy cropping and associated production processes and environmental impacts.

1 Introduction

1.1 Role and limits of renewable energy technologies in enhancing resource efficiency

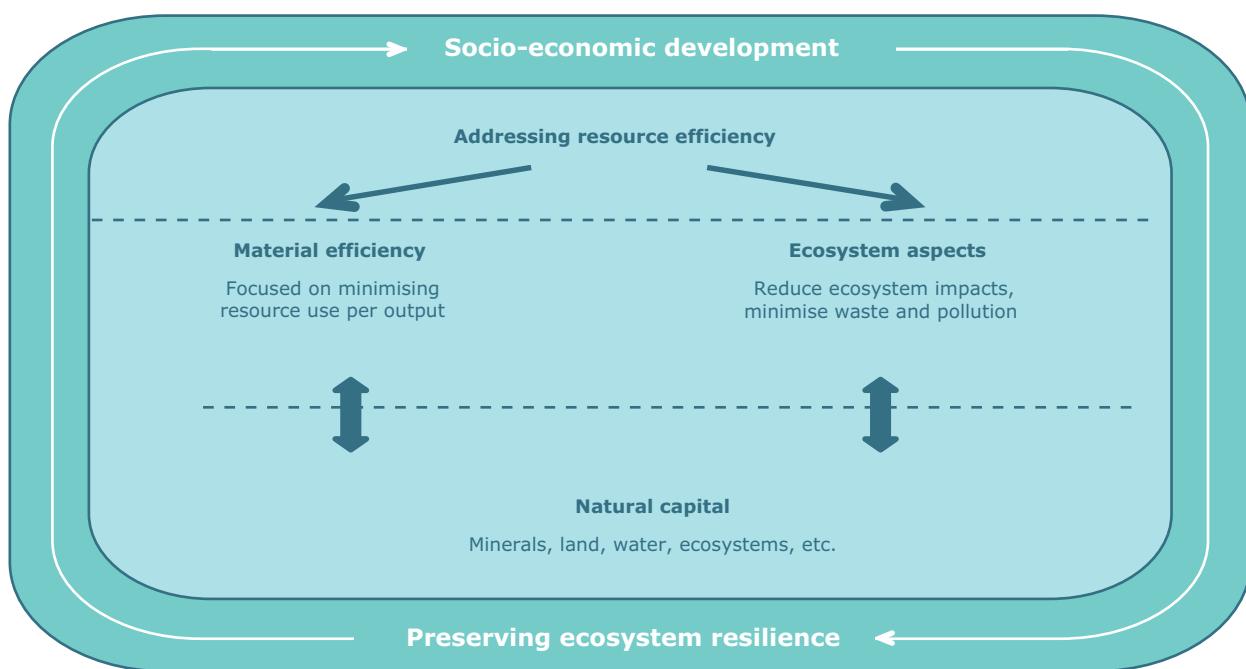
Humanity's greatest challenge in the years ahead arguably lies in finding ways to meet our needs while maintaining the natural systems that sustain us. In a world of finite resources and ecosystem capacity, resource efficiency is absolutely central to achieving that goal.

Enhancing resource efficiency essentially means finding ways to achieve more at lower costs to the environment. This implies reducing the amount of resources used to meet our needs. But it also relates to the environmental impacts — on water, air, soil and biodiversity — that result from extracting resources from natural systems and emitting wastes and pollution. Figure 1.1 shows how resource efficiency relates to the use of natural capital and ecosystem resilience.

Energy is a key concern in this context. Our economies and societies require energy to function and this has enormous implications for our resource use and broader impacts on ecosystems. Energy sources vary hugely in character: some are non-renewable sub-soil sources, such as coal and oil; some, such as biomass, are renewables but depletable if natural systems are not managed properly. Others, such as solar and wind, are in practical terms non-depletable.

The EU's Roadmap to a Resource Efficient Europe (EC, 2011a) outlines how we can make Europe's economy sustainable by 2050. It proposes ways to increase resource productivity and decouple economic growth from resource use and associated environmental impacts. The Roadmap analyses key resources from a life-cycle and value-chain perspective and illustrates how policies interrelate and build on each other. It sets out a vision for the structural and technological change needed up to 2050, with milestones to be reached by 2020 — more information

Figure 1.1 The two key aspects of resource efficiency



Source: EEA, 2013.

is available under: http://ec.europa.eu/environment/resource_efficiency/about/roadmap/index_en.htm.

Against this backdrop, renewable energy has a crucial role to play in sustaining economic output at lower environmental costs — meaning significant resource efficiency improvements relative to fossil fuels. The commitment to resource efficiency has two important implications for developing renewable energy, including bioenergy:

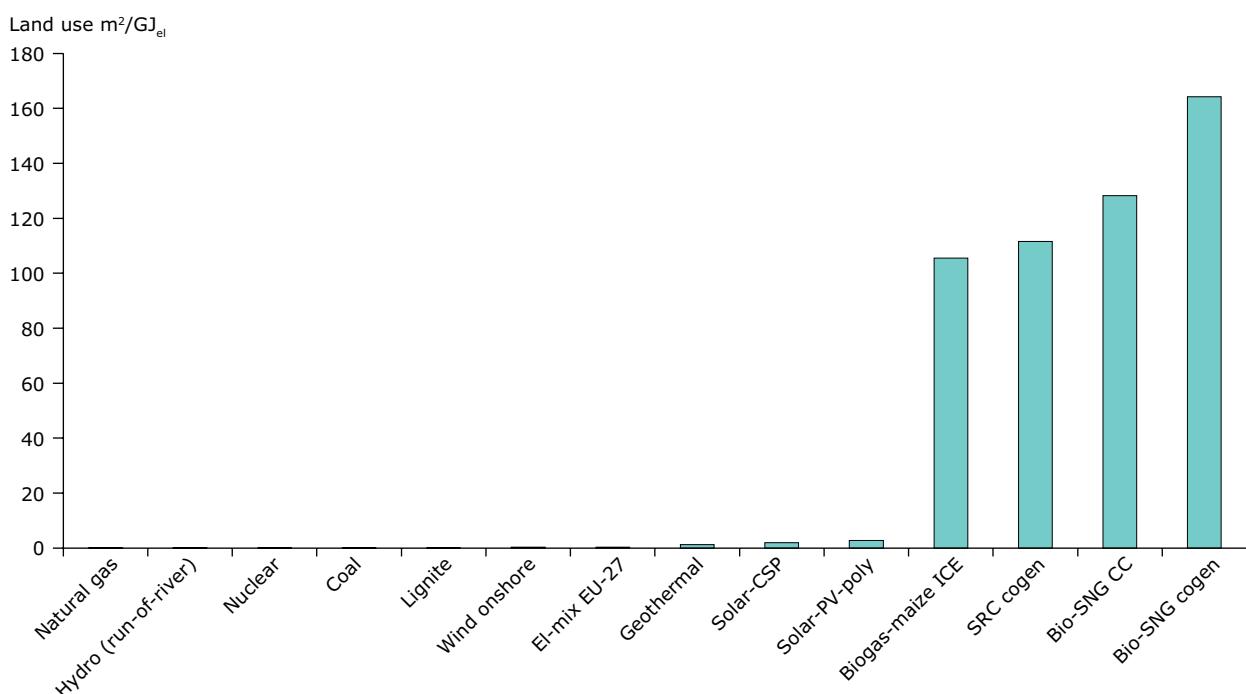
1. new energy sources should be as resource efficient as possible, which implies that small relative reductions in greenhouse gas emissions compared to fossil fuel-based energy systems are not sufficient;
2. renewable energy sources should not lead to medium- or long-term depletion of non-renewable resources or cause negative impacts on the world's natural capital, such as forests, productive soils, natural ecosystems, or water resources.

1.2 Extent and complexity of bioenergy's environmental impact

Renewable energy technologies potentially offer an important means of reducing humanity's burden on the environment while sustaining economic development. Nevertheless, all such technologies have advantages and limitations, which vary depending on how and where they are deployed.

Like all renewable energy sources, bioenergy offers a mixture of environmental and financial benefits and risks. Where bioenergy differs is in the extent and complexity of its impacts. Whereas most forms of renewable energy exploit geo-physical energy sources, such as solar radiation or wind, bioenergy often uses feed stocks cultivated on land which could be used productively for other purposes. Other renewable technologies do indeed use some land but the area is comparatively small. Figure 1.2 illustrates these differences in relation to electricity generation.

Figure 1.2 Projected life-cycle land use of fossil, nuclear and renewable electricity systems in 2030 ($\text{m}^2/\text{GJ}_{\text{el}}$)^(a)



Note: ^(a) SNG = substitute natural gas; cogen = cogeneration; SRC= short-rotation coppice; CC= combined-cycle; ICE= internal combustion engine; PV= photovoltaic; CSP= concentrating solar power.

The 2030 time horizon was chosen to include advanced bioenergy technologies such as bio-SNG, and solar CSP. The reasoning behind the calculations (including the assumptions regarding technologies available in 2030) is set out in ETC/SIA (2013). Note that potential ILUC effects of bioenergy systems are excluded here.

Source: Fritzsche, 2012a, based on GEMIS 4.8 data.

Box 1.1 Land as a resource

To understand the implications of increased bioenergy production, it is important to recognise that the land used for energy cropping is a natural resource, comprising soil, minerals, water and biota (MA, 2005). As such, it plays an essential role in delivering valuable ecosystem services, such as supporting the cultivation of biomass for food, energy and other products, and regulating the environment, e.g. via water filtration or carbon sequestration. Communities also often attach considerable cultural and religious value to local landscapes. Land's capacity to provide these services depends on its management for agriculture, forestry, transport, living and recreation.

From a physical and economic perspective, land is an inherently fixed and scarce resource. Competition for land is already projected to increase to meet the food and fibre needs of a global population of nine billion in 2050 (FAO, 2010), which could consume at least 50 % more food than today (Royal Society, 2009). Increased energy cropping implies an additional demand for land, necessitating either the conversion of natural ecosystems or more intensive use of existing farm and forest land (WGBU, 2008). Both will affect environmental quality and biodiversity, which must be reflected when analysing bioenergy's impacts.

Where bioenergy involves energy cropping it often necessitates changes to land use, with significant implications for related systems, such as water, nutrient and carbon cycles, and biodiversity. This can affect ecosystem functioning and resilience in diverse ways.

Understanding the full impacts of bioenergy on the environment therefore presents considerable challenges. Clearly, the effects of using biomass for energy will vary greatly from location to location. It could involve further intensification of existing land uses, both in agricultural and forest lands. It could mean converting directly or indirectly non-cropped biodiversity-rich land into cropped land or plantation forests.

There are also many types and sources of biomass and many different pathways for converting them into energy for diverse end uses. Net effects on greenhouse gas emissions will vary greatly as a result, as will the wider ecosystem impacts. The complexity of analysing bioenergy's full costs and benefits only grows when effects on local economic activity, employment and so on are also considered.

1.3 The EU framework for expanding bioenergy production

Determining where, how and how much to cultivate energy crops is evidently a very significant challenge but it is one that EU governments must confront. This is because, in addition to the generalised need for countries to enhance resource efficiency, EU Member States have agreed to specific, legally binding renewable energy targets — and they are substantial.

The Renewable Energy Directive (RED, EC, 2009) sets a general binding target for the European Union to derive 20 % of its final energy from renewable sources by 2020. This includes a sub-target of 10 % of EU transport energy to be derived from renewable sources. The RED also specifies that all biofuels and other bio-liquids counting towards the target must meet a set of mandatory sustainability criteria to achieve greenhouse gas reductions compared to fossil fuels and to mitigate risks related to areas of high biodiversity value and areas of high carbon stock. The mitigation criteria cover emissions related to direct land-use changes.

The European Parliament and Council asked the European Commission to examine the question of indirect land-use change and possible measures to avoid it. This resulted in an impact assessment and a European Commission communication (EC, 2010a) summarising the consultations and analytical work conducted on this topic since 2008. In this communication the European Commission acknowledge that indirect land-use change can reduce the greenhouse gas emissions savings associated with biofuels and bioliquids. This led to the publication of a Commission proposal (EC, 2012) for an amendment of the RED and the Fuel Quality Directive in which it is proposed (amongst other measures) to limit the contribution of food-based biofuels within the overall 10 % renewable transport target to 5 % in the future.

The general target of 20 % renewable energy for 2020 translates into individual targets for Member States, which range from 10 % (for Malta) to 49 % (for Sweden). In 2010 Member States adopted National Renewable Energy Action Plans (NREAPs), which indicate how much each bioenergy source

will contribute to achieving their renewable energy targets. From these NREAPs it is apparent that bioenergy will make up more than half of all renewable energy in 2020 — implying that it will account for about 10 % of the EU's total gross final energy consumption. Some Member States that have limited alternative renewable-energy options and large biomass resources significantly exceed the average EU share of biomass within their final energy consumption.

Looking beyond 2020, the EU's Energy Roadmap 2050 (EC, 2011b) likewise foresees a central role for bioenergy in delivering an 80–95 % reduction in EU greenhouse gas emissions by 2050. Such ambitious reduction targets underline the importance of developing bioenergy in a way that enables very substantial cuts in GHG emissions and does not impact on ecological resources.

1.4 The need to understand energy cropping's land use impacts

The planned growth in bioenergy output and the extent of its potential impacts clearly make it essential that we understand how much biomass can be produced sustainably in the EU, and how we can maximise bioenergy output within environmental constraints. In this context, it is also important to consider the environmental impacts of biomass imports.

To address this need, the EEA has produced a series of studies in recent years contributing to the knowledge base in this complex area:

- EEA (2006, 2007) investigated how much bioenergy the EU could produce without harming the environment. This was done by

developing scenarios for the agriculture, waste and forestry sectors for the period up to 2030, based on various assumptions about policies and environmental constraints.

- EEA (2008) explored the optimal use of biomass estimated in earlier studies, quantifying the amount of GHG emissions that could be avoided by exploiting the environmentally compatible bioenergy potential in a resource efficient manner.

Since 2008, scientific knowledge, public debate and the political landscape have all evolved, generating new insights and providing a context within which the environmentally compatible bioenergy potentials should be reassessed. In addition, two opinions of the EEA's Scientific Committee reviewed the development of bioenergy output in the context of more recent knowledge about indirect land use effects, ecosystem carbon cycles and greenhouse gas accounting standards. In these opinions the Committee recommended careful consideration of which bioenergy pathways and production volumes ensure real greenhouse gas savings (EEA SC, 2009 and 2011).

Since 2009, therefore, the EEA has invested substantial resources via its European Topic Centres on Air and Climate Change (ETC/ACC) and the ETC/SIA into updating its previous analysis. That work has pursued five main objectives:

- updating the estimate of the 'environmentally compatible' bioenergy potential from agricultural sources on the basis of recent data and technological insights;
- integrating current knowledge of indirect land use change effects into the analysis of likely

Box 1.2 Environmentally compatible bioenergy potential

In its 2006 report, the EEA sought to identify the 'environmentally compatible potential of bioenergy'. This potential is derived from the quantity of biomass that is available for energy generation if all technical options are exploited and imposes no additional pressures on biodiversity, soil and water resources compared to a development without increased bioenergy production.

'Environmentally compatible' implies that growing and harvesting the biomass is in line with the overall set of EU environmental policies and objectives and has practical management implications. For example, in forestry it means that a minimum share of deadwood has to remain in the forest and that the use of forest residues should not exceed a level that maintains soil fertility and organic content. In agriculture a 30 % share of low-input and/or organic farming is assumed, extensive farming systems are to be preserved and the choice of crops and farming practices is expected to take account of environmental considerations.

- greenhouse gas savings from different EU bioenergy pathways;
- reviewing recent scientific debates on the actual greenhouse gas benefits of using forest biomass to produce energy (i.e. the 'carbon debt' concept);
- exploring the resource efficiency concept with a view to an optimal design of EU and national bioenergy policies until 2020;
- comparing current bioenergy cropping trends and cropping projections to 2020 to scientific models of the environmental impact of agricultural land use.

In 2013, the ETC/SIA produced a report addressing these issues on behalf of EEA (ETC/SIA, 2013). The ETC/SIA report integrated the potential consequences of global indirect land use change (ILUC), adapted the earlier estimates of agricultural biomass potential and environmental constraints, and reflected the current timeline and objectives of EU policy. It also updated technology and cost data for bioenergy systems, and their respective life-cycles.

The new analysis primarily addressed the agricultural sector, which is, by some distance, the biomass source with greatest potential for growth and for adverse environmental impacts. However, it also included the estimated bioenergy potentials for the EU forest and waste sectors from the EEA's 2006 report. This enabled a complete analysis of the implications of the 2020 bioenergy targets for GHG balance and ecosystem impacts in different bioenergy pathways (ETC/SIA, 2013).

Aims and approach of this report

The main objective of this report is to review the implications of resource efficiency principles for developing EU bioenergy production. The results presented are primarily based on the 2013 ETC/SIA study, capturing key messages while excluding some of the more technical elements. The report aims to be a more accessible version of the ETC/SIA study, aimed at the non-technical reader.

The primary analytical focus is on energy cropping, since other biomass sources (waste and residues) are considered to have significantly lower environmental impacts. Nevertheless, the carbon effects of using forest biomass were explored in a qualitative manner. The report sets out key resource efficiency principles, develops

an analytical approach for applying these to bioenergy production and draws out key analytical outcomes for the development of a resource-efficient bioenergy sector.

Chapter 2 of the report reflects upon the range of bioenergy technology currently available and indeed expected in the coming years. This information sets the technical framework for the resource efficiency analysis to follow.

Chapter 3 allows the reader to reflect upon to the possibility of assessing the environmental performance of bioenergy against the two key aspects of resource efficiency as mentioned previously. The chapter focuses on potential ecosystem impacts and analyses the land use dimension of bioenergy production. It describes the types of direct and indirect impacts that can arise and summarises estimates of ILUC impacts and the carbon debt debate related to the use of forest biomass.

Chapter 4 describes the modelling chain that was employed to analyse efficiency aspects of bioenergy production. This provides insight into use of different models and the way ILUC effects were integrated into analysis. The chapter also discusses analytical and data uncertainties associated with the study.

Chapter 5 presents the relative energy and GHG balances of the use of biomass in the heat, power and transport sectors and illustrates the importance of the choice of energy crops for the overall environmental performance of energy pathways based on agricultural biomass.

Finally, Chapter 6 sets out key conclusions of the study with regard to the analytical approach and policy implications. The approach employed and the timeframe of the development of the underpinning technical study do not allow a direct evaluation of current policy proposals. Nevertheless, the analysis set out in this report is considered to be a potential input to current EU policy debates.

The ETC/SIA study utilised the development of three different storylines as a key methodological tool for exploring the influence of different environmental, technological and policy factors. These do not aim to forecast likely futures, but they explore plausible bioenergy development paths from a resource efficiency perspective under three specific sets of economic and political assumptions. Box 1.3 sets out the key characteristics of the three storylines.

Box 1.3 Storyline assumptions in brief

Bioenergy development in the 'Market first' (Storyline 1) is largely left to market forces. Energy cropping patterns follow projections that are derived from agro-economic modelling (the CAPRI model). Policy intervention is limited to the renewable energy targets for 2020 set out in the Renewable Energy Directive (EU, 2009a) and further specified in the NREAPs; reaching these targets is left to market forces and domestic quotas and indirect land use change is not addressed. Biomass feedstock will be used at a cost level of around EUR 3/GJ.

'Climate focus' (Storyline 2) assumes more policy intervention. Only biofuel pathways capable of mitigating at least 50% of GHG emissions (including an ILUC factor) compared with fossil alternatives are used. Areas with high biodiversity or high carbon stocks are not to be used for dedicated energy cropping. The 10 % target for transport biofuels is also relaxed to promote a shift in energy cropping towards the most appropriate pathways and areas. The storyline integrates a range of support measures such as a floor price for biomass feedstock of up to EUR 6/GJ. It also favours second-generation technologies and perennial energy cropping with very limited ILUC effects over alternatives that have limited GHG mitigation effects.

'Resource efficiency' (Storyline 3) assumes stronger policy intervention than 'Climate focus' and responds to the efficiency as well as the ecosystem resilience aspects of resource efficiency. All the conditions of Storyline 2 apply to biofuels as well as bio-heat and bio-electricity pathways. In addition, stricter requirements are imposed for converting land to energy cropping in order to ensure that there are no negative impacts on natural resources and biodiversity. Finally, while the aggregate bioenergy targets in NREAPs remain binding, the sectoral split is relaxed such that more heat could be produced and less electricity, if that proves to be more efficient.

2 Types of bioenergy and their role in the renewable energy mix

2.1 Bioenergy sources and technologies

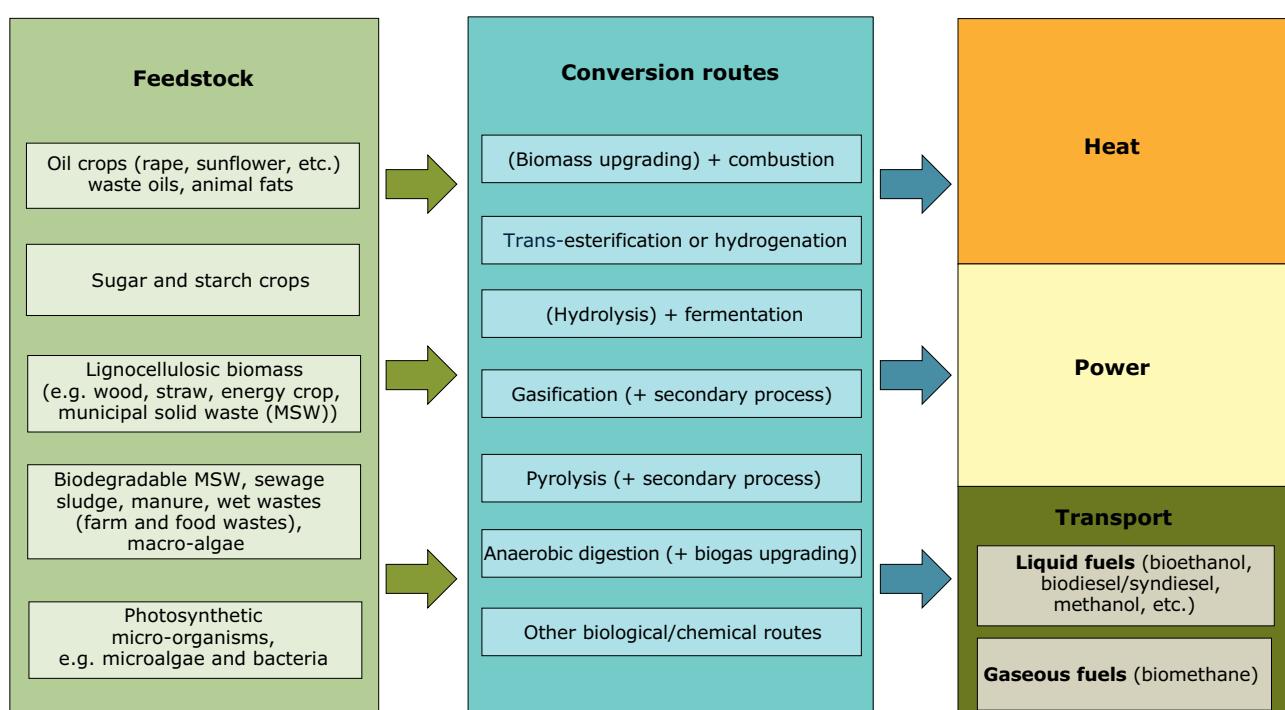
As explained in Chapter 1, determining how to develop resource-efficient renewable energy sources requires an understanding of the costs and impacts of alternative technologies. This chapter initiates the assessment of bioenergy options by outlining the technologies currently available, which feature in the storyline-based analysis. A more detailed summary of current technologies is presented in Chapter 4 of ETC/SIA (2013).

At present, the three different types of energy end-uses for which biomass can be employed – transport fuel, electricity generation and heating

– use different but overlapping types of biomass. However, it is expected that these markets will become more integrated in the coming decades as advanced conversion technologies, bio-refineries and cascading use of biomass become more prominent.

The diverse pathways for transforming different types of biomass into different forms of energy obviously imply a potentially wide range of environmental impacts. Figure 2.1 shows the most common biomass categories derived from agriculture, forests and wastes, and the conversion routes that are expected to become economic by 2020. The remainder of this chapter looks in more detail at the technologies used in each of the bioenergy sub-sectors.

Figure 2.1 Routes for converting biomass to energy



Source: IEA Bioenergy 2009, simplified by EEA, 2013.

2.2 Bioelectricity

Electricity is a versatile energy carrier. It is efficient in providing a variety of energy services such as communication, lighting and mechanical power, but also capable of powering rail and road transport and providing (cogenerated) heat. Partly because of this versatility, electricity's share in total energy consumption is likely to increase markedly from current levels, almost doubling to 37 % in 2050 (EC, 2011b).

Bioelectricity is generated from two bioenergy sources.

- **Solid biomass** — wood chips, pellets, straw, dry manure — can be co-fired in conventional coal-fired power plants. This is a low-cost option, requiring comparatively little investment. The conversion efficiency of biomass into electricity is practically the same as for the fossil fuel (IRENA, 2012). Smaller-scale dedicated biomass-to-electricity plants often employ cogeneration (combined heat and power generation, as described in Box 2.1) to make use of waste heat, thus compensating for lower electric efficiency and higher costs.
- **Biogas and biomethane** can be used both for electricity generation or co-generation, and for injection into the gas grid as a direct substitute for natural gas. Electricity generation from these sources is already quite efficient and low-polluting. The extent of methane leakages from biogas plants can be substantial, however, and the losses of this potent greenhouse gas influence the final GHG efficiency of this bioenergy pathway significantly.

Producing biogas from dedicated energy crops, such as maize, sugar beet or wheat, requires careful analysis due to their land use implications. The emissions of greenhouse gases and acidifying gases such as ammonia from these systems are substantial. Where manure or organic residential wastes are used, the greenhouse gas performance of biogas pathways is far better.

2.3 Bio-heating

Throughout history, humans have burned biomass for heating in small-scale systems. Today, the best option for generating heat from biomass in small-scale units is burning wood pellets or logs in specialised heating systems, although this requires high capital investment compared with fossil fuel

heating. Even traditional log stoves can reach a high efficiency (> 80 %) if operated properly, but produce significant air emissions, especially in terms of fine particles (PM_{10}) and black carbon, the latter having comparatively high short-term global warming implications.

Four bio-heating pathways are particularly relevant to the analysis presented.

- **Using woodchips in boilers for larger heating systems** such as multi-family houses is a widespread conversion route — it requires adequate emission controls to reduce local nitrogen oxide and PM_{10} loads.
- **Small-scale decentralised biomass heating** is included in the shape of advanced automated pellet systems.
- **District heating** can supply both large areas of densely-populated buildings, and smaller-scale neighbourhoods or larger building complexes using packaged co-generation. District heating is a very efficient system with low GHG emissions, in particular if operated on residues and wastes.
- **Biogas/biomethane** is not expected to play a prominent role due to its low overall resource efficiency, but can provide heat indirectly from cogenerated electricity. In principle, however, biomethane can be a resource-efficient transport fuel.

Looking beyond 2020, the limited availability of biomass and the resource-efficiency paradigm necessitate the most efficient design of biomass to heat pathways. This does not involve direct heating but rather using the waste heat produced in power generation and industrial processes for district heating (OEKO, 2010; EEA, 2008; IEA, 2012a). Co-generated heat of this sort can supply both large areas of densely populated buildings and smaller-scale neighbourhoods as well as process heat and steam for industrial sites. It is described in more detail in Box 2.1.

2.4 Transport fuels

Transport fuels derived from biomass can be split into two groups.

- **First-generation biofuels** which are commercially available rely on relatively simple technology and use dedicated feed stocks, such as sugar beet, oilseeds, and starch crops. Sugars in these crops

Box 2.1 Combined heat and power

Combined heat and power (CHP), also known as co-generation, is an efficient means of converting biomass into electricity while extracting waste heat to supply district heating or industry.

Biomass co-generation plants vary in technology and size, ranging from 0.01 MW_{el} to > 300 MW_{el}, and can use biogas or biomethane, wood and many waste products including straw and pellets. Combined heat and power co-firing also includes gas-based approaches, operating on a mix of natural gas and biogas, including biomethane.

Solid biomass for cogeneration can either be based on co-firing in coal CHP plants, or on dedicated biomass-only CHP systems which, due to logistical constraints, are typically medium-sized (1–50 MW_{el}). The CHP technologies for solid bioenergy are typically less efficient than those operating on biogas or biomethane. The latter involve higher investment but have lower operating costs.

An interesting option is to use straw as a co-feed with liquid manure in biogas fermenters to enhance conversion (DBFZ, 2012). This hybrid system is under development and could boost biogas-based energy output, especially in regions with large manure and straw surpluses.

are fermented to produce ethanol (EEA, 2008; OEKO, 2009; IEA, 2011), while oil crops provide oil that is trans-esterified to form fatty acid methyl ester (biodiesel, or FAME). The resulting ethanol and biodiesel are then generally mixed with fossil-based liquid fuels.

- Most **advanced or second-generation biofuels** are generally not yet commercially viable but are expected to play an increasing role in the coming decades. They use mainly ligno-cellulosic feed stocks, e.g. short rotation coppice, perennial grasses, forest residues and straw. This so-called cellulosic biomass has a characteristic composition of mainly cellulose, hemicellulose and lignin, with smaller amounts of proteins, fatty substances and ash. Cellulosic biomass is naturally resistant to being broken down, so requires advanced technologies to convert it into liquid fuels. Examples of these technologies include (IEA, 2010, 2011):
 - **Thermo-chemical conversion:** biomass is gasified to syngas at 600–1 100 °C, and then converted to biodiesel using Fischer-Tropsch synthesis. This 'biomass-to-liquid' process can be applied to woody or grass-derived biomass and cellulosic or ligno-cellulosic dry residues and wastes. Currently, there are no commercial biomass-to-liquid plants but several pre-commercial plants exist in Germany, Japan and the United States.

– **Biochemical conversion:** this involves pre-treatment of cellulosic biomass and enzymatically enhanced hydrolysis and subsequent fermentation to convert hemicellulose and sugar into ethanol. There are demonstration plants in the EU (Denmark, Spain and Sweden), and Canada. Other countries such as Brazil, China, Germany, Japan and the United States are also developing such 'second generation' ethanol technologies.

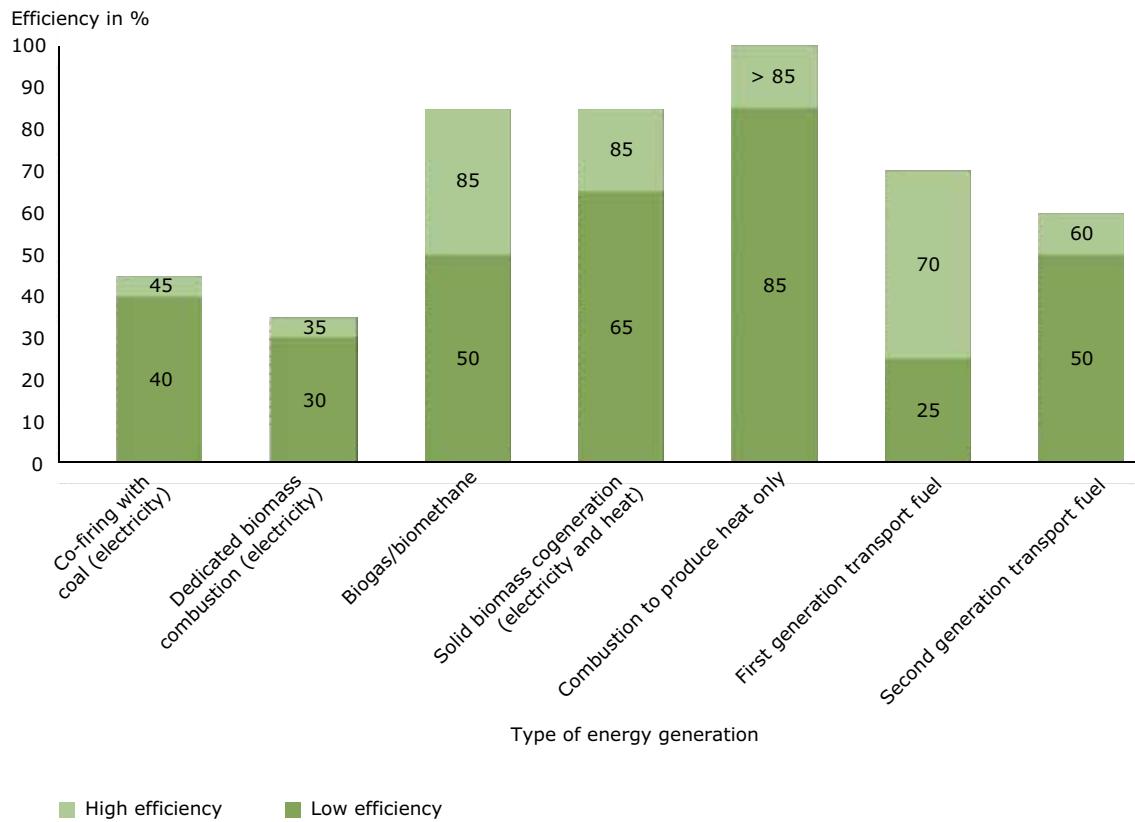
2.5 Summing up: a brief reflection on efficiency

The various bioenergy technologies differ substantially in their overall efficiency in terms of energy output per volume biomass input. This is due to the technical efficiency of different conversion technologies as well as the inherent efficiency of using biomass for different energy end uses (transport fuel, heat or power). This was one key conclusion of the 2008 EEA bioenergy report and is discussed in Section 4.3.

Figure 2.2 provides a first overview of the relative efficiency of different types of bioenergy. The data are derived from the GEMIS 4.8 life cycle database (Global Emissions Model for Integrated Systems), developed by the Ökoinstitut Germany (⁽¹⁾).

⁽¹⁾ GEMIS is now hosted by the International Institute for Sustainability Analysis and Strategy (IINAS).

Figure 2.2 Efficiency range of different biomass-to-energy conversion routes



Note: Data represent net efficiencies taking into account results of standard life-cycle analysis. This covers the production process from the point of harvest to energy end use. For land-use aspects please consult Figure 1.2.

Source: ETC/SIA, 2013.

3 Assessing the environmental performance of bioenergy

3.1 Introduction and framework

Analysing all the effects bioenergy can have on the environment is a complex undertaking as there are numerous types and sources of biomass, and diverse ways to convert them into energy. This study combines an assessment of ecosystem impacts with a GHG and energy efficiency focus to address the two aspects of resource efficiency — the efficiency of the bioenergy pathway and the wider ecosystem impacts associated with producing a given amount of energy.

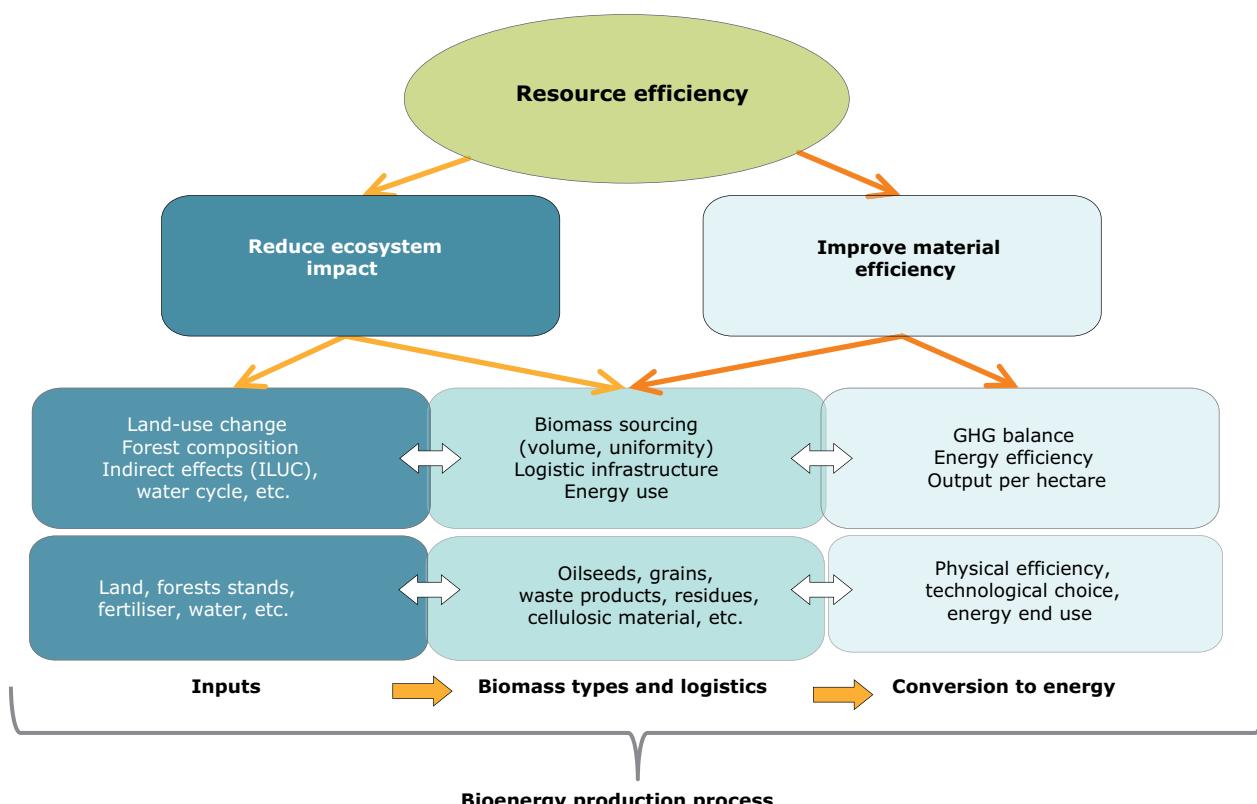
The analytical tools employed build on qualitative and quantitative approaches and include life cycle methodology, global and European land

use modelling as well as a qualitative assessment of EU energy cropping trends and of the global warming impact of using forest biomass.

These tools are applied to the entire bioenergy production process from initial resource inputs over biomass sourcing logistics to the final conversion of biomass to different energy outputs. Figure 3.1 outlines critical factors for the overall environmental performance of bioenergy and how the resource efficiency concept can be applied for environmental assessment.

The complexity of impacts is arguably greatest where biofuels are produced from cultivated energy crops. Expanding biomass feedstock production

Figure 3.1 Assessing the environmental performance of bioenergy



Source: EEA, 2013.

can imply substantial land use change, with direct and indirect impacts in Europe and globally. In particular the likely size of ILUC is very important for the overall GHG balance of different bioenergy pathways. The quantitative assessment in this study therefore focuses on land use impacts in Europe and worldwide.

The potential environmental impacts of increasing the use of forest biomass for bioenergy should, however, not be underestimated (EEA, 2006, Mantau et al., 2010). In particular the question of the potential 'carbon debt' associated with the use of forest biomass needs to be further investigated – as discussed in Section 3.5. On the other hand, exploiting biomass residues and wastes as well as agricultural byproducts for energy purposes carries very little environmental risk as long as appropriate environmental safeguards are observed.

The remainder of this chapter sets out the environmental assessment framework employed and discusses the land use component of bioenergy production, which includes most of the ecosystem aspects of resource efficiency. A more detailed account of the assessment framework summarised here is presented in Chapters 2 and 3 of the accompanying ETC/SIA (2013) report.

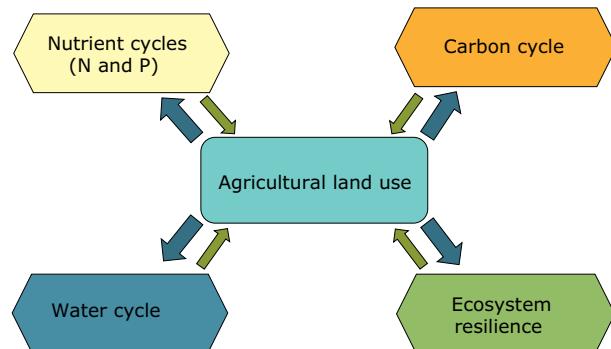
3.2 Effects of land use change

Managing and exploiting natural resources – land, water, forests and other ecosystems – in a sustainable manner is a key challenge for societies in Europe and globally (EEA, 2010a). Land use plays a central role in this endeavour as it interacts directly with natural cycles that determine the global climate, the availability and quality of water resources, the productivity of soil resources and the resilience of ecosystem processes that underpin food production. Figure 3.2 illustrates the interactions between land use and important environmental cycles.

Figure 3.2 demonstrates that land use has an impact on nearly all environmental media. In fact it is frequently the most important factor in human impacts on the environment – making the effects of bioenergy production on land use a critical component of its overall environmental performance.

Land use effects are often divided into direct and indirect effects. This distinction derives from the position of impacts in the cause-effect chain in the land use sector and related parts of the economy.

Figure 3.2 Land use and ecosystem cycles



Source: EEA, 2013.

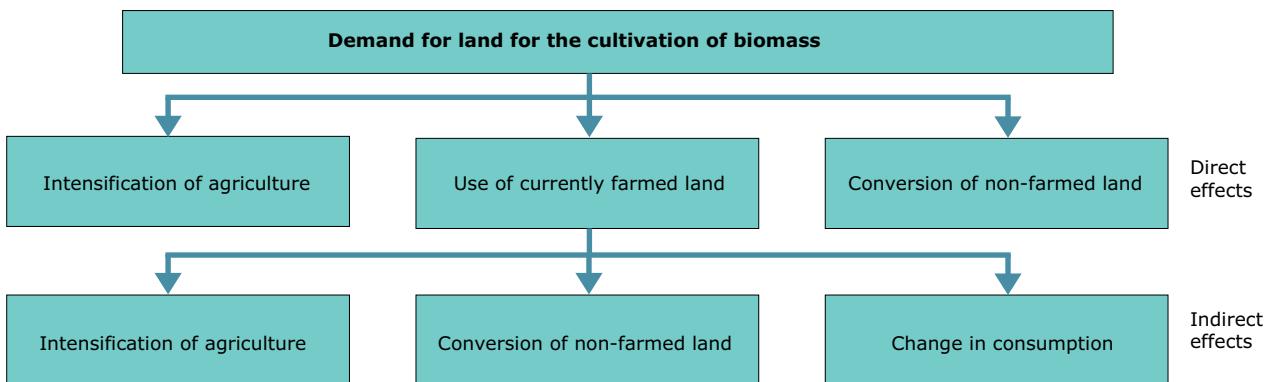
Direct effects represent the direct impact on land management as a consequence of the additional demand for output that is linked to bioenergy production (or other economic drivers). Depending on the scale of analysis such land use effects can be evaluated at the local, country or continental scale.

Indirect effects are the subsequent reaction by land managers to the changed situation caused by direct effects. Indirect effects generally include a wider range of impact types than direct effects and they can include effects in economic sectors beyond land use, such as consumer reaction to raised food or fuel prices. Figure 3.3 shows a simplified chain of effects that use of land for bioenergy production can bring about. Direct and indirect effects include:

- intensified food and fodder production on other land, leading to higher yields but no additional land use;
- conversion of additional uncultivated land to agricultural use elsewhere, both inside and outside the EU;
- changes in consumption, for example, reduced food consumption due to higher food prices.

The relative importance of different responses, e.g. intensification or land conversion, depends on many parameters, which vary between locations. They include such factors as the type and availability of land for agricultural conversion, legal restrictions on land conversion, national policies favouring use of particular inputs or land cultivation, the economic ability of farmers to buy inputs or invest in technologies, and the standards that biomass for energy purposes has to meet (including environmental criteria).

Figure 3.3 Direct and indirect effects of land use for bioenergy



Source: EEA, 2013, building on ETC/SIA, 2013.

As both direct and indirect effects can include very similar responses in terms of land use change both types lead to a similar range of environmental impacts. However, whereas direct effects can be evaluated through direct observations (if suitable monitoring programmes and statistical data collection are in place), the assessment of the type and size of indirect effects is far more complex – relying nearly exclusively on (agro-) economic and bio-physical modelling approaches.

The next two sections discuss direct environmental effects and review currently available knowledge of the effects of ILUC on the GHG balance of biofuels.

3.3 Direct environmental impacts of changes in land use and management

The net impacts of expanding energy cropping vary significantly depending on the type of biomass cultivated and the previous use of the land affected. If direct land use change is not induced then the environmental impact of energy crops depends very much on the types of crops chosen as well as the pattern and intensity of the current land use that they are replacing.

There are two potential approaches available for developing an overview of the direct environmental effects of energy cropping: reviewing the types of land management change that are likely to create environmental impacts or analysing the types of impact by different environmental media.

The types of land management change that are likely to create environmental impact can be

analysed by reviewing the following aspects (O'Connell et al., 2005; and EEA, 2007):

1. Effect on land use: changes in land use, whether between land cover classes (see above) or within one land cover class (e.g. within agricultural land) affect not only the carbon balance but also the risks of soil erosion, diffuse pollution of waters and loss of biodiversity.
2. Impact on land use intensity:
 - a) What is the choice and pattern of bioenergy crops? Are they grown in a diverse rotation, or do they have a dominant share in the overall crop area?
 - b) What is the management intensity of the bioenergy crop? For example, does it require high or low external inputs of fertiliser and/or water, is it harvested once or several times per year?
 - c) How do energy crops influence the structural diversity of the farmed landscape? Permanent crops, for example, can increase landscape diversity or contribute to closing up previously open landscapes, depending on the location.

The possible impact of bioenergy cropping on different environmental media is influenced by a variety of factors, including those set out below (EEA, 2007 and 2010b):

- **Climate:** Both land-use conversions and intensification can lead to additional GHG emissions. Land contains carbon which is stored in vegetation and soil. The amount of carbon depends on the type of soils and vegetation. Peat

land and forests, for example, are high in carbon. In general, agricultural land contains less carbon than land with natural vegetation cover, even if compared to natural grassland areas. According to the Global Carbon Project (2012) about 10 % of global greenhouse gas emissions in the period 2002–2011 were related to land use change – principally associated with deforestation and expanding agricultural land use.

- **Water:** Agriculture is the major source of nitrogen pollution of European water bodies, including lakes, rivers, ground water and the European seas (EEA, 2010b). The agricultural sector also accounts for a large proportion of water use across Europe, particularly in southern countries where the importance of irrigation means that agriculture can account for as much as 80 % of total water use in some regions (EEA, 2009).
- **Soil:** Farming exposes soils to water and wind erosion, and can lead to soil compaction and salinisation if inappropriate farming practices are used (JRC, 2010). All these factors contribute to soil loss, declines in soil organic carbon content and productivity as well as other environmental impacts (JRC, 2010).
- **Biodiversity:** Numerous studies have recognised that the changes to water tables, soil structure and the destruction of habitats that occur where land is converted to agricultural uses can have negative impacts on biodiversity (Bertzky et al., 2011; Fargione et al., 2009, 2010; Gallagher, 2008; van Oorschot et al., 2010).

It worth noting that bioenergy-induced land use change can have positive effects, for example if an area converted to energy crops was previously degraded land. If these lands are managed appropriately then it could lead to improved soil

quality and vegetation structure, and therefore enhanced habitat quality (Tilman et al., 2009). Increased cropping of perennial biomass, such as miscanthus, fast-growing poplar or reed canary grass, offers benefits as input requirements are generally lower than those of annual crops and perennial crops can be grown on low quality soils that are not suited for rotational arable crops. In addition, many perennials are also shown to improve soil quality, increase the amount of carbon sequestered in the soil, and reduce soil erosion. Because of these factors perennial crops are projected to play a strong role in the environmentally oriented storylines in this analysis.

Due to the importance of agricultural land use intensity for the environment in Europe previous EEA studies developed agricultural land use assumptions that were considered to ensure agricultural land management that was environmentally compatible and which included additional energy cropping (see Box 1.2). This perspective was expressed in the projected crop mixes, environmental safeguards and the significant use of crop residues foreseen in earlier EEA work (see EEA, 2006 and 2007). The present study applies variations of these strict environmental standards only in two of the storylines. Moreover, in addition to the assessment tools utilised in past reports, this study also employs bio-physical models of the impact of agricultural land use on key environmental media to assess the likely environmental impact of energy crop projections.

3.4 Estimates of ILUC effects on GHG emissions

A key argument for expanding bioenergy is that it will reduce net GHG emissions from the transport, energy and household sectors which still largely

Box 3.1 Introduction of new species via energy cropping

New energy crops are often selected because of their fast and productive growth but can have their origin in other continents. This means that some (e.g. miscanthus) are classified as invasive alien species (GISP, 2008). If such species escape from their confined cultivated environment they can dominate or push out native species and thus alter European ecosystems. The ecological impact of invasive species can be very significant and also lead to substantial economic damage (EEA, 2013).

For this reason, the likelihood of a species becoming invasive in Europe needs to be assessed before it is cultivated in new areas. That issue was not addressed specifically in this study but academic and field research is available on evaluating and mitigating the invasion risk posed by some biofuel crops (IUCN, 2009; Barney and DiTomaso, 2010; Quinn et al., 2013). This information can be utilised by national bodies responsible for the development of energy cropping.

depend on fossil fuel stocks. If, however, the GHG mitigation potential of bioenergy is diminished or even fully offset by effects of changes in land use, an important reason for promoting bioenergy loses its validity.

Various studies have generated estimates of GHG emissions arising from the conversion of different types of natural land to agriculture. According to these studies (Fargione et al., 2008; Searchinger et al., 2008; Van Minnen, 2008), converting forest to agricultural use typically results in average emissions over a 20 year period of 300–1 600 tonnes of carbon dioxide equivalent per hectare (t CO₂-equivalent per ha). Contrastingly, converting grassland or savannah generates 75–364 t CO₂-equivalent/ha.

Given the importance of land use change for global (and European) GHG emissions, understanding such processes is crucial for developing credible life cycle balances for different bioenergy pathways (e.g. Petersen, 2008; Leopoldina, 2012). The design of EU biofuel policies and national and EU environmental legislation makes it unlikely that significant indirect land use change, such as forest conversion, occurs as a consequence of bioenergy targets in EU-27 Member States. This implies that only direct land use change effects need to be considered for Europe. These are estimated in the current study by combining agriculture and energy cropping projections with bio-physical models that assess the carbon cycle connected to land use.

European and global agricultural markets are strongly connected via international trade flows as the EU is among the largest importers and exporters of agricultural products and food. This means that a change in EU cropping patterns can have important indirect effects by displacing 'lost production' to other continents. Building a robust knowledge base on indirect land use change effects

is therefore essential to analysing the GHG balance of EU bioenergy policies. However, analysing indirect land use change is complicated because:

- ILUC effects depend on many factors, such as the yield of the energy crop, the yield of crops previously grown on the land and their yield at new locations;
- effects will vary strongly between different regions and over time, and are likely to increase with growing demand for bioenergy if no safeguard policies are employed;
- local and international trade flows mean that land use impacts can occur in many different locations of the globe.

Review of recent studies of ILUC effects

Progress has been made in recent years in using modelling approaches to analyse the effects of ILUC on bioenergy's GHG balances. ETC/SIA (2013) reviewed a large number of studies published during the period 2008–2012 in order to derive an overview of ILUC-related GHG emissions for different biomass feedstock types in different regions of the world. The key findings of that review are presented here and provide an important input to the storyline-based analysis described in Chapter 4.

The results of the various studies are difficult to compare in detail because of differences in the types of models and approaches used and in the scenario assumptions. Partly for this reason, the ILUC-related GHG emissions calculated varied significantly. ETC/SIA (2013) judged, however, that all the studies reviewed were relevant in the context for which they were developed and that

Box 3.2 Agricultural intensification, GHG emissions and the environment

Intensification is often cited as a means of avoiding the expansion of agricultural land use but it can work against efforts to mitigate climate change. Intensifying output by applying more fertilisers increases emissions of nitrous oxide, which is a GHG. Generally, such increases are less (in CO₂-equivalent terms) than agricultural land expansion. They are not negligible, however, and in some cases might equal the effects of agricultural expansion, so should not be ignored (PBL, 2010).

Agricultural intensification can also lead to additional environmental impacts. These are often linked to reduced crop variety (as only very productive crops are grown) and the increased use of external inputs (fertiliser, pesticides, water etc.). Past intensification processes in European agriculture have had significant environmental impacts (e.g. EEA, 2006) and further agricultural intensification is likely to increase such pressures.

seven of the studies would be an appropriate basis for developing an estimate of average ILUC emissions. Viewed collectively, the studies provide strong evidence that ILUC-related emissions are substantial and cannot be ignored in the context of policies designed to mitigate climate change. This is also corroborated by the more recent study for the European Commission that estimated ILUC effects for typical EU biofuel feed stocks (Laborde, 2011).

Table 3.1 summarises the outcomes of the studies reviewed, presenting the extremes and median values for ILUC-related GHG emissions that were derived from the different studies. The median values presented are only indicative — the use of lower or higher values could also be justified, for example, in a policy context of taking higher or lower risk (Ros et al., 2010). At the same time median values suggest that most indirect land use change factors are similar in scale to the carbon dioxide emissions of fossil fuels: around 84 g CO₂ per megajoule (MJ). As such, indirect land use change effects alone can often negate the positive

contribution of bioenergy to greenhouse gas emissions reduction.

The median of the estimated values for ILUC-related GHG emissions for seven studies that are presented in Table 3.1 are taken as an upper boundary for the potential impact of ILUC. These represent in fact mid-range results, rather than high estimates of indirect land-use change. The results of the most recent IFPRI-MIRAGE analysis (Laborde, 2011) represent the lower-end boundary in the overall analysis and are taken as a starting point for the sensitivity assessment elaborated in Chapter 5.

ILUC emissions from perennial cropping

Most studies of ILUC effects focus on transport biofuels because they have been a central part of policy debate in recent years. The effect of standard transport fuel crops can also be more easily analysed with current modelling tools. In addition, renewable heat and electricity pathways are expected, in

Table 3.1 Estimated values for ILUC-related GHG emissions in studies reviewed

Type of biofuel	Minimum indirect land-use change emission factor (g CO ₂ -eq/MJ biofuel) derived from inventory of studies ^(a)	Maximum indirect land-use change emission factor (g CO ₂ -eq/MJ biofuel) derived from inventory of studies ^(a)	Median from average values (g CO ₂ -eq/MJ biofuel) derived from inventory of studies ^(b)	Average ILUC emissions from IFPRI-MIRAGE ATLASS (Laborde, 2011)
Biodiesel based on rapeseed from Europe	- 113	80–800	77	55
Ethanol based on wheat from Europe	- 158	337	73	14
Ethanol based on sugar beet from Europe	13–33	65–181	85	7
Biodiesel based on palm oil from South-East Asia	- 100	34–214	77	54
Biodiesel based on soya from Latin America	13–67	75–1 380	140	56
Biodiesel based on soya from the United States	0–11	100–273	65	56
Ethanol based on sugar cane from Latin America	- 49	19–95	60	15

Note: ^(a) A minimum value implies that there is a net mitigation in the total well-to-wheel emission which is usually caused by the allocation of by-products. In the E4Tech (2010) study for example the negative value for wheat ethanol from Europe is assumed to be - 79 g CO₂-equivalent/MJ. This is because the study assumes that wheat is produced on EU land that would otherwise have been abandoned. The Dried Distillers Grains and Solubles (DDGS) that is produced as a by-product is considered to prevent the soya area from being expanded in Brazil. In this way the carbon dioxide emission balance can become negative.

^(b) Where studies only reported a minimum and maximum value, the average was taken. Most studies report both the average and a range.

Source: ETC/SIA, 2013.

the short- and medium-term, to be based mainly on agricultural by-products such as manure and straw, organic wastes and wood residues (with the exception of biogas). Nevertheless, where perennial crops for heat and power pathways are grown on agricultural land the ILUC mechanisms discussed for biofuels also apply to these pathways.

Potential ILUC mechanisms are the same for all energy crops grown on agricultural land, whether annual or perennial crops are utilised and whatever bioenergy pathway the biomass is employed in. This study has therefore used the ILUC emission factor developed on the basis of biofuel modelling studies also for the life cycle analysis of other bioenergy pathways. Nevertheless, ILUC related GHG emissions constitute generally a lower share of total emissions for heat and power bioenergy pathways as only part of the biomass used in these pathways competes with food production. Another important factor determining the relative emissions of all pathways is total energy production per hectare. This is partly determined by the biomass yield per hectare, which is generally much higher for perennial crops.

Broader ILUC impacts on ecosystems

In addition to GHG mitigation, other policy goals also require the consideration of indirect land use change in environmental assessments of bioenergy pathways, for example the need to protect biodiversity. Such goals only strengthen the case for avoiding any conversion of land with (semi-)natural vegetation to agricultural production – either directly or indirectly. A further discussion of this issue can be found in Chapter 2 of the accompanying ETC/SIA report.

3.5 Forest biomass and the 'carbon debt' debate

European forests currently provide the largest share of biomass for energy purposes. Various studies and previous EEA work (EEA, 2006) have estimated a significant potential for increasing the use of forest biomass for bioenergy, even if strong environmental constraints are applied. The present analysis did not re-evaluate these quantitative estimates. However, a recent research project financed by the European Commission (the so-called 'EUwood' project) has provided an up-to-date analysis of demand for forest products in relation to the annual growth increment of EU forests.

The EUwood analysis predicts an undersupply of harvestable forest growth in relation to societal

demand (for energy and other purposes) in the coming decades (Mantau et al., 2010). This would indicate a likely intensification of the use of European forests in the coming years with potential impacts on the forest carbon pool and biodiversity. This would not allow the EEA criteria for an 'environmentally compatible' exploitation of European forests (EEA, 2006) to be met.

In this context it is important to discuss the concept of 'carbon debt' when estimating the GHG mitigation potential from the use of forest biomass for energy. Recent scientific papers show that the GHG saving potential of using forest biomass for energy can essentially be negated for several decades or even longer if stem wood is used for energy rather than being retained in forests or used for long-lived products, i.e. not burnt (e.g. Cherubini et al., 2011; Schulze et al., 2012).

This occurs due to the fact that when harvested wood or woody residues are directly combusted to provide energy, the carbon content of the wood is released as a one-time burst of CO₂ in a very short period, whereas forest regrowth takes place over several decades. This leads to a so-called 'carbon debt' which is initially large and then declines during the period of regrowth as CO₂ is absorbed again in plant biomass (the carbon 'payback'). It is important to note, however, that the extent of the 'carbon debt' depends strongly on the forest and energy system baseline against which additional forest bioenergy use is compared. This includes factors such as carbon stocks in forests, types of forest biomass used, decay rates of forest products, and substituted fossil energy systems, including their efficiencies.

A further potentially important consideration is that most carbon in forest ecosystems is stored in soils, except in tropical forests (Trømborg et al., 2011). Extracting residues, in particular stumps and roots, may alter soil fertility and negatively affect the overall forest carbon balance. Indeed, recent studies suggest that harvest residue removal could have implications for long-term carbon storage (Thiffault et al., 2011; Strömgren, Egnell and Olsson, 2012). Meta-analysis conducted by Nave et al. (2010) found that (increased) forest harvesting resulted overall in an average 8 % decrease in total soil carbon in temperate forest soils.

Figure 3.4 expresses the carbon debt effect in an idealised manner for two different types of forest biomass – forest residues and stem wood. For forest residues, the studies show typical carbon payback times of 5–20 years if coal is the reference

system, and 10–30 years for natural gas (Zanchi et al., 2010; Repo et al., 2012). This means that it takes 5–30 years of biomass regrowth before the initial carbon debt is eliminated. However, for bioenergy from additional fellings or intensified harvesting of older trees (i.e. stem wood), the payback time can be over one hundred years. This is illustrated by the two different carbon restocking curves in Figure 3.4.

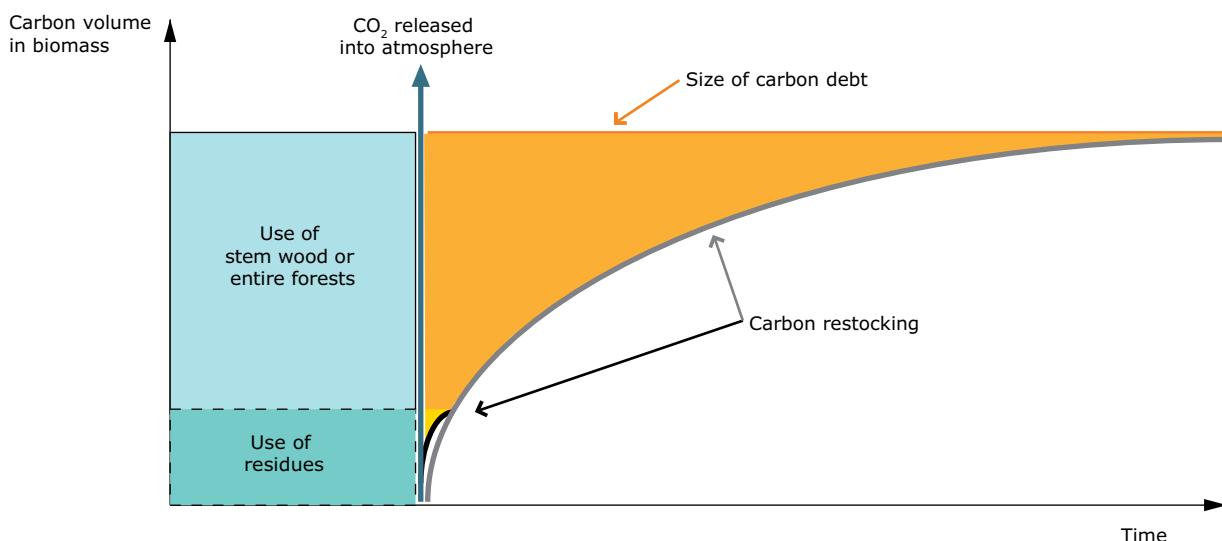
Currently, no overall European estimates are available regarding the implications of the carbon debt issue for GHG mitigation from using European forest biomass. Due to resource limitations it was not feasible to analyse the carbon debt potentially associated with current EEA estimates of forest biomass in a quantitative manner. As a consequence, this report probably over-estimates the GHG mitigation from using forest biomass to generate energy. This issue is discussed further in Section 4.4.2.

It is also important to note that, while exploiting forest residues avoids most of the potential carbon debt consequences, it may have other negative

environmental side effects. Maximising forest utilisation, whether via stem wood felling or use of harvesting residues, creates potential impacts on soil carbon stocks and forest biodiversity, in particular for species that live off biomass residues, such as dead wood, crop roots and harvest surpluses⁽²⁾. Estimates of forest bioenergy potential in previous EEA work therefore assumed certain environmental constraints to be in place (see EEA, 2006), which remain valid in the present study.

Tackling climate change is a key motivation for using forest (and other) biomass for energy production. This means that bioenergy production has to be developed in a way that it leads to real carbon savings. Scientific work over the last few years has shown that the use of forest biomass for energy can initially create a carbon debt in comparison with fossil fuels (e.g. Zanchi et al., 2010; McKechnie et al., 2011). There is therefore a need to develop analytical tools and accounting systems that reflect the complexities of carbon fluxes in forest-energy systems (Searchinger et al., 2010; EEA SC, 2011; JRC, 2013). Further work on this issue is clearly required.

Figure 3.4 The carbon debt



Source: EEA, 2013.

⁽²⁾ Sustainability requirements for bioenergy from forest residues are discussed in the output from 'Joint Workshops' on the EU level (Fritzsche and Iriarte, 2012), and in a recent WWF position paper (WWF, 2012).

4 Approach to analysing EU energy cropping potential

4.1 Introduction

The scientific understanding of the potential environmental benefits and costs of increasing bioenergy production has advanced substantially since 2008. In particular, better knowledge about ILUC effects associated with EU renewable energy targets marked them as a crucial factor for the overall GHG balance of different bioenergy pathways using (agricultural) land. Given the particular importance of ILUC effects for agricultural biomass, the main focus of the analytical update is on the agricultural potential while waste and forest biomass sources are included in the efficiency analysis.

The present study builds on previous work by the EEA⁽³⁾ in terms of the analytical approaches applied but combines them in a novel way. Combining biomass estimates with information on the efficiency of different bioenergy pathways allows the potential development of bioenergy production to be assessed from a resource efficiency perspective. Overall, the most important differences to previous work lie in the integration of estimated indirect land use change effects in the analysis, and an updated life cycle database.

This chapter sets out the modelling approach used for analysing the GHG and energy efficiency of different EU bioenergy pathways. In doing so it addresses three questions.

- What are the analytical approaches that can be used to assess the resource efficiency of bioenergy pathways?
- What are the critical factors for maximising bioenergy's potential — in terms of the most

efficient choice of biomass inputs, conversion pathways and end uses?

- What can we say about the impact of GHG emissions from ILUC on the volume of bioenergy that can be considered resource efficient in a climate perspective?

4.2 Tools used in the analysis

The flow diagram in Figure 4.1 describes the analytical chain employed in this study. Additional information on the methodological approach adopted is provided in Annex 2. A detailed description of the modelling chain and its different components is provided in Chapter 5 of the associated ETC/SIA report.

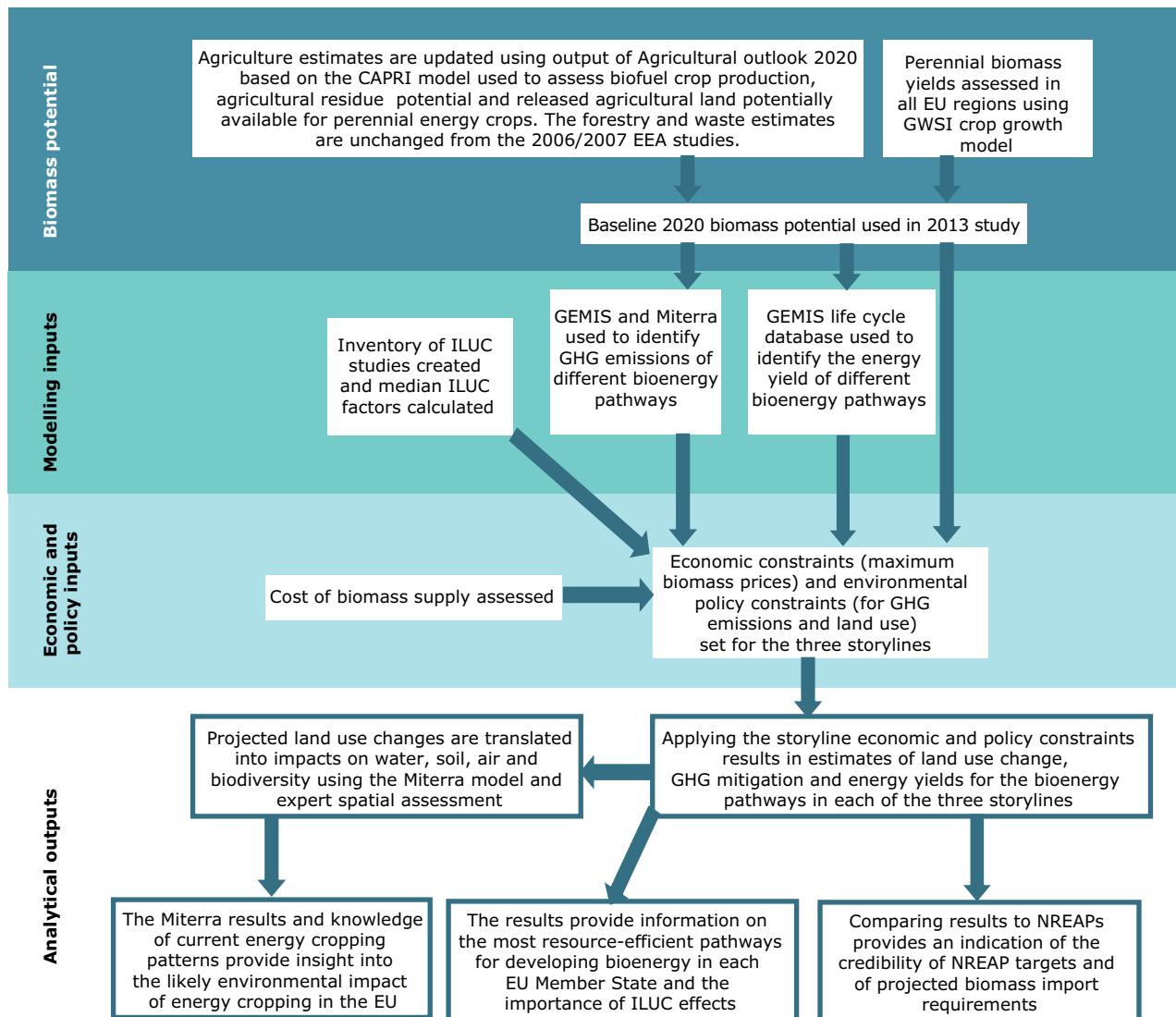
As set out in Figure 4.1, the analysis of EU bioenergy potential can be broken up into four steps. The first involves estimating a baseline projection of biomass potential in 2020. The forestry and waste estimates remained the same as those used in the 2006 and 2007 EEA reports and were based on the European Forest Information Scenario Model (EFISCEN) and national waste statistics (see EEA, 2006). In contrast, the agricultural potential was updated using agricultural land use projections from the agro-economic CAPRI model⁽⁴⁾. This is combined with estimates of perennial biomass yield derived from a crop growth model also employed by the EU Joint Research Centre (the European part of the Global Water Satisfaction Index system — GWSI).

The second step involves generating estimates of the greenhouse gas and energy implications of developing bioenergy. The GEMIS life cycle data

⁽³⁾ EEA (2006 and 2007) sought to identify the amount of bioenergy that could be produced in Europe without harming the environment. Despite applying quite strict environmental constraints the reports predicted a very substantial potential for the production of energy from European biomass. The analysis did not look into potential ILUC effects outside Europe, however, and with the benefit of hindsight some of the technological assumptions employed appear over-optimistic. EEA (2008) quantified the amount of GHG emissions that could be avoided by exploiting the environmentally compatible bioenergy potential. Again, it did not consider indirect effects in calculating GHG balances of alternative bioenergy pathways.

⁽⁴⁾ CAPRI stands for 'Common Agricultural Policy Regional Impact Analysis', which is also used in analysis for the European Commission, e.g. on *Prospects for Agricultural Markets in the EU 2010–2020* (EC, 2010b).

Figure 4.1 Analytical steps in assessing the EU bioenergy potential



Source: EEA and ETC/SIA, 2013.

base and the Miterra⁽⁵⁾ model were used together with baseline biomass potential to quantify direct emissions and energy yield from different pathways. The inventory of ILUC studies described above in Section 3.4 provided a basis for calculating emissions due to ILUC effects.

The third step comprises the development and application of simple economic and policy assumptions that serve as input to the three storylines. The cost of supplying different forms of biomass in 2020 was estimated by adapting data from the 7th framework EU research project

'Biomass Futures'. Along with the data on land use, energy yield and greenhouse gas emissions generated during the previous steps, the costs data were fed into three alternative storylines to test how different sets of economic and policy constraints could shape the development of bioenergy production and resulting environmental impacts. Each of the storylines assumes that Member States pursue and realise their NREAP targets. However, as described in more detail in Annex 2, they differ in terms of the constraints and support provided to maximise greenhouse gas efficiency and minimise ecosystem impacts.

⁽⁵⁾ The integrated nitrogen model Miterra-Europe was developed by the research organisation Alterra on behalf of the European Commission.

It is important to note that the three storylines presented in this study should not be considered as an exercise in forecasting likely futures. Instead they explore plausible bioenergy development paths from a resource efficiency perspective under three specific sets of economic and political assumptions.

This means that they aim to identify how different bioenergy technologies may fare in different market and environmental contexts, and what the resulting environmental impact of EU bioenergy production and consumption might be. It should be noted that these storylines do not intend to evaluate specific policy instruments as the available analytical models and key input data do not suffice for targeted policy analysis. Nevertheless, reflecting on the outcome of this analysis can help inform EU debates on the appropriate design of EU bioenergy policies in a resource efficiency perspective. Table 4.1 sets out the key characteristics of each storyline.

The fourth step involves combining different analytical outputs in an overall assessment. Applying the storyline assumptions enabled the different input data to be transformed into projections of land use change, biomass production, energy output and related GHG emissions. Using the Miterra model, the land use change anticipated in each storyline is translated into impacts on water, soil, air and biodiversity.

Taken together, these findings illustrate the potential environmental impacts of energy cropping, the most resource-efficient approaches to developing bioenergy, and the feasibility and implications of current bioenergy targets in NREAPs. Section 4.3 summarises how the different bioenergy technologies described in Chapter 2 were employed in the three storylines. This illustrates how the resource efficiency principles identified in this study feed through into the technological choices assumed for each storyline.

4.3 Summary of bioenergy pathways in each storyline

The efficiency of the energy conversion pathways is the principal guiding factor that determines their relative share in each storyline in ETC/SIA (2013) – the different technologies are assumed to be deployed accordingly in future markets. A summary of reasons for the inclusion of each conversion technology in the storylines is provided in Table 4.2.

To select relevant technologies for the three storylines, the technical options were screened with respect to their efficiency, life-cycle GHG emissions and production costs. Uptake of bioenergy technologies with high emissions or costs is projected to be small, while the share of improved and better performing technologies will increase over time, particularly

Table 4.1 Key characteristics of the three storylines

Storyline	Minimum GHG efficiency target	Consideration of ILUC effects	Technology and feedstock assumptions	Environmental constraints
Market first	None	None	Larger centralised installations	No special constraints
			Feedstock price up to EUR 3/GJ	No 'no-go' areas
Climate focus	50 % for biofuels only	Yes, for biofuels only	Smaller de-centralised installations; more technological innovation	No use of HNV farmland, peat land, permanent grassland or Natura 2000 areas; except use of cuttings
			Feedstock price up to EUR 6/GJ	
Resource efficiency	50 % for all bioenergy uses	Yes, for all bioenergy uses	Smaller de-centralised installations; more technological innovation	No use of HNV farmland, peat land, permanent grassland or Natura 2000 areas; except use of cuttings;
			Feedstock price up to EUR 6/GJ	keep minimum 10 % of fallow land; no irrigation of bioenergy crops

Note: Price for feedstock represents at-gate-price for heat and electricity pathways. For biofuels the feedstock prices are higher and determined by agricultural and oil prices assessed with the CAPRI model.

Table 4.2 Efficiency of output from biomass use, and implications for storylines

Type of energy generation	Efficiency (%)	Implication for storylines
Co-firing with coal (electricity) (IEA 2012, IRENA 2012)	40–45	Bridging technology, but still used in 2020 in Storylines 'Market first' and 'Climate focus' (Storylines 1 and 2) and only to a more limited extent in the 'Resource efficiency' storyline (Storyline 3).
Dedicated biomass combustion (electricity)	30–35 (Eurelectric 2011)	No specific implications.
Biogas/biomethane	50–85 (DBFZ 2012, IEA 2012)	Used for electricity and heat production, the latter only in co-generation not on its own due to low efficiency. This technology can also deliver transport fuels through the biogas-to-liquid route. This happens to a limited extent in Storylines 2 and 3 in order to reach the NREAP transport fuel targets.
Solid biomass cogeneration (electricity and heat)	65–85	No specific implications.
Combustion to produce heat only	> 85	Used in all storylines — woodchip boilers for larger buildings, otherwise pellets.
First generation biofuels	25–70	Only produced in the EU in Storyline 1, in other storylines mitigation targets are not reached because of the impact of indirect land-use change on greenhouse gas mitigation.
Second generation biofuels	50–60	Considered to be economically viable by 2020, although penetration will increase in Storylines 2 and 3, in which more incentives are given to technological development and deployment of novel bioenergy products.

Source: Based on GEMIS 4.8 data; biofuel efficiency data include by-products, allocated by energy content.

in Storylines 2 and 3. This is because more policy incentives and research investment are assumed to be in place in these storylines, which support technological developments towards the most GHG and resource efficient pathways.

Shifts towards lower costs and higher efficiency are expected to be gradual in the 'Climate focus' and 'Resource efficiency' storylines, since intervention effects and market shifts take time. This means that the most advanced technologies are projected to reach only a small share of bioenergy production in all storylines in the 2020 timeframe.

4.4 Review of uncertainty factors

Assessing complex interactions between different environmental factors and human actions leads to outcomes that carry analytical uncertainty. Such uncertainty is also associated with the analysis presented in this report. The main sources of uncertainty relate to the following three issues:

- the extent of the impact of indirect land use change on life-cycle GHG emissions;
- the impact of excluding potential carbon debt effects from the analysis of the GHG savings

potential of bioenergy pathways based on forest biomass;

- general limitations of available modelling tools and data.

4.4.1 Impact of ILUC factor estimates

Given that estimated indirect land-use change effects vary strongly between different studies this report includes a so called 'sensitivity analysis'. Such analysis involved running the model chain for estimating the most GHG efficient bioenergy pathways twice, using two different ILUC factors. The first one is taken from Table 3.1 and is considered to represent an assumption of a risk of higher GHG emissions resulting from the effects of ILUC. The second one builds on the results of the most recent ILUC analysis for the European Commission (developed by the ATLASS consortium, Laborde, 2011). This is an update of the IFPRI (2010) study and involves the EU biofuel mandates as further implemented in the NREAPs of the EU-27 Member States. Table 4.3 indicates that the ATLASS study results in considerably lower estimates for ILUC emissions related to starch and sugar crops used for the production of bioethanol. However, estimates for ILUC related GHG emissions of biodiesel from

oil crops are fairly similar, except for soya-based biodiesel.

Whether one takes the reported average ILUC emissions or the lower ATLASS values that were included in the 'sensitivity' run, it can be concluded that ILUC related emissions are substantial and cannot be ignored in the context of bioenergy-related climate change mitigation targets. However, the median values presented in Table 3.1 need to be considered indicative. Lower and higher values would also be justifiable, for example, in a policy context of taking higher or lower risk (Ros et al., 2010).

At the same time the results in Table 3.1 and in Table 4.3, particularly for biodiesel crops, show that most ILUC factors are already of the same order of magnitude as the carbon dioxide emissions of fossil fuels – around 84 g CO₂/MJ. As such, ILUC effects alone can often negate the positive contribution of biofuels to GHG emissions reduction. In addition to GHG mitigation, there are other policy goals that also support the consideration of ILUC in an environmental assessment of bioenergy pathways, one of which is biodiversity conservation (see European Commission, 2011b). From this perspective any conversion of highly bio-diverse land to agricultural production – either direct or indirect – should be avoided.

4.4.2 Potential impact of carbon debt on GHG saving potential

Complete and up-to-date information and statistics for understanding current forest biomass harvesting for bioenergy purposes is currently not available. This also applies to the volume of secondary and tertiary forest waste products from forest-based industries and the use of timber in construction and other industrial sectors. That makes it difficult to develop quantitative estimates for the size of the potential carbon debt associated with the use of forest biomass for energy based on real-life data. Instead one has to rely on modelling approaches that include best-available estimates and assumptions. This section therefore presents only qualitative estimates of the relevance of the carbon debt issue for the modelling outcomes presented in this study and discusses some conceptual points of relevance to that debate.

This study builds on the estimates for harvestable forest biomass contained in previous EEA reports. These reports estimated a large share of the bioenergy potential from wood to come from harvesting residues and forest thinnings which are considered not to create a relevant carbon debt. The technical potential estimated in 2006 is subjected to two different biomass cost thresholds in three storylines. While the 2006 EEA study estimated a technical potential of energy production from forest biomass

Table 4.3 ILUC GHG emissions per crop from the ATLASS consortium study

Type of biofuel feedstock	Average ILUC emissions from ATLASS (2011) (g CO ₂ -equivalent/MJ bioenergy)	% of median values set out in Table 3.1
Wheat	14	19 %
Sugar beet	7	8 %
Rapeseed	55	71 %
Palm oil	54	70 %
Soybean (from Latin America) (a)	56	40 %
Soya (from the United States) (a)	56	86 %
Sugar cane	15	25 %
Maize	10	17 %
Ligno-cellulosic cropped biomass (for second-generation ethanol) (b)	15	29 %
Ligno-cellulosic cropped biomass (for second-generation biodiesel) (b)	15	29 %

Note: (a) Laborde (2011) does not distinguish between the two sources of soya.

(b) In this study this refers only to second generation biofuels produced from dedicated crops. The figure mentioned in the column for the ATLASS study includes a much wider range of ligno-cellulosic feedstock, including waste, which is probably one of the reasons for its lower ILUC factor. This emission factor was actually not a result of the IFPRI-MIRAGE model application but was a factor reported in the EC Impact Assessment (Commission staff working document, SEC (2011)).

Source: ETC/SIA, 2013 and Laborde, 2011.

by 2020 of around 40 Million tonnes of oil equivalent (MtOE) in the EU-27, the technological and economic assumptions made in the current study lead to different outcomes depending on each storyline.

In Storyline 1 the potential for bioenergy from forests is estimated at around 33 MtOE whereas for Storylines 2 and 3 these estimates reach 50 MtOE and 27 MtOE, respectively. The potential for bioenergy from harvesting and use of stem wood is estimated at around 27 MtOE in the 'Market first' and 'Climate focus' storylines but only around 4 MtOE in the 'Resource efficiency' storyline. The high estimate for forest bioenergy potential in Storyline 2 is linked to the assumed higher purchasing price for forest biomass as well as the efficiency of the bioenergy pathways assumed. The low estimate in Storyline 3 is influenced by the biodiversity considerations integrated into this storyline. For further information please consult Chapter 6 of the accompanying ETC analysis (ETC/SIA, 2013).

The assumptions made in the present study lead to a high share of stem wood and derived industrial wood in total utilised forest biomass in 2020 for Storylines 1 and 2 compared to a low share for the Storyline 3 – see the accompanying ETC analysis. This additional use of biomass from stem wood is likely to create an initial carbon debt. How large this debt is and what its likely carbon payback time is depends largely on the type of stem wood utilised, and the reference case. One critical element of the reference case is the volume of wood used for bioenergy during the starting period of the analysis. Only additional wood harvesting will generate a potential carbon debt (traditional use being part of centuries old forest exploitation cycles that do not generate additional carbon releases). The type of wood used also matters: if it is young trees that arise from an additional thinning out of younger forest stands (a normal forestry practice) then the associated payback time may be around 10–40 years. If it is older trees that are part of the still growing European forest stock, the associated carbon debt will take considerably longer to be compensated, in some cases potentially over 100 years (see Section 3.5 for more details).

Clearly, reflecting the impact of carbon debt in the storylines would significantly affect the estimates of GHG mitigation potential from forest biomass. The reference case for this analysis relates to the exploitation of forest biomass for energy around the year 2005, which was already very substantial. Looking at available data sources an increase in the use of stem wood for bioenergy of 10 % to 20 % by 2020 is assumed. This means that the actual GHG mitigation potential may be reduced by a percentage

that corresponds to the additional use of stem wood assumed in each storyline. For Storylines 1 and 2 this could be up to one sixth and one tenth, respectively. A corresponding reduction in the overall GHG mitigation potential for these two storylines is estimated, while the mitigation potential in the 'Resource efficiency' storyline would hardly be affected at all.

These initial estimates distribute the potential carbon debt evenly across the entire volume of forest biomass for energy purposes estimated in the three storylines by 2020. This means that every single volume of forest biomass carries some carbon debt whereas in fact it is only additional use of forest biomass that generates an extra burst of carbon release. An alternative approach would be to allocate the extra carbon release only to the harvesting of forest biomass that is induced by EU and national bioenergy targets. This would lead to substantially higher estimates for the potential carbon debt associated with reaching current bioenergy targets via the increased use of forest biomass.

This brief discussion clearly shows that further research on the effect of carbon debt on the GHG mitigation potential from forest biomass is required (see also JRC, 2013). The brief analysis presented above suggests caution and points out a need to further investigate the issue, while underlining the key role of residues.

4.4.3 Limitations of available modelling tools and input data

Data and model limitations are a feature of many analytical studies on the environment and other fields. Such limitations have also influenced the current study. The list below highlights some important points to be aware of in this context.

- **Time horizon:** The timeline used for the current study only extends to 2020 compared to 2030 in previous EEA work. This is due to the fact that key modelling approaches used in the current study only allow projections to 2020. This period also corresponds well with the timeframe of the NREAPs.
- **Estimation of costs of available biomass:** The potentials estimated for forest and waste biomass for 2020 were derived from the EEA 2006 and 2007 studies. However, their deployment for reaching the NREAP bioenergy consumption targets depends on the maximum price biomass can be expected to command in 2020. Input data on the current cost of different types of biomass feedstock in different EU Member States are very

- difficult to obtain, hence the cost assumptions for 2020 carry substantial uncertainty.
- **Biomass transport logistics:** As biomass is generally a very bulky feedstock with low energy density the logistics for collecting and transporting biomass volumes are often resource-intensive. No resources were available for reviewing how associated technology and logistics chains are likely to develop by 2020. Consequently, the estimation of available biomass volumes from agriculture, forest and waste resources may be over-optimistic.
 - **Progress in biomass conversion technology:** The industrial-scale development and roll-out of second generation conversion technologies (e.g. biomass-to-liquid or Fischer-Tropsch processes) is difficult to predict and actual deployment has regularly lagged behind announcements from the bioenergy industry. The estimated share of such technologies in this study probably lies on the optimistic side but any such predictions are prone to potential errors.
- ### 4.5 Brief reflection on analytical system boundaries
- Having discussed data and model limitations associated with the current study it appears relevant also to take a look at the analytical boundaries of the chosen research approach. Such an evaluation helps to understand the strengths and limits of the adopted analytical framework and points to options for future analytical development. The following list discusses some key choices but does not aim to be comprehensive.
- **Use of biomass in different end uses:** This study has only looked at the use of biomass for energy purposes. In this context it needs to be noted that the emerging discussion on a bio-economy — as part of the broader green economy paradigm (EC, 2013b; UNEP, 2012) — goes well beyond bioenergy uses. The bio-economy concept encompasses, inter alia, new biomaterials such as biopolymers, the use of biomass as construction materials and for fibres and textiles, etc. Technological innovation should lead to bio-refineries which promise more resource-efficient, low-waste conversion of biomass for multiple uses (IEA, 2012b). Such uses of biomass generally replace materials that are also sourced from fossil fuels and hence provide alternative carbon saving options. Such a comparison is a very complex analytical task, however, and was therefore not tackled.
 - **Other options for increasing resource efficiency:** an example of such options is the cascading-use concept which foresees biomass to be utilised for various functions throughout its life cycle. These developments all require a broader view on biomass in a cross-sectoral way, requiring even more complex analysis of reference systems, trade implications and the dynamics of market interactions as well as demand-side responses.
 - **Reflections on changing consumption patterns:** In the context of humankind's ever increasing demand for energy and materials around the globe improving the efficiency of resource use alone will not bring total demand below sustainable levels of extraction or utilisation. Decreasing total demand via changing consumption and life style patterns therefore needs to be part of an integrated approach to resource management (EEA, 2012).
 - **Indirect effects and carbon balances linked to forest biomass:** Various types of biomass, including from forest sources, are already traded widely across the world. This implies that indirect effects on intensity of forest utilisation globally can be expected from an increasing use of European forests for bioenergy production. Linked to that effect is also the question of potential 'carbon debts' due to the delayed carbon re-stocking in forests after the utilisation of forest biomass for energy purposes. Both questions could not be tackled with quantitative analysis even though the carbon debt issue is reviewed in a qualitative manner (see Sections 3.5 and 4.4.2).
 - **Evaluation of policy measures:** Bioenergy production sits at the crossroads of various sectoral policy areas (e.g. transport, energy, forest, agriculture) and interacts with a variety of different environmental goals and policies. Policy measures to ensure the environmental sustainability of bioenergy production are often introduced with direct links to policy instruments that promote bioenergy. A complementary approach could be to provide additional guidance in other related policy areas, such as via the EU Common Agricultural Policy. This happens partly already but not much is known so far about the effectiveness of different policy tools and approaches. More analysis would therefore seem useful, such as looking at which kind of legislative and economic options in sectoral policy fields are most suitable to stimulate more resource-efficient bioenergy pathways and concepts (e.g. biorefinery and cascading use).

5 Key outcomes of storyline analysis

As described in the preceding chapters, bioenergy can be produced using diverse forms of biomass and biomass-to-energy conversion pathways. The environmental implications of generating bioenergy can therefore vary hugely, both in terms of GHG efficiency (i.e. the net GHG emissions per unit of energy produced) and the broader impacts on soil, water and biodiversity. For bioenergy to help the EU meet its energy needs with lower environmental impacts any increase in bioenergy production needs to be carefully managed. Setting a clear policy framework, with appropriate environmental standards as well as economic incentives, would shape the development of biomass sources in Europe, the conversion technologies to be deployed and its overall energy yield.

The findings presented below illustrate these points clearly, demonstrating that if bioenergy is to contribute to achieving the EU's climate change mitigation and resource efficiency goals then it is essential that ILUC effects be reflected in its further development. The elaboration of the three storylines further exposes the possibility for widely differing environmental outcomes (in terms of GHG efficiency and ecosystem impacts) depending on the policy and economic framework assumed. This indicates that

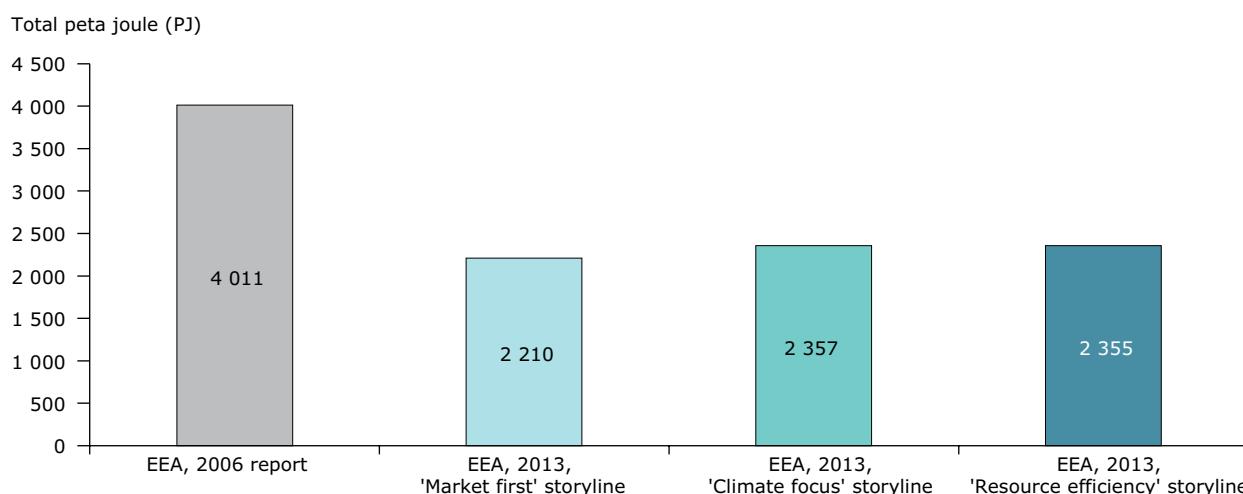
environmentally sound development of bioenergy is possible and need not involve a substantial cut in the bioenergy potential. Equally, however, clear political and financial commitments are needed to boost GHG efficiency and minimise ecosystem impacts.

5.1 The impact of ILUC effects on the GHG efficiency of energy cropping

A key goal of this study was to review the EEA's 2006–2008 estimates of environmentally compatible bioenergy potential from agriculture by integrating the impacts of ILUC, with additional economic and GHG efficiency constraints. Together with the updated agro-economic baseline from the CAPRI model these impact all three storylines to varying degrees.

The modelling refinements nearly halved the projected agricultural bioenergy potential compared to the estimates in the EEA's 2006 report. Whereas that report estimated the EU's agricultural bioenergy potential in 2020 to be around 4 011 PJ, the present study puts it at 2 210–2 358 PJ, depending on the type of environmental constraints and stimulation measures implemented (see Figure 5.1).

Figure 5.1 Domestic agricultural bioenergy potential estimates in the 2006 and 2013 studies



Source: ETC/SIA, 2013.

There are four main reasons for the substantial differences between the 2006 estimates and the results of the present study: a) changes in the EU policy framework, b) application of resource efficiency principles, c) advances in scientific understanding, and d) the integration of cost considerations into biomass supply estimates. These are briefly explained below:

- The EU policy framework now establishes clear targets for the share of renewable energy in national energy supply through the RED (including a 10 % renewable sub-target in transport) and for bioenergy via the NREAPs. These impose constraints on employing biomass in the most efficient pathways which were not considered in the 2006 study.
- Resource efficiency considerations led to the definition of a minimum mitigation target for biofuels in Storyline 2 and for all bioenergy types in Storyline 3. These exclude certain bioenergy pathways and biomass sources and hence reduce the overall potential.
- The current scientific understanding indicates that GHG emissions from ILUC are important for the overall GHG balance of bioenergy pathways. An ILUC factor is therefore included in the life-cycle GHG emission-mitigation analysis in Storylines 2 and 3, and bioenergy pathways and biomass sources with a heavy ILUC burden are again excluded from the overall potential.
- Economic considerations are taken into account in the present study by setting a threshold on the maximum price to be paid per feedstock category, for agriculture as well as forest and waste biomass. This is particularly constraining the potential in Storyline 1 whereas in the EEA 2006 study no such economic considerations were incorporated.

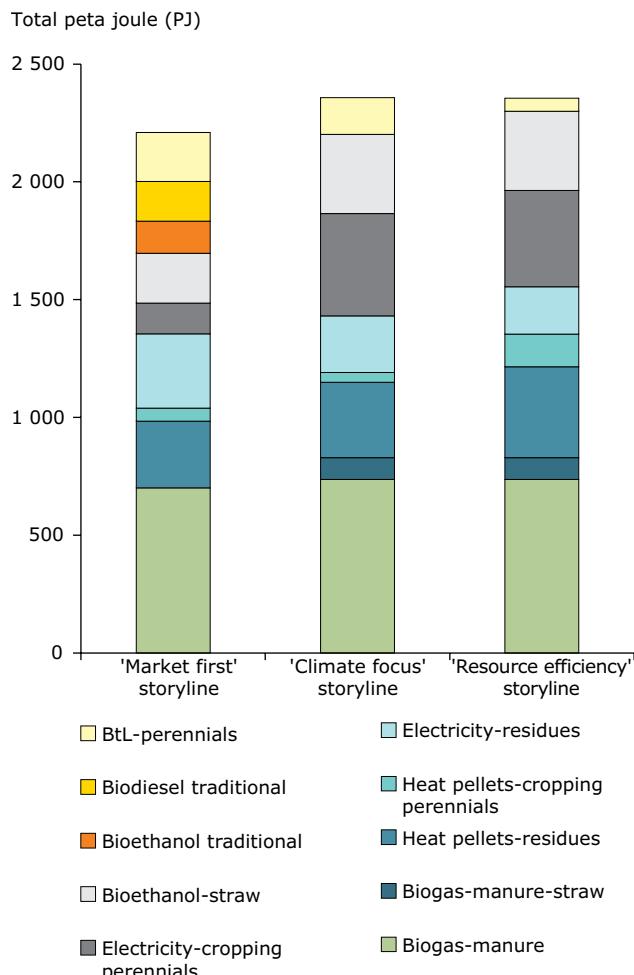
While the overall estimated agricultural bioenergy potential is similar between all three storylines, there is substantial variation in the composition of bioenergy crops, conversion pathways and the associated energy efficiency per ha and biomass volume. This is illustrated by the area required for the estimated total energy production from biomass which amounts to ca. 17 million ha in Storyline 1 whereas in Storylines 2 and 3 it is only about 11 million ha and 7 million ha, respectively. The factors underlying this very different land use efficiency between the three storylines are explained in Section 5.2.

5.2 Storyline outcomes for total EU bioenergy potential and energy crop mixes

As shown in Section 5.1, the different sets of economic and policy assumptions in the three storylines result in similar projected total agricultural bioenergy potential but require a very different land area to reach that potential. This links through to significant differences in the bioenergy mix, the use of different bioenergy sources and conversion pathways. In the 'Climate focus' and 'Resource efficiency' storylines the share of heat and power production is higher and residues with high greenhouse-gas efficiency serve as an important bioenergy source.

As Figure 5.2 shows the 'Market first' storyline is the only one that includes first generation biofuel production and it has a significantly smaller share of perennials as biomass source. In contrast, the

Figure 5.2 Total EU bioenergy potential from agriculture in 2020



Source: ETC/SIA, 2013.

requirements to avoid bioenergy production with heavy indirect land use change impacts result in the elimination of first generation biofuel production in the EU in the 'Climate focus' and 'Resource efficiency' storylines. In addition, higher price support in these two storylines makes the total availability of residues and dedicated crops larger and their use more efficient, leading to a high production of both heat and electricity from pellets based on straw and perennials.

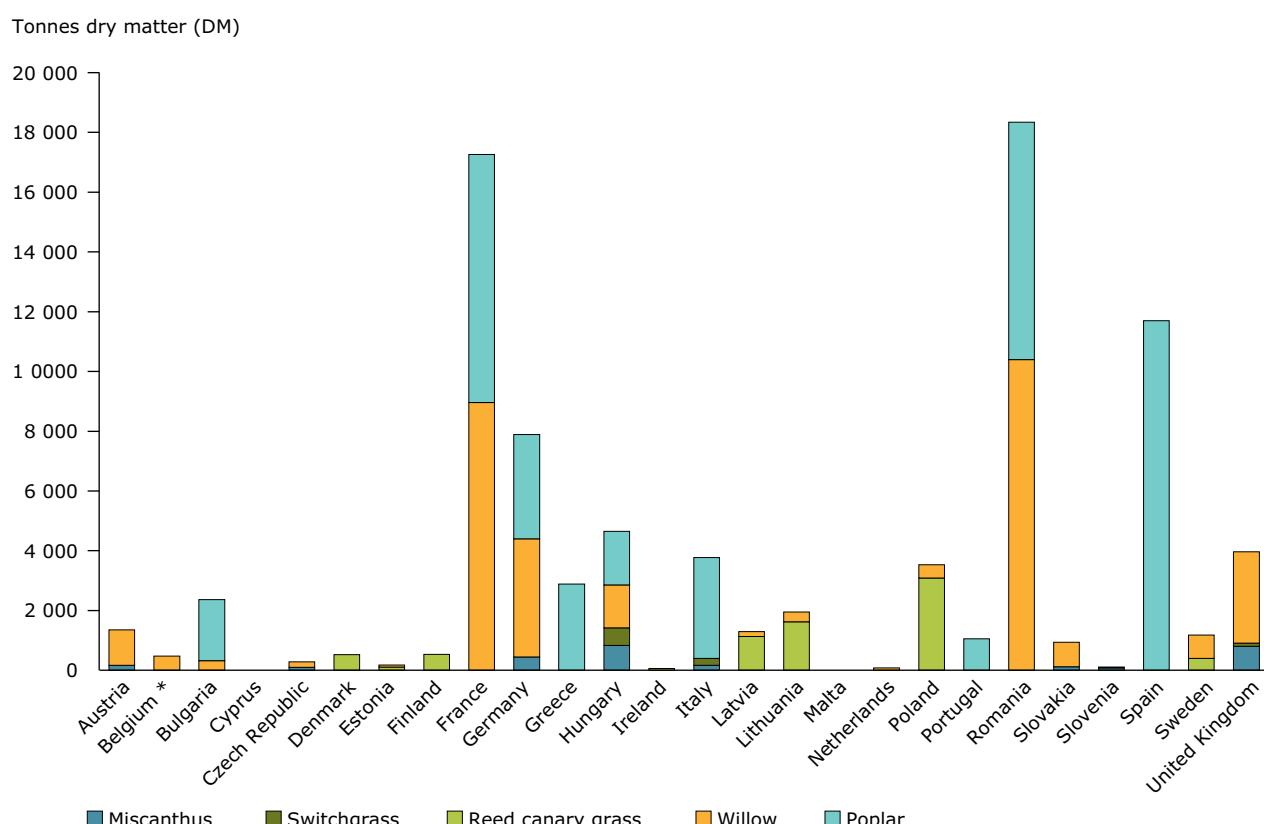
Larger production of biogas and second generation bioethanol from straw in these storylines is related with a stronger stimulation of second-generation technologies and higher support for more efficient pathways. Furthermore, the assumption of a more decentralised approach for these technologies implies less need for a strong spatial concentration of biomass production.

A closer look at the perennials shows differences not only in the conversion pathways but also the crop sources used in the different storylines.

Figures 5.3–5.5 illustrate that the mix differs strongly between countries, as does the relative size of the dedicated crop potential per country. In the 'Market first' storyline, willow and poplar dominate in the mix of perennials due to their lower per hectare production costs.

The other two storylines foresee much greater use of miscanthus, switchgrass and reed canary grass as these deliver higher GHG efficiency per tonne of dry mass on the types of lands available. The potential from perennials is largest in the 'Climate focus' storyline, which imposes no limits on the use of fallow land. It should be noted that in the 'Climate focus' and 'Resource efficiency' storylines about one fifth of the perennial potential is produced on land where indirect land use change is assumed to lead to displacement of crop production elsewhere. The GHG emissions linked to that indirect land use change need to be outweighed by the overall GHG savings in the bioenergy pathway under question for the related potential to be included in these two storylines.

Figure 5.3 National perennial cropping mixes in the 'Market first' storyline

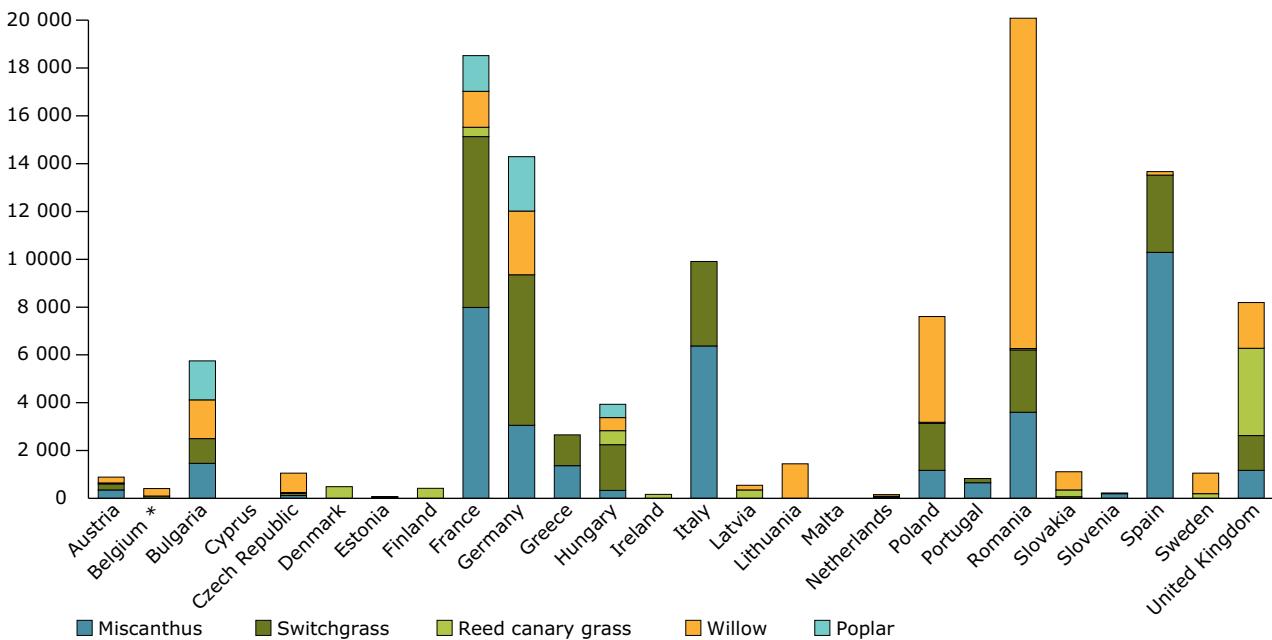


Note: * Due to its small size Luxembourg is grouped together with Belgium in this analysis.
Detailed results for all countries can be found in the accompanying ETC/SIA report.

Source: ETC/SIA, 2013.

Figure 5.4 National perennial cropping mixes in the 'Climate focus' storyline

Tonnes dry matter (DM)

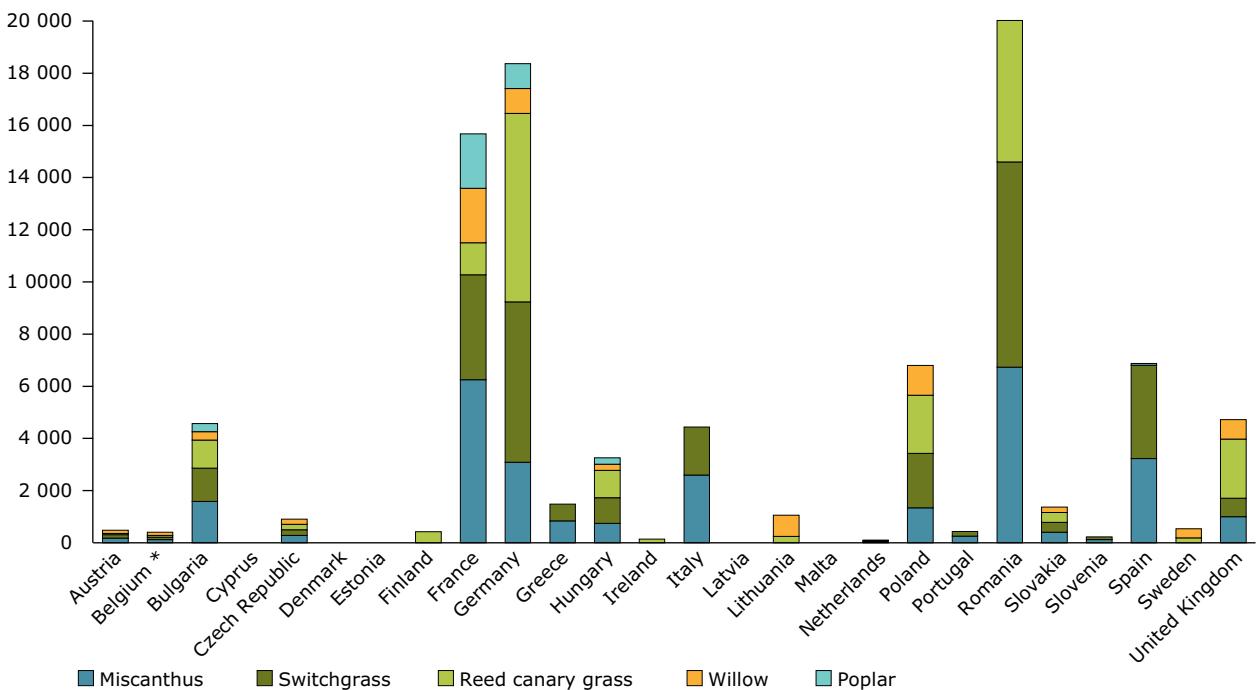


Note: * Due to its small size Luxembourg is grouped together with Belgium in this analysis.
Detailed results for all countries can be found in the accompanying ETC/SIA report.

Source: ETC/SIA, 2013.

Figure 5.5 National perennial cropping mixes in the 'Resource efficiency' storyline

Tonnes dry matter (DM)



Note: * Due to its small size Luxembourg is grouped together with Belgium in this analysis.
Detailed results for all countries can be found in the accompanying ETC/SIA report.

Source: ETC/SIA, 2013.

The differences in the perennial mixes between the 'Climate focus' and 'Resource efficiency' storylines result from the fact that the stricter GHG efficiency criteria apply only to biofuels in the 'Climate focus' storyline but also to the electricity and heat sectors in the 'Resource efficiency' storyline.

The importance of stimulating higher efficiency also becomes clear from the total energy produced from perennial biomass sources, which ranges from 4.6 MJ of energy delivered by one tonne of dry matter in the 'Market first' storyline to 6.2 MJ in the 'Resource efficiency' storyline.

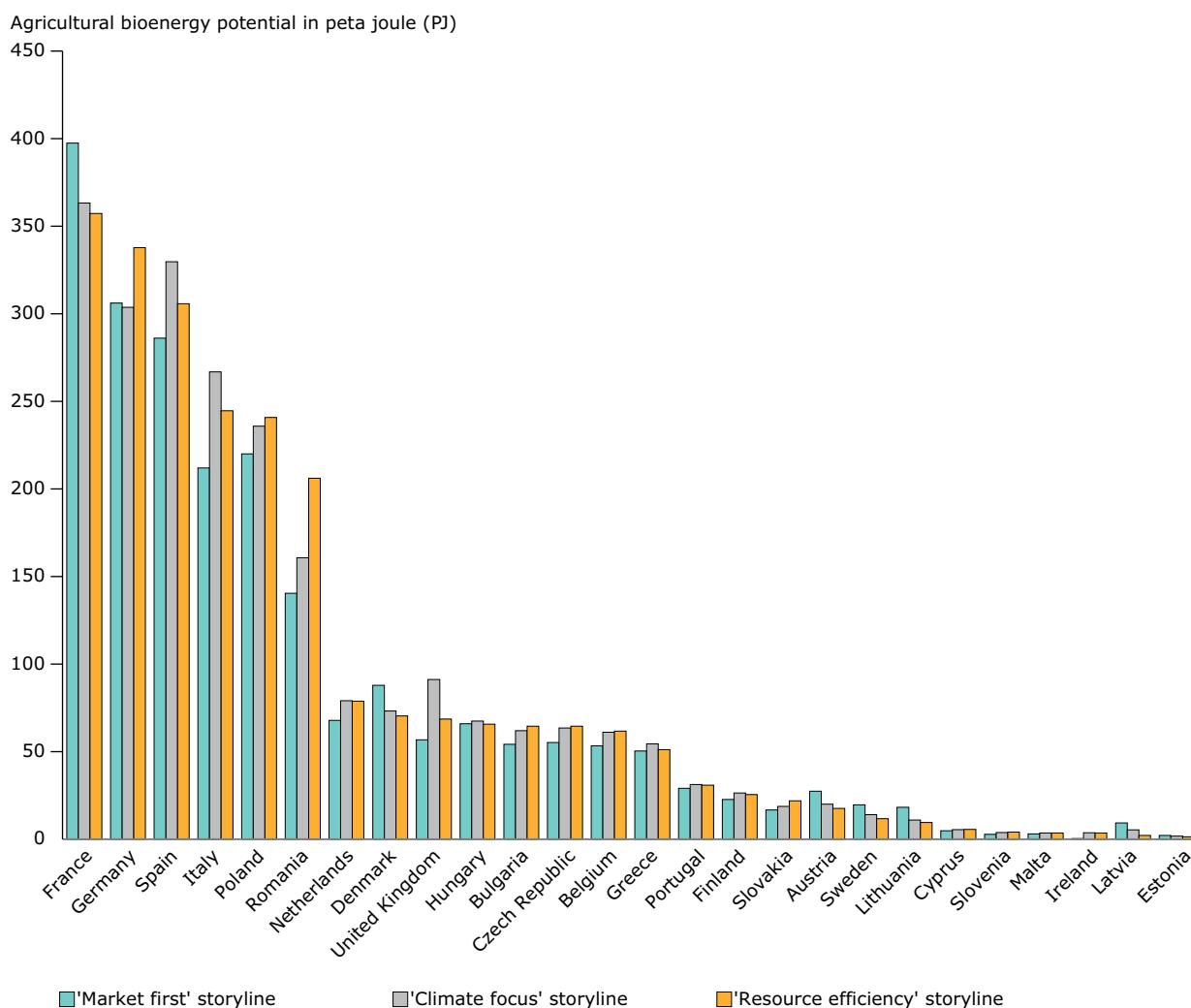
The countries contributing the largest dedicated cropping potentials are Romania, France, Germany, Spain and Italy. However, setting a limit on the

use of fallow land and irrigation in the 'resource efficiency' storyline does imply that the perennial biomass contribution declines significantly for Spain, Italy, France, the United Kingdom and Bulgaria.

Figure 5.6 shows the differences in terms of the contribution to the overall EU domestic agricultural potential. France, Spain, Germany, Italy, Poland and Romania have the largest contributions.

In the current report the analytical focus is on the contribution of the agricultural sector for reaching renewable energy and GHG mitigation targets. Nevertheless, bioenergy potentials and technology mixes for the forest and waste sectors were also examined in all three storylines.

Figure 5.6 Total domestic agricultural bioenergy potential per country in 2020 (PJ)



Source: ETC/SIA, 2013.

Key outcomes of storyline analysis

The forest potential varies according to input prices. In terms of technology pathways, in the 'Climate focus' and 'Resource efficiency' storylines smaller scale plants and the use of forestry residues are assumed to be more widespread. Figure 5.7 shows the projected technology mix per storyline for use of forest biomass.

For waste, the bioenergy potential is the lowest in the 'Resource efficiency' storyline due to a lower level of available waste. However, inefficient pathways, such as municipal solid waste combustion, are completely absent here which means a more optimal technology mix and a much better performance in terms of resource efficiency compared to the 'Market first' storyline. Figure 5.8 shows the projected technology mix for use of waste biomass in the different storylines.

Figure 5.7 Forest potential (PJ) and technology mix per storyline in 2020

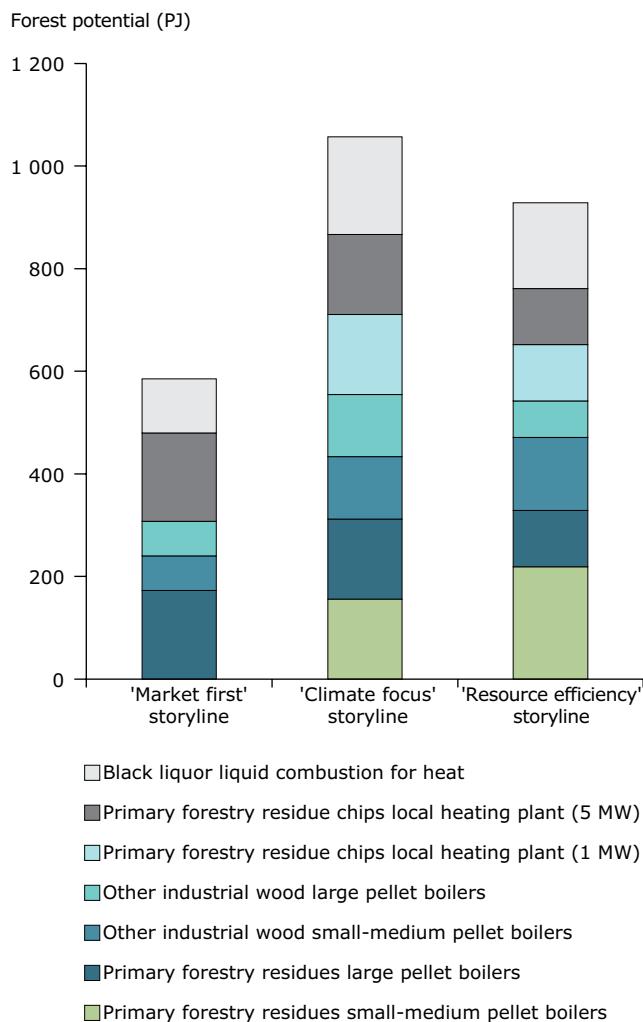
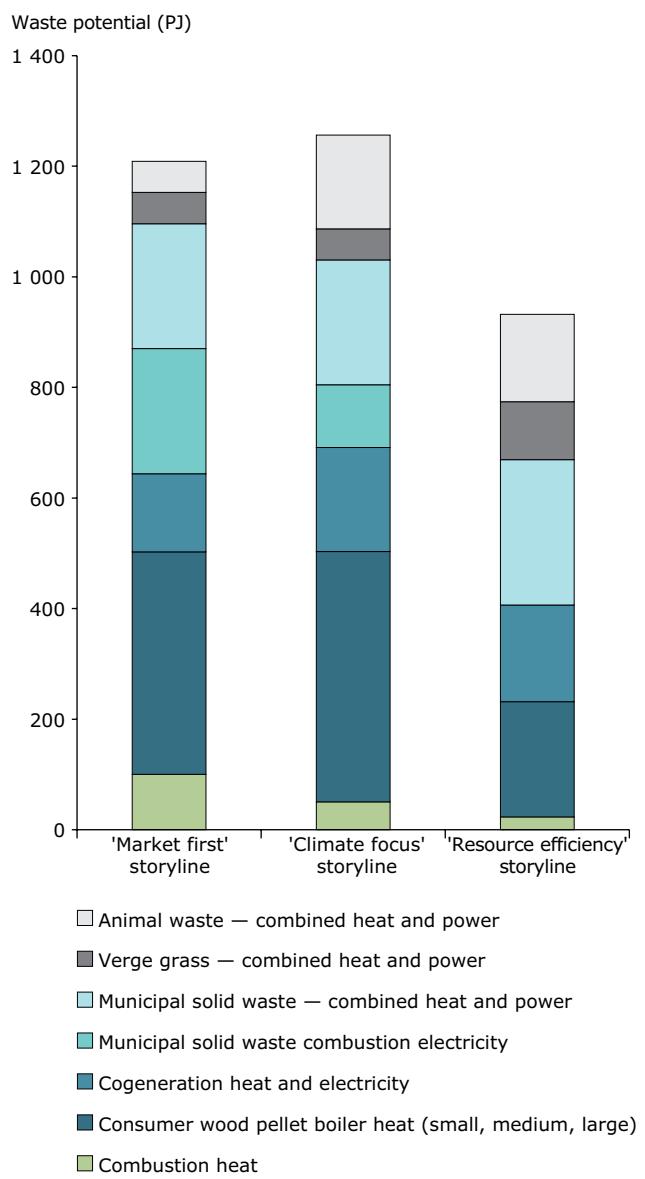


Figure 5.8 Waste potential (PJ) and technology mix per storyline in 2020



5.3 Strong variation of bioenergy GHG performance between storylines

The preceding sections demonstrated that varying the environmental standards and economic incentives assumed in the three storylines results in wide differences in the bioenergy pathways adopted. This also leads to very different resource efficiency outcomes, as explained further in this section.

GHG efficiency of bioenergy output

This section presents the GHG emissions that are associated with the different mixes of biomass sources, technologies applied and environmental constraints in the three storylines. This is achieved by presenting the total 'well-to-wheel' emissions of the biomass sources used to reach the NREAP targets in 2020. This is discussed for the biomass potential from the agriculture, waste and forest sectors together with the emissions associated with imports needed to completely fulfil the NREAP targets in 2020. All emissions presented here include both land-based and downstream (life-cycle) emissions.

The total mitigation potential of bioenergy production in the three storylines is assessed by comparing it to the fossil comparator taking account of the fossil emission factors specific to each EU-27 Member State. The fossil comparators are based on the Global Emissions Model for integrated Systems (GEMIS) developed by Oeko-Institut⁽⁶⁾ which includes full life-cycle emissions. GEMIS 4.8 is a life-cycle analysis program and database for energy, material, and transport systems. When putting all domestic potentials together with the import needs required for reaching the NREAP targets in 2020 we see that the different environmental constraints applied per storyline deliver different solutions. In Storyline 1, assuming no environmental constraints and letting the market do its work will lead to an average emission of 44 kg CO₂-equivalent per GJ, while in the most strict Storyline 3 this

target is reached with only 25 kg CO₂-equivalent per GJ (see Table 5.1). The latter, however, will lead to extra costs, but will also yield much better results in relation to other environmental impacts. A comparative analysis reveals that the assumed policy measures in the 'Climate focus' and 'Resource efficiency' storylines deliver substantial cuts in the total GHG emissions relative to the 'Market first' storyline (see Table 5.1).

The total amount of energy estimated to be generated is lower in the more environmental Storylines 2 and 3. This is enabled by the possibility to let certain biofuel pathways count double for the 2020 renewable transport fuel target. This makes reaching the target more feasible, but also reduces the overall potential for energy from biomass as less fossil energy is replaced by renewables. The double counting option also explains why biofuel imports can be more limited in Storylines 2 and 3. The use of lignocellulosic biofuels (e.g. straw, perennials) and gas-to-liquid applications in these storylines lowers the risk for increased greenhouse-gas emissions and other pressures related to increases in land use.

The pathways foreseen for biofuel imports are a significant factor for GHG emissions per storyline. The much higher biofuel GHG emissions in Storyline 1 are logical as they are based on first-generation biofuels. These are mostly based on cheaper palm oil and soy-based biodiesel which have very high direct and indirect land-use change effects. In Storyline 3, imported biofuels can only be based on crops produced in sustainable systems

Table 5.1 Energy potential from domestic and imported biomass and average GHG emissions per storyline

Domestic agriculture, forest, waste biomass and imports	Energy potential, total (PJ)				Total emissions (ktonne CO₂-equivalent)				Average emissions (kg CO₂-equivalent/GJ)			
	Heat	Elec-tricity	Biofuels	Total	Heat	Elec-tricity	Biofuels	Total	Heat	Elec-tricity	Biofuels	Total
'Market first' (Storyline 1)	3 692	1 753	1 219	6 664	81 368	114 681	96 781	292 830	22.0	65.4	79.4	43.9
'Climate focus' (Storyline 2)	3 282	2 124	492	5 898	65 005	98 758	22 508	186 271	19.8	46.5	45.7	31.6
'Resource efficiency' (Storyline 3)	2 750	2 016	556	5 322	56 880	77 828	- 147	134 561	20.7	38.6	- 0.3	25.3

Source: ETC/SIA, 2013.

⁽⁶⁾ GEMIS includes the complete life-cycle in its calculation of impacts — i.e. biomass/fuel delivery, materials used for construction, waste treatment, transports/auxiliaries and includes by-product allocation (based on energy value). A further description of GEMIS and the calculated GHG emissions is given in Fritzsche and Rausch, 2009.

using degraded lands, otherwise they will not reach the mitigation targets. This should be feasible if the right incentives are in place and the demand remains modest. These conditions are fulfilled in Storyline 3 because of double counting of advanced biofuels against the transport fuel sub-targets.

The domestic forest potential is entirely used to reach the heating targets, which is the most efficient choice. In Storylines 2 and 3 the prices paid for biomass are higher than in Storyline 1 making it possible to utilise more domestic potential and rely less on imports. Since there are not many choices in relation to the pathways to convert forest biomass to heat in all storylines, practically the same efficiency is reached for the domestic part across the three storylines. This is different for the imported pellets converted to heat as greenhouse-gas emissions for these pellets may differ strongly according to the region from where they are imported. Most of the imports in Storylines 2 and 3 are therefore assumed to come from the United States. A higher import share in total use of forest biomass for heat in Storyline 1 leads to higher average emissions in this storyline. This is due to the fact that domestic forest products for heat generation are more diverse and provide very efficient pathways, such as all secondary and tertiary forest products, including black liquor converted into heat.

The GHG mitigation results for forest biomass presented in Table 5.1 could not be re-analysed in detail against the recent concerns linked to carbon debt. The risk of a carbon debt arising from the use of domestic or imported forest biomass is closely related to the type of forest material employed. Residues carry very little risk whereas the use of stem wood can generate a substantial carbon debt. As Storyline 3 includes much stricter criteria on removing stem wood from protected forest areas this makes forest residues the largest forest resource in this storyline. The opposite is the case

for Storylines 1 and 2 where the domestic forest potential consists for more than half of stem wood which carries a carbon debt risk. Further details and a discussion of forest GHG mitigation results in a carbon debt perspective can be found in Sections 3.5 and 4.4.2.

Potential CO₂ mitigation gains relative to fossil fuels

The significant variation in GHG efficiency between the three storylines means that national decisions about how to achieve NREAP bioenergy targets will have a substantial influence on overall GHG mitigation. Table 5.2 reveals the relative impacts on GHG emissions in the three storylines very clearly.

The 'Market first' storyline delivers a 61.9 % cut in emissions relative to generating the same amount of energy using fossil fuels. Contrastingly, the 'Climate focus' measures increase that reduction to 74.6 %, while the 'Resource efficiency' storyline increases the mitigation gain to 79.9 %. The gains are largest in the transport fuel sector but the heat and electricity sectors also contribute.

The overall outcome again confirms the higher efficiency and therefore better GHG mitigation potential of the heat and power sectors over transport biofuels. However, it also illustrates the importance of the technology and pathways chosen in each energy sub-sector, as exemplified by the high GHG mitigation potential of biofuels in the 'Resource efficiency' storyline.

5.4 Effect of bioenergy choices and environmental constraints on ecosystem impacts

Finally, it is very relevant to explore the broader environmental impacts of the land use change

Table 5.2 Energy potential from domestic and imported biomass and average GHG emissions per storyline

Domestic agriculture, forest, waste biomass and imports	Gain in CO ₂ -equivalent mitigation compared to fossil fuels (%)			
	Heat	Electricity	Biofuels	Total
'Market first' (Storyline 1)	77.0	63.2	5.3	61.9
'Climate focus' (Storyline 2)	79.3	73.9	45.4	74.6
'Resource efficiency' (Storyline 3)	78.4	78.3	100.3	79.9

Source: ETC/SIA, 2013.

anticipated in the three storylines. The analysis addresses five important elements of ecosystem health:

- effects on water quality (measured as nitrate concentration in water);
- effects on water quantity (measured as water used in irrigating energy crops);
- land-based GHG emissions (measured as changes in soil organic carbon and fertiliser emissions);
- effects on soil (measured as changes in soil erosion);
- effects on farmland bird diversity (measured as a combination of threat levels to species, their landscape and habitat type dependence, and land use in farmland).

As Table 5.3 shows, the three storylines vary relatively little in terms of their impacts on water quality and land-based GHG emissions. The adjustments in these two indicators in the period to 2020 in all three storylines appear to result primarily from the reform of the EU's Common Agricultural Policy (CAP) and market changes, rather than the extent and form of energy cropping. It should be noted, however, that the land use changes simulated with the help of the CAPRI model already start from a substantial biofuel cropping baseline (assumed in the business as usual projection), so that no real

comparison with a no-energy cropping option was possible. Instead the land use situation in 2020 in the three storylines is compared against the land use situation in 2004, the reference year from which the CAPRI projections were developed.

The storylines differ far more in terms of their impacts on water quantity, soil erosion and farmland bird diversity. The 'Market first' storyline produces markedly worse environmental impacts in these areas. Equally, it becomes apparent that focusing on GHG emissions only, as in the 'Climate focus' storyline, will not always deliver wider environmental benefits. That storyline is characterised by strong environmental impacts from water abstraction and loss of farmland bird diversity. The 'Resource efficiency' storyline appears to come closest to an environmentally beneficial approach to achieving the bioenergy targets across EU Member States.

An interesting example of potential ecosystem impacts is the estimated effects of perennial biomass production, particularly on land released from agriculture and former abandoned farm land⁽⁷⁾. Such production may potentially increase the demand for irrigation water beyond sustainable levels, particularly where large increases in high yielding perennial plantations such as switchgrass and miscanthus occur. These crops are efficient in water use but would still need irrigation, implying additional water demand if grown on land released from food and fodder production that was not irrigated in 2004.

Table 5.3 Environmental impacts of energy cropping in each storyline

	'Market first' (Storyline 1)	'Climate focus' (Storyline 2)	'Resource efficiency' (Storyline 3)
Water quality	+/-	+	+/-
Water quantity	-	--	0
Land-based direct GHG emissions	+/-	+	+/-
Soil erosion	-	+	+/-
Farmland bird diversity	--	-	+

Note: '+' denotes a positive impact, '+/-' denotes a mixture of positive and negative impacts, '-' denotes a negative impact, '--' denotes a very negative impact, '0' denotes zero impact.

Source: ETC/SIA, 2013.

⁽⁷⁾ A recent study on ozone emissions from perennial cropping has investigated other potential impacts from perennial cropping ('Impacts of biofuel cultivation on mortality and crop yields' — see <http://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate1788.html>).

This implies that most of the irrigation water needs for perennials are additional to the irrigation water demands for food and feed crops, which may also increase towards 2020. In addition, most anticipated land releases and abandoned land stock lie in the more arid regions of the EU, such as the Mediterranean and eastern Europe. While using these lands may not lead to any ILUC effects elsewhere, they could increase irrigation water demand considerably if crops are chosen that require extra water during dry periods.

The estimated trend in farmland bird populations across the three storylines illustrates again the potentially serious ecosystem impacts resulting from energy cropping. The present study shows that unconstrained development of bioenergy (as occurs in the 'Market first' storyline) leads to farmland bird losses in a majority of EU regions and also on average across Europe. A focus on bioenergy production with perennials (the 'Climate focus' storyline) does considerably better, but still leads to overall farmland bird losses. Contrastingly, the 'Resource efficiency' storyline, with strict requirements on the maximum use of fallow land and mitigation targets for all bioenergy pathways (including heat and electricity) shows that biodiversity losses are not an inevitable consequence of bioenergy production. Under such an overall sustainability concept, farmland bird biodiversity might even slightly improve on average across Europe, although some regions may still experience local losses compared to 2004.

5.5 Environmental aspects of current energy cropping trends

Statistical data on energy cropping trends in the EU-27 Member States are difficult to obtain and often outdated (a brief review of this issue and available data sets can be found in Annex 8 of ETC/SIA, 2013). Available EU-level data indicate that dedicated energy cropping for biofuels and electricity and heat generation covered approximately 5.5 million hectares of agricultural land in 2008 (ETC/SIA, 2013). This amounts to 3.2 % of the total cropping area (not the utilised agricultural area) in the EU-27. Practically all of this land was used for dedicated biofuel cropping. Oil crops for biodiesel accounted for 82 % of the land used for energy cropping. The remainder was used for producing ethanol crops (11 % of energy cropping) and biogas (7 %), with perennials (1 %) going mostly into electricity and heat generation.

More recent data at EU-27 level (EC, 2013a) indicate that the EU biofuel production has increased further by 2010 although growth has slowed down in the

last years. Associated land use for energy crops in the EU-27 is also expected to have increased but overall statistics for recent years were not available at the time of writing. The available data indicate that the share of crops used for first-generation biofuels (principally oilseed rape, wheat and sugar beet) in total energy crop area has remained largely the same. The area covered by perennial crops has only increased marginally whereas biogas crops (mainly maize) have further expanded in some countries, in particular in Germany.

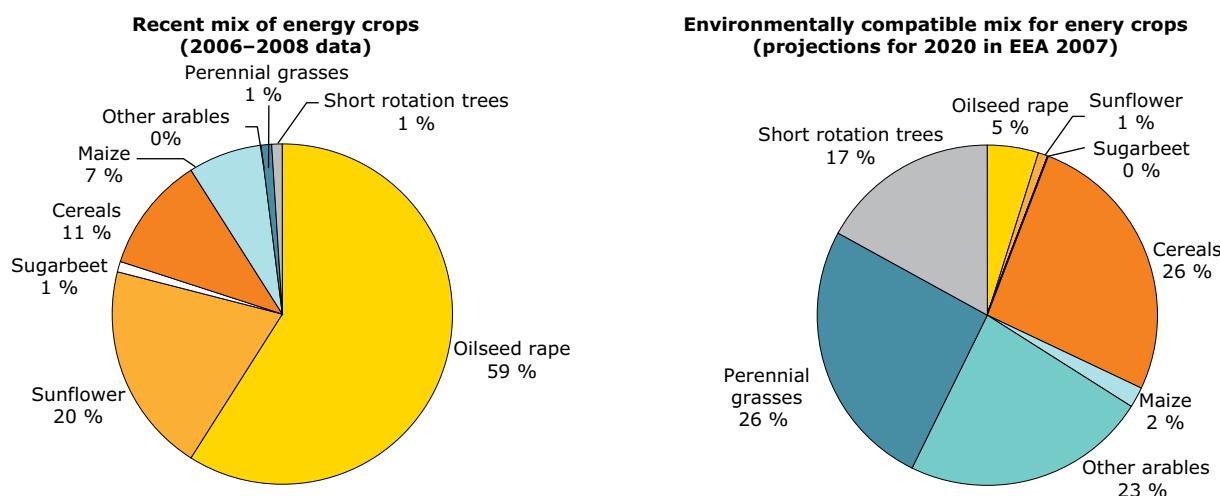
A comparison of these recent energy cropping trends with the 'environmentally compatible' energy cropping scenario that was developed by the EEA (2007) shows some interesting qualitative results. The energy cropping data from the period 2006–2008 show a clear dominance of annual arable crops in the energy crop mix, with perennial grasses and short rotation coppice occupying just 2 % of the total (Figure 5.9, left).

Among conventional annual crops used as energy crops, cereals (rye and barley) and sunflowers usually have a better environmental profile. The characteristics of, and management practices for, wheat, grain maize, potatoes, sugar beet and oilseed rape lead to a relatively higher negative impact on the environment (EEA, 2006). Unfortunately, the latter group of crops dominate biofuel feedstock production in most EU regions. In contrast, the 'environmentally compatible' energy cropping scenario developed by the EEA for 2020 includes a much larger share of perennial grasses and short rotation trees (under coppice management) in total energy crop mix at about 40 % of the total (Figure 5.9, right). In the 'environmentally compatible' scenario, oilseed rape accounts for approximately 5 % share of the envisaged energy crop mix, with maize contributing 2 % and sunflower 1 %. Furthermore, these crops are projected to disappear completely in the earlier EEA vision for environmentally compatible energy cropping in 2030 (EEA, 2006).

The difference between today's energy crop mix and the EEA's projections for 2020 and 2030 indicates that current energy cropping cannot be considered 'environmentally compatible' when applying the criteria developed for the first EEA bioenergy report (EEA, 2006).

Information on the environmental consequences of current dedicated energy cropping is limited. Effects can be expected in countries such as France and Germany, where production has increased tremendously in the last decade. That biofuel demand

Figure 5.9 Mix of energy crops, 2006–2008 (left) and EEA scenario for environmentally compatible energy cropping in 2020 (right)



Source: ETC/SIA, 2013.

has undoubtedly led to tremendous increases in oilseed rape cropping area. Eurostat statistics show that EU production of oilseed rape almost doubled (increasing by 93 %) between 2000 and 2009 and the cropping area increased by almost 50 %. Most energy cropping in the EU-27 takes place on already intensively farmed land, including land used to produce oilseed rape and cereals. As a consequence the environmental impacts in the EU itself are limited though not negligible. Where energy crops have replaced previous set-aside or fallow land negative impacts on farmland bird communities are expected in particular. In addition, there are some reports of

the conversion of grassland for biomass cropping, for example NABU (2009) cites the example of maize production for biogas in Germany.

Where energy cropping leads to a more intensive exploitation of traditional agricultural landscapes under extensive management it can affect elements of high conservation value (e.g. field borders and structural elements of the agricultural landscape). This is likely to be the result of a high concentration of energy crops in total agricultural land use but no reliable monitoring data are available to evaluate the occurrence of such impacts.

6 Key lessons learned and issues for further research

This study has analysed bioenergy production from the perspective of the EU's resource efficiency concept, which requires that society finds ways that meet its needs while reducing both resource use and wider ecosystem impacts. Delivering both aspects of resource efficiency is a challenge for all renewable energy systems but a particular one for bioenergy. This arises from the relatively low energy conversion efficiency of bioenergy pathways and the considerable land use change often associated with biomass production, which results in complex direct and indirect impacts on ecosystem state and functioning.

This chapter presents the key conclusions of the present study, clustered into three groups:

- bioenergy and resource efficiency;
- implications for bioenergy policy;
- reflections on methodology and scope for further analysis.

6.1 Bioenergy and resource efficiency

This section reviews how bioenergy performs in a resource efficiency perspective: a) in terms of the efficiency of the use of inputs for generating energy and reducing GHG emissions; and b) in terms of the broader ecosystem impacts from bioenergy production. In assessing either aspect, it is necessary to review the full life cycle of bioenergy production.

a) *Using fewer resources to generate more output*

This study demonstrates that the choice of biomass feedstock, conversion technology and end use has a huge influence on the efficiency of bioenergy production. Specifically:

- The choice of bioenergy pathway and feedstock source matter strongly for overall efficiency:

Bioenergy heat and power pathways are considerably more efficient in GHG mitigation than transport fuel pathways in the 2020 timeframe.

- Using organic waste and agricultural residues as feedstock is highly advantageous as it does not augment pressure on land and water resources and offers very high GHG mitigation gains.
- The productivity of different energy cropping systems, expressed in terms of harvestable biomass volume per hectare of cultivated area per year, can vary hugely. Low-yielding cultivation systems combined with inefficient conversion may provide 10–25 GJ per hectare per year (GJ/ha/yr) of useful output, while high-yielding options with efficient conversion can deliver 200–250 GJ/ha/yr (IFEU et al., 2012). This represents a huge divergence, with land resources delivering more than 20 times more energy in the best case compared to the least efficient case.
- ILUC effects have a very important impact on the greenhouse gas balance and mitigation capacity of land-based bioenergy chains. This report shows that GHG emissions from ILUC significantly decrease, or even negate, the potential contribution of bioenergy sources to realising EU greenhouse gas mitigation targets, particularly in the transport sector.
- Converting bioenergy feed stocks into useful energy carriers often results in losses of heat or residues. From a resource efficiency perspective, increasing total output from a given input requires that such losses be minimised and/or used productively. Cogeneration of heat and electricity is an important option for converting biomass feedstock efficiently. In the long term advanced biofuel technologies making use of (nearly) all biomass and bio-refineries with 'zero waste' approaches are possibilities.
- Biomass is a bulk good, making transport logistics a key issue for improving overall

efficiency. The energy density of at-gate bioenergy feedstock can be enhanced via prior compaction, pelletisation and other options. Complex logistical arrangements are required to bring bulky biomass sources together and energy costs will impose efficiency limits on the size of biomass-based energy production.

b) Generating energy while preserving ecosystem functioning

The land use associated with biomass production is closely related to environmental cycles and ecosystem functions, such as organic carbon flows, maintaining soil productivity or landscape diversity. Consequently, the land use component of bioenergy production has the biggest impact on ecosystem processes. Sound management of bioenergy development therefore needs to pay close attention to land use issues. The analysis in this report offers the following key lessons.

- The GHG balance, soil, water and biodiversity impacts of energy cropping systems depend strongly on the land-use change associated with their cultivation, meaning that the location and type of energy crops matter strongly.
- Today's energy cropping patterns are not 'environmentally compatible' according to the criteria of the 2006 EEA study. First generation biofuel crops dominate the current energy crop mix and maize cultivation for biogas takes a prominent second place in Member States with well-developed biogas production.
- Perennial bioenergy crops can provide environmental benefits in intensively exploited agricultural landscapes and help to increase

landscape diversity. This can support the creation of stepping stones for biodiversity through biomass production (see also EEA, 2007).

- Additional bioenergy cropping with perennials, however, can also create additional environmental pressures, e.g. with regard to scarce water resources in arid regions or the closing up of landscapes in forest-rich regions. This shows that the creation of perennial biomass plantations requires careful planning with detailed knowledge on the production system and the local environmental situation.

c) Further issues that require attention

This report mainly explored the overall environmental performance of agricultural bioenergy pathways. Other issues that merit further attention include the following:

- The question of carbon debt is crucial in considering the GHG mitigation potential of bioenergy derived from forest biomass. This could only be discussed qualitatively in this study and requires further investigation.
- Indirect land use change not only affects the GHG balance of bioenergy pathways but also has substantial impacts on soil and water resources as well as biodiversity wherever it takes place. Such indirect effects have not yet been sufficiently studied.
- The monitoring of energy cropping trends is currently not sufficient to be able to analyse their environmental impact or the effectiveness of (environmental) policy measures in this regard. This has negative repercussions on

Box 6.1 Summing up: bioenergy production can be resource-efficient but only if carefully managed

Bioenergy's greenhouse gas efficiency and ecosystem impacts can vary enormously. Where feedstock is sourced from organic waste or agricultural residues, it implies zero land use change and substantial advantages over fossil fuel energy in terms of both GHG efficiency and ecosystem impacts.

Conversely, where biomass derives from energy cropping, some bioenergy pathways can result in minimal climate benefits or even lead to additional GHG emissions. Indirect land use change effects are particularly important in this context.

From a resource-efficiency perspective, the core message from this study is clear: bioenergy can play a valuable role in meeting society's energy needs while preserving our natural capital — but only if it focuses on the most resource-efficient approaches and pathways.

- our ability to improve policy design and implementation.
- It is recommended, therefore, that further investment in such monitoring systems at EU and country level is carefully considered.

6.2 Implications for bioenergy policies and practice

This section looks at the practical implications of the general conclusions presented in the previous section. Rather than being fully comprehensive, it merely aims to list key points that emerge from this analysis. More detail is provided in the accompanying ETC/SIA report.

a) Prioritise and facilitate the use of waste and residues

Wastes and by-products are currently underused and can contribute significantly to reaching EU bioenergy targets. This report projects that agricultural residues and organic waste would contribute 44 % of the total supply for meeting the NREAP targets in the 'Market first' and 'Resource efficiency' storylines and 52 % in the 'Climate focus' storyline⁽⁸⁾. Further effort is needed in several areas, however, to facilitate exploitation of the large EU waste and residue potentials.

b) Stimulate the most resource-efficient technologies and pathways

Since there is a limited (sustainable) volume of biomass available for use as feedstock, it is clear that the most resource-efficient bioenergy pathways must be favoured.

In the heat and electricity sectors, the overall increase in bioenergy is already leading to significant mitigation gain, even where less advanced technologies are used. This is certainly true in countries where a large part of the heat and electricity is based on dirty brown coal, although deploying more efficient bioenergy technologies would enhance the gains.

Looking ahead, the storyline-based analysis in this report did not foresee the use of bio-refinery and cascading use concepts in the period up to 2020,

as those will be commercially available only later. Nonetheless, expected progress in developing bio-cascading and bio-refining approaches up to 2020 offers the potential of large efficiency improvements in energy conversion technologies beyond that timeframe.

The efficiency of converting biogenic residues and wastes into bioenergy carriers could be considered in terms of percentage of useful energy output per energy input. A minimum conversion efficiency requirement of this type would safeguard against developing bioenergy options that are efficient in reducing GHG emissions but still inefficient in terms of resource use. An example to avoid would be co-firing solid bioenergy in old electricity-only power plants rather than in combined heat-and-power plants.

c) Integrate ILUC effects into the further development of bioenergy

The ILUC effects of European bioenergy production are very important for its overall environmental profile. It is therefore important to consider which mechanisms are available for minimising potential negative impacts outside Europe, including reducing EU bioenergy targets and integrating ILUC factors into bioenergy greenhouse gas balance calculations.

A debate is underway on how to address ILUC effects via additional policy measures. This analysis does not directly contribute to that debate but it seems worth considering that such policy aims can be supported through complementary measures, including:

- significant financial incentives for increasing the collection and use of by-products and wastes and for stimulating dedicated cropping on land where ILUC risks are low;
- more effort in developing advanced biofuel and other highly efficient conversion technologies to reduce biomass feedstock needs for a given demand (Fritzsche, 2012b).

As land is a finite and increasingly scarce resource and non-bioenergy uses such as food, feed and fibre production compete with bioenergy for land, it is necessary to consider whether there is a maximum

⁽⁸⁾ Note that this does not take into account bioenergy derived from primary and secondary forestry residues, and waste-based imported bioenergy (e.g. pellets). When considering those, the share would be even higher.

level of energy cropping that can be sustained without creating too much competition with other uses of productive farmland.

d) Incentivise environmentally compatible energy cropping systems

The choice of energy crops and cropping systems plays a key role in the wider environmental profile of energy-crop based bioenergy pathways. The development of environmentally compatible energy cropping systems has been a focus of previous EEA analysis (e.g. EEA, 2007), and builds on maintaining environmentally friendly agricultural land uses and on shifting from annual energy crops to perennial systems.

Perennial plantations offer environmental benefits but need to be developed carefully, without excessive soil disturbance and associated loss of soil carbon, particularly on land categories where soil carbon resources have built up for several years (e.g. on long-term set-aside or abandoned land). Practices such as ploughing and tilling should ideally be avoided and low-impact techniques (drilling or injection for planting and seeding) applied.

Large-scale perennial biomass plantations potentially increase the demand for irrigation water beyond sustainable levels. This is particularly a problem for establishing high yielding perennial plantations such as switchgrass and miscanthus as these require additional irrigation if produced in the more arid parts of Europe. Other energy crops more adapted to the precipitation patterns in these regions are preferable, therefore, even if of somewhat lower productivity.

The protection of farmland bird populations requires additional measures, particularly the prevention of the loss of fallow land. The results of this study show that unconstrained development of bioenergy (such as in the 'Market first' storyline) leads to farmland bird losses in a majority of EU regions while such negative impacts can in principle be avoided by favouring more efficient bioenergy pathways (see the example of the 'Resource efficiency' storyline).

e) Consider less-explored environmental concerns

Environmental impacts linked to the use of forest biomass were not re-analysed in detail in this study, but environmental constraints from previous work were considered to apply. Foremost among the

issues to be further investigated is the question of carbon debt than can arise from the use of stem wood for bioenergy production.

In view of the expected increases in imports and use of solid biomass for energy it seems necessary to ensure that the use of biomass in the heat and power sectors is subject to clear environmental standards. Previous EEA work can provide useful background in that regard, such as in relation to biodiversity safeguards in forest ecosystems.

Residue removal should not result in environmental risks. Too much biomass removal from fields or forests may reduce soil fertility and increase soil degradation, and release carbon from the soil. Indirect land use change not only affects the GHG balance of bioenergy pathways but also has substantial impacts on soil and water resources as well as biodiversity wherever it takes place. Such indirect effects have not yet been sufficiently studied and should be addressed in further research.

f) Set up efficient production systems and logistics chains

Bioenergy feed stocks need to be converted into useful energy carriers, which causes energy losses. From a resource efficiency perspective, it is essential to minimise such losses and to use them productively where they are inevitable. This applies not just to material losses (e.g. residues such as fibres) but also to energy (e.g. heat), with the aim being to increase total output for a given input.

Similarly, it is important to make progress in setting up the right infrastructure for bringing together a sufficiently large and continuous amount of biomass feedstock to supply bioenergy systems operating at competitive cost levels. The following key points need to be considered in this context:

- Cogeneration is the most efficient option to convert biomass feedstock while advanced biofuel technologies making use of (nearly) all biomass, and bio-refineries with 'zero waste' approaches are possibilities in the longer term.
- Together with the most productive cultivation systems (without LUC-related GHG emissions and biodiversity impacts), these conversion systems allow for more than 75 % GHG mitigation compared to fossil-based systems.
- The concept of cascading use for biomass proposes to combine several uses of biomass in an efficient cascade where one use builds on the

Box 6.2 Summing up: translating resource-efficiency principles into bioenergy policy

This report illustrates that policies aimed at making upstream parts of the bioenergy chain (i.e. the sourcing of biomass) environmentally compatible cannot achieve all aspects of resource efficiency alone. They need to be accompanied by measures that stimulate improvements in other parts of the chain, particularly the downstream conversion steps but also including all logistical steps and final end-uses of bioenergy.

Potentially adverse environmental effects connected to direct land uses, including changes in land management, currently fall outside the EU bioenergy policy framework. Additional policy incentives and safeguards are needed to address such environmental impacts, particularly with respect to water resources and farmland biodiversity.

In the present study, the most environmentally beneficial bioenergy production is secured by the measures comprised in the 'Resource efficiency' storyline. That package of regulations and incentives offers the lowest emissions to air and water from European bioenergy crops, limited loss of soil organic carbon and erosion, protection of water resources from additional irrigation requirements and conservation of farmland bird populations.

Finally, it is important that the policy framework addresses the less obvious impacts of promoting bioenergy production. One key factor here is indirect land use change — the most 'resource-efficient' pathways in the present study all take account of the GHG emissions associated with ILUC. Another important concern is the question of carbon debt associated with the use of forest biomass. This issue clearly requires further investigation as it potentially negates the short and medium term GHG mitigation gains from a substantial part of the currently estimated forest bioenergy potential.

other. For example, timber may be first used in construction, then re-used for secondary wood products (e.g. transport pellets) and finally be converted to energy. Such 'cascading re-uses' would ensure a very efficient utilisation of the original resource.

- Many stakeholders are involved in the complex logistical arrangements required to bring bulky biomass sources together. Success in this area requires joint and organised action at a regional level, including local policy support and planning permission.
- Improving technology can help in collecting and processing residues efficiently. For example, the energy densities of feedstock delivered to bioenergy plants can be enhanced via prior compaction, pelletisation and other means at the point of collection.

6.3 Reflections on methodology and scope for further analysis

Developing a methodology to evaluate bioenergy's resource efficiency impacts is a complex task due to the variety and complexity of potential bioenergy pathways, the substantial range and complexity of required analytical tools, and the different spatial

scales at which impacts occur. This section reflects on methodological and analytical questions associated with the present study, moving from a review of the approach used to potential analytical developments.

Advances and limits of the analytical approach employed:

In comparison with previous EEA work this study has aimed to develop several methodological improvements:

- the methodological approach incorporated an additional spatial scale, the global level, into the analysis by integrating indirect land use change as a key factor for the total GHG balance of bioenergy pathways;
- the efficiency of different bioenergy pathways was analysed with the help of updated life cycle databases and by using different storylines to explore how changing the relative role of different bioenergy pathways influences overall GHG efficiency;
- whereas ecosystem impacts were previously addressed via assumptions regarding 'environmental constraints', the current study also employed biophysical models to analyse the

impact of land use patterns associated with the three storylines developed in the study on water, air emissions, soil erosion and biodiversity;

- the conceptual model allowed different resource efficiency aspects to be drawn together in an integrated analysis of developing bioenergy production.

While the sophistication of the analysis has advanced, there are nevertheless areas where the methodological approach could be enhanced. Areas for improvement relate to the quality of available input data and the suitability and limits of the modelling tools used.

Key input data that were found to be of limited quality or missing include time series on energy cropping trends as well as cost estimates for biomass as input to bioenergy production. The latter had to be developed on very limited published information and expert based extrapolations of cost levels to all EU regions. Better field data could improve these estimates substantially but without extra data collection it will remain challenging to make good cost estimates of biomass resources which are not (yet) traded on existing markets.

The more difficult the validation of input data, whether from statistical approaches or derived from modelling exercises, the higher the uncertainty of assessment results. The present study includes a sensitivity analysis regarding the impact of different ILUC factors but did not attempt to evaluate the potential influence of uncertainties arising from limited knowledge about yields of different energy crops in Europe or associated biomass feedstock costs at gate. Improving such basic field data is often a resource-intensive exercise but should be a priority for future updates.

Another key question that is not tackled in the present analysis is a consideration of the costs of the policy measures in the three storylines (e.g. price supports), which would obviously influence the desirability of expanding bioenergy compared to other renewable energy sources.

In addition, some analytical questions were not tackled, notably:

- quantifying how carbon debt influenced the GHG balance of the forest biomass used in the three storylines;
- comparing the GHG savings from using biomass for energy to the use of biomass as replacement

of fossil fuel inputs in other processes, e.g. as an input to the chemical industry or as a building material;

- expanding the time horizon of the study to 2030, or even beyond;
- analysing the invasive potential of some of the new energy crops.

Expanding analytical boundaries

All types of integrated analysis need to set analytical boundaries in order to be manageable, respect the limitations of input data and modelling tools, and focus on key questions. This is obviously also true of the present study.

The list below sets out a number of analytical questions and developments that could be tackled in the future.

- Utilisation of biomass in different end uses:** This study has only looked at the use of biomass for energy purposes. In this context it needs to be noted that the emerging discussion on a bio-economy — as part of the broader green economy paradigm (UNEP, 2012; EC, 2013b) — goes well beyond bioenergy. The bio-economy concept encompasses, *inter alia*, new biomaterials such as biopolymers, the re-introduction of biomass as basic material in construction and textile production, etc.
- Reflections on changing consumption patterns:** In the context of humankind's ever-increasing demand for energy and materials globally, more efficient resource use alone will not bring total demand down to sustainable levels of extraction or utilisation. Decreasing total demand via changing consumption and life style patterns therefore needs to be part of an integrated approach to resource management (EEA, 2012).
- Creating an effective policy framework:** The three storylines were developed on the assumption that appropriate economic incentives and environmental rules would exist to bring about the depicted bioenergy future. In practice, more work and analysis has to be carried out to determine which kinds of legislative and economic incentives are most effective in stimulating the development of more resource-efficient bioenergy pathways and concepts (e.g. biorefinery and cascading use).

- **Providing analytical standards for evaluating progress towards resource efficiency:**

This study has explored how to define resource-efficient bioenergy production. However, the analytical approach taken cannot necessarily be directly translated into the policy domain. Research challenges that are relevant in this context include the question whether one

can develop a composite measure of the 'total resource efficiency impact' of different potential bioenergy pathways; or whether it is feasible to determine certain thresholds or standards above which the use of bioenergy in different pathways or locations can be considered to be 'resource-efficient'.

Box 6.3 Summing up: analytical progress and remaining analytical challenges

Significant analytical progress has been achieved in this study, including the development of a methodological approach for reviewing the resource-efficiency of bioenergy production and of an integrated modelling chain from local to global level. This has enabled improvements in the analytical approach compared to previous EEA work, such as

- the integration of an ILUC factor in calculating GHG life cycle balances for bioenergy pathways;
- the improvement of logistical and technological assumptions;
- the use of a storyline approach to explore alternative futures.

In spite of these improvements some methodological shortcomings and uncertainties have to be acknowledged. These include the limited field data on biomass availability and cost levels, the uncertainty of the ILUC factor to be employed and the size of the potential carbon debt associated with the use of forest biomass. It is recommended that future research tackles the following analytical issues:

- the likely carbon debt effect associated with the use of forest biomass;
- the carbon efficiency of different biomass end uses beyond energy production;
- options for further increasing the resource efficiency of biomass utilisation, e.g. via the cascading use approach;
- the possibility of identifying absolute environmental boundaries and minimum resource efficiency thresholds;
- approaches for evaluating the effectiveness of existing and potential policy measures to improve the environmental performance of bioenergy production.

Glossary

Bioenergy: renewable energy produced from material derived from biological sources.

Biofuel: transport fuel derived from biological sources — these include wood, wood waste, agricultural crops, straw, manure, sugarcane, organic waste and by-products from food and feed production. They are often divided into first generation biofuels (based on current technology) and second generation biofuels (based on more advanced biomass conversion technologies that are mostly still under development).

Biomass: biological material derived from forestry and agriculture output and by-products as well as municipal and industrial waste streams. It includes: trees, arable crops, algae and other plants, agricultural and forest residues, effluents, sewage sludge, manure, industrial by-products and the organic fraction of municipal solid waste.

Bioenergy pathway: technical route for converting biomass to energy. These vary a lot depending on the type of primary biomass, the conversion technology used and the energy end use (for heating, power or transport).

Carbon stock: pools of carbon, i.e. the overall carbon content accumulated in ecosystems. These pools include carbon in living biomass (above and below ground), dead organic matter (e.g. deadwood and litter) and soil organic carbon.

Carbon debt: the GHG emission peak that can arise from the combustion of biomass when the replacement of the biomass through plant growth (which captures carbon) takes a long time. This is not relevant for plant material with a short life cycle but can reach 100 years and more if mature trees are harvested for energy production. During the period when the plant material regrows there will be a carbon debt arising from the original combustion of biomass.

Ecosystem resilience describes two aspects of ecosystem stability: 'engineering resilience' and 'ecological resilience'. Engineering resilience

describes the time it takes for an ecosystem to recover to a quasi-equilibrium state following a disturbance. Ecological resilience denotes the capacity of ecosystems to absorb disturbance without collapsing into a qualitatively different state that is controlled by a different set of ecological processes.

ILUC: stands for indirect land use change — this term describes the displacement of (agricultural) land use to third countries that results when (agricultural) production capacity in one country is eliminated due to the diversion of original output to other uses (such as diverting wheat or oilseed rape area from food to energy production).

NREAP: national renewable energy action plans. Article 4 of EU Directive 2009/28/EC on Renewable Energy required EU Member States to submit national renewable energy action plans by 30 June 2010. These plans provide detailed roadmaps of how each Member State expects to reach its legally binding 2020 target for the share of renewable energy in their final energy consumption.

Energy crops: plants grown with the explicit purpose of producing biofuel or other forms of bioenergy. These can be traditional agricultural crops or special crops that are cultivated for energy production only.

Perennial crops: agricultural crops that have a multi-annual growth cycle, i.e. do not need to be planted every year. Their lifetime can be a few years (e.g. some energy grasses) to several hundred years (e.g. olive trees). Perennial cropping generally reduces topsoil losses due to erosion, increases biological carbon sequestration within the soil and reduces waterway pollution from leaching of nutrients.

Payback time: the time it takes to 'pay off' the carbon debt, i.e. the time it takes for biomass to grow and absorb CO₂ so that the initial burst of GHG emissions that resulted from the combustion of the biomass is fully absorbed again in plant biomass. Achieving this balance may take decades or even

centuries in the case of forest biomass and greenhouse gases will therefore reside in the atmosphere for a long time.

SRC: stands for short rotation coppice which is plants grown under a coppicing regime — which means that they are harvested every few years rather than when they are fully grown. High yield varieties of poplar and willow, for example, are grown as an energy crop under a coppicing regime with a short-term (5–8 year) cycle.

Storyline: storylines are employed in forward-looking analysis to vary the factors that could influence the trends to be investigated. They allow the construction of alternative futures that help to understand how

different combinations of external and internal factors change future trends.

Residues: these are by-products from the harvesting of agricultural crops (annual and perennial) and from forest operations (e.g. thinning of stands or felling trees). These are normally left in the field or forest but can be employed as biomass for energy generation.

Resource efficiency: this term stands for an approach that focuses on increasing the efficiency of using natural resources and while decreasing associated environmental impacts. The approach covers production processes over their entire life cycle and has been adopted as a key policy goal in the EU 'Roadmap to a Resource Efficient Europe'.

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Annex 1 Key differences with earlier EEA studies

The storyline-based approach — involving testing the implications of different environmental and economic constraints — matches the methodology of the EEA studies during the period 2006–2008 in many respects. This report differs, however, in using insights from the most recent research and modelling to integrate new environmental aspects, such as ILUC.

Table A1.1 below provides a detailed comparison of the 2006 EEA report and this analysis. The principle differences between this report and its predecessors can be summarised as follows.

- The **time horizon** extends to 2020 rather than 2030 because the modelling results that underpin the present analysis only extend that far. This period also corresponds to the NREAP timeframe.
- The **estimates of available forest and waste biomass** match those in the 2006 and 2007 studies but reaching the NREAP bioenergy consumption targets will depend on the maximum price they are expected to command in 2020. In this respect the incorporation of forest and waste potentials also differ in the present study as compared to the 2006 EEA study.
- The **estimates of available agricultural biomass** follow the same approach but are updated on the basis of new insights on energy crops and the technology of biomass conversion pathways.
- The **environmental constraints applied to the waste and forestry potentials** match those in the previous studies.
- The **environmental constraints used to estimate agricultural potential** vary in the three different storylines, with the resource efficiency storyline being close to the 2006 and 2007 studies. ILUC-related GHG emissions also constrain the agricultural biomass available in two of the storylines. In addition, environmental impact assessments were conducted to determine the effects of direct land-use change on GHG emissions, water, air, soil and biodiversity.
- The **introduction of new EU policies** has altered the framework for analysis. The EU bioenergy policy framework and NREAP 2020 targets enable the analysis of environmentally compatible bioenergy supply to be complemented with a focus on projected demand. In addition, the EU's *Roadmap to a Resource Efficient Europe* (EC, 2011a) informed the analytical approach for determining biomass availability and the choice of optimal bioenergy conversion pathways.
- Biomass and bioenergy carriers are already traded widely across the world creating an important **global dimension to analysing impacts**. In contrast to previous work, the current study therefore includes ILUC effects in its analytical approach. Analytical studies on the importance of this effect were used to calculate an indirect land-use change factor that was integrated in the analysis of the overall greenhouse gas efficiency of bioenergy pathways built on different biomass sources and conversion technologies. The outcome of that analysis was applied to the estimated overall bioenergy potential developed for the different storylines.

Table A1.1 Comparison of the studies by EEA (2006) and ETC/SIA (2013)

Considerations	EEA 2006 study	2013 analytical approach
Reference year	2010, 2020 and 2030	2020
Policy starting point	Biomass Action Plan (EC, 2005b), Kyoto protocol (2002) and Directive 2003/30/EC on the promotion of the use of biofuels or renewable fuels for transport.	'Directive on the promotion of energies from renewable sources' (Directive 2009/28/EC) (RED) and National Renewable Energy Action Plans (NREAPs).
Scenarios	Development of one environmentally compatible future (for assumptions see environmental constraints) which applied to whole sectors rather than for bioenergy production only.	Three storylines: Storyline 1: 'Market first' Storyline 2: 'Climate focus' Storyline 3: 'Resource efficiency'
Environmental constraints for agricultural biomass	<p>At least 30 % of the agricultural land is dedicated to 'environmentally oriented farming' in 2030.</p> <p>Extensively cultivated agricultural areas are maintained.</p> <p>Approximately 3 % of the intensively cultivated land is set-aside for establishing ecological compensation areas.</p> <p>Bioenergy crops with low environmental pressure profile are used.</p>	<p>Depending on storyline:</p> <p>All agricultural residues are used (e.g. straw, manure, cuttings) available below 3 EUR/GJ or 6 EUR/GJ (depending on storyline)</p> <p>Minimum 50 % mitigation target set for biofuels in Storylines 2 and 3 including ILUC compensation. GHG mitigation balance is based on complete life cycle assessment.</p> <p>In Storyline 3 a minimum 50 % mitigation target is set for all bioenergy types (biofuels for transport use, heat and power generation)</p> <p>In Storylines 2 and 3 use of biomass is always directed towards the most GHG efficient pathway.</p> <p>In Storylines 2 and 3 no use of biodiverse land or land of high carbon stock</p> <p>Released agricultural land (between 2004 and 2020), fallow and (part of) abandoned lands can be used for dedicated bioenergy cropping provided mitigation requirements and other constraints (depending on storyline) are met.</p> <p>In Storyline 3 it is not allowed to reduce the total fallow land area of a region to less than 10 % of total arable land.</p> <p>On released and fallow land crops with lowest GHG emissions (e.g. perennials) are used in Storylines 2 and 3. In Storyline 1 the crops are chosen according to the lowest costs (EUR/GJ).</p> <p>In Storyline 3 no irrigation for dedicated bioenergy cropping is allowed.</p>
Environmental constraints for forest biomass	<p>Current protected forest areas are maintained: residue removal or complementary felling are excluded there.</p> <p>Forest residue extraction rate is adapted to local site suitability (foliage and roots are not removed at all).</p> <p>Complementary felling is restricted by increased share of protected forest areas and minimum levels of deadwood.</p>	Based on EEA (2006) forest potential estimates. But only the forest potential is used which was estimated to be available at 6 EUR/GJ and below.
Environmental constraints for waste biomass	Ambitious waste minimisation strategies are applied.	Based on EEA (2006) waste potential estimates, except for agricultural residues, which was re-calculated. It was assumed that all waste potential would be used first before imports.
Economic considerations	Technical environmental potential. Costs were only calculated in a follow-up study (EEA, 2008).	Economic environmental potential is estimated by setting maximum 'at-gate-price' paid for feedstock per storyline (3 EUR/GJ for Storyline 1 and 6 EUR/GJ for Storylines 2 and 3).

Considerations	EEA 2006 study	2013 analytical approach
Inclusion of downstream conversion pathways	Not applied. The efficiency of the full pathway was considered in estimating the overall bioenergy potential from waste. However, this was not done in a quantified way, but only based on expert knowledge and expectations on technological learning. A quantified estimate of the GHG performance (and costs) of the full pathways using the different 2006 potentials was only developed in a later post-assessment (EEA, 2008).	The most efficient feedstock-conversion pathways were chosen on the basis of a full life cycle analysis (LCA). The full LCA of the feedstock-pathway combination was also taken to calculate the minimal mitigation requirement for inclusion of the feedstock in Storylines 2 and 3.
Stimulation measures and assumptions	<p>Further reform of the CAP towards further liberalisation.</p> <p>Assumption that the right policy measures are taken to avoid potential environmental drawbacks and increase the potential environmental benefits of bioenergy production.</p> <p>Competition between food/fodder and bioenergy production would only take place on land that produces food and feed output for exports.</p>	<p>Higher carbon credit payments in Storylines 2 and 3.</p> <p>ILUC effects are accounted for in Storylines 2 and 3 for all biomass crops produced on land in competition with food/feed.</p> <p>Double counting of second generation and waste based biofuels and green gas used in public transport (only in Storylines 2 and 3).</p> <p>High support levels to technological research leading to faster introduction of second generation transport biofuels in Storylines 2 and 3.</p>
Impacts assessed	No quantified assessment of the potential impacts on environment of using the different identified biomass potentials. Only qualitative descriptions are given of the environmental risks involved when producing biomass feedstock on agricultural land.	Model-based impact assessments are used to estimate the implications for water quality and quantity, soil quality, biodiversity, GHG emissions and mitigation potential of the use of the biomass potentials in the three storyline situations.

Annex 2 Overview of main storyline assumptions

Cost thresholds feedstock	Energy conversion routes and economies of scale	No-go areas	GHG mitigation efficiency and ILUC consideration	Double counting for renewable energy target	Other environmental considerations
1. Market first					
3 EUR/GJ feedstock costs for heat & electricity	Mostly large and medium scale installations	No	No	No	No
Biofuels; CAPRI baseline scenario run in Agricultural Outlook 2020	Minimum thresholds in feedstock availability for second generation conversion plants				No use of abandoned lands (too little stimulation)
2. Climate focus					
6 EUR/GJ feedstock costs for heat and electricity	Large, medium and small scale	HNV farmland/ Natura 2000/ permanent grassland areas, except for use of cuttings	Prioritise most GHG efficient pathways	All waste categories and second generation technologies, based on woody materials	Use of (part of) grassland cuttings
	More decentral plants	Peatlands (histosols) and forests (but overlap with HNV farmland)	Avoid biofuel production with heavy indirect land use change impacts	Biogas used in public transport	Stimulation of use of abandoned farmlands provided GHG target is met and appropriate management is used
	More technology research support for bioenergy leading to faster introduction of second generation biofuels and more efficient bioenergy conversion routes		Minimum 50 % greenhouse gas mitigation as compared to fossil fuels for biofuels only		
3. Resource efficiency					
6 EUR/GJ feedstock costs for heat and electricity	Large, medium and small scale	HNV farmland/ Natura 2000/ permanent grassland areas (except for use of cuttings)	Prioritise toward most GHG efficient pathways	All waste categories and second generation technologies based on woody materials	Use of (part of) grassland cuttings
	More decentral plants	Peatlands (histosols) and forests (but overlap with HNV farmland)	Avoid bioenergy production with heavy indirect land-use change impacts	Biogas used in public transport	Stimulation of use of abandoned farmland provided greenhouse-gas target is met and appropriate management is used
	More technology research support for bioenergy leading to faster introduction of second generation biofuels and more efficient bioenergy conversion routes	Not allowed to reduce fallow area to less than 10 % of arable land	Minimum 50 % greenhouse gas mitigation as compared to fossil fuels for all bioenergy (biofuels, liquids, solids and gaseous)		No irrigation for bioenergy crops

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