BEYOND THE BIOFRONTIER: BALANCING COMPETING USES FOR THE BIOMASS RESOURCE

Nikita Pavlenko, Sammy El Takriti, Chris Malins, Stephanie Searle

icct
THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

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International Council on Clean Transportation
1225 I Street NW Suite 900
Washington, DC 20005 USA

communications@theicct.org | www.theicct.org | @TheICCT

PREFACE BY THE EUROPEAN CLIMATE FOUNDATION

In December 2015, world leaders agreed a new deal for tackling the risks of climate change. Countries will now need to develop strategies for meeting their commitments under the Paris Agreement, largely via efforts to limit deforestation and to reduce the carbon intensity of their economies. In Europe, these climate protection strategies will be developed via the EU's 2030 climate and energy framework, with a view to ensuring an integrated single market for emissions reduction technologies.

Existing EU energy policy for 2020 foresees an important role for bioenergy as a means of reducing carbon emissions from heating, power, and transport, and yet there are concerns that this has led to a number of negative consequences related to the intensification of resource use. If bioenergy is to continue to play a role in EU energy strategies for 2030, it seems wise to learn from the past to ensure that this is done in a manner that is consistent with the EU's environmental goals, including the objective of limiting temperature rise to no more than 2 degrees C.

With this in mind, the European Climate Foundation has convened the BioFrontiers platform, bringing together stakeholders from industry and civil society to explore the conditions and boundaries under which supply chains for advanced biofuels for transport might be developed in a sustainable manner. This builds on work developed in the ECF's Wasted platform in 2013-2014, which focused on waste- and residue-based feedstocks for advanced biofuels. This time around, there is an additional focus on considering land-using feedstocks and novel fuel technologies.

As the name BioFrontiers suggests, this discussion enters new territory and is faced with numerous gaps in knowledge. To facilitate a transparent and constructive debate between industry and civil society, the ECF has commissioned a number of studies to help fill such knowledge gaps. This is one such study. It does not represent the views of the members of the BioFrontiers platform, merely an input to their discussions. If this research also helps inform the wider debate on the sustainability of bioenergy, that is a bonus. I would like to thank the ICCT for using the resources provided by the ECF to improve our understanding of these important issues.

Pete Harrison

Programme Director, Transport

European Climate Foundation

EXECUTIVE SUMMARY

Recent studies have shown that utilizing sustainably available biomass to replace fossil fuels is a promising method to mitigate climate change, but biomass is (and will remain) a limited resource. The sustainable availability of residual and waste material is limited by the overall amount produced and the role of much of this material in existing markets and to support ecosystem services, while the production of biomass from energy cropping will be limited by competition for land resources. As Europe seeks to reduce its carbon emissions in the coming years, biomass is likely to be in high demand for a variety of uses. In addition to the various existing uses for biomass in agriculture and elsewhere, there is growing demand for biomass to convert into liquid fuels, to combust directly for energy, or as feedstock for industrial production of biomaterials and biochemicals.

With a limited stock of sustainably available biomass and a variety of competing uses, policymakers will be expected to make decisions about how and whether to prioritize some biomass uses over others. In making these decisions, it is vital that policymakers should identify utilization pathways that offer the greatest environmental and societal benefits and minimize risks. Some previous studies have noted that greater carbon savings can be achieved by using biomass to replace centralized coal power instead of transport fuels. However, estimating the benefits of using biomass for energy is extremely sensitive to assumptions about precisely which fossil alternatives may be displaced. More generally, characterizing each biomass conversion pathway through the lens of one analytical metric alone—such as near-term greenhouse gas (GHG) savings—fails to take into account a multitude of other factors, such as comparative economics of different conversion processes, the role of short-term technology development in meeting long-term climate goals, and any secondary, non-GHG environmental impacts of biomass use.

We assess the implications of three potential competing use categories: liquid fuels, combustion of biomass for heat and power, and the production of biomaterials (and in particular biochemicals). Each of these three competing uses could, in principle, grow to use all the sustainably available biomass in Europe in the long term. We consider optimal end uses for biomass resources in Europe by assessing only the *downstream* impacts of using sustainably available biomass. The purpose of this analytical choice is to identify the optimal use for biomass rather than to compare the performance of individual feedstocks. It is therefore assumed within this report that the biomass that is available will be sustainable. In practice, sustainability is not automatic, and therefore delivering the benefits outlined in this report is predicated on the implementation of effective systems to ensure the sustainability of the European biomass supply. Approaches to guarantee the sustainability of European biomass are discussed in more detail in a companion report within the Biofrontiers project by Allen et al. (2016).

Based on this report's findings, we draw the following conclusions for each impact category we assess:

> **Greenhouse Gas Impact:** Our life-cycle assessment shows that no conversion pathway has a decided advantage over the other, as shown in Figure A. There are lower energy inputs associated with preparing biomass for combustion relative to conversion into liquid fuels, and if bioenergy were to displace current grid-average electricity, then this would deliver a marginally (10% on average) greater carbon saving than displacing petroleum. In contrast to bioenergy, the production of biomaterials is in a relatively new stage of commercialization, and our literature review indicated a wide range of results

depending on the exact product produced and fossil-derived material displaced. On average, biochemicals generated roughly the same GHG reductions as the heat and power pathways. However, the differences between specific biochemicals within the chemicals sector exceeded the magnitude of the average GHG reduction, indicating that the sector's GHG mitigation potential was highly variable and uncertain.

The benefits of biomass use for heat and power are highly sensitive to assumptions about the mix of electricity that will be displaced by increased bioenergy generation. Assuming that coal power would be preferentially displaced would make heat and power appear to be the most attractive use for biomass, but in reality it is likely that increased bioenergy capacity will displace a mix of energy sources. However, if the marginal electricity production displaced by the increased supply of biomass electricity becomes less coal-intensive over time, liquid biofuels will start to deliver a greater level of GHG reductions per tonne of feedstock used.

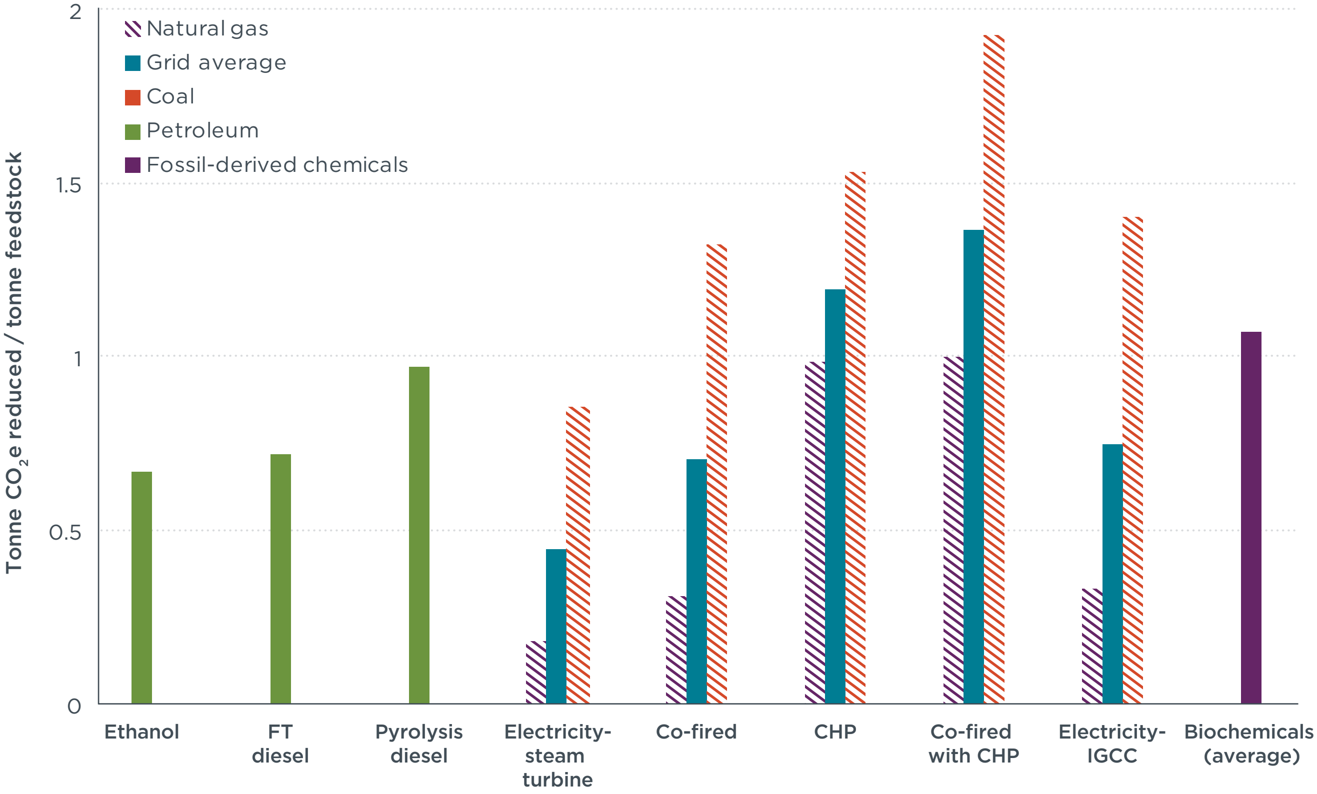

Figure A. GHG Reductions From Fossil Fuel Displacement Across Biomass Energy Conversion Pathways

» **Non-GHG Environmental Impact:** Both biomass for heat and power and liquid biofuels offer opportunities to reduce the emissions of some air pollutants relative to the combustion of fossil fuels, though as with carbon emissions, the benefits are very sensitive to what system is replaced, as shown in Figure B. The environmental benefits are particularly pronounced in cases where coal is displaced, with benefits decreasing if gas and/or renewable energy sources are partly displaced instead. Overall, though, the value of the air pollution reductions from replacing fossil fuels with biomass is on a smaller scale than the climate benefit deliverable. As bio-based materials are not combusted as part of their use, their air emissions are comparable to the materials they displace and lower than for bioenergy pathways.

One opportunity associated with biomass energy is the use of combustion residues and processing by-products to restore nutrients to soils. Similarly, advanced liquid fuels pathways that produce either biochar or lignin as a co-product can direct the material to soil remediation in lieu of energy recovery. This type of nutrient recycling would allow some of the benefits normally associated with anaerobic digestion or composting to still be delivered when biomass is used for energy generation. Some bio-plastics, such as polylactic acid (PLA) or polyhydroxybutyrate (PHB), can be composted instead of landfilled in order to restore nutrients, whereas others are more similar to petroleum-derived plastics and must be landfilled or incinerated at end of life.

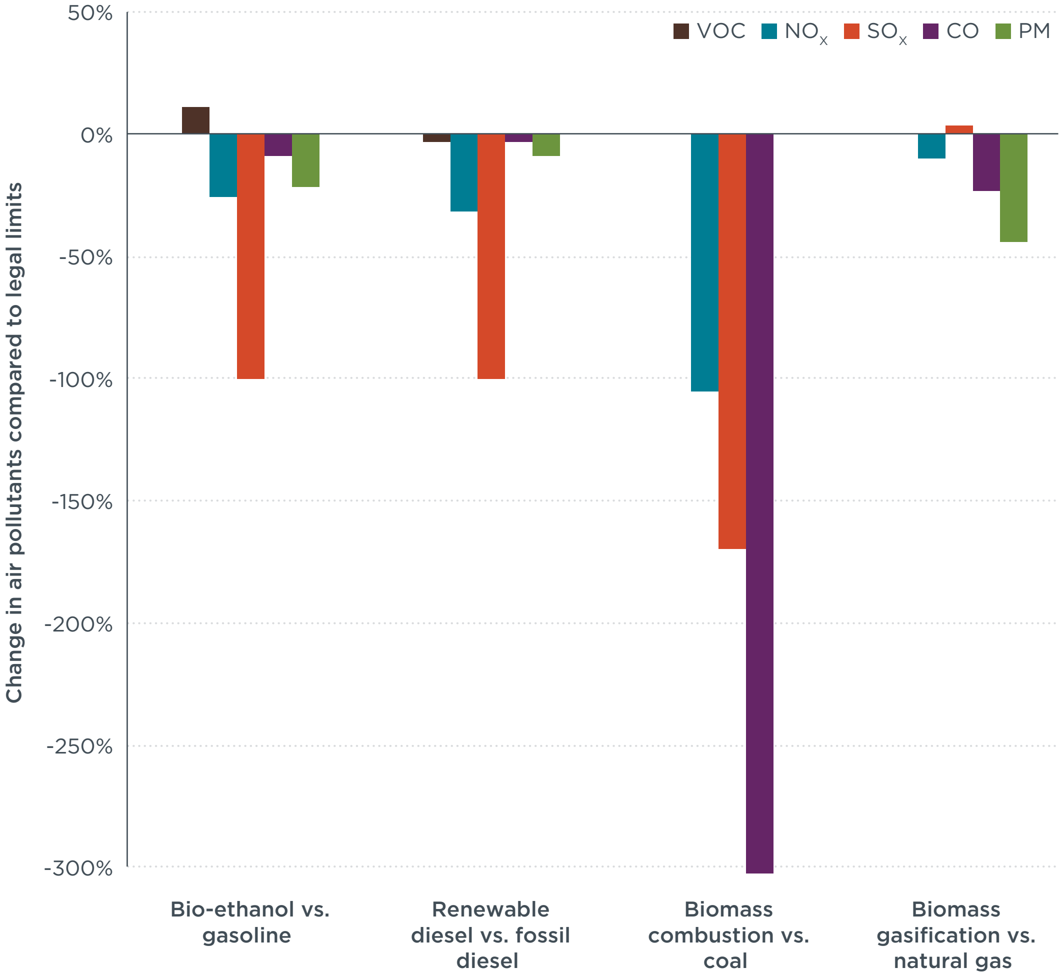

Figure B. Comparison of Air Pollutant Emissions Reductions for Biomass Energy Conversion Pathways

- **Economic Impact:** The largest contribution of the biomass sector to employment is expected to be in feedstock collection and cultivation, jobs that will be created regardless of biomass end use. Nevertheless, biomass use for either energy or materials will support a large number of jobs, both temporary work in construction and a smaller number of permanent positions in operations. There is considerable range in the literature in estimates of the numbers of jobs that any given biomass use pathway will generate, but generally it is fair to conclude that more complex processes such as manufacturing biomaterials or liquid fuels are more labor-intensive than combustion for heat and power.

In terms of import displacement and the financial value of the material produced, liquid biofuels offered superior performance than other energy applications because they displace oil imports. Figure C illustrates the import displacement impact of different products (based on 2020 futures prices), showing that the EU's high reliance on imported petroleum yields the largest benefit to import displacement from bioenergy. Utilizing biomass resources in higher-value markets such as transport fuels and chemicals, rather than heat, power, or compost, may also be able to support higher feedstock prices and thus higher rates of sustainable biomass use. However, this will also be dependent on other costs associated with each process.

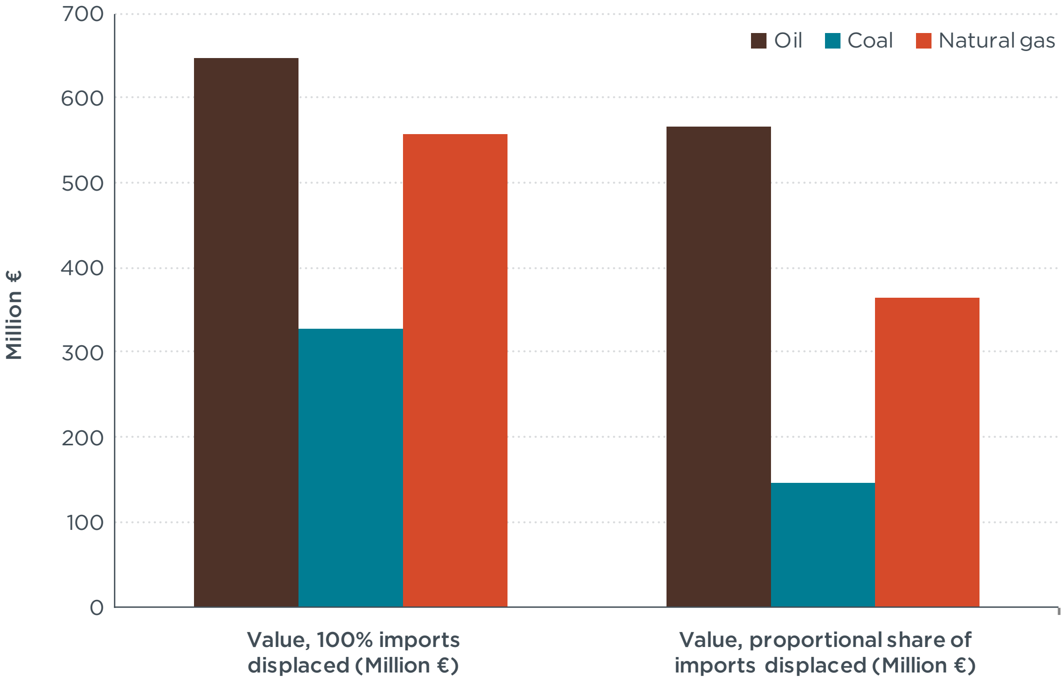

Figure C. Import Displacement Impacts for Fossil Fuels

- **Long-Term Decarbonizaton:** Looking forward to 2050, we find that despite the expected development and market penetration of other low-carbon technologies, it is highly likely that fossil energy will remain in demand for both heat and power and liquid fuels through to 2050. Therefore, the amount of fossil fuels still to be displaced in 2050 will likely exceed the amount of sustainably available biomass in Europe. Even in aggressive policy scenarios for biomass use in 2050, most projections predict a substantial amount of residual fossil fuel use.

  There are niches in both the 2050 transport energy and heat and power mix where biomass could deliver added value. In transport, biofuels could have a particular role in allowing deeper decarbonization of modes that are likely to remain reliant on liquid fuels in the longer term, notably aviation but also shipping and heavy-duty transport. In heat and power, the expansion of intermittent renewables will be associated with demand for low-carbon baseload power, with centralized biomass combustion facilities being one baseload option.

> Compared with energy applications, the manufacture of bio-based materials such as biopolymers is still in relatively early stages of commercialization. The biochemical sector is changing quickly, but the technological feasibility of a wide variety of biologically derived replacements for conventional chemicals has been demonstrated. Furthermore, bioproducts may be combusted at end of life in order to recover energy. As the technology matures, biopolymers could take a growing share of the global plastics market as soon as the economic feasibility catches up with technological progress, and other biomaterials could take an important role in applications such as construction material.

Overall, there are potential advantages to each of the three utilization options for biomass resources, but there is not such a clear advantage that policy should be structured to support one solution to the exclusion of the others. In the short term, biomass for heat and power may deliver the largest carbon benefit if it displaces coal directly, but this relationship may not hold true in the longer term as other options for low-carbon power generation emerge. In contrast, there are fewer competing energy sources in the transportation sector, and it will be difficult even in 2050 to completely replace petroleum in transport without low-carbon liquid fuels. Still, depending on the development of storage options for electricity, there may be additional value for baseload biomass power generation as a complement to intermittent renewables.

In economic terms, liquid biofuels represent a higher-value market and offer the potential for a higher value of import displacement than can be achieved by displacing coal and gas imports. Liquid biofuels will also require more investment and production complexity, and thus support a higher number of jobs than centralized combustion. On the other hand, the high investment required to deploy the advanced biofuel industry is a limiting factor on the rate of commercialization, and especially in the short term there is more than enough biomass in principle to support heat and power generation in parallel to a developing advanced biofuel industry.

In producing this report, it has been constantly challenging to find a sufficient amount of data on biomaterials options that is comparable to that available on energy applications, in order to allow a fair comparison and evaluation. We have not found compelling evidence that biomaterials use offers any fundamental environmental advantage over energy applications, and indeed in most case we expect that energy applications will have a comparable carbon benefit as displacement of materials. Still, biomaterials is a much more diverse space than bioenergy, and it is likely that specific cases will be found that offer enhanced benefits and are therefore proportionately more worthy of governmental support. In some cases, the same technologies that need to be developed to produce liquid biofuels will be instrumental in making new biomaterials applications possible, and there is the potential for a virtuous complementarity in which biofuel markets offer potential for volume of sales and biomaterial co-products offer increased revenues which together can push deployment faster than would be possible for either market on its own.

For the foreseeable future, encouraging the broader use of biomass that meets sustainability criteria without singling out a particular pathway can lead to the expansion and development of sustainable biomass supply chains that will in turn improve the viability of all three options. At some point in the future, choices may be necessary at the policy level about how sustainably available biomass resources should best be used. However, given the many uncertainties involved in the evolution of the European energy supply, attempts to preempt that future decision point should not be given excessive weight when shaping near-term policy.

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1. INTRODUCTION

In order to avoid the most dangerous effects of climate change, scientists and policymakers have recommended that global surface temperature rise must be capped at 2° Celsius over pre-industrial levels—necessitating an 80% decrease in greenhouse gas (GHG) emissions worldwide by 2050 relative to 1990 levels. Biomass resources could play a key role in reducing Europe's contributions to global climate change. A growing body of evidence suggests the strong GHG-reduction potential of biomass technologies that can harness Europe's unused agricultural residues and waste in order to displace fossil fuels. However, the availability of biomass and the competition between its different uses (food, bio-based materials, and bioenergy) are major concerns for the development of a bio-based economy.[1] Looking beyond 2020, the future of the European Union's climate policies is in flux, and the exact role of biomass in Europe's energy sector continues to be debated. The purpose of this report is to develop a robust, multi-factor analysis of the impacts of using biomass for different competing uses in order to inform the policy discussion on how the EU should prioritize biomass use in its forthcoming climate policies.

The degree to which the existing fossil fuel-based economy can be replaced by a bio-based economy will certainly be constrained by the overall limited availability of sustainable biomass in the EU (Scarlat et al., 2015). Biomass is a renewable but limited resource. For instance, not all wastes and residues are considered sustainably available, but only those that can be recovered without undue impact on other uses or unacceptable environmental damage (e.g., soil carbon loss with high crop or forestry residue removal). The total sustainably available cellulosic biomass in the EU was estimated to be about 156 million tonnes per year, with the majority coming from crop residues (see Table 1.1) (Searle and Malins, submitted). European waste streams can generate significant amounts of low-carbon energy—as much as 1,536 petajoules (PJ) of liquid fuel or 382 terawatt-hours (TWh) of electricity in 2030—without significant indirect effects on the market (Harrison et al., 2014). This is the equivalent of approximately 36 million tonnes of oil. Sustainably available biomass from other sources such as energy crops could further contribute to meeting the EU's decarbonization targets over the coming decades.

Table 1.1. Extant and future (2030) sustainable availability of wastes and residues in the EU.

Category	Current availability (Mtonnes/yr)	2030 availability (Mtonnes/yr)
Waste	64	25
Crop residues	83	115
Forestry residues	9	5
Sum	**156**	**145**

Source: Searle and Malins (2016)

Note: The numbers in the above chart are updated from the original Wasted report and reflect ongoing development of the methodology

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[1] As defined by the OECD (2013), the bio-based economy (or bioeconomy) is a policy concept that "links advances in biotechnology to innovation and 'green growth' via the use of renewable biological resources and innovative bioprocesses in industrial scale biotechnologies, firstly to produce sustainable products, jobs and income, and secondly to address global challenges such as climate change."

This report compares three “pathways”: heat and power, liquid fuels, and bio-based materials. These three alternatives were selected because the potential resource demand in those sectors in the long term (2050 and beyond) could outstrip the amount of sustainably available biomass in Europe. The diversion of biomass to any one of these uses is unlikely to saturate that sector. It is therefore inevitable that if there is aggressive growth in any one of these biomass uses, it will start to compete with other uses. In contrast, alternative uses of biomass such as composting, animal bedding, and anaerobic digestion are considered not to represent such large potential markets as the three chosen categories and would be more easily saturated. Near-term policy decisions to divert biomass to either heat and power, liquid fuels, or bio-based materials would be diverting biomass to a sector that has substantial room for growth.

Many analyses of biomass conversion pathways look at a given impact independently, such as life-cycle GHG emissions, and fail to contextualize it to other impacts or see how it varies between pathways. In that example, a simple accounting of carbon savings does not identify the extent to which biomass resources displace other materials, the comparative economics of competing technologies, or the relationship between short-term technology development and long-term policy goals. A carbon intensity analysis can also be highly sensitive to assumptions about the energy systems being replaced. This report takes a more holistic approach, expanding on existing research and combining a comparative assessment of GHG emissions with similar analysis of other factors, such as economic performance and emissions of non-GHG pollutants into the environment. The primary functional unit in this report is a tonne of feedstock material—where possible, the results of the analysis are normalized by the amount of feedstock input into a given process. The purpose of using these units is to allow policymakers and others to compare outcomes between competing uses for a given quantity of available feedstock. Other units commonly used in the literature, such as carbon intensity in grams of carbon dioxide per megajoule of energy delivered (gCO_2e/MJ), or calculated percentage emissions savings, may be misleading when used for such a comparison.

To address these varied factors associated with biomass use, this study assesses one key factor in each chapter. The structure of the chapters is as follows:

- **Greenhouse gas (GHG) impacts:** The collection, processing and use of biomass resources generates GHG emissions as well as offsets associated with the displacement of fossil fuels and use of co-products. This report uses a life-cycle assessment (LCA) model in conjunction with a literature review to compare the life-cycle GHG emissions from each of the three pathways relative to one another, as well as to the fossil fuel-derived products that could be displaced by biomass. The results are normalized into units of *net* CO_2–equivalent emissions per tonne of feedstock input into a pathway—in order to provide a consistent basis of comparison across the various competing uses of biomass.
- **Economic impacts:** Each competing use for biomass has its own set of capital and operational expenditures, ability to add value to biomass resources, as well as other considerations that may impact its feasibility within the European market. This component of the analysis includes several different metrics, including economic size of sectors, employment generation, production cost, and import displacement.
- **Non-GHG environmental impacts:** Biomass utilization can release non-GHG pollutants to air, water and soils, depending on the conversion method and use chosen. This analysis compares these emissions among pathways, as well as to the

fossil fuel-derived materials that they would replace. Furthermore, this analysis evaluates the tradeoffs associated with diverting biomass from other alternative uses such as composting and anaerobic digestion.

- **Role in long-term decarbonization:** The value of developing biomass conversion technologies goes beyond their present-day contributions to reducing GHG emissions, as they must also play a role in Europe's deep decarbonization goals in the long term. Technological change and policy uncertainty pose the risk of making near-term decisions about a given conversion pathway less beneficial in the long run. This component of the analysis reviews a variety of long-term projections of energy demand and technological change to determine the structure of European energy demand in 2050 and the most likely roles needed for biomass.

1.1. COMPETING USES OF BIOMASS

This study considers three large categories for biomass use, though within each category there are a wide variety of technologies and uses that play an important role in determining the impact for that conversion pathway. The following section defines each competing use and provides a brief overview of the available technologies and level of commercialization within that sector.

1.1.1. Heat and Power

The heat and power category refers to the combustion of biomass to energy at centralized combustion facilities to generate some mix of heating and electricity. The 2020 Climate and Energy Package, which mandates a 20% reduction in EU GHG emissions (from 1990 levels) and a 20% share of EU energy production from renewables, has encouraged the use of biomass in the heat and power sector.

The heat and power sector in Europe uses biomass either for direct combustion or indirectly through the combustion of gas derived from biomass (syngas). This sector includes a variety of centralized combustion technologies, including direct combustion of biomass in a boiler, co-firing of biomass with coal, combustion with heat recovery (combined heat and power, or CHP) and biomass-based integrated gasification combined-cycle (IGCC). There is significant variation in the degree of commercialization and adoption of these technologies. Biogas generation from anaerobic digestion is considered outside the scope of this study, as it is primarily used for waste management rather than energy production. Low-efficiency domestic heating with biomass is excluded from the analysis, as it is small-scale and decentralized.

To date, heat and power from biomass has supplied the majority of renewable energy in the EU and is expected to grow in order to meet the EU's 20% target (EC, 2014a). EU bioenergy demand in 2012 reached 99 million tons of energy equivalent (Mtoe)—approximately 8.7% of total energy consumption. The majority of this energy—74.9 Mtoe—went to heat and cooling, of which the majority was consumed by low-efficiency residential combustion.[2] Biomass contributed 11 Mtoe to EU electricity generation—similar to the amount of biomass combustion by industrial heating units. The EU relies mostly on wood pellets for biomass-generated heat and power, though in the future it could make greater use of other types of biomass, such as wastes, residues and energy crops. National Renewable Energy Action Plans (NREAPs) for various EU nations anticipate that increased collection of waste materials, crop residues, and sustainably harvested woody biomass

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[2] This figure excludes electricity used to generate heating and cooling

will be necessary to meet renewable energy targets. For example, Germany's National Biomass Action Plan (highlighted within the its 2012 NREAP) outlines a large role for renewable biomass in the heat and power sector—new buildings are obligated to source a portion of their heat from renewable sources, and electricity from CHP plants now receives a bonus grid-feed payment over other sources (BMEL, 2009).

1.1.2. Liquid Biofuels

The liquid biofuels sector in this analysis refers to transport fuels made from biomass that can partially displace the use of petroleum-derived gasoline and diesel fuels. Over the past decade, biofuel use in the EU has expanded in response to policies such as the Renewable Energy Directive (RED), which mandates a minimum share of renewable energy consumption within the transportation sector, and the Fuel Quality Directive (FQD), which encourages suppliers to incorporate biofuels into the fuel mix. In order to be counted towards meeting the targets in either of these directives, biofuels from new facilities must be assessed as providing life-cycle GHG savings of 60% relative to fossil fuels, while biofuels from older facilities must deliver a 35% emissions reduction at the moment, and 50% from 2018.

In 2012, the EU produced 4.8 billion liters of fuel ethanol, primarily from wheat, corn, and sugar beets, while capacity has quadrupled from 2006 to 2012 (USDA, 2013). The EU blend rate of ethanol (the ethanol content in an average liter of gasoline) reached 3.4% in 2012 (USDA, 2013). Biodiesel is even more prevalent in the European market, with production of 10.5 billion liters in 2012 and a blend rate of 5.9%.

In order to convert biomass into a liquid fuel, either thermochemical or biochemical processes are used to either break down the biomass into hydrocarbons, fats for esterification, or into sugars for fermentation. "First generation" biofuels, which account for the majority of the bio-ethanol and biodiesel production above, generally include those made from food crops (e.g., wheat) or oil seeds (e.g., soy) using established technology. First-generation fuel production processes have already been commercialized—this includes fuels ethanol made from maize or soy biodiesel.

For the biomass resources relevant to this report, second-generation fuel production processes offer the potential for conversion to liquid fuels as an alternative to heat and power. There is no single accepted definition of "second-generation" or "advanced" biofuels. Within this report, we consider biofuels made from potentially sustainable feedstocks such as agricultural residues, forest residues, waste, or energy crops. Where there are data gaps on the use of sustainably available feedstocks for a given technology, we supplement the data with results from first-generation feedstocks. Generally, second-generation biofuels require more complex technologies to convert sustainably available feedstocks into viable fuels, due to the cellulosic or lignocellulosic content of the material. However, use of these feedstocks can offer greater environmental benefits than many first-generation feedstocks, while having fewer impacts in other sectors. Therefore, the majority of the data and literature assessed in this study characterizes second-generation conversion technologies. Where first-generation technologies are discussed, it is in an illustrative sense where existing data on advanced conversion technologies is insufficient or unavailable. Production of biofuels from cellulosic material has been limited to date, but the first generation of facilities has now started to come online.

1.1.3. Bio-Based Materials

Bio-based materials include a wide variety of materials that can or could be derived from biomass feedstocks, and that offer similar performance to existing non-biomass products. While the scope of bio-based materials is broad, this analysis focuses on biochemicals and biopolymers because they are currently relatively well-documented production pathways and provide a similar scope of analysis to bioenergy pathways. Examples of materials covered in our analysis include polylactic acid (PLA) and bio-ethylene. A wide variety of other materials would fall within our scope of analysis, but are not sufficiently characterized within the literature to warrant inclusion. Woody biomass used directly for building materials or finished goods (e.g., furniture, paper) was not included.[3] Bio-based materials are a young technology and have thus far achieved limited commercialization and small-scale production for research or corporate social responsibility (CSR) purposes. As a result, the EU does not have the same level of policy guidance for bio-based materials as for bioenergy. The European Commission's Bioeconomy Strategy and Action Plan lays out general recommendations for the expansion of the bio-based products sector, including green procurement, financial support for conversion facilities, and development of consistent product standards (EC 2012).

Bio-based chemicals, also called renewable chemicals, can be produced from sugar and starchy feedstocks. Cellulosic feedstocks (agricultural, forestry residues, or municipal solid waste) offer an alternative feedstock to sugars and starchy biomass, but require additional treatments such as hydrolysis, gasification, or pyrolysis in order to produce intermediate chemicals that can be converted into end-use chemicals or materials (see Figure 1.1) (Nexant, 2014b).

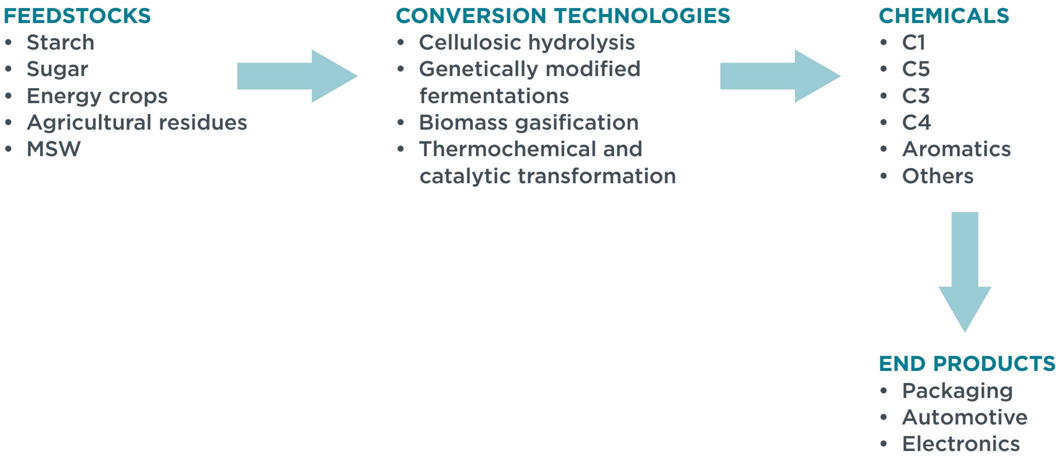

Figure 1.1. Bio-based chemicals value chain

Source: Nexant (2014b)

A potentially significant bio-based product is bio-ethylene, which is chemically equivalent to petroleum-derived ethylene (i.e., it is a "drop-in"). Petroleum-derived ethylene accounts for slightly less than half of global chemical trade volumes and is the

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[3] Saw timber, which is used for building materials, is not economically viable as an energy source due to the higher value markets available. In any case, use of good quality saw timber for energy would not deliver an acceptable level of GHG reductions (cf. Baral and Malins, 2013), and we would therefore look to avoid direct competition between timber and energy markets. The extraction and processing of roundwood to manufacture finished products generates significant amounts of sawdust and other residue materials that are suitable for bioenergy; therefore these materials can be understood as more of a complementary use to bioenergy than a competing one. The market for paper is not considered to have the same type of growth potential as that of novel biomaterials.

most vital raw material in the downstream plastics industry (Euler Hermes, 2013). The production of ethylene from ethanol is an alternative to the more common production of ethylene via steam cracking of naphtha from crude oil (mostly in Europe and Asia), or via steam cracking of ethane and, to a lesser extent, propane and butane (from natural gas and from crude oil) in the Middle East and North America (see Figure 1.2) (IEA-ETSAP and IRENA, 2013). A bio-ethanol-based refinery can further serve as the basis for conventional products such as ethylene, EO (ethylene oxide) or MEG (monoethylene glycol)—or it can be used as a link for many other industrially important derivative products (Schneider et al. 2014). Figure 1.3 depicts the range of products that can be derived from bio-ethanol.

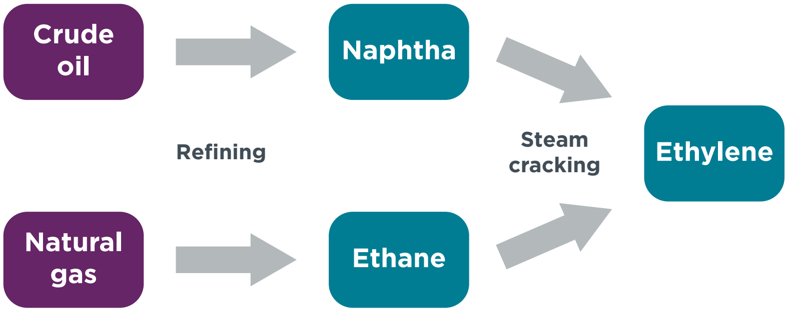
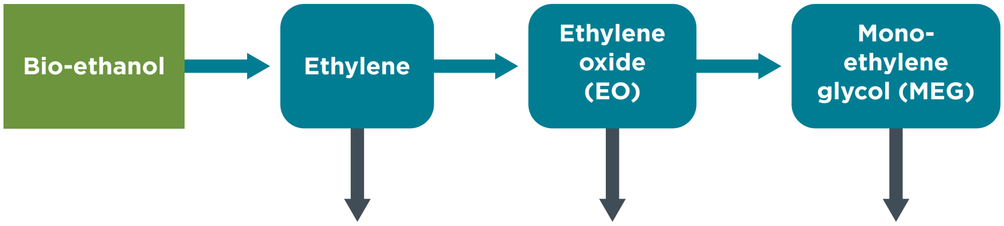


Figure 1.2. Production of ethylene from fossil fuels

Source: Adapted from Euler Hermes (2013)



- High-density Polythylene (HDPE)
- Low-density Polythylene (LDPE)
- PVC
- Vinyl acetate (adhesives, coatings)
- Styrene (plastics, bio-rubber)

- Ethocylates (textile industry)
- Polyglycols (cosmetics industry)
- Ethanol amine (pharmaceuticals, detergents)

- Polyester fibers
- PET (plastic bottles)
- Coolant
- Solvent for paints and inks
- Byproduct: DEG and TEG

Figure 1.3. Integrated bio-refinery for the production of ethylene and derivatives

Source: Adapted from Nexant (2014b) and G.I. Dynamics (2015a)

Some biochemicals, such as the bio-ethylene described above, can be converted to plastics. These bioplastics can be divided into three main groups (European Bioplastics 2015b):

- » Bio-based or partly bio-based non-biodegradable plastics such as PE (polyethylene), PP (polypropylene), or PET (polyethylene terephthalate). For example, biobased PET, produced from sugarcane, is the same as that derived from fossil sources and can be recycled in the same processes (BIO-TIC, 2015).
- » Bio-based and biodegradable plastics, such as PLA (polylactic acid) and PHA (polyhydroxyalkanoate).

- Fossil-based and biodegradable plastics, such as PBAT (polybutyrate adipate terephthalate).

The global production capacity of bioplastics was estimated at 1.62 million tonnes in 2013 (see Figure 1.4) (European Bioplastics 2013). Drop-in bioplastics (PET and PE), which are chemically identical to their fossil fuel counterparts, represent the largest share of the production and are mostly used in packaging applications. Without accounting for biomass availability, bioplastics have the technical characteristics to displace 90% of petrochemical plastics (Shen et al., 2010).

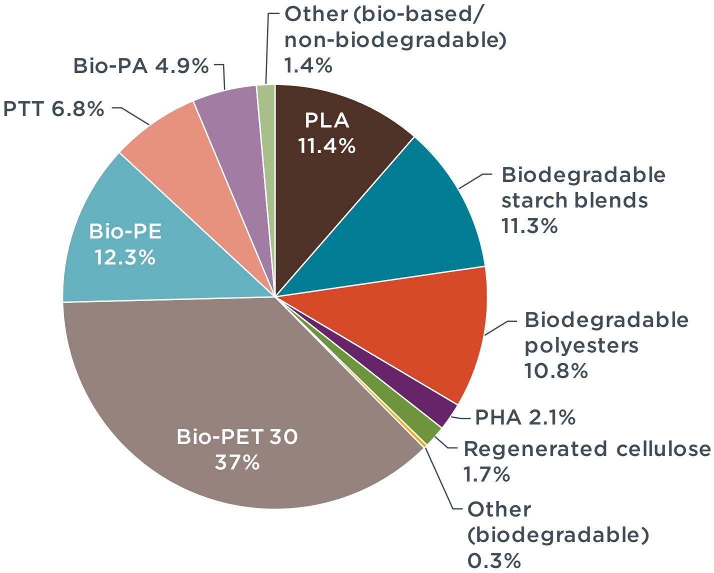


Figure 1.4. Global production capacities of bioplastics 2013 (by material).

Source: European Bioplastics (2013)

2. GHG IMPACTS FROM COMPETING USES OF BIOMASS

2.1. INTRODUCTION

A growing body of evidence indicates the strong GHG reduction potential of biomass conversion technologies that can harness Europe's stream of unused agricultural residues and waste. Biomass heat and power, liquid biofuels, and bio-based materials can be used to displace carbon-intensive materials, thus reducing Europe's GHG emissions. Sustainably available biomass can generate significant amounts of low-carbon energy—wastes and residues alone can contribute as much as 225 million tonnes of sustainably available biomass in 2030 (Harrison et al., 2014). Those wastes and residues alone could provide as much as 382 TWh of electricity, 36.7 Mtoe of liquid fuel, or 31.3 million tons of bio-ethylene.[4]

In many applications, there is significant potential for the use of biomass instead of fossil resources to provide GHG reductions. The limited stock of sustainably available biomass means that in future there will need to be tradeoffs as different pathways compete for the available material. This chapter compares the potential to achieve carbon reductions through use of biomass to produce heat and power, liquid fuels, or biomaterials.
To compare the energy pathways, we characterize a set of eight liquid biofuel and biomass-to-energy conversion pathways used for 11 different feedstocks. We quantify their energy intensity and GHG reduction values via a life-cycle assessment (LCA) model. The LCA approach normalizes energy use and GHG reduction results between feedstocks and pathways in order to facilitate a comparison between competing uses of biomass. To compare the biomass-to-energy pathways to alternative biomass pathways for biomaterial production, which fall outside the scope of the LCA model, this chapter incorporates a literature review that summarizes the life-cycle GHG emissions the manufacture of several bio-based materials. In addition to the three primary competing uses considered in the report, we also review reported carbon savings available for composting and anaerobic digestion. Calculating how much carbon can be saved requires the establishment of counterfactuals, so this chapter also considers which processes and energy sources may be displaced by increased biomass use.

Using the outputs from the LCA model and the literature review, we determine which conversion pathways offer the greatest GHG reductions and returns on energy per ton of feedstock used. Normalizing the results in terms of emissions reductions per tonne of feedstock input into the process allows us to consistently assess the difference between the upstream emissions associated with the processing of biomass and the emissions associated with the materials it displaces.

2.2. GOAL AND SCOPE

2.2.1. Overall Scope

The purpose of this chapter is to determine the greatest emissions reductions potential for a variety of biomass conversion pathways on a quantitative basis. Emissions savings are calculated by taking the net emissions from each pathway—heat and power, liquid fuels, or manufacturing of bio-based materials—and comparing them with the baseline

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[4] These figures assume an average biomass energy density of 17.5 MJ per dry kilogram (kg), an electricity generation efficiency of 35 percent, and a conversion efficiency from ethanol to ethylene of 1.8 tonnes per 1 tonne of ethylene.

emissions from the materials that each biomass conversion pathway displaces. While the choice of biomass feedstock has an important role in determining the net emissions for a given pathway, this chapter focuses on comparing conversion processes, not feedstocks. For the two bioenergy pathways, carbon savings are estimated for the use of sustainably available wastes and residues, which are assumed to have low upstream emissions associated with them. Estimates of conversion emissions for biomass wastes and residues are applicable and illustrative for the use of energy crops, provided that the upstream production emissions for those crops do not substantially exceed those from conversion and distribution.

This chapter assesses non-energy pathways via a literature review that focused on life-cycle assessments of composting, anaerobic digestion, and the production of bio-based materials. For composting and anaerobic digestion, this chapter incorporates results from a literature review, normalizing them per tonne of feedstock input into the process. For those two pathways, we focused on the use of green waste (i.e., biomass, not food waste or manure) and assumed that they did not displace fossil fuels. For the review of bio-based materials, we considered the processing and manufacture phases, as well as the displacement of fossil fuel-derived materials. The literature review incorporates some results from the processing of first-generation biomass feedstocks due to data gaps associated with a new and emerging field. The GHG emissions and energy balance of various biomass-to-energy pathways are estimated using an LCA model developed for this analysis, which is described in more detail in Section 2.2.2 below.

2.2.2. Scope of LCA Model for energy pathways

The goal of the LCA model is to provide a better understanding of the comparative GHG benefits of different feedstocks and biomass energy conversion pathways within the context of EU’s goals and policies for expanding the production and use of bioenergy. To determine the optimal *downstream* pathway for a given feedstock, we focused on waste and residual feedstocks rather than biomass crops. Properly assessing the carbon intensity of systems based on bioenergy cropping requires a detailed examination of feedstock cultivation, which has been left outside our scope here. The impact assessment therefore focuses on the GHG results from a given feedstock from only its processing and end use—all other upstream factors are considered equal. However, provided feedstock cultivation can be achieved at low carbon intensity, with low indirect emissions, and the results for waste and residual material can be treated as indicative for energy cropping given that the additional upstream emissions per tonne of feedstock produced would be the same regardless of end use of the material.

A robust analysis of the energy and GHG impacts of competing conversion pathways will help to formulate a rational strategy on the use of biomass towards 2030. The model assesses a set of eight biomass energy conversion technologies for liquid fuels and heat and power using eleven of the most common waste feedstocks in Europe, shown in Table 2.1.

Table 2.1. Feedstocks and pathways assessed in LCA model

	Liquid Fuels			Heat and Power				
Feedstock	Pyrolysis diesel	Fischer-Tropsch diesel	Cellulosic ethanol	Electricity-steam turbine	Co-fired	Combined heat and power (CHP)	Co-fired with CHP	Integrated gasification combined cycle
Agricultural residues	✓	✓	✓	✓	✓	✓	✓	✓
Forest residues	✓	✓	✓	✓	✓	✓	✓	✓
Municipal solid waste (MSW)	✓	✓		✓	✓	✓	✓	✓

Note: Agricultural residues comprise eight different types of straws and stovers. Forest residues comprise sawdust and slash. MSW is assumed to undergo processing into RDF (refuse-derived fuel) prior to conversion; cellulosic ethanol conversion was not modeled for MSW.

In order to normalize the results between different energy pathways, which can produce either liquid fuel or power in the form of electricity, the functional unit of the LCA is one dry tonne of biomass feedstock. This functional unit was chosen because it allows us to explore the optimal use for a given tonne of feedstock across a variety of pathways depending on the final GHG emissions reduction. The GHG emissions for each pathway consist of the emissions that are attributable to the end product as determined by the hybrid-displacement allocation method (see Section 2.3.3 below for more information). The GHG reduction per tonne of feedstock incorporates other sources of emissions and reductions within the product system (such as energy recovery from heat capture in CHP systems), in order to more accurately reflect the impact of diverting biomass to that pathway.

The scope of the LCA model is cradle-to-grave for the heat and power conversion pathways.[5] The "cradle" in this case is feedstock collection, which includes the necessary energy and emissions needed to collect the residues and wastes and prepare them for processing. Because all of the materials being assessed are waste products, the upstream emissions and energy use for producing the crops from which they are derived (e.g., corn produced alongside corn stover) are not allocated to them.

The residual feedstocks assessed in the LCA model have low value, and this additional residue demand is not expected to induce further production of the main crop. These residues are typically left in place within the system (e.g., on the field after crop harvesting), and we expect that increased demand would increase overall removal rates. Leaving biomass residues in place to decompose allows some restoration of nutrients to the soil. The LCA model compensates for the removal of biomass from the system by estimating emissions for the amount of fertilizer required to offset nutrient loss, as described in Baral and Malins (2014). It is assumed that good practice in residue removal is followed, meaning that removal rates are limited to a level that is sustainable in the local context. Up to these sustainable removal rates, using residues for biomass feedstock should not affect soil carbon formation, and thus the LCA model assumes that soil carbon is unaffected by sustainable removals.

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[5] Because municipal solid waste (MSW) is not harvested, the boundary for that feedstock begins with material processing and collection.

Beyond the harvest stage, the LCA model includes storage, feedstock transport, feedstock processing, fuel transport, fuel dispensing, and fuel combustion in a vehicle or a power plant. The production of co-products, which (depending on the pathway) include biochar, electricity, or heat, is factored into the final energy and GHG results through a hybrid energy and displacement approach. Co-product allocation is discussed in more detail in the Methodology section. Figure 2.1 provides an overview of the components of the life cycle and product system.

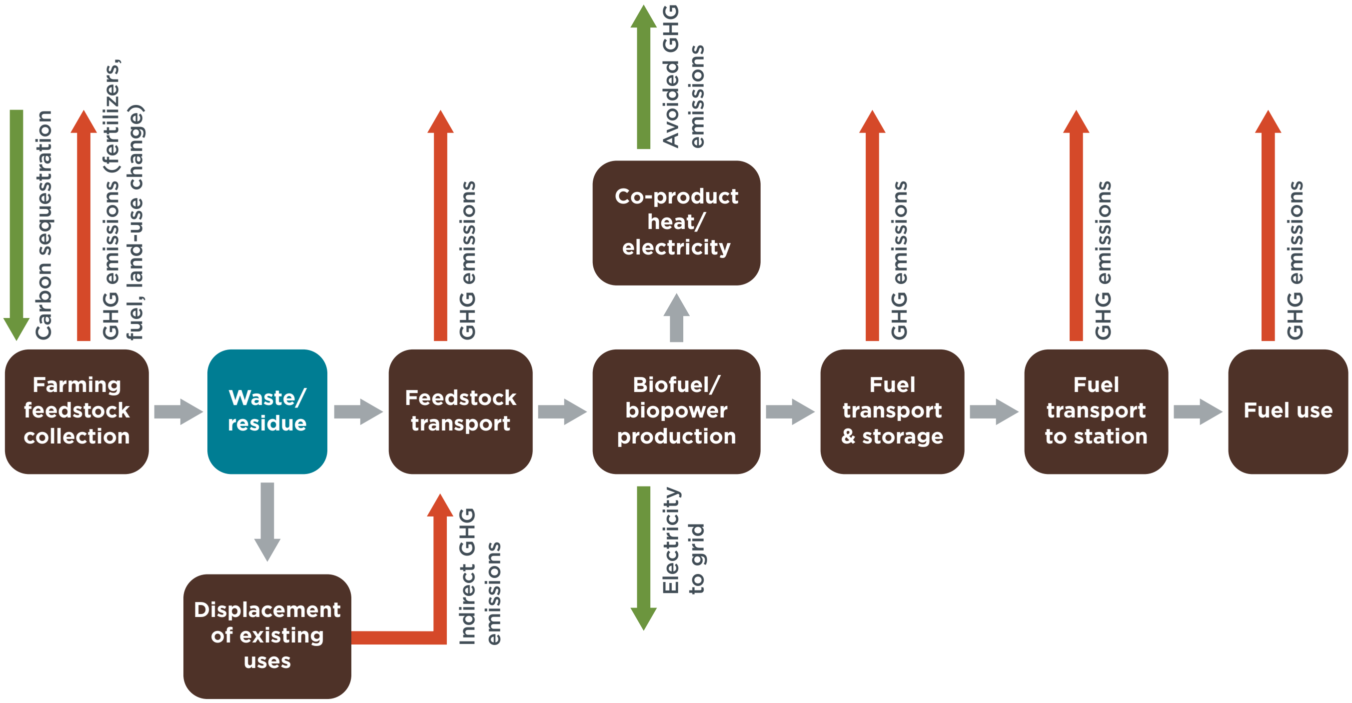

Figure 2.1. An illustration of the system employed in the LCA model

The technologies assessed in this chapter include three liquid biofuel conversion pathways and five heat and power pathways:

1. **Pyrolysis diesel:** Fast pyrolysis involves rapid heating of biomass to temperatures of about 400–500ºC in the absence of oxygen. This step causes a thermal decomposition of the biomass, resulting in bio-oil, biochar, and residual gas. Residual gas is consumed onsite to meet the process energy requirements. Depending on those requirements, biochar may be consumed onsite and excess biochar can be used for soil amendment. Bio-oil has higher oxygen content than crude oil and is acidic. It is upgraded via hydrotreating and hydrocracking to produce gasoline and diesel-range fuels. Both gasoline and diesel are the primary products of this process; however, the LCA model uses allocation to examine the results for diesel (See 2.3.3 below).[6]

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[6] Bio-oil produced from the pyrolysis and Fischer-Tropsch conversion pathways is the liquid condensate of the vapors of a pyrolysis reaction. Bio-oil is energy-dense but contains high levels of impurities, water, and acids that make it difficult to use. In order to prepare it for use as a fuel, it is typically hydrocracked and hydrotreated in a bio-refinery, which produces both diesel fuel and renewable gasoline. The renewable gasoline produced from this conversion is different from cellulosic ethanol and is considered a "drop-in" fuel.

The purpose of hydrotreating is to remove impurities such as nitrogen and sulfur, whereas the purpose of hydrocracking is to produce smaller-chain hydrocarbons that meet the specifications of diesel and gasoline (Hsu, 2011). Hydrogen consumed in hydrotreating and hydrocracking is assumed to come from natural gas, although biomass could be used for hydrogen production. In the latter case, overall liquid fuel yield would be lower (per tonne of biomass input) since a portion of the biomass would be used for hydrogen production.

2. **Fischer-Tropsch diesel:** The FT-diesel pathway involves gasification of biomass feedstock to produce syngas. Gasification for FT involves heating biomass at high temperatures (700–1600° C) in the presence of limited amount of oxygen and/or steam. Gasification produces syngas, which is mainly a mixture of carbon monoxide (CO) and hydrogen. The higher the temperature of the gasification, the higher the proportion of hydrogen and CO in the syngas (a desirable outcome for FT synthesis, while less important for syngas combustion). If the proportion or ratio of hydrogen and CO in the syngas is insufficient, the syngas's properties may be further modified with a water-gas shift reaction or the use of an iron catalyst. The FT-synthesis reaction uses a catalyst in conjunction with high pressure to produce a mixture of liquid fuels from the syngas. Liquid fuels are upgraded via hydrotreating and hydrocracking to produce a variety of products, including diesel, kerosene, gasoline, diesel, naphtha, and wax. Both gasoline and diesel are the primary products of this process; however, the LCA model uses allocation to examine the results solely for the renewable diesel produced from this process (see Section 2.3.3 below).

   The composition of final products is largely determined by type of catalyst, operating temperatures and type of reactors used in FT synthesis. To produce gasoline, olefins and chemicals, FT synthesis is carried out at high temperatures (350°C or above) in the presence of an iron-based catalyst in a fixed-bed reactor. To produce diesel, kerosene, naptha, and waxes, FT synthesis is carried out at lower temperatures (220–240°C) in the presence of cobalt-based catalysts in a fluidized bed reactor (Fedou et al., 2008).

3. **Cellulosic ethanol via biochemical conversion:** In this pathway, the feedstock is pretreated using acids, alkalis, or steam (Kumar and Murthy, 2011) to soften the feedstock and make (hemi)-cellulose amenable for hydrolysis. Commonly used pretreatment chemicals include sulphuric acid, hydrochloric acid, and ammonia. At the pretreatment step, hydrolysis of hemicellulose into pentose sugars may occur. The separation of lignin from the substrate may also occur at this stage

   In the LCA model, pretreatment with dilute sulphuric acid is modeled. The pretreatment step is followed by hydrolysis using cellulase enzymes. Cellulase enzymes hydrolyse cellulose and hemicellulose into simple sugars, leaving behind lignin and other products. Sugars are fermented using yeast to produce ethanol, which is separated from the mixture using distillation. Lignin, a byproduct, is used to produce steam and electricity to meet process energy needs. Any excess electricity produced is sold to the grid.

4. **Biomass combustion via stoker boiler with a steam turbine (electricity-steam turbine):** A stoker boiler is a conventional boiler used for steam production. Here, biomass is burned on a grate, producing flue gas. The flue gas is used to produce steam, which in turn drives turbines to produce electricity. The air for biomass combustion can be fed from either below or above the grate.

Depending on how a feedstock is fed to the furnace and the type of grate, various configurations of stoker are available. These include spreader stokers, chain-grate or traveling grate stokers, and pulverized fuel boilers. Based on the GREET model database, we assume an electric efficiency of 22% (LHV) for the stoker boiler/steam turbine technology.

5. **Biomass co-firing with coal:** For this pathway, we assume that biomass is co-fired with coal in an existing coal plant at a biomass-to-coal ratio of 15%. Biomass can be used in existing coal plants up to this 15% ratio without a need for major retrofits (Cuellar and Herzog, 2015). An electric efficiency of 33% (LHV) is assumed.
6. **Combined heat and power (CHP):** This option models an electricity-steam turbine that recovers low-grade heat in hot exhaust gases from the generation of electricity, thus increasing overall system efficiency. The recovered heat is used to produce steam or heat, which in turn is used for space heating, water heating, and other industrial processes. An electric efficiency of 18% and a thermal efficiency of 65% (i.e., overall system efficiency of 71%) are assumed. Although the overall system efficiency increases due to heat capture, electricity production decreases as the power plant is configured to generate steam as its primary product (U.S. EPA, 2015a).
7. **Biomass co-firing with CHP:** This case is identical to biomass co-firing with coal, but adds the efficiency gains from waste heat recovery via CHP. This improves the overall system efficiency to 75%: 30% for the electric efficiency and then a 65% thermal efficiency applied to the recovery of waste heat.
8. **Integrated gasification combined cycle (IGCC):** We have included IGCC to model the impact of a more efficient biopower technology in future climate change mitigation. IGCC attains higher electric efficiency by utilizing a combustion gas turbine and a steam turbine. First, biomass is gasified in a gasifier to produce syngas at temperatures over 700°C. Gasification for centralized heat and power requires lower temperatures than for FT synthesis, as combustion is not as sensitive to hydrogen and CO ratios as the FT-synthesis reaction. After purification, the syngas is burnt in a combustion turbine to produce electricity. The hot exhaust gas from the combustion turbine is sent to a heat recovery steam generator to generate steam from the waste heat. This steam, along with the process steam generated in the gasification step, is sent to a steam turbine to produce additional electricity. For IGCC, an electric efficiency of 35% is assumed, which is 60% higher than that of a stoker boiler with steam turbine (Wang, 2013).

2.3. METHODOLOGY

2.3.1. Upstream Emissions

Agricultural and Forest Residues

In the LCA model, upstream emissions come from several categories, listed in Table 2.2 below. The inputs of materials, energy, and emissions per hectare are scaled by a 5% loss factor (1% for MSW) to signify losses during harvesting, as well as a subsequent 1% loss factor to signify losses during transport.

The diversion of agricultural residues and sawdust from existing uses can lead to indirect emissions. Even where there is enough feedstock available in principle that energy generation could coexist with existing uses, in practice there may be a degree of competition given limits on rate of supply chain development. In the case of agricultural residues, we assume that 50% of advanced biofuel production results in diversion of residues from their existing uses and that the remaining production comes from additional harvest from agricultural fields (Baral and Malins, 2014). We would hope to see much low rates of displacement from existing uses, but we assess 50% displacement in order to be conservative.

Indirect emissions are therefore included as an input per unit of feedstock harvested as described in Baral and Malins (2014). The nutrient loss from feedstock diversion is calculated by first determining the lost nutrient content by mass for each feedstock in terms of nitrogen, phosphorus (P_2O_5), and potassium (K_2O) and then converting that loss into new fertilizer demand on a mass basis (Baral and Malins, 2014). The model assumes that sawdust does not require fertilizer replacements for its diversion, so there are no emissions for fertilizer replacements for that feedstock.

Table 2.2. Upstream inputs for biomass conversion

Input	Data Source
Farming inputs, fertilizer	Baral and Malins (2014); GREET Model
Harvesting, diesel energy	Baral and Malins (2014); GREET Model
Feedstock transport	UK Biofuel Carbon Calculator
Feedstock preparation	GREET Model
Bioenergy production (i.e., conversion)	GREET Model
Chemical inputs	GREET Model
Co-product generation	GREET Model
Distribution and fuel handling	UK Biofuel Carbon Calculator
Indirect emissions	Baral and Malins (2014)

Inputs that are provided in terms of energy or material inputs (e.g., chemicals) are converted into GHG emissions by multiplying them by an emission factor. Then, all of the upstream GHG emissions and energy inputs are normalized in terms of tonnes (for liquid fuels) or gigajoules (GJ) per tonne of feedstock fed into the conversion process.

Municipal Solid Waste

The upstream emissions for MSW are handled somewhat differently than those for the biomass wastes and residues. To make MSW more suitable for biofuel production via gasification or pyrolysis, and for electricity production, the waste can be pre-treated to produce a refuse-derived fuel (RDF). This step is accounted for in the LCA model. Due to its homogeneity and low moisture content, RDF can be readily used for thermochemical conversion and biopower. MSW can also be directly burned in a waste-to-energy facility to produce electricity, but this scenario has not been modeled.

The RDF facility is assumed to be co-located at the MSW collection center. At the RDF facility, wastes with low or zero calorific values, such as glass and metal, and high moisture content, such as kitchen and yard waste, are removed from MSW to obtain RDF. After processing, the RDF facility yields 54% RDF, 2% recyclables such as ferrous metal and aluminum, and 44% organic residuals (Pressley et al., 2014). While glass and metals are recycled, the separated residual organic waste (including high-moisture organic waste unsuitable for energy conversion) from the RDF facility is sent to a landfill.

The resulting RDF, predominantly paper and plastic, is shredded and pelletized and sent to a biofuel or bio-power production facility via truck. Since the composition of MSW varies from country to country, a notional RDF with composition similar to that reported by Pressley et al. (2014) is assumed (Table 2.3).

Table 2.3. Composition of RDF

Component	Mass (%)
Fiber	67%
Plastic	18%
Other organics	15%

Source: Pressley, 2014

2.3.2. Biomass Conversion Co-Products

Several of the pathways characterized in the LCA model also yield co-products that have significant economic value in addition to the value from the main product. Additionally, several of the pathways produce wastes or byproducts that have little energy or economic value but may be associated with non-GHG environmental impacts (positive or negative). Those materials are further discussed in the Non-GHG Environmental Impacts section.

The eight biomass conversion processes produce a mix of different co-products, as shown in Table 2.4. The key co-products produced include the following:

1. **Biochar:** Biochar is a solid co-product of pyrolysis generated during the carbonization of the biomass when heat is applied. It consists mostly of carbon, but also has some trace nutrient content, depending on aspects of the conversion process and the feedstock used. Biochar can be consumed directly as a fuel, as it has some energy value, but it can also be applied as a soil amendment, allowing sequestration of carbon and providing benefits through nutrient cycling and soil-structure enhancement. The LCA model only considers biochar in terms of its energy content when combusted for electricity, though other uses (such as soil amendment) are described in the Non-GHG Impacts chapter. Using biochar as a soil amendment provides stable sequestration of carbon in soils, thus providing greater carbon reductions than displacing other energy sources when combusted for energy.
2. **Electricity:** Some liquid biofuel conversion pathways may generate excess electricity from the on-site combustion of either the solid or gaseous byproducts of a chemical reaction. This electricity is likely consumed on-site to power the bio-refinery, with any excess sold back to the grid.
3. **Recovered Heat:** Recovered heat refers to the heat recovered by a CHP plant that would otherwise be emitted to the environment and wasted. Heat recovery raises the overall operating efficiency of a given power plant. The recovered thermal energy can be used to generate heat or cooling depending on system need. Because the cooling or heating is generated with "waste" heat instead of on-site fossil fuel combustion or grid electricity, it is thus considered to displace some amount of power generation.

The allocation process for considering the emissions implications of these co-products is described in more detail below in Section 2.3.3.

Table 2.4. Pathways and co-products

Conversion Pathway	Co-Products
Pyrolysis diesel	Biochar
Fischer-Tropsch diesel	Electricity
Cellulosic ethanol	Electricity
Electricity-steam turbine	N/A
Co-fired	N/A
CHP	Recovered heat
Co-fired with CHP	Recovered heat
IGCC	N/A

2.3.3. Allocation

Allocation refers to the partitioning out of the impacts of a production system to the different products produced. Here, partitioning is applied to the products and co-products of each fuel system described above: renewable diesel, renewable gasoline, biochar, heat, and electricity. The Renewable Energy Directive (RED) methodology uses energy content-based allocation: If a co-product has one-third of the total energy value of the products leaving the production system, one-third of the impacts are allocated to it. However, if one of the co-products is excess electricity, the RED methodology uses the displacement method to calculate avoided emissions.[7]

The LCA model used for this analysis uses a hybrid-displacement method to allocate energy and emissions to co-products of the biomass conversion pathways assessed. Any avoided emissions due to electricity export and on-site combustion of biochar co-product[8] are subtracted from the gross emissions from the system, and the remaining net emissions are allocated between co-products according to energy content:

$$GHG_{co\text{-}product} = \frac{Energy_{co\text{-}product}}{Energy_{total}} \left(GHG_{Gross} - \Sigma_{i\text{-}1}^{n}\, GHG_{avoid}\right)$$

Here, GHG_{Gross} are the total GHG emissions associated with the system, GHG_{avoid} are the GHG emissions credits due to displacement by co-product electricity, $GHG_{co\text{-}product}$ is the carbon intensity assigned to a given co-product, and $\frac{Energy_{co\text{-}product}}{Energy_{total}}$ is the fraction of the useful chemical energy leaving the system with each co-product.

The allocation approach was used in this analysis to calculate the life-cycle GHG emissions for each combination of feedstock and pathway, normalized by the energy delivered (in MJ) by the product or co-product of interest (renewable diesel, ethanol, or electricity). However, the life-cycle emissions for a unit of biomass-derived energy

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[7] In the displacement method, all emissions from extraction to final use are assigned to the main product. Then emissions that co-products avoid by displacing other products in markets are determined. Avoided emissions would be the emissions associated with the production of displaced products. The avoided emissions are subtracted from the gross emissions assigned to the main product to arrive at net GHG emissions.

[8] While bio-char may be removed from the system and used to restore nutrients to soils, for the purposes of the life-cycle assessment here we consider it combusted within the system in order to offset the use of natural gas, similar to co-product electricity generation.

represents an absolute value of emissions and does little to contextualize the process in terms of the emissions benefits from displacing other energy sources.

To assess the total GHG reductions for each conversion approach, the LCA model does not use allocation. Instead, the GHG reduction value for a given process includes the net carbon savings from the main product generated from the conversion of one tonne of feedstock, along with the impacts from the use of all other co-products. The latter approach, which incorporates the impacts of the entire system, better represents the actual net carbon impact of the entire system (as opposed to one product from that system) because it includes the emissions reductions generated from the use of co-products.

As part of the sensitivity analysis for the LCA model, other allocation methods were used to test the sensitivity of the GHG emissions and EROI to various allocation methods. The other methods used were mass-based allocation, economic allocation and energy allocation—all forms of value-based allocation, though using different values. The sensitivity of the model to these methods is discussed in Section 2.4.2 below (Sensitivity Analysis).

2.3.4. Fossil Fuel Displacement

A key factor that affects the final results for many of the biomass conversion pathways is the carbon intensity of the electricity grid, which affects displaced electricity of the biomass for heat and power pathways, as well as the displacement for several co-products. Carbon intensity assumptions made during the modeling of the electricity grid can have a profound impact on the final results for GHG reductions delivered by a pathway. Assuming that renewable power generation displaces electricity from coal as opposed to displacing renewables or natural gas can make the difference between reporting a large emissions saving or an emissions increase. In reality, we believe it is appropriate to assume a central case in which a mix of electricity sources is displaced. In addition to the grid average results, the emissions estimates for biomass heat and power include estimates for the displacement of only coal-derived electricity as well as the displacement of electricity from efficient, CHP natural gas power plants.

For the grid-average results, the model assumes that the carbon intensity equals a weighted average value for grid electricity in the EU (EEA, 2014). Unlike intermittent renewables, biomass combusted for electricity can be used to provide baseload power; therefore, it is easier to plan for and would not necessarily displace only “peaking” electricity generators. In the longer term, the net carbon savings from biomass heat and power is highly dependent on the composition of the electricity grid. The degree to which biomass power would strictly displace coal is highly uncertain and dependent on both economic and policy factors. Co-firing, for example, still necessitates coal use in conjunction with biomass and could therefore prolong reliance on coal combustion. If the electricity grid becomes less reliant on coal generation, the relative benefits of heat and power pathways would decrease (this consideration is explored further in Section 2.4.2 below). In a case where the EU has a set goal for a percentage of electricity that must come from renewable sources, biomass heat and power could compete with other electricity sources to meet that target, even though alternatives such as wind and solar have lower carbon intensities.

For the electricity and recovered heat displaced as a co-product, the model assumes that efficient natural gas production will be displaced, at a value of 290 gCO_2e per kWh (IPCC, 2011). This is a conservative assumption, but makes some allowance for the possibility that electricity and heat produced as co-products may not be exportable in all cases.

The modeling of liquid fuel displacement was more straightforward than the heat and power pathways. Liquid fuel displacement was estimated on a per-MJ basis, using a value of 94.1 gCO_2e/MJ to represent the displaced liquid fuel combustion and the associated upstream production emissions (EC, 2014c). The assumption of a 1:1 displacement of other sources of energy by biomass may introduce some inaccuracies. This analysis does not consider indirect effects that influence demand, such as the price effect (also known as the "rebound effect"), wherein a decline in fossil fuel demand in response to biomass use could lower fossil fuel prices and thus spur a partial increase in their use (Malins et al 2015). This effect would therefore create some "leakage" in biofuel deployment, such that every MJ of biomass energy use would displace less than 1 MJ of fossil fuels.

2.3.5. Other Uses of Biomass

Bio-Based Materials

The LCA model does not cover the use of biomass for non-energy applications due to data limitations associated with modeling the wide variety of alternative uses for biomass consistently with the energy pathways. A multitude of bio-based materials may be manufactured from biomass; additionally, biomass may be instead diverted to compost or anaerobic digestion in order to reduce GHG emissions and cycle nutrients. Another complicating factor for bio-based materials is the sheer variety of both feedstocks and products in conjunction with the lack of life-cycle data on production relative to the pathways and feedstocks modeled in the LCA model. Some bio-plastics, such as bio-ethylene, can completely replace petroleum-derived plastics (in this case ethylene), whereas others are entirely new products with somewhat different properties than the materials they replace. This section uses data from a literature review to provide several data points for the GHG emissions from alternate uses of biomass, though due to data limitations (i.e., different feedstocks from the LCA model), they should not be considered directly comparable to the results from the LCA model.

Polylactic acid (or polylactide), which is manufactured using corn, is a bio-plastic that can displace the production of petroleum-derived alternatives, polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). Posen et al. (2016) suggests that PLA most commonly displaces either PS or PET. Polyhydroxybutyurate (PHB) can also be manufactured from corn, though it generally requires more energy and has lower yields than PLA (Posen et al., 2016). LCAs that estimate the cradle-to-grave emissions associated with PLA production show a wide variance in the upstream production emissions associated with PLA, depending on the scope of that LCA. The studies assessed did not incorporate indirect land-use change (ILUC) for the corn used to produce the PLA.

Depending on which plastic PLA displaces, its use would either increase or decrease the net life-cycle emissions for a given product. The net GHG impact is based on three separate factors: the upstream emissions for manufacturing PLA, the upstream sequestration from the corn feedstock; and the avoided emissions from the petroleum-derived plastics that PLA displaces. According to the U.S. EPA's Waste Reduction Model (WARM), the upstream emissions for PLA production from corn in the United States are approximately 3.84 tonnes CO_2e/tonne of PLA (U.S. EPA, 2015b).[9] After factoring in the upstream sequestration (1.82 tonnes CO_2e per tonne of PLA) from crop production, the net result for PLA is 2.02 tonnes CO_2e/tonne of PLA (Vink et al. 2007). [10,11] Posen et al. (2016) estimates a range of 1.0 to 2.9 tonnes CO_2e/tonne of corn PLA, depending on allocation and methodology.

The upstream emissions associated with the manufacture of various petroleum-based plastics modeled in WARM ranges from 1.53 to 2.56 tonnes CO_2e/tonne, depending on the plastic (U.S. EPA 2015b).[12] Therefore, the net impact of displacing the production of these other plastics with PLA would range from -0.54 to 0.49 tonnes CO_2e per tonne of PLA. The net emissions from biopolymers such as PLA can be highly variable and depend highly on methodological parameters such as allocation and treatment of co-product residues—as well as the plastic that the bio-polymer would displace. The wide range of emissions is on the same order of magnitude as the mean emissions from petroleum-derived polymers (Posen et al., 2016). Therefore, the greatest benefits come from displacing the most GHG-intensive forms of plastic, such as polystyrene (PS).

As the production technology matures, the manufacturing emissions for bioplastics could decrease over time. GHG emissions from corn PLA can be further reduced by recovering unfermented residue and using it to generate energy on-site. Changing to switchgrass as a feedstock could further decrease the production emissions to a range of -0.2 to 1.3 tonnes CO_2e/tonne of PLA, a substantial decrease from corn manufacture. The low end of the range includes cases where the unfermented residue is collected for energy.

Unlike petroleum-based plastics, some types of biopolymers are biodegradable, allowing for either composting or landfilling. PLA can be composted and thus generate some carbon sequestration, which results in an emissions reduction of 0.19 tonnes CO_2e/tonne. Composting infrastructure for PLA, which requires sustained high temperatures, may not be available in all locations. In regions where industrial composting is not an option, the PLA would instead be landfilled and sequester some of its carbon content.[13] Other biopolymers may degrade in landfill conditions, thus releasing methane over time.

Bio-based ethylene, a polymer produced from ethanol, can directly displace petroleum-based ethylene. The ethylene can then be polymerized into polyethylene (PE), as well as a wide variety of polyethylene materials, including high-density polyethylene (HDPE) and low-density polyethylene (LDPE). Similar to PLA, ethylene is typically produced from starchy biomass rather than ligno-cellulosic biomass, which has not yet been commercialized (IRENA, 2013). One tonne of bio-ethylene requires 1.74 tonnes of bio-ethanol (with yields of 99% ethylene from the bio-ethanol feedstock observed); therefore, 0.17 tonnes of ethylene can be produced from a tonne of feedstock assuming the biomass conversion rates for ethanol used in the LCA model used for this chapter(IRENA 2013).[14] Posen et al. (2016) compared the potential GHG savings

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[9] WARM only models the manufacture of PLA thermoplastic resin (i.e., 2002D and 2003), extruded for use as packaging and utensils. There are other PLA grades that were not included in WARM.

[10] This value does not include renewable energy certificates (RECs) purchased to offset Scope 2 and Scope 3 electricity emissions from PLA production, which were included in the LCA but would be inconsistent to include here.

[11] This value does not include any indirect emissions associated with corn production, such as ILUC.

[12] The plastic resins modeled in WARM include HDPE, LDPE, PET, LLDPE, PP, PS and PVC. The lower- and upper-bound emissions estimates are for HDPE and PS, respectively.

[13] Landfill conditions have been shown experimentally to result in zero degradation for the PLA thermoplastic resin.

[14] The LCA model assumes that 1 tonne of feedstock can be converted into 0.3 tonnes of ethanol.

from manufacturing polyethylene from first-generation cornstarch or lignocellulosic switchgrass, finding that in cases where the bio-ethylene displaced ethylene-intensive plastics such as PE, bio-ethylene could reduce net GHG emissions, depending on co-product allocation. The study did not consider the upstream ILUC associated with using agricultural land to produce the feedstock inputs.

Dunn et al. (2015) developed a bioproducts module within the GREET model to estimate the emissions for a variety of biochemicals and their fossil fuel-derived equivalents, using the same methodology as the GREET model uses for transport fuels. The products modeled included plastics and plastic precursors such as ethylene and succinic acid, as well as other industrial materials made from corn stover. The model assumes a relatively conservative conversion rate for corn stover to ethanol (1.7 tonnes per tonne). The emissions reductions are calculated by subtracting the cradle-to-grave emissions for the biochemicals from the baseline GHG emissions for manufacturing a range of comparable fossil-derived chemicals.

The authors find that various bio-products reduced GHG emissions, on a cradle-to-grave basis, by 27–86%, excluding the upstream emissions used to produce catalysts and end-of-life disposal emissions (see Figure 2.2 below). The largest driver in the emission reductions was the decreased use of fossil fuels to power the conversion process. For example, conventionally manufactured propylene glycol requires 11.3 million British thermal units (MMBtu) of electricity and natural gas to produce one tonne of product, whereas its bio-based alternative requires only 8.3 MMBtu per tonne. This reduction is due in part to the cogeneration at the integrated biorefineries and export of excess electricity and heat to the grid. The mix of biochemicals required 8–80% less fossil fuel-derived energy to manufacture than the conventional products. Another factor for the GHG reductions was the modelling assumption that corn stover is essentially an agricultural waste product and generates no upstream emissions—a small amount of indirect emissions occur from increased fertilizer addition to fields to offset corn stover removal (as done in the LCA model for agricultural residues).

Pathways that incorporated a stage in which clean sugars (i.e., a mix containing primarily water, glucose, and xylose) were derived from corn stover in an integrated biorefinery that exported heat and electricity generally provided the greatest GHG reductions. The greatest GHG reductions in the GREET bioproducts module come from the use of both types of bio-succinic acid derived from corn stover in place of adipic acid—which typically emits high amounts of N_2O during its production. The study also assumed a 100-year time horizon in which all of the embedded carbon in both fossil and biogenic products would be returned to the atmosphere at product end-of-life, increasing the carbon intensity of both pathways, though the actual decomposition process could take more or less time depending on the product.

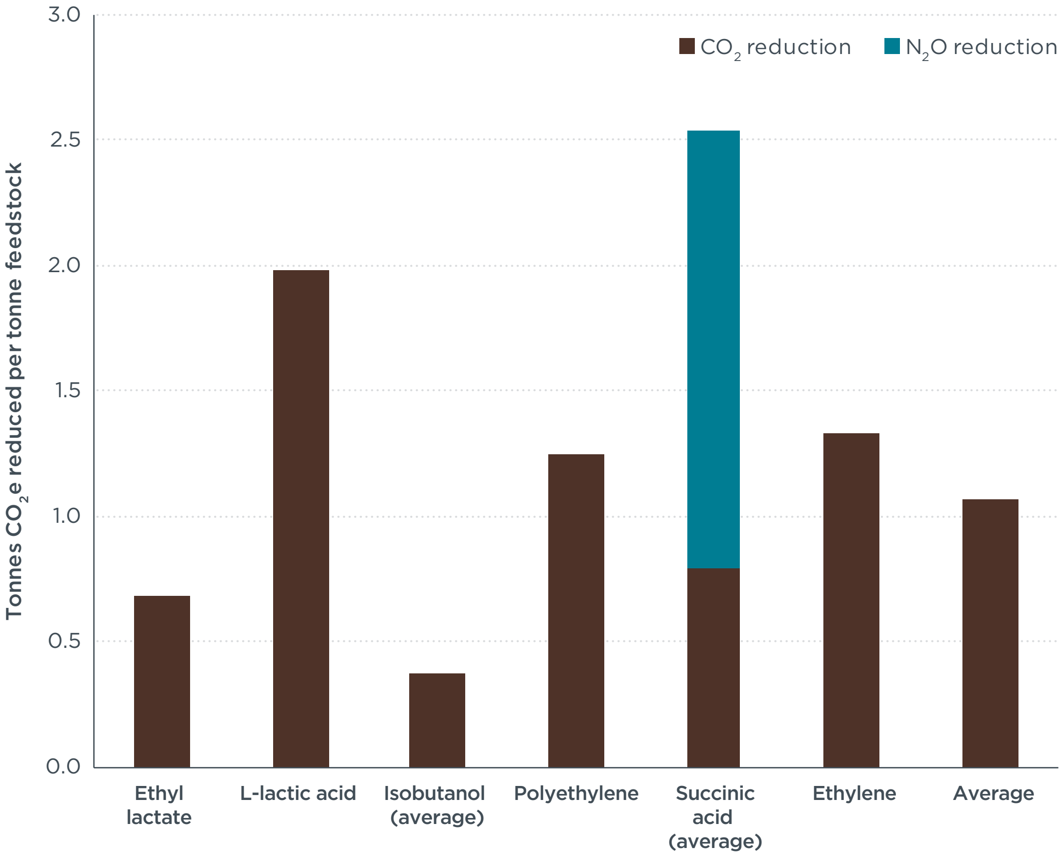

Figure 2.2. GHG reductions from biochemical displacement of conventional products

Source: Dunn et al., 2015

Composting

Composting generates both emissions and carbon sequestration. A large-scale composting facility generates emissions from the operation of composting machinery, as well as trace emissions of nitrous oxide (N_2O) and methane from the breakdown of organic matter. Compost application on soils results in emissions sinks from increased humus formation and carbon storage in the soil. Assessments of the life-cycle greenhouse gas emissions from composting organic matter are highly divergent and dependent on the makeup of the waste being composted.

A meta-analysis of various LCAs of waste management systems (Bernstad and la Cour Jansen, 2012) reported significant variation in published results on the life-cycle GHG emissions from composting food waste.[15] Averaging the results of the 25 studies in the analysis, the authors found that estimates of net composting emissions ranged from 0.090 tonnes carbon dioxide equivalent (CO_2e)/tonne to 0.175 tonnes CO_2e/tonne, depending on the assumptions (i.e., only including scenarios without fertilizer replacement or only by including scenarios with carbon sequestration). The net average emissions for composting in the study was 0.144 tonnes of CO_2e per tonne of waste. However, the study notes that significant carbon savings are achieved by the diversion

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15 It is important to note that food waste and biomass behave somewhat differently in compost and landfills because of the difference in their moisture content.

of waste materials from landfills, which emitted by far the highest average emissions in the meta-analysis. Assuming that diverting MSW from landfills reduces GHG emissions by 0.1 tonnes per tonne of waste, this would mean that net life-cycle composting emissions would range from -0.010 to 0.075 tonnes CO_2e/tonne for food waste (Manfredi et al., 2009). This result is likely to be somewhat different for diverted green waste, as it would have lower moisture and would not necessarily be diverted from a landfill. However, using a more likely indirect emissions estimate of -0.9-kgCO_2e/tonne biomass for biomass left on a field would not change the impact of composting from the net 0.09—0.175 tonnes CO_2e/tonne emissions estimate above (Baral and Malins 2014).

The U.S. EPA's WARM model, which draws upon the CENTURY agroecosystem model of long-term carbon storage, provides estimates for the composting of biomass in addition to other wastes. The model estimates that the life-cycle emissions for composting green waste are a net negative (-0.13 metric tonnes of CO_2 equivalents per tonne of biomass), even after accounting for fugitive emissions of methane and nitrous oxide resulting from microbial activity (U.S. EPA, 2015c).[16] WARM assumes that the finished compost does not directly offset carbon-intensive synthetic fertilizers and is instead considered to be more of a soil amendment, though it does result in some soil carbon storage. If the green waste used for composting was diverted from a landfill, the net emissions would therefore be -0.03 tonnes CO_2e per tonne (Manfredi et al., 2009). However, if that biomass was instead left on the field, using the same -0.9-kgCO_2e/tonne biomass assumption for indirect emissions as above, that would mean that the GHG benefits essentially remain unchanged.

Anaerobic Digestion

Anaerobic digestion reduces GHG emissions by avoiding any direct methane emissions from decomposition in landfills or the open, as well as through energy recovery of the captured methane. Electricity generated from captured methane can be sold back onto the electricity grid, thus displacing some amount of grid electricity. A meta-analysis of various LCAs of waste management systems (Bernstad and la Cour Jansen, 2012) found that anaerobic digestion emissions vary widely depending on a variety of operational conditions. Net emissions from anaerobic digestion averaged 0.07 tonnes CO_2e/tonne, but could be as low as -0.1 tonnes CO_2e/tonne if only including studies that considered carbon storage from digestate application to soils (similar to compost application) It is important to note, however, that this study considered food waste, which has higher moisture content than biomass and thus has somewhat different behavior during anaerobic digestion than green waste.

Looking at the operational conditions for anaerobic digestion in more detail, Møller et al. (2009) found that the range of net GHG estimates for anaerobic digestion could range from -0.375 to 0.111 tonnes CO_2e/tonne of wet waste. The key uncertainties influencing the wide range of results were whether the digestate could be used as a replacement for fertilizer and the degree to which fugitive methane emissions would be emitted from the digester.

Böhni Energie and Umwelt (1999) investigated the energy yields from a farm-based anaerobic digestion system, estimating the energy recovery from utilizing farm byproducts and energy crops in the system. The study suggests that corn silage

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[16] This assumes that the composting of branches, leaves, and grass would have similar emissions to biomass.

generated significantly more electricity than dairy manure. The authors found that corn silage produced 180 cubic meters of biogas per wet tonne of material, generating 335 kWh of electricity and 425 kWh of heat (assuming a conversion rate of 35% for energy and 45% for heat) for a total of 760 kWh per wet tonne of corn silage. Relative to that total, 10.2% of those 760 kWh was required to produce and digest the crop (OMAFRA, 2013). Assuming that the electricity displaces grid-average European electricity and the heat displaces CHP-derived heat, the net carbon emissions are -0.330 tonnes of CO_2e per tonne of dry feedstock input.[17] This result does not consider other factors such as fugitive methane emissions or carbon sequestration from digestate use, assessing anaerobic digestion strictly in terms of its energy balance.

Gerin et al. (2008) consider a similar case, assessing the net energy balance from the anaerobic digestion of both corn silage and a grass energy crop. Looking only at the biogas yield of the feedstocks, anaerobic digestion yielded from 230 to 350 cubic meters of biogas per tonne of grass and corn silage, respectively. Per the study, running the digester only took about 3 MJ of diesel fuel per feedstock, with much of the remaining energy coming from the feedstocks. Assuming an energy conversion efficiency similar to the above example, that biogas generated from 971 to 1,478 kWh of electricity and heat combined (or 3,496 to 5,321 MJ). These results could be expected to vary significantly depending on the actual mix of feedstocks in the digester, as various studies have shown a wide range of expected biogas yields depending on feedstock (e.g., crop residues, manures, and MSW sludge) and feedstock mixtures.

Overall, anaerobic digestion and composting offer GHG reductions on average, but the reductions vary significantly depending on the assumptions of the studies. The net emissions from composting and anaerobic digestion in particular are sensitive to the composition of feedstocks in a given system. For composting and anaerobic digestion, the GHG reductions are lower than for energy conversion because they are not primarily displacing the combustion of GHG-intensive fossil fuels such as diesel and gasoline (though the biogas generated as part of anaerobic digestion does generate power). On the other hand, bio-based materials can offset the consumption of petroleum-derived materials. However, their processing and manufacturing emissions are similar to those of the materials they are intended to displace. Thus, the benefit of bio-based materials is dependent on upstream carbon sequestration for the biomass feedstock used. The choice of a feedstock that offers carbon sequestration and generates minimal indirect effects is thus critical for producing bio-based materials that reduce GHG emissions.

2.4. RESULTS AND DISCUSSION

The results of the LCA indicate that if biomass heat and power displaces grid-average electricity, the average heat and power pathway (averaged across all feedstock categories) reduced GHG emissions per unit of feedstock 13% more than liquid biofuels. Carbon intensity provides a measure of the net life-cycle emissions for a given MJ of output energy, but does not directly address the emissions benefits of displacing fossil fuels, and does not always correlate with the energy efficiency of the conversion process. For instance, inefficient use of biomass for process energy could reduce the reported carbon intensity, but represent a lost opportunity for overall emissions reductions. On a life-cycle basis, the heat and power pathways emitted slightly more GHGs per unit of

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[17] This assumes that the wet feedstock has a dry matter content of 85% and that the carbon savings from grid average electricity and CHP power displacement match the values from the LCA model.

energy generated, but the emissions of both pathways were substantially less than those of the fossil fuels they displaced, thus making that distinction negligible (see Figure 2.3 below). Both heat and power and liquid fuels pathways provided substantially more carbon savings than the manufacture of bio-based materials.

Moving beyond the baseline case, alternative assumptions on displaced electricity changes the carbon savings of heat and power pathways relative to liquid fuels. For example, assuming that biomass-derived electricity displaced natural gas-derived electricity changed the results so that on average, biomass heat and power only reduced 50% as much GHGs as liquid biofuels per tonne of feedstock input. On the other hand, assuming that coal-derived electricity was displaced would greatly increase the relative benefits of the heat and power pathways, to nearly double the benefit of using liquid biofuels. Figure 2.4 shows an overview of the GHG reductions for each pathway.

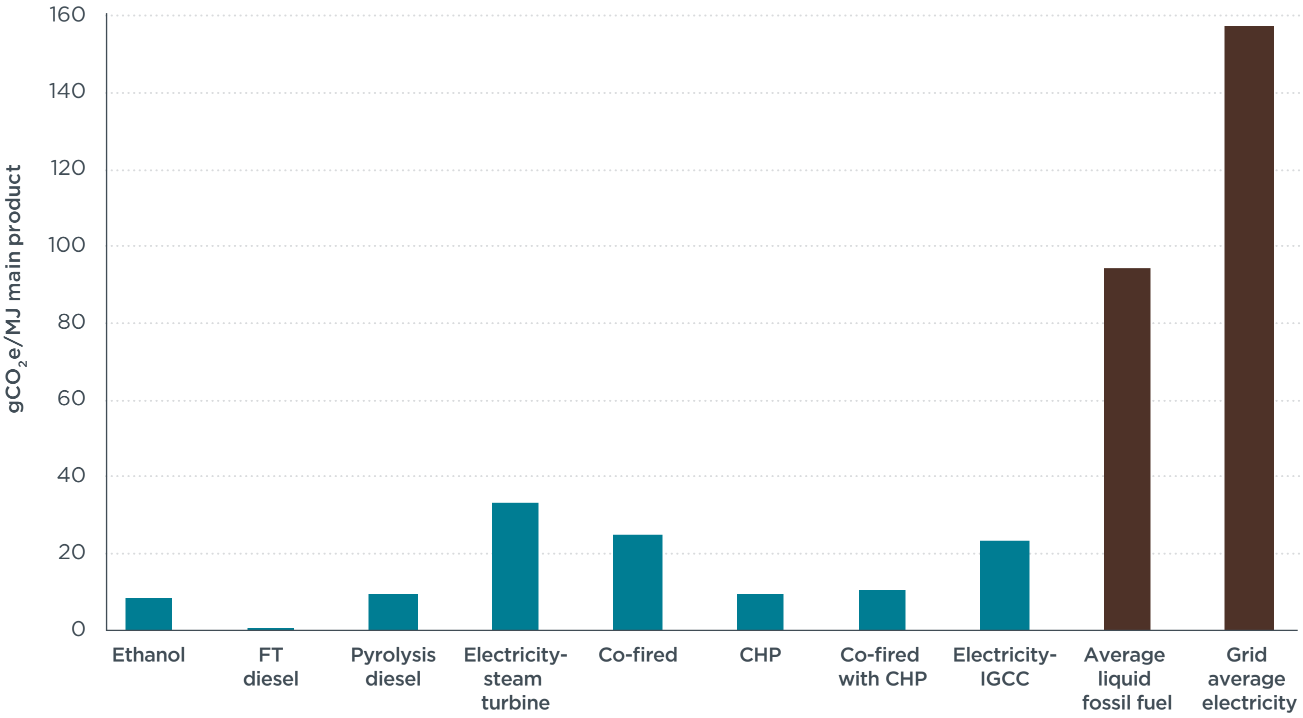

Figure 2.3. Life-cycle GHG emissions for biomass pathways and displaced fossil fuels

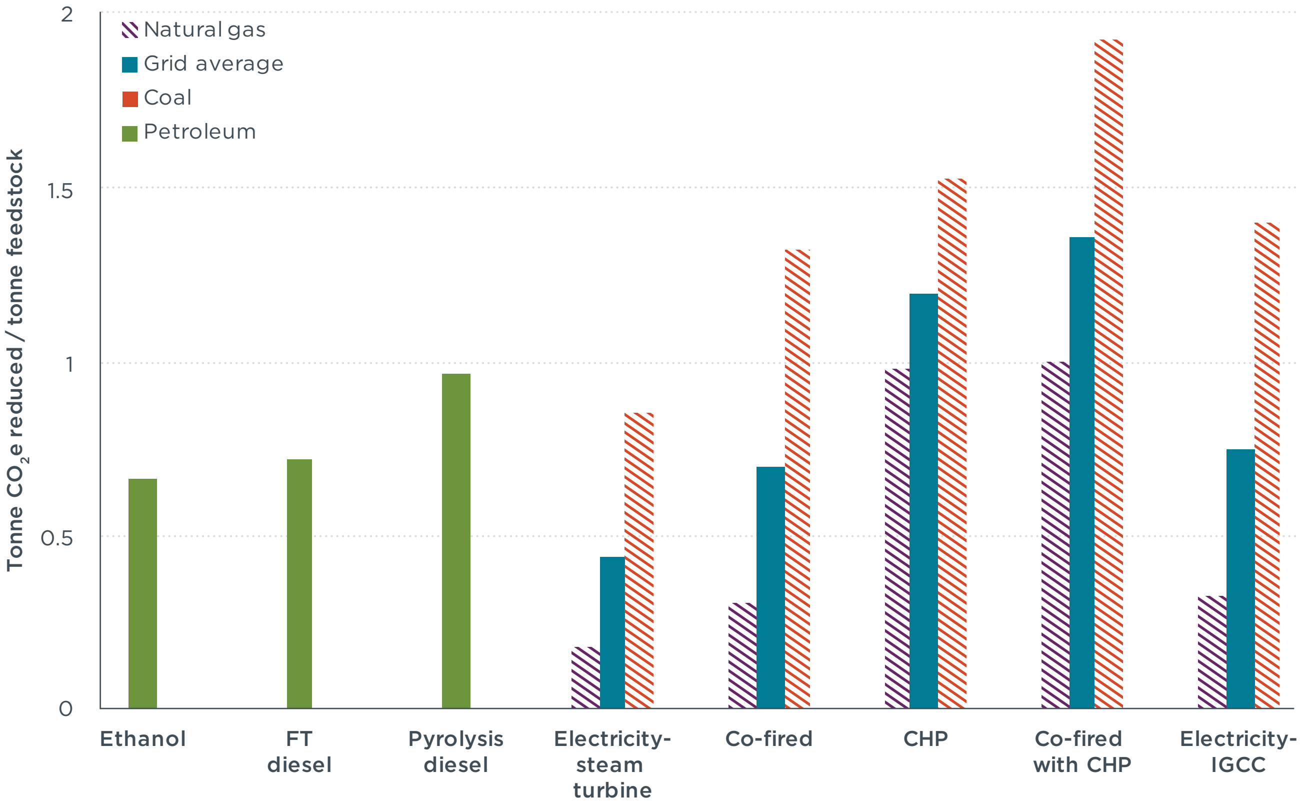

Figure 2.4. Average GHG reduction for biomass energy pathways

Table 2.5 and Table 2.6 present a range of values for biomass-to-liquid fuel and biomass-to-heat and power pathways, incorporating upper and lower limits among different feedstocks and conversion pathways. While the GHG reductions per tonne of feedstock input was the primary metric for this analysis, the LCA model also assessed several other metrics, including carbon intensity (gCO_2e/MJ), percent GHG reduction, and energy return on investment (EROI). These additional metrics can help illustrate further the advantages and disadvantages of the different pathways.

As described above, the carbon intensity results provide a measure of the net life-cycle emissions for a given MJ of output energy, but provide an incomplete picture of the energy efficiency and displacement associated with each pathway. The percentage GHG reduction can similarly become disconnected from conversion efficiency, such that the pathway with the highest percent benefit per MJ of output is not necessarily the pathway that delivers the most absolute carbon emissions reduction. We have also calculated EROI, as a measure of the energetic efficiency of conversion process—however, considered alone EROI may overemphasize the relative benefits of heat and power pathways because of the fact that less energy is used to process biomass for heat and power. Indeed, we find that EROI show little correlation to absolute GHG reductions. The main reason to assess EROI is to confirm that pathways deliver an energy return much greater than the energy input required to run the system—the marginal benefit of very high EROI is limited.

As well as variation between categories of energy use technology (heat and power or liquids), there is considerable variation in the GHG reduction delivered between the individual technologies and specific feedstocks. The rice straw feedstock incorporates an avoided emissions credit for methane caused by the decomposition of rice straw on rice paddies. This additional offset increases the emissions savings from rice straw and is responsible for the high upper bound on the agricultural residues results in both tables below. In contrast, the use of MSW as a feedstock—particularly in the heat and power sector—is associated with a higher carbon intensity because of the emissions of fossil-derived carbon (primarily from the plastic component of waste) during combustion. This is based on an assumption that fossil carbon in the plastic component of waste would otherwise be subject to long-term carbon sequestration in landfill. While the combustion of plastic waste may not deliver carbon benefits directly, there may still be other justification for using energy recovery as part of the waste management system for fossil plastics.

Table 2.5. Key metrics for biomass-to-liquid fuel pathways

Feedstock	Carbon intensity (gCO_2e/MJ)	% GHG reduction	EROI	GHG reduction (CO_2e tonne/ tonne feedstock)
Agricultural Residues	-59.5 to 27.6	78 to 163	2.0 to 16.4	**0.52 to 1.37**
MSW (RDF)	6.1 to 9.1	90 to 94	3.9 to 4.7	**0.45 to 0.64**
Slash	6.7 to 14.1	85 to 99	3.4 to 9.9	**0.63 to 1.06**
Sawdust	17.0 to 19.6	79 to 87	4.2 to 82.3	**0.59 to 1.02**

Table 2.6. Key metrics for biomass to heat and power pathways, average grid electricity carbon intensity

Feedstock	Carbon Intensity (gCO_2e/MJ)	% GHG reduction	EROI	GHG reduction (CO_2e tonne/ tonne feedstock)
Agricultural Residues	-113.1 to 54.9	65 to 172	3.7 to 27.3	**0.40 to 1.53**
MSW (RDF)	50.7 to 171.8	-9.1 to 68	1.3 to 4.5	**-0.02 to 0.48**
Slash	10.2 to 34.6	78 to 94	4.7 to 17.6	**0.51 to 1.64**
Sawdust	14.1 to 46.7	70 to 91	223.8 to 739.0	**0.43 to 1.53**

For the feedstocks considered here, GHG reductions per tonne feedstock range from 0.45 tonnes to 1.06 tonnes CO_2e for liquid biofuel pathways, and from -0.02 to 1.64 CO_2e tonnes for biomass heat and power pathways (assuming displacement of EU average grid electricity).

The comparison between liquids pathways and heat and power pathways offers mixed results. Assuming grid-average electricity displacement, heat and power applications tend to offer the greatest benefit, but not for all possible technologies—liquids outperform CHP and steam turbine technologies. Even more important than technology choice, though, is the electricity source that gets displaced. If biomass for heat and power directly results only in reduced coal use, then the GHG benefit is substantially greater than in the transport sector. If, on the other hand, biomass power generation reduces natural gas use, then the benefits in the transport sector are probably higher. Our conclusion from this is that on climate grounds, there is a case for using biomass resources in both stationary and mobile (i.e., transport) applications. Within heat and power, the most effective policy options would specifically target coal displacement.

The results of the literature review indicate that composting and anaerobic digestion offer GHG reductions, but of a smaller magnitude than any of the liquid biofuel or heat and power pathways. This is due to the fact that composting does not offset fossil fuel use or provide sufficient nutrients to completely displace synthetic fertilizers. Anaerobic digestion is able to offset some grid electricity via the combustion of biogas, but even the greatest net carbon savings for anaerobic digestion found in the literature review (-0.375 tonnes CO_2e/tonne waste) were still lower than any of the dedicated biomass energy pathways (with the exception of MSW combustion). The literature review also indicated that composting and anaerobic digestion might complement the energy pathways, because they utilize organic material such as food waste and sewage that is less suitable for energy conversion.

Bio-based materials such as biopolymers offer possibilities for significant GHG reductions via the displacement of petroleum-derived plastics and sequestration of carbon in durable products. However, the literature review suggested that conversion technologies for second-generation feedstocks have not yet been commercialized. We found that with current manufacturing technologies, bio-based material production emissions were similar to those of their petroleum counterparts.

Comparing the results of the literature review and LCA model indicated that the liquid biofuels and heat and power pathways offered greater GHG reductions per tonne of feedstock than alternative uses of biomass. However, it is important to note that pathways such as composting and anaerobic digestion may rely on feedstocks with different properties (i.e., higher moisture content) that are not in demand for energy. Bio-based materials performed similarly to their fossil fuel counterparts in terms of manufacturing emissions, and only when factoring in their upstream carbon sequestration did they offer carbon savings.

We found that the heat and power pathways offer slightly higher GHG reduction benefits on average than the liquid fuel pathways. However, due to the significant variation in the GHG emissions reductions between the various technology pathways and the further variation depending on the exact feedstocks processed, there may not be sufficient evidence to decide between liquid biofuels and heat and power based on the results from the LCA model. Rather, the results are more useful in determining the optimal pathway once a feedstock and need (i.e., power or liquid fuel) has been decided after the consideration of other factors, such as feedstock supply and economic viability.

2.4.1. Sensitivity Analysis

Two of the key factors that influence the net GHG reduction for each of the conversion pathways are the composition of the EU's marginal electricity supply (i.e., which electricity source is being displaced) and the allocation method chosen. This section assesses the extent to which each of these assumptions made in the LCA model affects the final results.

For example, when biomass electricity displaces the average electricity mix from the grid in the EU, natural gas electricity or coal electricity, GHG reductions per tonne of biomass would significantly increase. If coal electricity is displaced, the GHG reduction becomes quite large—averaging 1.14 tonnes CO_2e/tonne feedstock (See Figure 2.5). On the other hand, if biomass electricity displaces efficient fossil fuel energy, such as natural gas combusted at a CHP power plant, the average magnitude of reduction would only be 0.29 tonnes CO_2e/tonne feedstock. These values represent a range of 40-82%

of the average emissions for biomass electricity when it displaces the EU grid-average electricity, as shown in Figure 2.5.

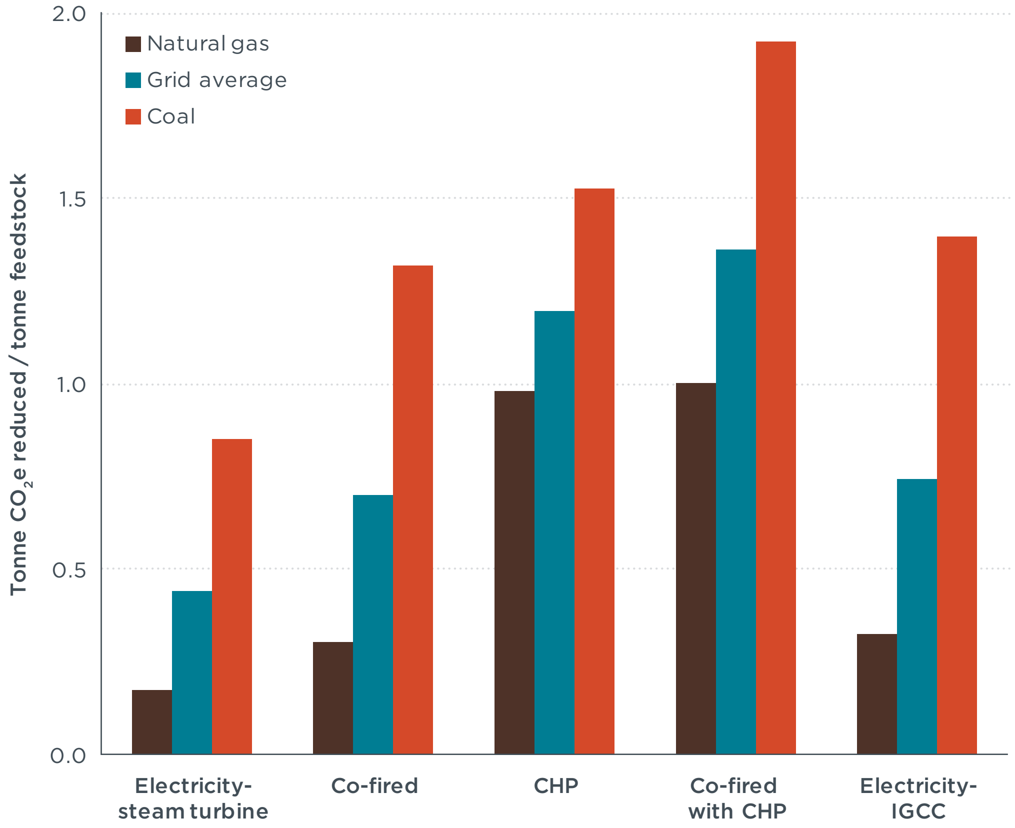

Figure 2.5. Average GHG reductions for three different electricity grid assumptions

Modifying the assumptions of the electricity grid's carbon intensity may also affect the GHG reductions for the liquid fuel pathways, though not to the same extent as the heat and power pathways. The model assumes that co-product electricity and biochar are used within a system in order to displace the electricity consumption of the production facility. The analysis used a conservative baseline assumption that the co-product electricity would offset efficient, natural gas-derived electricity. Altering this assumption so that exported electricity would instead displace electricity with a grid-average carbon intensity increased the GHG reductions for every pathway that either exported heat or electricity (including both CHP pathways, ethanol production, and Fischer-Tropsch diesel). As shown in Figure 2.6, the GHG reduction increases for liquid fuels are relatively minor—only 10% for ethanol and 6% for Fischer-Tropsch.

For the two CHP pathways, the analysis assumed conservatively that excess heat would displace CHP natural gas-derived electricity, as co-product heat is not necessarily exported to in all cases (i.e., if the demand is not there). Altering this assumption so that electricity from CHP generation displaced grid average or even coal emissions increased the total GHG emissions offset by co-product heat. Relative to liquid fuels, the increase for CHP pathways in this part of the sensitivity analysis is much more substantial, as the energy value of co-product heat produced from the process (and consequently, the potential amount of grid electricity displaced) greatly exceeds the amount of electricity produced. The GHG reduction benefit from CHP and co-firing with CHP increased by 62% and 47%, respectively, when grid-average electricity was displaced.

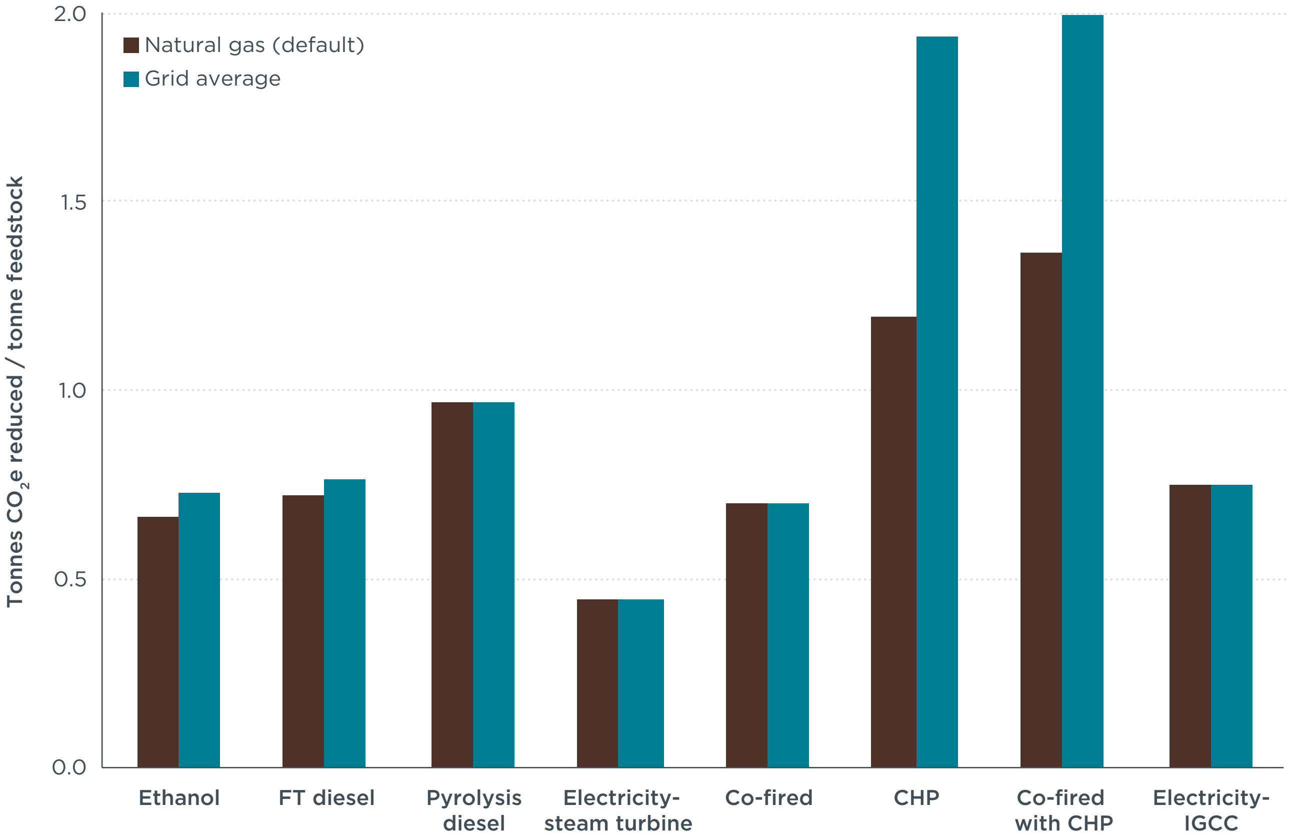

Figure 2.6. GHG reductions for liquid fuels pathways with different electricity export assumptions

Looking forward to 2050, as Europe's electricity grid is expected to decrease in carbon intensity, it could be argued that the relative benefits of biomass conversion to heat and power may decrease accordingly if increased biomass capacity were to continue to displace grid-average electricity. The EC's 2013 Trends to 2050 assessment of the future of the European energy grid projects that based on current trends, electricity supply should shift to a greater proportion of renewable sources by 2050. Table 2.7 provides an overview of how this shift will happen. It would have a large impact on the emissions reduction potential of heat and power pathways, reducing their net GHG reductions to only 43% of the average for the three liquid fuel pathways.

Table 2.7. Projected shares of electricity production in Europe in 2050

Power Source	Share of Electricity Production (%)
Solar and other Renewables	9
Wind	26
Hydropower	10
Biomass	8
Derived gases	1
Natural gas	18
Petroleum	1
Coal and lignite	7
Nuclear	21

Source: European Commission, 2013. Trends to 2050.

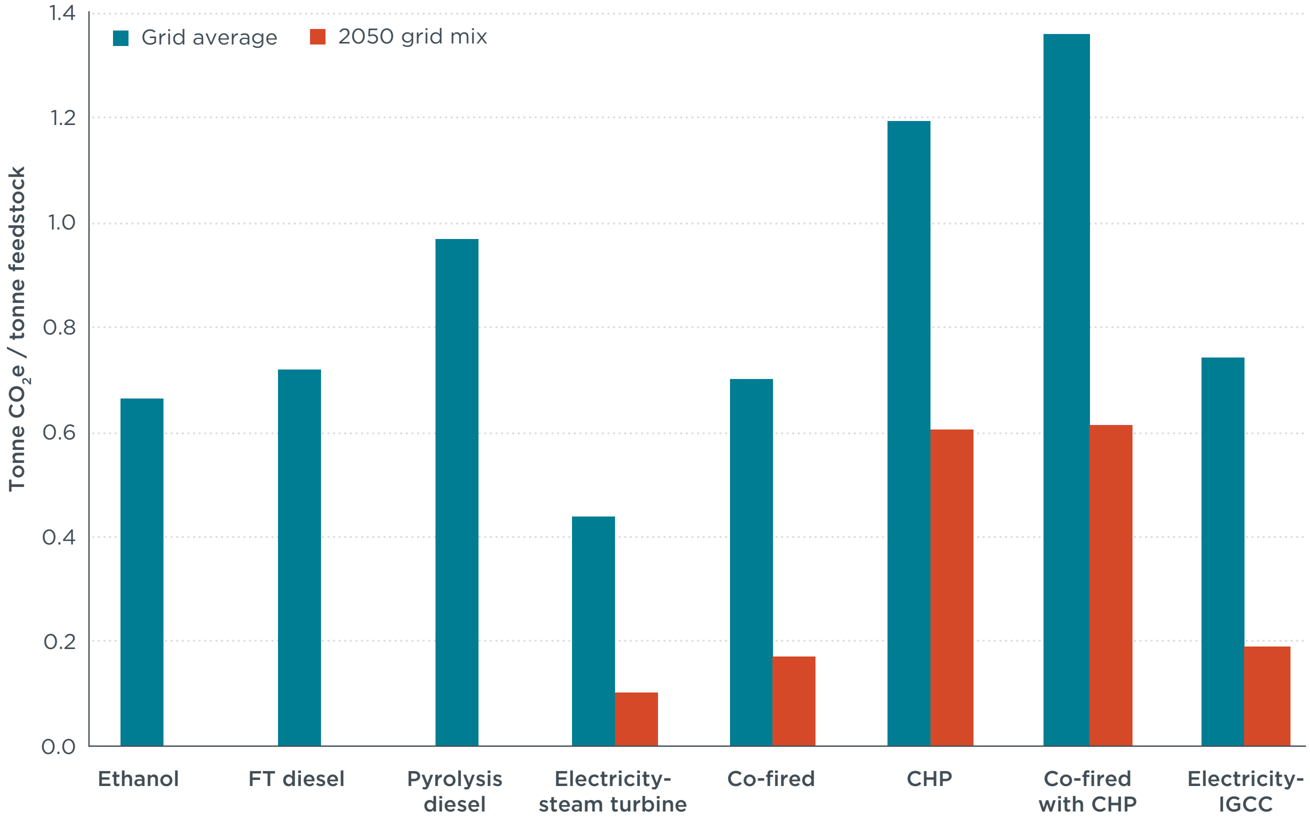

Figure 2.7. Comparison of GHG reductions averaged across feedstocks for current grid average carbon intensity and projected 2050 grid average carbon intensity

Allocation methods can have significant impacts on the performance-based metrics where co-products are produced in large quantities. Here, the impact of the four allocation methods on carbon intensity of advanced biofuels and electricity derived from wheat straw is examined. Impacts of differences in allocation methods can be pronounced when co-products are produced in large quantities.

A FT-diesel process produces renewable gasoline and electricity as co-products. Hence, the carbon intensities are different for different allocation methods (Figure 2.8). For example, the carbon intensity is lower using the hybrid-displacement method than with other allocation methods.

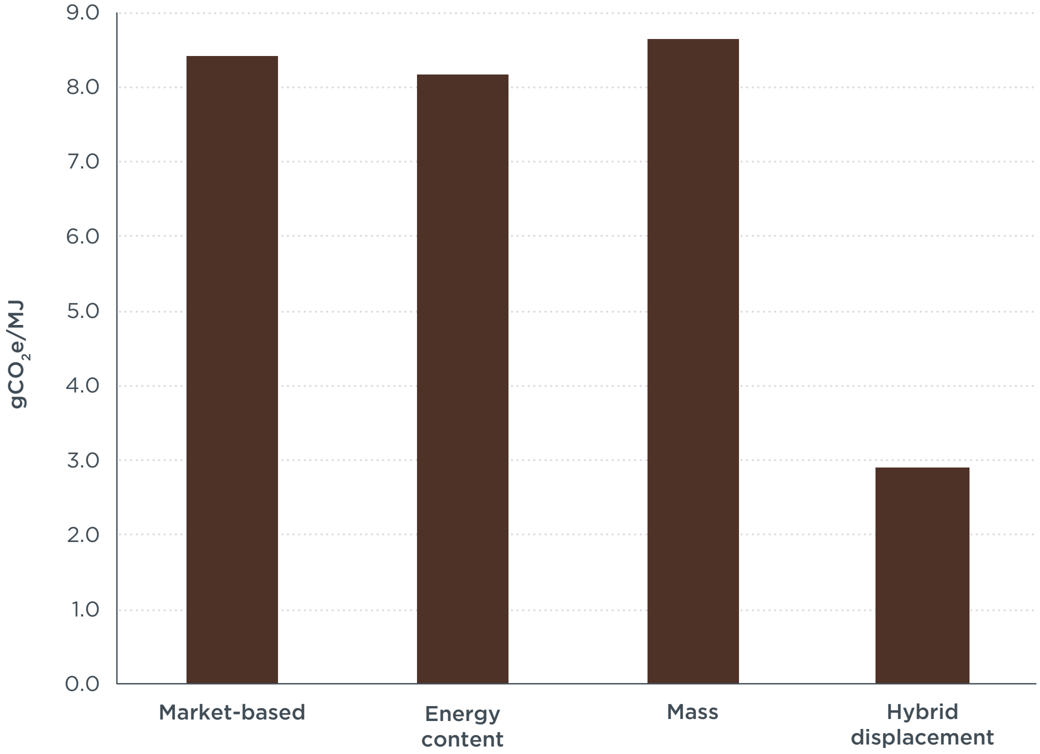

Figure 2.8. Life-cycle emissions for Fischer-Tropsch diesel from wheat straw, across allocation methods

The carbon intensity of wheat straw FT diesel is lower and the GHG reduction is larger for the hybrid displacement method, because the GHG emissions avoided by the use of co-product electricity and char within the system are significant. For the electricity and char used internally, the avoided emissions come from the displacement of the electricity produced from natural gas CHP.

The gross GHG emissions for wheat straw FT diesel after allocation between renewable diesel and renewable gasoline are 45.8 kg CO_2e per tonne of wheat straw processed, whereas avoided emissions associated with co-product electricity are 45.6 kg CO_2e per tonne of wheat straw processed. In the hybrid displacement method, this emissions offset is attributed to both co-products based on their energy values.

For the other allocation methods shown in Figure 2.8, emissions avoided by co-products are not factored into the carbon intensity and the gross emissions from a process are allocated among all products based on their share of mass, energy, or market value. The hybrid-displacement approach yields a carbon intensity of 2.9 gCO_2e/MJ, whereas the other approaches yield values ranging from 8.2 to 8.7 gCO_2e/MJ. The slight variation among the value-based approaches is due to the shifts in percentage shares of renewable diesel relative to other co-products on the basis of mass, energy content, and market value. These shares are 72%, 67%, and 69% respectively.

3. ECONOMIC IMPLICATIONS OF DIFFERING BIOMASS USE

Using biomass to produce liquid fuels, heat and power, or biochemicals/biomaterials could have widely varying economic implications depending on the production pathway chosen. In this chapter, we consider the implications of different biomass uses on job creation, improving the balance of trade, and overall economic activity. Because sustainably available biomass is a limited resource, we consider the comparative benefits of investing in different biomass utilization pathways.

3.1. SCOPE OF ANALYSIS

The economic impacts of using the available sustainable biomass vary according to how that biomass is used. The aspects that we analyze here are: employment creation, import displacement and impact on GDP, returns to rural communities, and capital and production costs. The pathways considered include biofuels, heat and power, and bio-based materials; the corresponding feedstocks consist of agricultural residues, forest and waste residues, and energy crops. The values in U.S. dollars and other currencies were converted to euros using an average exchange rate[18] for the year 2014 (Statista, 2015).

3.2. CONTEXT—ECONOMIC SIZE OF SECTORS

This section examines the economic size and contribution of the biofuels, heat and power, and biochemicals sectors. Biochemicals are discussed as an example of a potential growth sector within biomaterials more broadly. There is a focus within biochemicals on bioplastics and ethylene in particular, as examples of biomaterials for which useful data is available.

Scarlat et al. (2015) estimated the total contribution of the bio-based economy in the EU in 2012, in terms of annual turnover, value added, and employment, as shown in Table 3.1.

Table 3.1. Estimated contribution of the bio-based economy in the EU in 2012

Sector	Annual turnover (€ billion)	Value added (€ billion)	Employment (thousands)
Agriculture	404	157	10,200
Agro-industrial products	231	62	2,092
Forestry logging	42	22	636
Wood-based industry	473	136	3,452
Biochemicals	50		120
Bioplastics	0.4	1.4	
Biolubricants	0.4	0.6	
Biosolvents	0.4	0.4	
Biosurfactants	0.7	0.9	
Enzymes	1.2		
Biopharmaceuticals	30	50	142
Biofuels	16		132
Bioenergy	34		350
Total	**1,283**		**17,124**

Source: Scarlat et al. (2015)

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[18] 1.33 $/€ and 0.806 £/€.

Clever Consult (2010) did a similar assessment for the year 2009 in Europe, estimating the employment in biochemicals and bioplastics at 150,000 and the employment in biofuels at 150,000.

3.2.1. Liquid Biofuels

The existing biofuels sector in Europe is overwhelmingly dominated by first generation biofuel technologies. These technologies use food commodities and some wastes and residues as feedstocks—and as discussed in Section 1, most of these biofuels are outside of the scope of this report. However, the existing biofuels sector can be seen as a first-order indicator of the level of employment and other metrics that might be delivered by an advanced biofuel industry of a comparable size.

Observ'ER (2014) estimated the 2013 EU biofuel sector sales turnover at €14.3 billion with a workforce of around 100,000 people, taking into account the supply-side activities of the agricultural sector. Biofuel consumption for transport in the EU amounted to 13.2 Mtoe in 2013, with a breakdown of 20.2% bioethanol—in direct blends with gasoline or converted into ETBE (ethyl tertiary butyl ether—and 78.5% biodiesel. According to the data gathered by Observ'ER, biofuel accounted for a 4.6% share of fuel consumption in 2013 road transport in the EU. Figure 3.1 shows the primary production of biofuels.

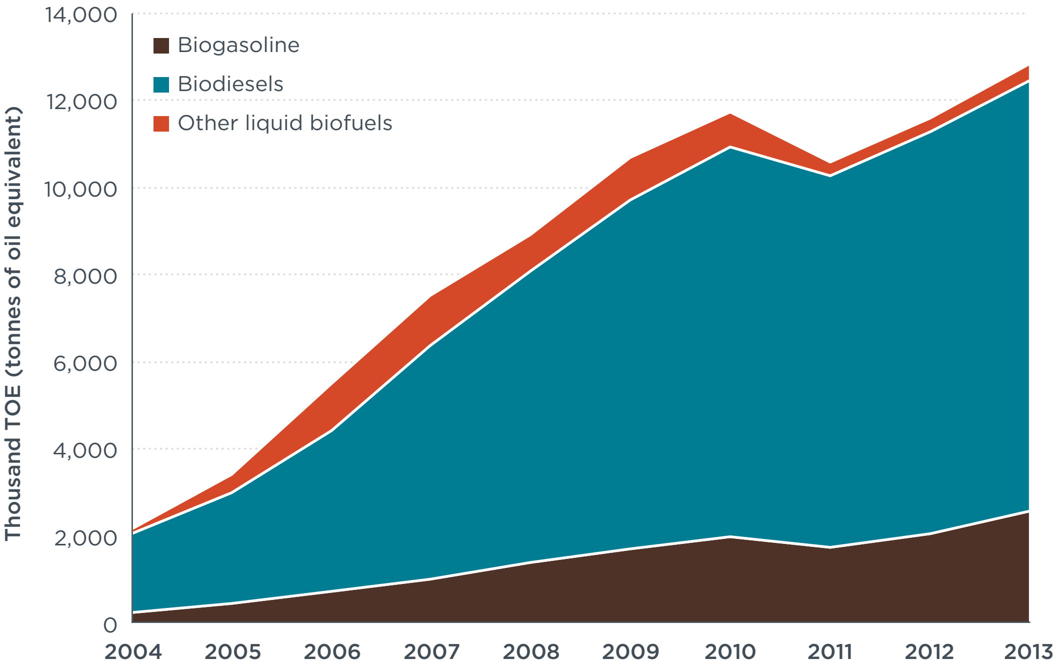

Figure 3.1. Primary production of liquid biofuels in EU-28

Source: Eurostat (2015c)

The EU accounts for about 5% of global ethanol production using mainly grain starch and beet sugar as feedstocks. The EU is the world's leading biodiesel producer: Of the 0.4 million barrels per day of biodiesel produced globally in 2011, around 0.2 million were produced in the EU (IEA Bioenergy, 2014). The EU represents 44% of global biodiesel production, but is also the main importer of biodiesel; the main exporting countries are Argentina, Indonesia and Malaysia (JRC, 2015).

The global production of second-generation ethanol is still very low. In 2014, four new 2G facilities became operational with a combined nameplate capacity approaching

300,000 tonnes/year. The feedstocks include bagasse, straw, corn stover, *Arundo donax*, and waste from the food industry (BIO-TIC, 2015b). Additional facilities have come online since then, and the sector has potential for rapid growth.

3.2.2. Heat and power

The primary energy production from solid biomass in heat and power (including wood, wood waste, wood pellets, black liquor, bagasse, animal waste, and other plant matter and residues) in the EU was estimated in 2013 at 88.4 Mtoe, with a turnover of €36 billion and a work force of 315,000. The work force of the municipal waste-to-energy recovery sector was estimated at around 15,500 jobs (Observ'ER, 2014). In 2012, wood and solid biofuels accounted for 47.2% of total primary energy produced by renewable energies in the EU (Eurostat 2014).

3.2.3. Bio-Based Materials

The total annual turnover related to bio-based materials in Europe was estimated by EUBIA (2014) at €21 billion in 2008, and €32 billion in 2014. The related impact on employment was estimated to be around 39,000 jobs.

3.3. IMPACT ON EMPLOYMENT

This section analyses the impact on employment for competing uses of sustainable biomass feedstocks. A variety of liquid fuel and biomaterial pathways are considered. These include the use of agricultural and forest residues to produce biochemical ethanol or thermochemical drop-in fuel; the use of RDF to produce thermochemical drop-in fuel; and the production of three bio-based materials: succinic acid, PLA, and ethylene derived from ethanol.

A key distinction between employment generated by different biofuel pathways relates to the role of agricultural employment (NNFCC 2013). In general, where feedstock acquisition requires additional farming (biomass crops) or additional collection of agricultural materials (agricultural and forestry residues), the employment impacts are much higher in feedstock acquisition than in fuel processing. Advanced biofuel pathways based entirely on wastes or residues that are already collected (e.g., municipal waste) are therefore likely to deliver much less employment than many first generation pathways.

Data were taken from surveys, literature reviews, and estimates published by manufacturers. Generally, the types of employment considered are divided in two categories: direct and indirect employments. The distinction between permanent and temporary jobs is also sometimes made; in that case, the temporary jobs are employment during projects' construction phases, and the permanent jobs are all the others.

There is some disagreement in the literature as to what constitutes direct versus indirect employment. For example, employment related to feedstock provision is considered direct by Thornley et al. (2014), but indirect by IISD (2013). Thornley et al. (2014) have defined the terms of direct and indirect as follows. Direct employment consists of:

- Design and construction phase: Employment at the facility during the design and construction phases
- Plant operation: Direct employment at the facility during operation
- Feedstock provision: Labor input required to process and deliver the feedstock directly to the plant

On the other hand, Thornley et al. (2014) defines indirect employment (also called induced employment) as:

- Upstream supply chain employments: Manufacturing industries supplying the plant, service industries in repair and maintenance
- Induced employment created by additional economic activity from the direct employment

Another approach by the IISD (2013) is to classify the biofuel-related jobs into the following categories:

- Direct employment: Those employed by the project itself
- Indirect employment: People employed to supply inputs to the project or sector
- Induced employment of type 1: People employed to deliver goods and services to meet additional consumption occurring from directly and indirectly employed workers
- Induced employment of type 2: Where increasing prices for transportation reduces consumption and hence production and employment in these sectors

Several sources do not always clearly define which categories are included in their assessments of employment. However, most of them make the distinction between direct and indirect jobs, even though they do not clearly define direct and indirect jobs as explicitly as the two studies described above. In our analysis, we aggregated the data where it was possible to make a distinction between operational, feedstock, and construction (temporary) jobs, instead of using terms such as "direct" and "indirect" which can be confusing and have different meanings according to the author. The aggregated employment results are presented in Figure 3.2.

Our analysis incorporates estimates of employment impacts, which are converted into values of jobs per million tonnes of dry matter (tdm), in order to facilitate the comparison between different pathways. This was done using conversion factors for different pathways, which are illustrated in Table 3.2.

Table 3.2. Conversion factors

Pathway	Value	Unit	source
Agricultural residues—biochemical ethanol	3.25	Tonne feedstock/tonne fuel	Ecofys, 2015
Agricultural residues—thermochemical drop-in (Fischer-Tropsch conversion)	4.5	Tonne feedstock/tonne fuel	Ecofys, 2015
Forest—biochemical ethanol	3.25	Tonne feedstock/tonne fuel	Ecofys, 2015
Forest—thermochemical drop-in	4.5	Tonne feedstock/tonne fuel	Ecofys, 2015
RDF—thermochemical drop-in	6.3	Tonne feedstock/tonne fuel	Searle et al., 2015
Succinic acid	2.5	Tonne feedstock/tonne succinic acid	S2Biom, 2015
PLA (polylactic acid)	2.5	Tonne feedstock/tonne PLA	S2Biom, 2015; Gerssen-Gondelach et al., 2014
Ethylene from ethanol produced from agricultural residues	6.9	Tonne feedstock/tonne ethylene	S2Biom, 2015

3.3.1. Employment by Sector

A variety of literature sources have attempted to quantify the employment associated with various bio-based industries in Europe. This section provides an overview of different estimates of employment impacts by industry and considers the factors that drive the differences. Because the processing of second-generation biomass feedstocks (e.g., wastes and residues) has not been commercialized thus far, we include literature that considers the employment generated from the production of first-generation biomass products from starchy biomass and energy crops. Where possible, job impacts are divided into direct employment at the operation of the plant, employment for the collection and transport of feedstock, and temporary construction jobs. The findings from each study are then harmonized to show results in units of jobs created per million tonnes of feedstock. We anticipate that estimates of employment for first-generation biomass would represent a conservative, lower-bound estimate for job creation, as processing and collection job creation should be similar for second-generation biomass feedstocks. However, wastes and residues would not generate employment within the agricultural production sector.

According to JRC (2015), there are two types of studies on the effects of biofuels on employment. The studies that account for the increase in taxation or in transport fuel prices to support biofuel supply conclude that employment effects are neutral or even negative (they also find a negative net welfare benefit). In contrast, JRC argue that the studies that consider biofuel subsidies funded by public spending increases without a corresponding increase in taxes (i.e., deficit spending) show a significant gain in employment. Employment estimates are also sensitive to the choice of counterfactual. JRC note that if employment in first generation feedstock cultivation is treated as additional this gives a very different employment answer than if it is assumed that much of the material would have been still produced but for export markets in the alternative case. The first question, net impact on employment across the economy, could only be addressed by a broader economic analysis than we present here, including counterfactuals on jobs supported by fuel production in the fossil sector, or by alternative materials production, and assumptions about overall changes in global energy supply related to increased biomass use. It should be assumed that the gross number of jobs supported by an emerging biomass technology will represent an upper limit on the potential to support net job creation. The second issue, additionality of jobs in the supply chain, will generally be less relevant to the biomass use pathways considered in this report. In general, we are not discussing resources that are already being produced or collected, and therefore putting in place new sustainable biomass cropping systems or new residue and waste collection and handling systems will require genuinely new jobs to be created.

The International Renewable Energy Agency (IRENA, 2015b) gives the following estimates for the gross employment (direct and indirect jobs) in the biomass sector, for all feedstocks, in Europe in 2013: biomass for heat and power generation (excluding biogas) supported 342,100 jobs; liquid biofuels 98,000 jobs; and biogas 66,000 jobs. The employment estimate for the liquid biofuel sector in the EU 28 given by Observ'ER (2014) is approximately the same: 98,900 jobs.

The nova-Institute (2015a) estimated the total feedstock demand for EU biofuels (first-generation) to be around 26.8 million tdm (16.5 million tonnes of plant oil for biodiesel and 10.3 million tonnes of sugar/starch for bioethanol), and the total direct employment for the manufacture of biofuels to be around 23,000 (19,000 for biodiesel and 4,000 for bioethanol). This corresponds to 860 jobs per million tdm of feedstock (1,150 jobs per million tdm for biodiesel, and 390 jobs per million tdm for ethanol), only for the manufacture of biofuels. When including the employment generated in agricultural production, their estimation amounts to 6,500 jobs per million tdm of feedstock for biofuels. Assuming that the employment per tonne ratio is similar for second-generation biomass feedstocks (excluding agricultural production), we extrapolate that the 156 million tonnes of feedstock sustainably available per Searle and Malins (submitted) could support as many as 134,000 jobs for the manufacture of biofuels.

A study by the NNFCC (2013) concluded that if all the available residual resource could be utilized for biofuel production in the EU, this would create between 147,000 and 307,000 additional full-time jobs, 38–43% of which would be primarily in the rural community and associated logistics companies. These represent only the direct employment associated with feedstock collection, transport, and processing. For feedstock collection, the estimated ranges are 470-680 jobs per million tonnes of agricultural residue, and 340-620 jobs per million tonnes of forest residue. Based on these results, Searle and Malins (2015) estimated a potential for up to 130,000 permanent jobs and 350,000 two-year construction jobs in 12 EU countries, with a considerable variation across the analyzed countries.

The Advanced Ethanol Council (AEC, 2013) provided an overview of the cellulosic biofuel production facilities operating commercially in the U.S. in 2013. The feedstocks used include agriculture and forestry residues, municipal solid waste, and energy crops. When given in jobs per million tonnes of feedstock, the values range from 150 to 490 jobs per million tonnes of feedstock for the operational jobs at the plant, and from 770 to 4,000 jobs per million tonnes of feedstock for the construction jobs.

According to a survey done by E2 Environmental Entrepreneurs (2012) for 24 advanced biofuels (biodiesel, cellulosic ethanol, drop-ins from non-food sources) commercial facilities in the United States, a million gallons of production capacity is expected to generate on average 2.24 permanent jobs, 10.29 construction jobs, and nearly 15 indirect jobs (which include feedstock production). Converting those values to jobs per tonne of feedstock gives 230 operational jobs at the plant (excluding feedstock delivery), 1060 construction jobs, and 1540 indirect jobs (including feedstock production) per million tonnes of feedstock.

Hodur et al. (2009) estimated the economic impact of a biorefinery for lignocellulosic ethanol production, using an economic-engineering model originally developed by the U.S. National Renewable Energy Laboratory (NREL). They calculated that a cellulosic plant has direct economic impacts (i.e., expenditures to in-state entities) that are more than three times those of a conventional corn ethanol plant, with nearly twice as many direct employees (excluding the employment in harvest and transportation of feedstock), five times the number of secondary workers (the article does not define what secondary employment means), and double the construction costs. Feedstock collection and transportation were a major reason why the impact is far greater for cellulosic ethanol, because of the high volume of feedstock necessary to fuel the plant. The authors did not include the purchases of corn in the assessment, considering that the corn would otherwise have been sold to markets outside the state. According to the authors, other studies have shown that the local economic impacts of corn-based ethanol facilities are small for this reason.

A study by Thornley et al. (2014) estimated that in general, wood biorefineries result in higher levels of employment than straw-based facilities, but the study includes employment in forestry (weighted by forest product value), whereas no straw production employment has been included (only collection and transport of straw feedstock). The study points out that the jobs estimated are not independently self-sustaining, but rather enhance the viability of existing arable farming or forestry activities. Compared with a previous article focusing on the electricity pathway (Thornley et al., 2008), the study estimates that the most economic biorefineries create two to five times as many jobs as the straw-to-electricity pathway. Assuming an operational lifetime of 25 years for the plants, the job creation values estimated by the two studies correspond to values of 820 jobs per million tonnes of feedstock for the straw-to-electricity pathway, and 2,000 to 4,100 jobs per million tonnes of feedstock for the biorefineries (liquid biofuel and biochemicals pathways). The report concludes that biorefineries would be very attractive from an employment creation perspective, primarily due to the higher capital investment associated with the technology. The study also estimated that about one-third to one-half of jobs created are long-term and that there is generally more job creation impact in the agriculture sector than the engineering sector (the study does not define what sort of employment the engineering sector includes), although straw-based plants have higher engineering impact.

Some studies have compared the employment potential of bio-based products with that of bioenergy and biofuels. For example, Sormann (2012) reported that, in Flanders, bio-based products (such as paper, bioplastics and biochemicals) create five times more added value (based on gross margin calculations) and ten times more employment than bioenergy (electricity or heat and biofuels).

Similarly, Carus et al. (2011) reported that the production and use of bio-based products (renewable raw materials) can directly support five to ten times more employment and four to nine times the value added (per mass flow or hectare) compared to the production and use of bioenergy, principally because of longer, more complex supply chains associated with the production of bio-based products.

According to a report by the OECD (2013), policy approaches that do not favor the production of bioenergy and biofuels over other potential outputs are needed to stimulate the development of higher added-value products and the more extensive employment opportunities associated with their longer value chains.

In a communication from the EU Commission (2005), it was estimated that in terms of direct employment, biofuels (first generation) are typically 50-100 times as employment-intensive in the EU as fossil fuel alternatives; biomass electricity 10-20 times as employment-intensive; and biomass heating twice as employment-intensive. This would mean that biofuels are 25-50 times as employment-intensive as biomass heating, and five times as employment-intensive as biomass electricity. However, these comparisons may include the impact of agricultural production on job creation and thus may overstate the impacts of biomass utilization relative to fossil fuels. The document points out that regarding the indirect effects, commentators are divided: Some point to multipliers or export opportunities which could double the size of the direct effect, while others argue that jobs in bioenergy will replace other jobs and the net employment effect will be zero.

The nova-Institute (2015a) also estimated that employment based on the same amount of biomass input is about 8 times higher for bio-based chemicals compared to biofuels (first generation) if only the manufacturing stage is taken into account. If agricultural production is also considered, this factor decreases because employment in agriculture per tonne of biomass can be considered the same for both sectors. In that case, the employment per million tonnes of biomass is only twice as high for chemicals than for biofuels. When considering only non-food-based feedstocks, the employment potential at the production site could potentially be higher due to the more advanced technologies employed in the sector. Likewise, temporary construction jobs could increase because of higher spending. However, agricultural production employment would be lower.

We collected data on the employment generated in the different sectors, and adapted the classification proposed by Thornley et al. (2014) as explained above, i.e., dividing into the categories of "construction," "operations," and "operations plus feedstock provision." The values for the different pathways are presented in Figure 3.2. The blue category in the figure includes both operations and feedstock provision jobs, because in those cases, the literature provided only the values for both categories, and not separately.

Figure 3.2. Employment per million tonnes of feedstock for different biomass utilization strategies

As a general trend across pathways, the largest share of jobs created is temporary and occurs during the construction phase of the plants. NNFCC (2012) also noted that, in the bioenergy sector in the United Kingdom, a large proportion of the employment occurs during the construction and commissioning phase of plant development.

The employment created by collection and transport of feedstock represents the largest share of permanent jobs. This suggests that the use of residual biomass provides a potential for rural development. As pointed out by OECD (2014), there are valid reasons for locating biorefineries in rural environments, since this allows them to be as close as possible to the main agricultural or forestry areas. An example regarding the returns to rural communities is given by NNFCC (2013), which assessed that biofuels production from agricultural and forestry residues could generate a net revenue to agriculture and forestry land owners of between €900 million and €7.5 billion annually, if the costs of replacement fertilizer and transport are accounted for and assuming all labor and costs for straw collection are borne by the landowner.

NNFCC (2012), in a study related to employment in the bioenergy sectors in the UK, noted that there is also significant uncertainty in the labour intensity of this sector as supply chain structures can vary considerably. For example, if a feedstock is used in its raw form within 20 miles of where it is grown, then far fewer people will be employed than if it was processed intensively and/or transported 200 miles to the end user.

There is no clear trend from the literature when comparing the estimates for employment per tonne of feedstock between biofuels and energy (heat and power). Despite this, the consensus in the literature is that a larger workforce is associated with the biofuels pathways for a variety of reasons, including more advanced and capital-intensive conversion technologies.

For biofuels and bioenergy, the numbers of operational jobs at the plant do not seem to be strongly affected by the plant size. This was also pointed out by NNFCC (2013) in the case of advanced biofuels, and explained by the fact that automation and increased storage, treatment, or fermentation capacity do not have a concomitant increased labor demand. The report indicated that the number of full-time employees in an advanced biofuel plant is likely to range between 30 and 80. We observed a very similar range in the literature (30 to 70 employees for cellulosic ethanol plants), and a range of 15 to 150 employees in bioenergy (heat and power) plants.

The data on employment in bio-based chemicals is very scarce; additionally, all of the values included in this analysis are based on production from sugar feedstock—no biochemicals production from cellulose occurs on a commercial scale at the moment. Another high uncertainty arises from the conversion factors used to convert the values reported in jobs per tonne of product to jobs per tonne of feedstock. For example, the conversion factor for succinic acid is based on lignocellulosic biomass, but the succinic acid in that case is produced from glucose feedstock. Therefore the values in this chart should be considered as illustrative only. However, several of the studies described above agree that there is generally more employment associated with biochemicals than with biofuels, and it seems reasonable to assume that in general the processes required to produce biochemicals and bioplastics will require more labor than the chemically simpler processes to produce biofuels.

3.4. IMPORT DISPLACEMENT

More than half of the EU-28's energy comes from countries outside the EU (Eurostat 2015a). The European Commission (2014b) communication on the European Energy

Security Strategy, published in May 2014, highlights an objective to reduce reliance on fuel imports to the EU. There are also concerns in some quarters about the potential economic and political impact of the threat to energy supplies and fuel price stability posed by conflicts and potential conflicts in the Middle East and on the eastern borders of Europe (European Biofuels Technology Platform).

The European Commission (2013a) has stated that Europe spends the equivalent of €406 billion (3.2% of GDP) on imports of oil, gas and coal every year, and that Europe's import dependence is set to grow to more than 80% for both oil and gas by 2030 (see Figure 3.3).

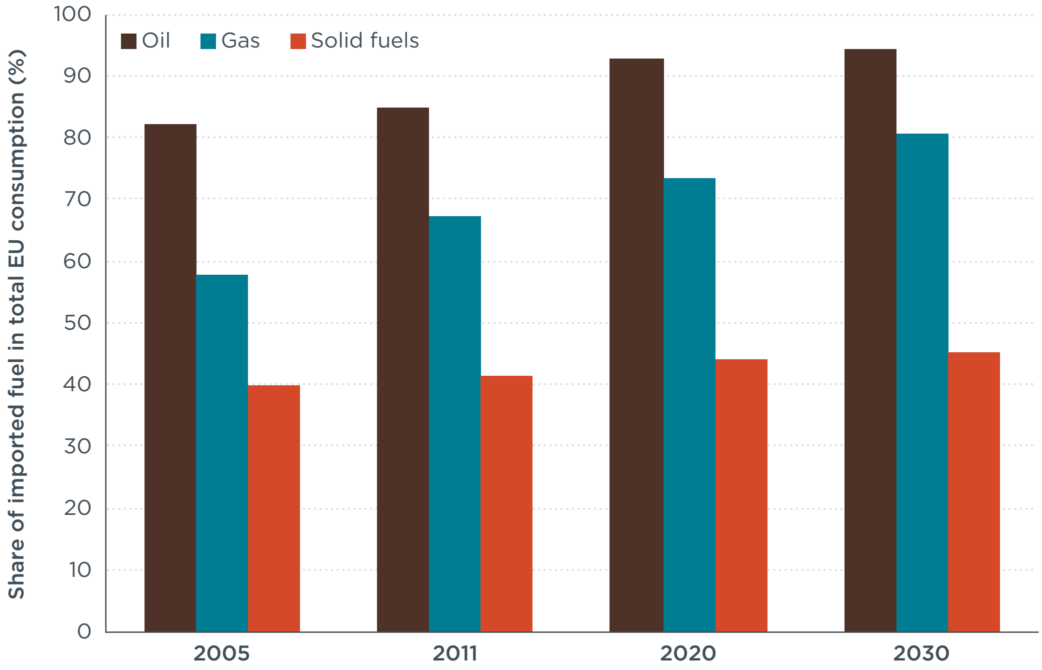

Figure 3.3. Share of imported fuel in total EU consumption ("business as usual" scenario)

Source: European Commission (2013a)

For biomaterials, we again focus on the case of biochemicals as an example. While Europe is a net importer of energy, it is a net exporter of chemicals. In 2013, the extra-EU (outside the European Union) trade surplus of chemicals amounted to €48.7 billion; see Figure 3.4 below (Cefic 2014). Therefore, while increased bioenergy supply is likely to reduce imports, increased biochemicals production may be more likely to increase exports (depending on the extent to which the bioeconomy supplements rather than replaces existing chemical industries). Both import reduction and export increase contribute to increasing the European trade surplus, but import reduction is generally given a higher policy priority. Surpluses and deficits in other materials that could be replaced by biomaterials production (e.g., construction material) are not associated with the level of policy attention given to energy security. On the question of balance of trade, therefore, energy applications of biomass are likely to be seen as more beneficial than chemical and material uses.

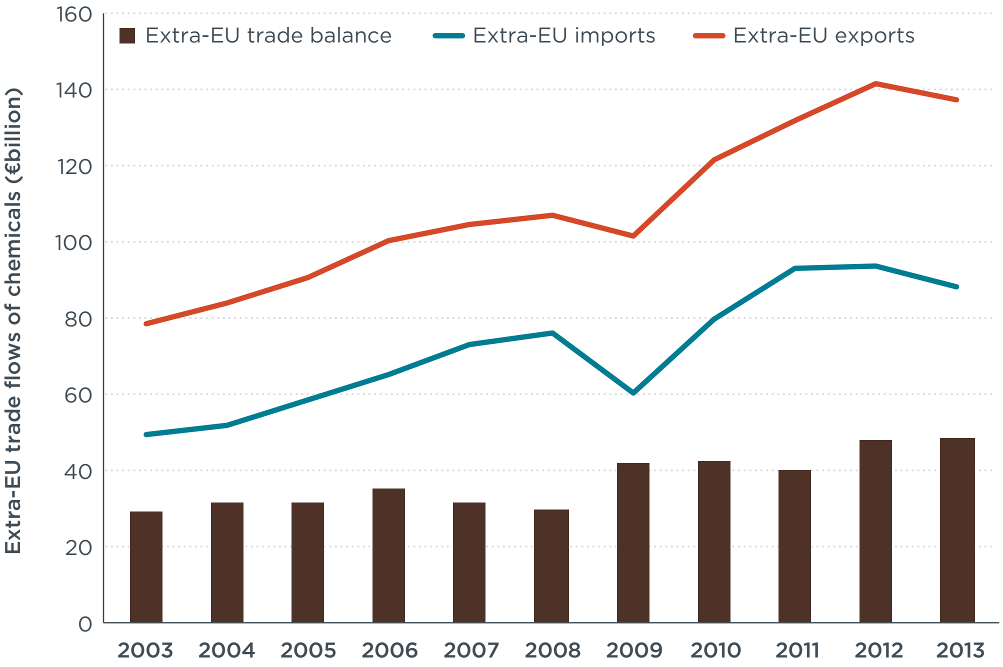

Figure 3.4. Extra-EU28 chemicals trade balance (excluding pharmaceuticals)

Source: Cefic (2014)

3.4.1. Import Displacement—Liquid Fuels

Biofuels can reduce fossil petroleum use by displacing the crude oil needed to manufacture gasoline and distillate fuels (diesel and jet fuel). For regions such as Europe that are net oil importers, this can reduce dependence on foreign oil, which some stakeholders see as a policy goal in its own right. In this regard, biofuels can be said to improve energy security.

Several authors have given estimates of the benefits of oil displacement resulting from the production and use of biofuels. Most of those estimates are based on first-generation biofuels, and do not take into account the fact that the domestically produced biomass that was used to produce biofuels could have been exported instead in the absence of incentives (contributing to the trade balance, if not directly to energy security). This particular issue is less relevant for waste and residues, considering that they were underutilized in the first place.

Cardno ENTRIX (2012) estimated that the global production of 110.8 billion liters of ethanol and biodiesel in 2010 would have displaced the equivalent of 1.2 billion barrels of crude oil, valued at $135.4 billion at 2011 prices. The report states that the impact of biofuels on displacing crude oil has a positive effect on the balance of payments and international financial health of net oil importers. The authors calculated that, without the production of biofuels, the current account deficits[19] of the net oil importers countries would have been 14% higher for the year 2010. These net oil importers countries produced the equivalent of 821 million barrels of crude oil in the form of biofuels valued at $91.3 billion. For EU-27, the estimate is at 6.3% for the biofuel share of oil trade deficit in 2010.

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[19] The current account records a country's net trade in goods and services, plus net earnings from rents, interest, profits, and dividends, and net transfer payments (such as pension funds and worker remittances) to and from the rest of the world (Cardno ENTRIX 2012).

Thornley et al. (2014) have estimated the impact on GDP in Europe from biorefineries of a scale of 500,000 tonnes/year based on straw and wood feedstocks. They estimated that the most economically viable biorefinery configurations could result in increased trade in biorefinery products of 0.002% to 0.057% of national GDP for a single biorefinery in the analyzed countries (Germany, Netherlands, UK, Spain, Poland). If the cumulative impact of establishing several biorefineries is taken into account, there is potential for a modest impact on trade. For example, the UK would have a potential for up to nine straw-based systems and one wood-based system, which would result in a trade impact of around 7% of agricultural GDP and 0.1% of national GDP from traded biorefinery products.

While biofuels could be said to improve energy security, the IISD (2013) argued that this kind of analysis is overly simplistic, because just as a range of factors contribute to the security of supply of crude oil at any given time, biofuels have security-of-supply issues that must be taken into account. Besides, the report states that the role of biofuels has been so far limited in terms of improving the energy security in Europe. In 2012, biofuels produced in the EU met about 4 per cent of the demand for motor fuels (5% if imported biofuels are included). Their estimate is that the EU's biofuel production in 2012 replaced the output of two or three large fossil-fuel refineries, reducing EU expenditure on petroleum products by €2.7 billion on gasoline and €8.5 billion on diesel.

Similarly, Brannigan et al. (2012) concluded that biofuels were unlikely to be a major contributor to the long-term energy security of the EU. Using a scale indicator derived from a multi-criteria analysis for energy security in the transport sector, they estimated that biofuels score better than natural gas, gasoline, diesel, and LPG, but lower than electricity (as a fuel for electric vehicles), hydrogen and energy demand reduction initiatives. The study assessed the quality of different fuels in terms of energy security, which includes criteria of sufficiency, affordability and sustainability, over the period 2010 to 2050. The study argues that electricity and hydrogen fuels become more secure in the long term because of increased contributions from renewable technology production. On the other hand, biofuels show a reduction in energy security in the long term, because they could potentially:

- Increase resource concentration, based on a prediction that resources will be highly concentrated in North, South, and Central America (particularly in the United States and Brazil);
- Lower resilience to supply disruptions; and
- Lack of surplus supply capacity over demand.

The issue on resource concentration might not be applicable to second-generation biofuels in Europe. However, according to the amount, type, and availability of waste and residues used to produce biofuels, the two other risks might have some pertinence. As pointed out by IRENA (2013), advanced biofuels will be less sensitive to variations in feedstock prices, and will also be able to secure biomass feedstocks in long-term contracts that also significantly reduce the feedstock price volatility compared to conventional food-based feedstocks.

More optimistically, Bloomberg (2010) estimated that by 2020 the EU27 could theoretically generate up to €31 billion internally by displacing 62% of its fossil gasoline consumption with next-generation ethanol. This is based on an assumption that by 2020, the EU27 region builds the biorefinery capacity to annually produce 90 billion liters, from an available 270 million tonnes of biomass. Clearly, the required expansion of cellulosic ethanol capacity to deliver such volumes by 2020 has not taken place, so this estimate should be considered only as an indicator of what a longer-term supply growth might achieve. Furthermore, the estimated overall biomass availability of 270 million tonnes is higher than other estimates, such as the 155 million tonnes of waste and residues estimated by Searle and Malins (submitted).

3.4.2. Import Displacement of Oil from Advanced Biofuels

In the ILUC legislative resolution of 28 April 2015, the European Parliament (2015) provides an indicative sub-target of 0.5% of transport energy demand to be met with advanced biofuels by 2020. Assuming that this target is met with advanced biofuels in 2020, the resulting displacement of crude oil can be estimated.

JRC (2014) estimated the total transport energy demand in the EU27+2 in 2020; the lowest estimate is 376 Mtoe (see Table 3.3 below). Under the assumption that 0.5% of this total is provided by advanced biofuels, this corresponds to an energy content of 79 PJ, or 13.7 million barrels of oil (with a crude oil density estimated at 32.9º API in Europe in 2015 (Cerić 2012)). With an assumption given by the World Bank for the average price of crude oil in 2020 at $62.70 per barrel (in real 2010 dollars) (World Bank 2015), or about €47 per barrel, this means that the displacement of crude oil with advanced biofuels could be valued at €648 million.

Table 3.3. Total transport energy demand projections [Mtoe] in EU27+2

2010 Eurostat	2020 JEC (2011 JEC study)	2020 DG TRen (2011 JEC study)	2020 JEC (2013 JEC study)	2020 DG ener (2013 JEC study)
381	390	439	376	395

Source: JRC (2014)

3.4.3. Import Displacement of Coal and Natural Gas from Electricity Generation

In this section, we assume that all the feedstock used to produce the 0.5% share from advanced biofuels is used instead to generate electricity, displacing coal or natural gas. We then estimate the potential value of this displacement.

The 0.5% of the estimated total transport energy demand in 2020 (376 Mtoe) corresponds to an equivalent volume of ethanol of 3.7 billion liters. Assuming a conversion rate of 3.25 tonnes (dry mass) of feedstock per tonne of ethanol (see Table 3.2), meeting the 0.5% target for Europe would require about 9.5 million tonnes of agricultural residues. This represents about 11% of the estimated 83 million tonnes of current yearly available crop residues in the EU (Searle and Malins, submitted).

If this amount of feedstock was used to generate electricity, it would produce 10 TWh, assuming that wheat straw has an energy content (LHV) of 17.2 MJ/kg (ECN, 2011), and an electric efficiency of 22% (LHV) for the stoker boiler/steam turbine technology (Wang, 2013). Those 10 TWh represent about 0.30% of the estimated total electricity generation in the EU in 2020: 3,300 TWh estimated by the European Commission (2013b).

The value of 10 TWh of electricity can be provided by a mass of 4.7 million tonnes of coal, assuming an efficiency of 0.47 tonne/MWh (EIA, 2015). With an estimated price of coal in 2020 at $93.50 (or €70) per metric tonne (DECC, 2014), this means that the displacement of coal could be valued at €329 million. Regarding the price of coal, Euracoal (2013) points out that "coal prices today still reflect a period of tight supply and it is difficult to predict future prices. However, in its outlooks, the IEA assumes real coal prices will rise steadily over the next twenty years to reach 10% to 20% above the 2012 average."

The 10 TWh of electricity can also be provided by a quantity of about 103 million mmbtu of natural gas, assuming a thermal efficiency of 33% (0.0101 Mcf/kWh) (EIA, 2015). With an estimated price of natural gas in 2020 at $7.20/mmbtu (in real 2010 dollars) (€5.4/mmBtu) (World Bank, 2015), this means that the displacement of natural gas could be valued at €558 million.

Alternatively, if the electricity from biomass was produced with a more advanced technology such as IGCC, with an electric efficiency of 35% (Wang 2013), the electricity produced would amount to 16 TWh. Following the same reasoning as above, the results give higher displacement values for coal (€525 million) and for natural gas (€892 million). The higher associated value is due to the fact that, IGCC having a higher efficiency, the amount of fossil fuel it would displace is higher than with a less efficient technology like stoker boiler.

3.4.4. Import Displacement—Bio-Based Chemicals

Depending on whether bio-based chemicals complement existing fossil-based production or are substituted for it, it could be argued either that the production of bio-based chemicals displaces imports of fossil fuels used as petrochemical feedstock, or that bio-based chemical production solely increases exports—or, perhaps most likely, some combination of the two.

For example, ethylene is mostly produced through steam cracking of hydrocarbons. In Western Europe, naphtha and condensates provided 41,000 kilotonnes, or about 68%, of the feed to the ethylene crackers in 2014 (see Figure 3.5). In 2008, Europe was a net importer of naphtha, with about 8 million tonnes imported (European Commission, 2010). However, recently the closure of several small steam crackers has reduced naphtha consumption. Ethane competes with LPG and naphtha as a feedstock for the chemical industry. Ethane is generally cheaper, but cracking crude oil-based feedstocks such as naphtha yields co-products including propylene, butylene, and butadiene, as well as the aromatic products benzene, toluene, and xylene (Lloyd's Register, 2014). According to CONCAWE (2013), the declining EU demand for gasoline is expected to provide a surplus of refinery-produced naphtha, which eliminates the need for imports as petrochemical feedstock. The study estimates that 2.5 million tonnes per year of ethane would be imported as steam cracker feedstock in the period 2010 to 2030. Nexant (2014a) also estimated that imports of U.S. ethane would grow to 2-3 million tons per year from 2015. However, currently only 3% of European crackers use ethane, which amounts to 50,000 barrels per day of ethane consumption (ICIS News 2014), and ethane is difficult to transport due to its low boiling point and high vapor pressure, while naphtha is highly available in Europe and is much easier to transport across long distances (T.A. Cook, 2014).

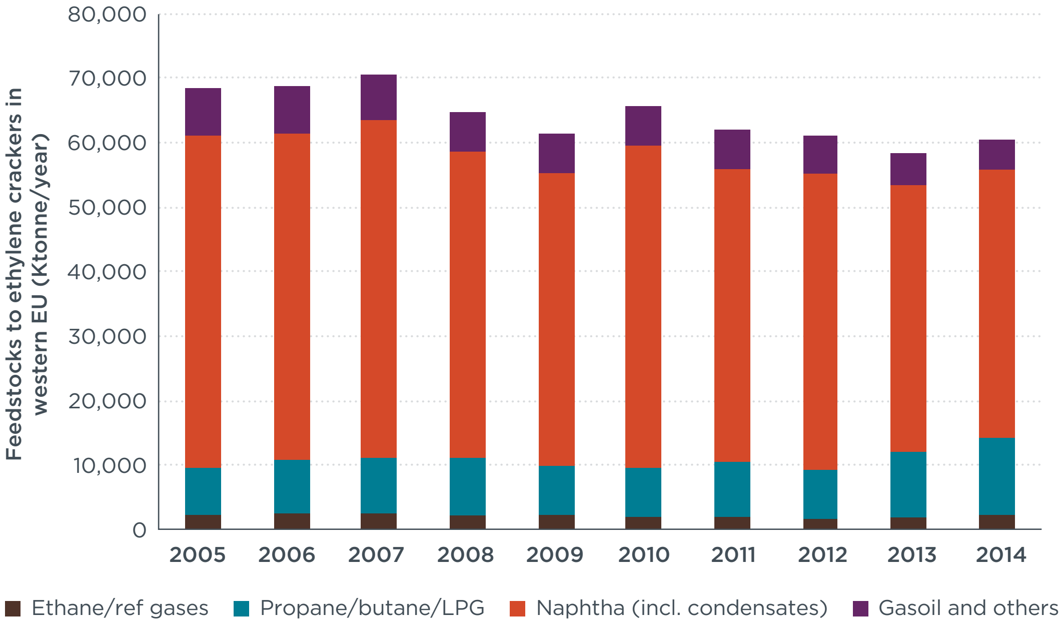

Figure 3.5. Cracker feedstocks for the production of ethylene in Western Europe, 2005-2014

Source: Petrochemicals Europe

Ethylene can be produced instead through catalytic dehydration of ethanol. The economic benefit can be estimated for the case where the 3.7 billion liters of ethanol (the 0.5% share from advanced biofuels as indicated in the ILUC resolution) are used to produce ethylene, instead of being used as a fuel.

Assuming a conversion factor of 1.8 tonne ethanol for each tonne of ethylene (Schneider et al., 2014), the quantity of bio-ethylene produced this way would amount to 1.6 million tonnes, or about 9% of the annual total ethylene production in Europe (19 million tonnes in 2012 (CIEC 2015a)).

With a conversion of 3.2 tonne naphtha/tonne ethylene (IPPC 2003), the naphtha displaced would amount to 5.1 million tonnes. With a price of about $412/tonne (€310/tonne) in June 2015 (Allan et al., 2015), this amount of naphtha can be evaluated at about €1.6 billion.

Alternatively, supposing that the production of ethylene from biomass displaces ethane instead of naphtha, the value can be calculated with a conversion factor of 1.3 tonne ethane/tonne ethylene (CIEC, 2015b, Lloyd’s Register, 2014) and assuming a price of ethane at $0.19 per gallon (Financial Times, 2015). The value of ethane displaced would thus amount to €144 million.

The relatively high value associated with naphtha displacement (€1.6 billion) does not take into account the value of the other associated products resulting from the steam cracking of naphtha, such as aromatics, propylene, and butadiene. Those products have a much lower yield when they are produced from ethane (Fattouh et al., 2014). The displacement of naphtha would thus require additional costs related to alternative feedstocks needed for the production of those other products. If that was taken into account, the net economic benefit would be much lower than the estimated €1.6 billion.

3.4.5. Import Displacement—Two Scenarios

The values of displacement estimated above represent a hypothetical case where all of the fuels displaced are fuels that would be imported from outside the EU. Alternatively, we could examine a scenario where only a proportion of the fuels displaced are imports. A simple approach to estimate the fraction of production that may displace imports is to assume it is proportionate to the share of fuels/materials imported into Europe.

In 2013, EU production of natural gas made up 34% of the total net supplies in the EU (see Figure 3.6) (Eurogas, 2014), with imports accounting for the other 66%.

Eurostat (2014) provides values of energy dependency in Europe, which is calculated using the following formula: net imports/(gross inland consumption + bunkers). The energy dependence in 2013 was 87.4% for petroleum products, 65.3% for gas, and 44.2% for solid fossil fuels (Eurostat, 2015b).[20]

Table 3.4 below summarizes the estimated values of fossil fuels displaced, following the two scenarios described above.

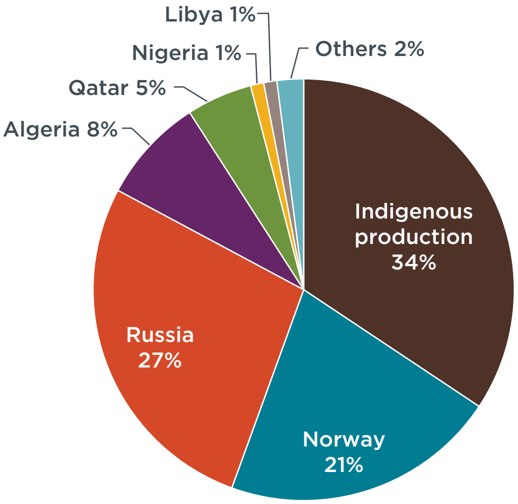

Figure 3.6. Breakdown of EU-28 natural gas supply, 2013

Source: Eurogas (2014)

Table 3.4. Estimated values of fossil fuels displacement resulting from the use of 9.5 million tonnes of agricultural residues (wheat straw) in 2020

	Crude oil	Coal	Natural gas	Naphtha	Ethane
Quantity displaced	13.7 Mbarrel	4.7 Mtonnes	103 million mmBtu	5 Mtonnes	2 Mtonnes
Equivalent energy displaced (PJ)	79	106	109	Not applicable	Not applicable
Value, 100% imports displaced (million €)	648	329	558	1,593	144
Imported fraction (%)	87.4	44.2	65.3	Not applicable[21]	Not applicable[22]
Value, proportional share of imports displaced (million €)	566	145	364		

Under the first scenario, where the energy from biomass displaces only imported fossil fuels, the highest displacement value is associated with naphtha, followed by crude oil and

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[20] Solid fuels include coking coal, other bituminous coal and anthracite, sub-bituminous coal, lignite, peat, and other derived fuels.

[21] This value is not included, because it is assumed that the EU will not import naphtha in 2020, progressively switching to ethane imports, as explained above.

[22] No estimates are given because of the high uncertainty of the future evolution of ethane imports (as feedstock to ethylene crackers) in the EU.

natural gas. In energy applications, coal was far behind the other products—displacing approximately 50% of the value of crude oil and 59% of the value of natural gas.

Despite the fact that the total quantity of energy displaced is higher for natural gas in heat and power applications (109 PJ in equivalent energy) than for crude oil in transport applications (79 PJ), the monetary value of crude oil displacement was higher than that of natural gas. This is because crude oil has a higher value per energy unit than natural gas.

In the second scenario, where the economic value of displaced fossil fuels is adjusted to the share of imported fuel, the crude oil displaced shows an even higher value (€566 million) than natural gas (€364 million), because Europe is more reliant on crude oil imports than natural gas imports.

While the impact of crude oil import displacement exceeds that of natural gas displacement when estimated by using projections of commodity prices in 2020, short-term fluctuations can change this relationship. An estimate of import displacement for both imported crude oil and natural gas using spot prices for February 2016 found that the value of import displacement for both was more or less equal, at approximately €320 million using the import shares in the second scenario. The long-term projections of commodity prices provided by the futures market are much more stable than monthly spot prices, however, and thus provide a more conservative estimate with respect to the impact of future economic policy.

Those results are highly sensitive to the input parameters used, but the following parameters are of particular importance due to their higher associated uncertainty:

- The conversion factor for the production of ethanol from agricultural residues (biochemical pathway): Here the assumption is of 0.31 tonne ethanol/tonne feedstock, but several different values can be found in the literature, ranging from 0.20 (Schnepf 2010) to 0.34, the latter a theoretical ethanol yield based on corn stover feedstock (AFDC, 2013). Zhao et al. (2015) also noted that this was the most important source of uncertainty in their techno-economic evaluation of eight cellulosic biofuel pathways.
- The price of the different fossil fuels: The values are projections for the year 2020, and are obviously subject to a high volatility, for example as experienced recently in the drop of crude oil, naphtha, and ethane prices between 2014 and 2015.

3.5. CAPITAL COSTS

In this section, the capital costs are analyzed for the categories of liquid biofuels, heat and power, and bio-based chemicals. The total investment costs (capital expenditure, or capex) are the total costs of developing and constructing a plant, excluding any grid-connection charges in the case of power generation (WEC, 2013).

The costs have been converted to cost per tonne of feedstock, using the conversion values described in Table 3.2, in order to allow easier comparison between the different pathways considered.

3.5.1. Capital Costs—Liquid Biofuels

According to SCOPE (2015), the capital costs of advanced biofuel conversion technologies are currently estimated to be four to five times higher than commercial ethanol plants, so capital cost will contribute more to the cost of advanced biofuel production cost, depending on the conversion plant size, among other factors. The report argues that anticipated improvements will progressively reduce operating and capital costs, thereby improving profitability and attracting additional investment. Because it may take five years or more to design, locate, build, and bring online a biorefinery, the report estimates that a major expansion of lignocellulosic biofuels will not begin before about 2020, but after that time there could be a rapid expansion of capacity worldwide with the potential for cost reductions as the technology matures.

IRENA (2013) compiled the capital costs of current or near future commercial-scale advanced ethanol plants. The results are presented in Figure 3.7, after a conversion from cost per liter produced to cost per tonne of feedstock.

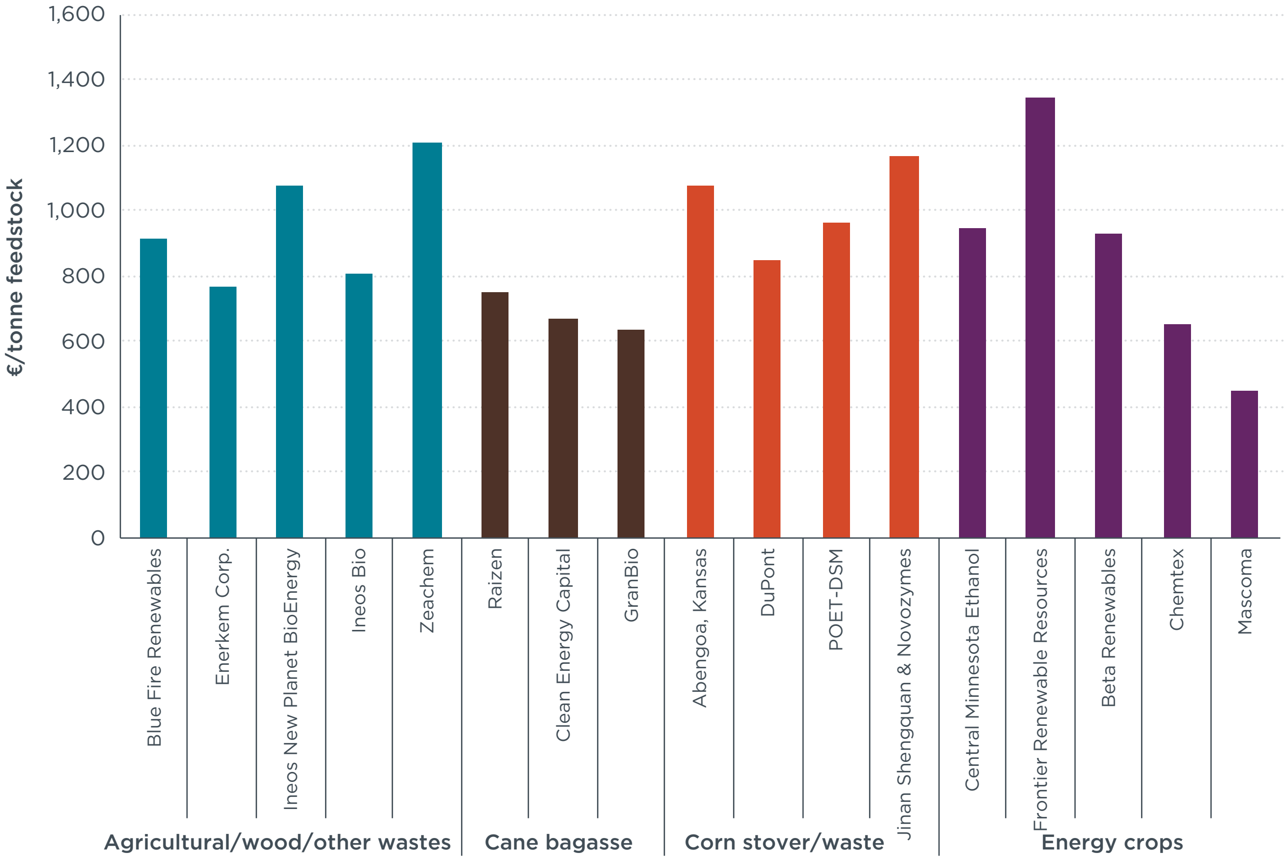

Figure 3.7. Capital costs for current or near future commercial-scale advanced ethanol plants

Source: IRENA (2013)

The advanced biofuel plants have capital costs in the range of €1.20 to €3.50 per litre per year of capacity. After converting to costs per tonne of feedstocks, the costs range from €450 to €1,350 per tonne of feedstock for the energy crops, and from €640 to €1,200/tonne feedstock for the agricultural and wood residues. IRENA (2013) notes that the capital costs of advanced cellulosic biofuels are currently two to six times higher than for corn ethanol plants, reflecting the more complicated pre-treatment and processing needs required to produce bioethanol from lignocellulosic feedstocks. This may be partly due to the fact that these plants are typically first-of-a-kind, unlike the more mature technologies used in conventional ethanol plants.

However, there may already be progress in reducing the capital expenditures associated with advanced biofuel production relative to the above estimates. Biochemtex built a plant in Brazil to produce cellulosic ethanol from sugarcane straw, with an investment cost of €115 million, which corresponds to about €550/tonne feedstock (Beta Renewables, 2013). This value is lower than the range of capital costs given by IRENA (2013) for ethanol from agricultural wastes in Figure 3.7.

Ecofys (2015), in an investment analysis, estimated the capital costs at about €100 million for an n^{th}-of-a-kind cellulosic ethanol plant capacity of 210,000 tonnes feedstock/year (agricultural residues). This corresponds to a €480/tonne feedstock processing capacity.

Ecofys (2015) also estimated the capital costs for a Fischer-Tropsch renewable diesel plant at €385 million for an n^{th}-of-a-kind plant, with 825,000 tonnes feedstock/year, which corresponds to €467/tonne feedstock. This is based on an assumption that a 30% capex reduction can be achieved for a n^{th}-of-a-kind plant compared to a first-of-a-kind, as technology providers are likely to have built in significant contingency. According to Ecofys, the likely areas of capex reduction include the process steps that are not yet proven, such as the gasification stage, but probably not the feedstock pre-treatment and hydrocracking stages.

NNFCC (2013), in a model of biofuel production costs, estimated that the capital costs of biochemical ethanol amount to €90 million for a 650,000-tonne-feedstock processing capacity, which corresponds to €140/tonne feedstock. For a Fischer-Tropsch renewable diesel plant, the capital costs are €390 million, and correspond to €440/tonne feedstock.

IRENA (2013) estimated that the indirect gasification of biomass to produce a syngas that can be synthesised into ethanol and other mixed alcohols is around 10% more capital intensive than the enzymatic hydrolysis and fermentation route, once fully commercialized. The report gives a capital cost for fast pyrolysis of biomass at around €0.9/litre/year of production capacity for a plant with annual capacity of 289 million litre/year. For an n^{th}-of-a-kind plant, capital costs for a 123 million litre/year biomass-to-liquids low-temperature plant would be €3.10 per litre per year, and a 158 million litre/year biomass-to-liquids high-temperature plant at would be €3 per litre per year. The fast pyrolysis route is much less capital-intensive, and even the first-of-a-kind commercial plants are estimated to have lower capital costs in absolute and percentage terms than future gasification and Fischer-Tropsch synthesis biomass-to-liquids plants.

3.5.2. Capital Costs—Heat and Power

IRENA (2012), in a cost analysis of power generation technologies from biomass, concluded that the investment costs vary significantly by technology and country (see Table 3.5). The total investment costs consist of the equipment, fuel handling and preparation machinery, engineering and construction costs, and planning (IRENA, 2012).

For a mature and commercially viable technology such as direct combustion in stoker boilers, the investment costs were estimated between $1,880 (€1,400) and $4,260 (€3,200) per kW. To compare the data, the investments costs are here converted into costs per tonne of feedstock, assuming a capacity factor of 80%[23] (WEC, 2013) and an electrical efficiency of 22% for steam turbine, and 18% for CHP.[24]

Table 3.5. Typical capital costs of biomass power technologies

	investment costs (€/KW)	Capital costs (€/tonne feedstock)
Stoker boiler	1,410–3,200	210–480
Bubbling and circulating fluidized boilers	1,630–3,380	240–500
Fixed and fluidized bed gasifiers	1,610–4,290	240–640
Stoker CHP	2,670–5,130	360–690
Gasifier CHP	4,190–4,920	560–660
Landfill gas	1,440–1,830	Not applicable
Digesters	1,940–4,590	Not applicable
Co-firing	110–640	Not applicable

Source: IRENA (2012)

3.5.3. Capital costs—Bio-based chemicals

According to IEA-ETSAP and IRENA (2013), the capital costs for bio-ethylene production range from $1,100 to $1,400 (€830 to €1,050) per tonne. The capital cost of Braskem's 200,000 tonnes/year PE plant in Brazil was $290 million (corresponding to $1,450, or €1,100 per tonne of ethylene) (Braskem 2012). Mitsui and Dow announced in 2011 a joint venture to produce 350,000 tonnes per year of ethylene from sugarcane, with an estimated capital cost of $400 million ($1,140, or €860, per tonne of ethylene) (IEA-ETSAP and IRENA, 2013), but the original plans for the joint venture's expansion into downstream derivative products have been postponed (Dow, 2014).

In August 2015, BioAmber Inc. announced the opening of its BioAmber Sarnia plant in Canada (BioAmber, 2015). The plant will produce 30,000 tonnes/year of bio-based succinic acid from glucose sourced from southern Ontario agricultural suppliers. The construction cost amounted to approximately $141.5 million ($4,717, or €3,550) per tonne of succinic acid). Succinic acid is a high volume chemical mostly produced by catalytic hydrogenation of petrochemical maleic acid or anhydride (IEA Bioenergy, 2012); in 2011 97% of its production was petrol-based (Weastra, 2013). It can be used in industries producing food and pharmaceutical products, surfactants and detergents, or green solvents and biodegradable plastics (Zeikus et al., 1999).

In Adria, Italy, in the country's northern Rovigo province, Novamont will open a plant to produce 30,000 tonnes/year of 1,4 bio-BDO (butanediol) in 2016 (Polimerica, 2015; Novamont, 2013). The capital cost is estimated at €85 million (corresponding to €2,830 per tonne of bio-BDO).

In 2014, Corbion Purac announced its intent to construct a 75,000 tonnes/year PLA production plant in Thailand, with an estimated capex of €60 million (corresponding to €800/tonne PLA) (Corbion 2014).

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[23] The capacity factor of a specific power plant depends on its design and feedstock availability, quality and cost over the year. WEC (2013) gives averages of 85% capacity factor for incineration and 80% capacity factor for gasification of biomass in Western Europe.

[24] Note that although the efficiency for electricity generation for a biomass CHP plant is 18%, the overall system efficiency is 71% when the energy of the captured heat is considered for the entire system.

Those capital costs are in euros per tonne of product. In order to compare with the fuels and energy pathways, a conversion can be made into euros per tonne of feedstock. Table 3.6 provides an overview of the conversion yields used for this analysis. The converted costs are then shown in Figure 3.8. For the production of ethylene from ethanol, the conversion factor used for the production of ethanol was based on biochemical conversion from agricultural feedstock (3.25 tonne feedstock/tonne ethanol), as given in Table 3.2.

Table 3.6. Conversion yields for biochemical processes

Product	Yield	Unit	Reference
Succinic acid (from hexose)	0.4	(tonne/tonne feedstock)	S2Biom, 2015
PLA (from hexose)[25]	0.4	(tonne/tonne feedstock)	S2Biom, 2015; Gerssen-Gondelach et al., 2014
Ethylene	1.8	(tonne ethanol/tonne ethylene)	Schneider et al., 2014

3.5.4. Capital Costs Compared

Figure 3.8 below gives the capital costs for all the pathways analyzed previously. The blue bars represent ranges of estimated costs as provided in the literature, whereas the triangles represent isolated values.

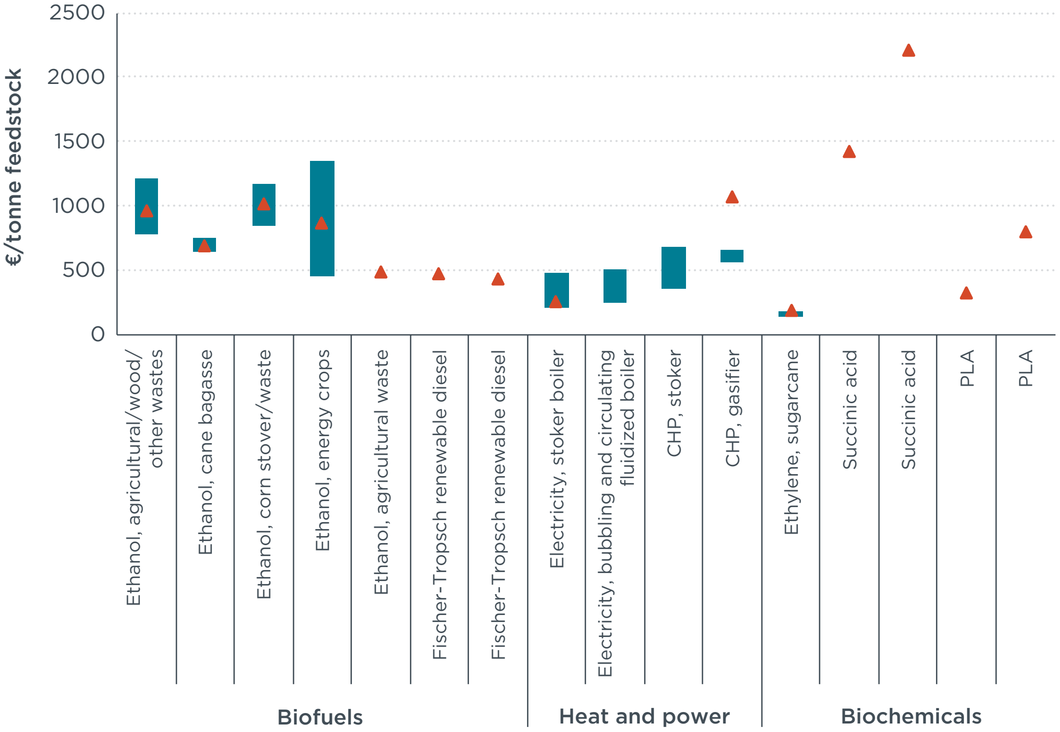

Figure 3.8. Capital costs of different pathways, normalized in €/tonne feedstock

It should be emphasized that for biochemicals, the capital expenditure in euros/tonne feedstocks is derived from capex of plants converting mostly starchy or sucrose

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[25] Conversion from biomass containing: 40% cellulose, 30% hemicellulose, 30% lignin.

biomass. The conversion processes of lignocellulosic feedstock require additional pretreatment steps, and the associated capex is expected to be higher. The results calculated here should therefore only be considered as a lower indicative value, and not as actual capex of bio-based chemicals.

There is currently no certainty over what pathways represent the most promising development options from a capital point of view. In general, higher capital costs (per tonne of feedstock processing capacity) seem to be associated with biofuels pathways than with heat and power. Regarding the biochemicals, there is a high capital cost associated with succinic acid. A very low capital cost seems associated with ethylene, but this might be due to the fact that the capital costs found in the literature are based on starchy or sucrose biomass, as explained above. The capital costs for the production of ethylene from lignocellulose are expected to be substantially higher.

3.6. PRODUCTION COSTS

This section examines the production costs for the categories of liquid biofuels, heat and power, and bio-based chemicals. As with the capital costs, the costs have been converted to cost per tonne of feedstock, using the conversion values described in Table 3.2, in order to allow easier comparison between the different pathways.

3.6.1. Production Costs—Liquid Biofuels

According to JRC (2015), although biomass feedstock for second-generation biofuels is cheaper per tonne than crops for first-generation biofuels, at least 80% of the production cost of second-generation biofuels is a capital charge on the initial investment (if this is not reduced by grants and loan guarantees).

Ecofys (2015) analyzed the production costs of three different advanced biofuels pathways. The production cost calculations take into account the capital costs, operational costs, and plant performance data, for a next-generation commercial facility (n^{th}-of-a-kind plant, assuming that the pathway is technology-mature), which means that some assumptions for future cost and efficiency improvements are made. The results for the three pathways are as follows:

- Hydrotreated pyrolysis oil (HPO) (from woody biomass, leading to the production of gasoline and diesel) has an estimated production cost of €1,647/tonne (taken from a study by Pacific Northwest National Laboratory for the US Department of Energy, Jones et al., 2015). This means that, according to Ecofys (2015), it is currently difficult to produce HPO at commercial scale. However, significant cost reductions have been achieved in recent years and if this trend continues, costs will have come down to €1,100/tonne in 2017 and will fall lower in subsequent years.
- Cellulosic ethanol (from agricultural residues) has an estimated production cost of €734/tonne for an n^{th}-of-a-kind plant. The production costs for a first-of-a-kind plant are considerably higher, estimated at around €1,000/tonne. The cellulosic ethanol pathway assumes that surplus electricity is exported to the grid (through the combustion of lignin), and this greatly reduces the operational costs. Ecofys argues that another reason for the lower cost than the other pathways analyzed is the fact that cellulosic ethanol is to some extent based on the existing technology for first-generation biofuel production and involves less extreme process conditions (lower temperatures and pressures).
- Fischer-Tropsch (FT) renewable diesel (from forestry residues) has an estimated production cost for an n^{th}-of-a-kind plant of €1,315/tonne, which is double the

market price of fossil diesel. This high cost is explained by a relatively more complex and capital-intensive process that involves feedstock gasification and fuel synthesis. The study indicates that cost reductions are needed to make this technology attractive for investors.

The study points out that there is a degree of uncertainty in estimating nth-of-a-kind costs given the limited cost data that is currently available for first-of-a-kind plants, in particular for Fischer-Tropsch renewable diesel and HPO.

The production costs are presented in Figure 3.9, in euros/tonne feedstock, together with the range of values obtained from a sensitivity analysis carried out by varying the capex cost, feedstock cost, and interest rate levels. The costs described above have been converted to cost per tonne of feedstock, using the conversion values described in Table 3.2, i.e., 3.25 tonne feedstock/tonne fuel for cellulosic ethanol, and 4.5 tonne feedstock/tonne fuel for FT and HPO. The analysis showed that capital costs and feedstock costs have the largest impact on the total overall production costs and that the impact of financing costs is relatively low.

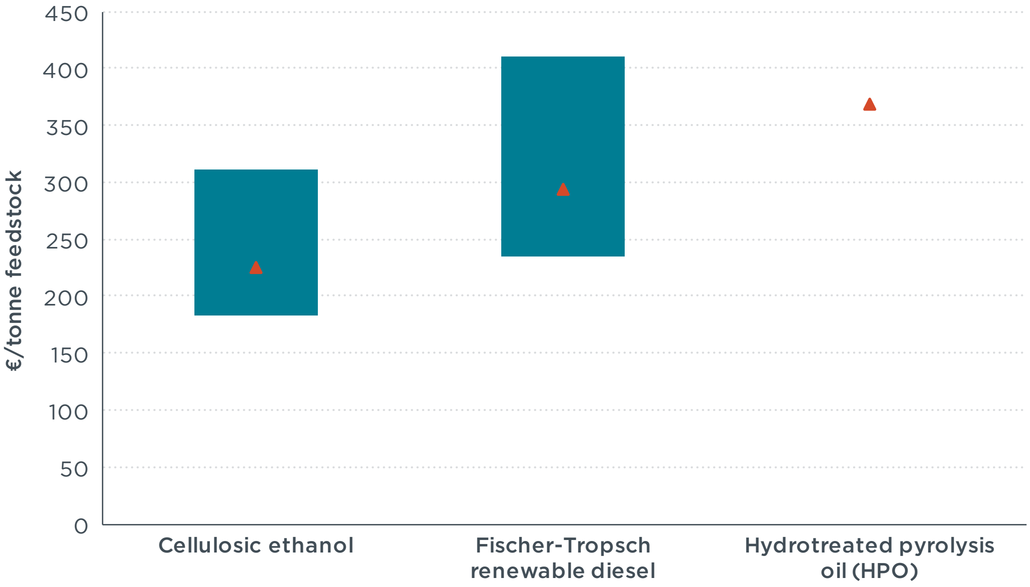

Figure 3.9. Production costs of advanced biofuels

Source: Ecofys and Passmore Group (2015)

IRENA (2013) estimated that the production cost for ethanol via the enzymatic hydrolysis of lignocellulosic feedstocks is in the range of $0.75 to $1.45 per liter of gasoline equivalent (lge), based on the investment cost data for operating, under-construction, and planned plants that were anticipated to be online by 2015. This is approximately equivalent to a range of €90 to €180/tonne feedstock.

Their estimate for the production costs of indirect gasification and mixed alcohol synthesis (propanol, butanol, pentanol and hexanol) of the resulting syngas ranges between $0.60 and $0.90/lge for feedstock costs of $30 and $100/dry tonne, respectively. This is approximately equivalent to a range of €50 to €80/tonne feedstock (assuming that the output is only ethanol, and that the applicable conversion factor is 4.5 tonne feedstock/tonne fuel as per Table 3.2). IRENA (2013) points out that this technology is less advanced than enzymatic hydrolysis to ethanol and the costs are therefore more speculative.

The JRC (2015) stated that recent cost projections, together with uncertainty in advanced biofuels policy, have caused major oil companies in Europe to reduce their investments in the field and to cancel joint agreements and advanced biofuels projects. Those companies are, however, making significant investments in both first- and second-generation ethanol projects in Brazil, where the cost base is lower.

3.6.2. Production Costs—Heat and Power

The LCOE (average lifetime levelized cost of electricity generation) is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate (IRENA, 2012). It is calculated from the capital and operating costs (operations and maintenance expenditures and fuel expenditures) and the generated electricity. The LCOE represents the total life-cycle costs of producing one kWh of power using a given technology (WEC, 2013).

IRENA (2012) estimated the LCOE of biomass-fired power plants (Table 3.7). They range from €0.05 to €0.22/kWh depending on capital costs and feedstock costs.

Table 3.7. Levelized cost of electricity of biomass power technologies

	LCOE range €/kwh	Production cost (€/t feedstock)
Stoker boiler	0.05–0.16	47–165
Bubbling and circulating fluidized boilers	0.05–0.16	55–165
Fixed and fluidized bed gasifiers	0.05–0.18	55–189
Stoker CHP[26]	0.05–0.22	146–606
Gasifier CHP	0.08–0.21	230–586
Landfill gas	0.07–0.09	Not applicable
Digesters	0.05–0.11	Not applicable
Co-firing	0.03–0.10	Not applicable

Source: IRENA (2012)

The World Energy Council (2013) also assessed the LCOE for four biomass conversion technologies; the values for Western Europe are presented in Table 3.8. The values are very similar to the ones given by IRENA (2012).

Table 3.8. Levelized cost of electricity of biomass power technologies in Western Europe

	LCOE range €/kwh
Incineration	0.04–0.15
Landfill gas	0.03–0.07
MSW	0.06–0.16
Gasification	0.04–0.11

Source: WEC (2013)

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[26] To account for the value of the heat from biomass-fired CHP, IRENA (2012) assumed a credit for heat ranging from between USD 10 to 45/MWh_{th}. The methodology used for allocating costs between electricity and heat production can have an important impact on the estimated LCOE.

To allow for a comparison with the other pathways, we converted the LCOE into costs per tonne of feedstock, using a conversion efficiency derived from the calorific value of biomass and the electric efficiency of a heat and power technology (e.g., for stoker boiler using wheat straw, it is about 1 MWh/tonne biomass). For the stoker boiler, for example, this results in a range of production cost of electricity between €47 and €165/tonne biomass.

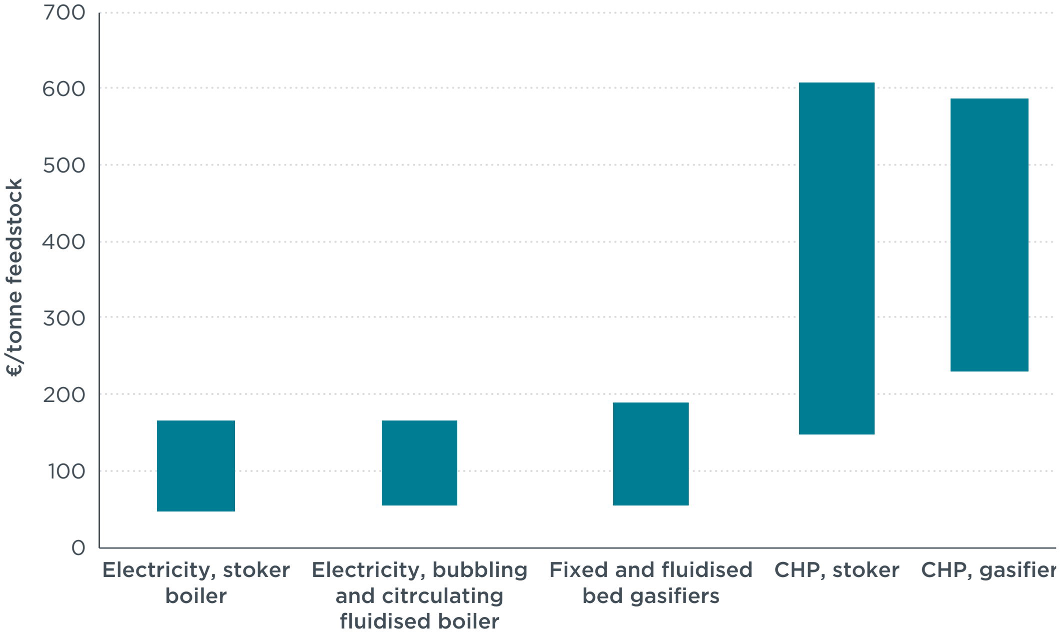

Figure 3.10. Levelized cost of electricity of biomass power technologies, converted in cost per tonne of feedstock

One difficulty associated with the conversion to cost per tonne of feedstock is related to CHP technologies. The ranges of LCOE costs in euros/kWh are relatively similar between CHP and the other technologies (Table 3.7), however the conversion to euros/tonne feedstock shows a considerably higher cost range for CHP, as seen in Figure 3.10. This is due to the efficiency of CHP (53%, derived from U.S. EPA, 2007), which takes into account both the heat and electricity produced. This results in a conversion factor of 2.8 MWh/biomass, assuming a feedstock of sawdust with a net calorific value of 19 MJ/kg (ECN database).

3.6.3. Production Costs—Bio-Based Chemicals

IEA-ETSAP and IRENA (2013) estimated the production costs of bio-ethylene from starchy, sucrose, and ligno-cellulosic feedstocks. The costs range around $1,200 (€900)/tonne ethylene in Brazil and India (sugarcane feedstock), $1,650 (€1,240)/tonne in China (sweet sorghum feedstock), $2,000 (€1,500)/tonne in the United States (corn feedstock), and $2,500 (€1,900) in the EU (sugar beet feedstock). The production of ethylene from ligno-cellulosic biomass via biochemical processes was estimated at $1,900 (€1,400)/tonne. In comparison, the cost of petrochemical ethylene is substantially lower (i.e., $600–$1,300 (€450–€980)/tonne ethylene), depending on the region with a global average of $1,100 (€830)/tonne.

The study estimates that the biomass feedstock accounts for about 60% of the bio-ethanol production costs, while the bio-ethanol cost accounts for about 60–75% of the bio-ethylene production cost, depending on the region (65% on average). The final polymerization step is a relatively small part of the PE production cost (E4tech et al., 2015).

According to IRENA (2015a), compared with petrochemical equivalents, the production costs of ethylene from biomass feedstock is on average 30% higher. In a few regions, the production cost of bio-ethylene is cost-competitive (similar or about 10% lower), but in most regions the production costs could be doubly more expensive.

Schneider et al. (2014) give an estimate of USD 1,015 to 1,360 (€760-1,020)/tonne for the production cost of ethylene, and a market price of ethylene of USD 1,050 to 1,450 (€ 790-1,100)/tonne. The production cost depends upon the local cost of ethanol production or the purchase price of ethanol. Besides, the combination of an ethylene plant and an ethanol plant into one refinery instead of using stand-alone plants would reduce the energy costs (Fan et al. 2013).

IRENA (2015a) estimates that, with increasing fossil fuel prices and technological developments such as the increasing conversion efficiencies of sugar to chemicals, bio-ethylene and PLA are expected to be cost-competitive in more regions.

3.6.4. Production Costs Compared

The capital costs for all the pathways analyzed previously are given in Figure 3.11 below.

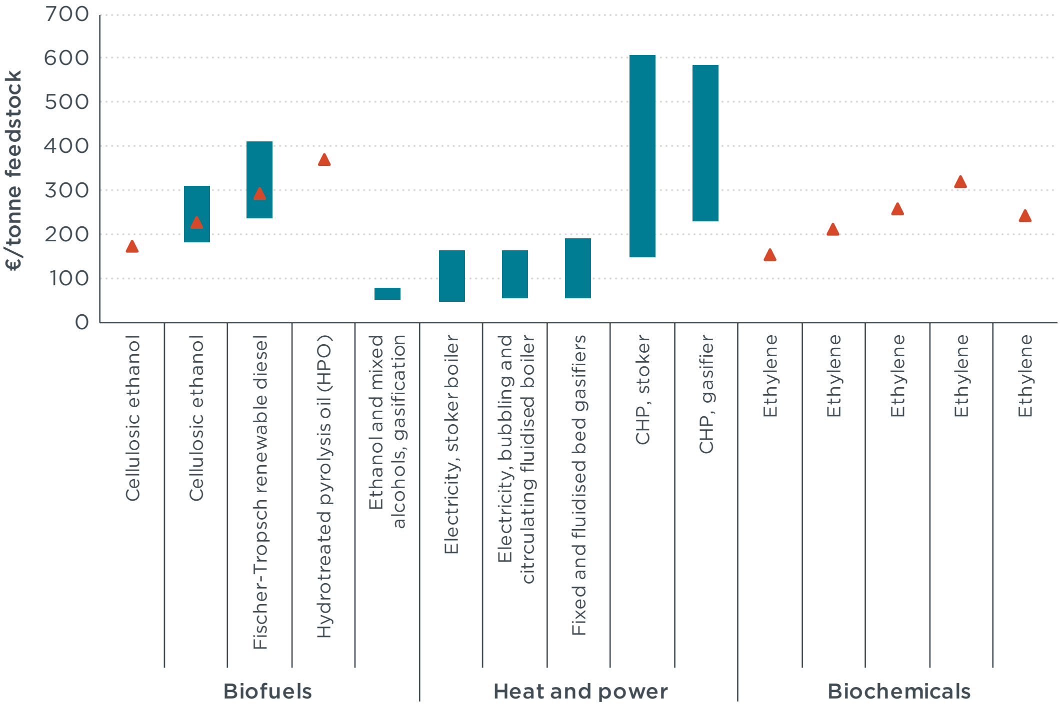

Figure 3.11. Production costs of different pathways, normalized in €/tonne feedstock

In general, the production costs of biofuels pathways are higher than the costs for electricity generation, except for the low cost of mixed alcohols produced by gasification. The CHP pathways have a high production cost, but this is mainly due to the applied conversion factor as explained above.

Because of a lack of data for biochemicals production cost, only production costs of ethylene were included in the figure in the category of biochemicals. The range of costs per tonne feedstock is higher than conventional electricity generation, and within the range of cellulosic ethanol production costs. This last finding is unexpected, because the production of ethylene from lignocellulosic feedstock requires as a first step the production of ethanol, hence the total production cost should be higher than bio-ethanol. This result is explained by the conversion of the production cost to cost per tonne feedstock, and shows the limitations of using this metrics to compare biochemicals with other pathways.

3.7. RESULTS AND DISCUSSION

In this section we analyzed different economic impacts related to the use of sustainable biomass, in particular employment creation, import displacement, and capital and production costs.

The employment created by collection and transport of feedstock represents the largest share of permanent jobs, suggesting that the use of residual biomass provides potential for rural development. There is no clear trend from the literature when comparing the numerical estimates for employment per tonne of feedstock between biofuels and energy (heat and power), but the narrative consensus in the literature is that a higher workforce is associated with the biofuels pathways for reasons such as more advanced and capital-intensive conversion technologies. The data on employment in bio-based chemicals is very scarce, principally because there is currently no biochemicals production from cellulose on a commercial scale. However, as a general trend, the literature indicates a higher employment associated with biochemicals than with biofuels.

Regarding the impacts on the displacement of imported fossil fuel, biofuels show a higher value associated with crude oil displaced (€566 million) than natural gas (€364 million) or coal (€145 million) displaced by the generation of electricity from biomass. This underlines the higher energy dependence of Europe on crude oil imports than on natural gas or coal imports.

The comparison of capital costs in euros/tonne feedstock shows that in general, higher capital costs are associated with biofuels pathways than with heat and power.

In general, the production costs of biofuels pathways are higher than the costs for electricity generation, except for the CHP pathways, but this may be due to the conversion factor used. The production costs of ethylene are higher than conventional electricity generation, and within the range of cellulosic ethanol production costs.

Biochemicals production and capital costs are scarce and show a great variability according to the compound analyzed. They also demonstrate the limitations of applying conversion factors to cost per tonne of feedstock in order to compare the costs of different pathways that use fundamentally different feedstocks, such as starchy vs. lignocellulosic biomass.

4. NON-GHG ENVIRONMENTAL IMPACTS

The purpose of this chapter is to compare the non-GHG air pollution and other environmental burdens of using biomass for heat and power, liquid fuels, or bio-based materials, as well as to contextualize those impacts by comparing them with fossil fuels. Beyond the questions of economic performance and carbon intensity assessed in the GHG Impacts and Economic Impacts sections, the diversion of biomass to biofuel, heat and power, and bio-material pathways offers a variety of tradeoffs relating to air pollution, water use, and soil quality. Furthermore, for all pathways the diversion of organic materials away from existing nutrient recycling pathways such as composting may carry an opportunity cost, and this is also discussed.

To evaluate the downstream impacts from biomass pathways, we evaluate the direct pollution associated with producing and using biomass, as well as the indirect impacts and benefits derived from the co-products and wastes generated via each pathway. Lastly, we assess the alternate pathways for biomass that lie outside the core three studied in this report, identifying any opportunity costs associated with diverting biomass to fuels, power, and industrial uses.

4.1. SCOPE OF ANALYSIS

This analysis considers the non-climate environmental impacts of biomass use across three categories, defined in further detail below. Where possible, the impacts are quantified on the basis of a functional unit of one tonne of biomass; the remaining impacts are described qualitatively. It is assumed that the upstream impacts of biomass production or collection are the same regardless of end use, and therefore outside the scope of this paper. Issues around sustainable use of waste and residual material are discussed in Searle and Malins (2014), while case studies of the sustainability of examples of energy cropping are given in Searle, Petrenko, and Malins (2016).

1. **Direct pollution:** This impact category refers to environmental impacts immediately attributable to the processing and use of biomass for the purpose of providing fuel, heat and power, or as a chemical (e.g., NOx emissions from the direct combustion of corn stover).

2. **Indirect impacts from wastes and byproducts:** Indirect impacts occur outside of the use phase of a given biomass product, and can occur during waste disposal or during the beneficial reuse of a byproduct.[27] This category assesses environmental impacts from wastes and other byproducts generated by the biomass pathways assessed in this paper.

3. **Other uses of biomass:** Existing waste management options for biomass such as composting and anaerobic digestion already divert a portion of the waste stream for biomass feedstocks. If the EU further incentivizes the use of biomass for energy or industrial processes, this could divert additional biomass away from these options. This impact category considers the environmental benefits of alternative pathways and the implications of loss of those benefits if feedstock is displaced.

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[27] "Beneficial reuse" refers to the reclamation of materials for use that would otherwise be considered solid waste.

Each subsection assesses the extent to which liquid fuels, heat and power, and bio-based materials each contributes to the listed impact categories, as well as identifies which of the major pathways has the fewest negative impacts.

4.2. DIRECT IMPACTS

This analysis characterizes the emissions to the environment of pollutants that have a negative impact on human health or the environment and which are directly attributable to the processing and use of biomass in a variety of pathways. Where possible, this section quantifies the environmental impacts of each pathway in terms of pollutant emissions to air and water for each functional unit of one tonne of biomass.

4.2.1. Air Pollution

Manufacturing

For both ethanol and biodiesel production, biorefinery operation results in emissions from the use of energy from electricity, natural gas, or biomass combustion to operate the biorefinery, as well as the direct emissions of volatile organic compounds (VOCs) from the production process.[28] Biofuel refining produces a different mix of VOCs than petroleum refining. VOCs at a biorefinery are by nature a mixed assortment of compounds emitted through a variety of chemical and physical processes.

Cellulosic ethanol production is a maturing process, and production quantities are so small that representative data may not exist. Furthermore, the maturation of the technology means that current emissions estimates may not reflect the performance of future biorefineries. Small demonstration biorefineries are likely to produce higher emissions of air pollutants on a per-gallon basis relative to large-scale refineries. Jones (2010) reviews the air permits and supporting documentation for seven cellulosic ethanol biorefineries in North America slated to produce between 330,000 and 100 million gallons of ethanol annually. Jones (2010) notes that there is significant variation in estimated air pollution performance between the seven biorefineries in question, and that as the production process matures the performance of individual facilities will both improve and converge.

On a per-gallon basis, cellulosic ethanol production (at a demonstration-level scale) generates more particulate matter (PM), SOx, NOx, CO, and VOCs than either petroleum refining or traditional corn ethanol production (Jones 2010). These pollutants affect local air quality and public health. Table 4.1 below illustrates the differences in emissions between the three pathways in terms of emissions on a per-gallon production basis. Table 4.2 normalizes the estimates for cellulosic ethanol into units of emissions per ton of biomass feedstock.[29]

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[28] VOC emissions possess a highly variable impact on human health depending on their chemical composition, ranging from highly toxic or carcinogenic to no measurable effect.

[29] For the purposes of the normalization, the feedstock was assumed to be corn stover with a conversion efficiency of 0.3 tonnes of ethanol produced per tonne of feedstock used.

Table 4.1. Demonstration-scale processing emissions for cellulosic ethanol, compared to corn ethanol and petroleum refinery emissions

Manufacturing Process	Emissions (lb/1,000 gallons of fuel)					
	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	VOCs
Cellulosic ethanol, demonstration-scale	3.4	0.6	2.0	11.8	11.3	19.1
Corn ethanol, commercial-scale	0.6	-	0.5	1.2	1.4	1.4
Petroleum refinery (gasoline)	0.4	0.2	1.1	1.7	0.6	0.3

Source: Jones 2010

Table 4.2. Demonstration-scale processing emissions for cellulosic ethanol refineries

Manufacturing Process	Emissions (kg/tonne feedstock)					
	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	VOCs
Cellulosic ethanol, demonstration-scale	33.4	5.9	20.3	117.5	112.9	189.7

Source: Jones, 2010

As shown in Table 4.1, demonstration-scale cellulosic ethanol production generates more non-GHG emissions than conventional corn ethanol production or petroleum refining. The two highest relative emissions are PM and VOCs. PM emissions are likely higher due to the direct on-site combustion of lignin, a byproduct of cellulosic ethanol production, for energy to power the refinery.

Cellulosic ethanol production emits a greater total volume of VOCs but also results in a different composition of VOCs. Relative to petroleum refining, cellulosic ethanol production generates greater emissions of acetaldehyde and formaldehyde, but lower amounts of benzene. This effect is a product of the cellulosic ethanol conversion processes and would not occur as a result of drop-in hydrocarbon production such as from pyrolysis.

Looking forward towards more mature technologies, the U.S. EPA's regulatory impact analysis for the RFS2 regulation characterizes the non-GHG air pollutants associated with a variety of liquid biofuel production pathways, including cellulosic ethanol and biodiesel production. Table 4.3 below provides an overview of the emissions of the same pollutants as above for biodiesel and cellulosic ethanol production, across a range of feedstocks. Unlike the demonstration-scale estimates based off of permits, these estimates incorporate assumptions of commercial-scale producers operating in 2020, resulting in lower emissions. The largest decrease projected for commercial-scale biorefineries occurs for VOCs, followed by SOx emissions.

VOC emissions for biodiesel are further described in the regulatory impact analysis for the U.S.'s RFS2 regulation. As shown in Table 3, the overall emissions from biodiesel production via the Fischer-Tropsch process are slightly higher but similar to cellulosic ethanol production. While VOC emissions for ethanol and biodiesel production are within an order of magnitude of one another, the composition of those VOC emissions differs from one to the other.

Table 4.3. Estimated processing emissions from biofuel refineries, 2020

Manufacturing Process	Emissions (kg/tonne feedstock)					
	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	VOCs
Cellulosic ethanol, enzymatic (energy crops)	16.6	5.5	2.6	70.3	49.1	14.5
Cellulosic ethanol, enzymatic (agricultural and forest residue)	16.2	5.3	2.5	66.8	46.6	14.4
Cellulosic ethanol, thermochemical	11.6	5.8	3.7	99.9	69.6	4.9
Cellulosic diesel (thermochemical, Fischer-Tropsch)	23.8	12.0	17.9	201.4	133.4	9.1

Note: The "agricultural residue" and "energy crops" emissions estimates for cellulosic ethanol production refer to production using switchgrass or corn stover and forest residues, respectively.

Source: Results adapted from US EPA (2010)

In contrast to the production process for liquid fuels, the preparation of biomass for heat and power is associated with much lower emissions. This is because of the reduced need for pre-processing associated with heat and power pathways. These pathways have not been assessed in the scientific literature to the same extent as liquid biofuels. Biomass processing that consists solely of drying prior to direct combustion for heat and power is likely to produce fewer air pollutants (beyond those of the electricity used to power the drying system) than the extensive processing associated with biomass conversion to liquid fuels.

Biomass drying is typically performed prior to combustion because it improves the efficiency and performance of the biomass within the boiler system while making the feedstock lighter and easier to transport. The majority of dryers are either conveyor belt systems or rotary systems, both of which require energy in order to power the system and provide warm air to remove moisture from the treated feedstock. Both types of dryers may emit PM and VOCs, though the magnitude and breakdown of the individual VOCs emitted varies greatly depending on the biomass type as well as operating procedure for the dryer in question. For example, rotary dryers tend to emit higher levels of VOCs than conveyor belt systems, while higher operating temperatures result in higher emissions across all dryer systems (Roos, 2008).

For biomass that is converted into pellets for combustion, the necessary processing can be responsible for additional air emissions. For example, pellet mills may produce PM, VOCs, CO, and NOx. Beauchemin and Tampier (2010) provide an estimate of the emissions associated with the pelletization of woody biomass in the U.S., developed by using the U.S. EPA's AP-42 emission factors for the wood drying of oriented strand board as the closest approximation to pellet manufacture. The predominant source of PM emissions at the mill, assuming that stockpiles of wood are well controlled (i.e., under a cover), is from the drying process. Beauchemin and Tampier find that the largest sources of PM emissions from pellet mills come from the feed bins, followed by the rotary dryer system. For existing wood pellet mills operating in North America, the average permitted PM emissions totaled 0.72 kg per tonne of feedstock, with the dryers contributing 0.55 kg of that total.

At a pellet mill, VOC emissions may occur during the breakdown of plant material and the heat treatment process. Beauchemin and Tampier estimate the VOC emissions from the pelletization using the same approach as for PM. The total VOC emissions are 0.540 kg per tonne of feedstock processed, with emissions of formaldehyde exceeding 1% of the total emitted.[30] The emissions of acetaldehyde, phenol, acrolein, and benzene all fall below 1% of the total. Table 4.4 summarizes the estimates for air emissions from wood pellet mills.

Table 4.4. Estimated emissions from wood pellet mills

Manufacturing Process	Emissions (kg/tonne feedstock)		
	PM_{10}	PM, total	VOCs
Wood pellet mill	0.517	1.859	0.540
Wood pellet mill, with emissions controls	0.157	0.904	0.540

Note: Emission controls in this case refer to measures taken to reduce the dispersion of dust and other particulate matter, such as covered storage.

Source: Beauchemin and Tampier, 2010.

The overall trend of manufacturing and processing emissions associated with biomass for energy is that more complex, process-intensive liquid fuels generate greater emissions in this phase than biomass used for heat and power. Emissions of air pollutants, VOCs, and PM are approximately an entire order of magnitude below those of liquid biofuels. In comparison to the production and processing emissions for coal cleaning, emissions of VOCs, SOx, NOx, and CO are higher; only the PM emissions are reduced. Similarly, the production of cellulosic liquid biofuels—at least at demonstration scale—does not offer emissions reductions relative to petroleum refining.

Combustion

Additional air pollution results from the use phase of biomass for energy. Biomass that is combusted in either liquid or solid form can emit a variety of exhaust pollutants, including PM, NOx, CO, and VOCs. These pollutants are emitted either through the process of incomplete combustion (VOCs, CO, PM) or due to reactions with air at elevated temperatures (NOx). Like diesel or gasoline, the combustion of liquid biofuels in vehicle engines generates emissions—but the profile of these pollutants varies depending on the fuel. Likewise, the extent and type of air pollution emitted from stationary combustion for heat and power varies based on the feedstock input and mode of combustion.

Relative to gasoline, ethanol combustion emits less CO and significantly less PM. However, ethanol combustion does result in higher emissions of VOCs, though the profile of those emitted varies. Of those VOCs, ethanol combustion releases more acetaldehyde and formaldehyde but less benzene and the carcinogen 1,3-butadiene than gasoline (Stein et al., 2013).

Whether ethanol combustion emits more or less NOx than gasoline is complicated by several factors. The consumption of ethanol blends higher than E10 (for example, E15 or E20) in older gasoline vehicles (pre-2001, and certainly pre-1990 in the EU) can lead to enleanment. This problem occurs because ethanol has a higher oxygen content and lower energy density than gasoline, and when the fuel injector injects the usual amount of fuel into the cylinder, there is a lower fuel to oxygen ratio than normal. When the fuel combusts, the mixture does not provide as much evaporative cooling as the usual amount of gasoline, and as a result the exhaust gas has a higher than normal temperature. The catalytic converter, which is an emissions control device that scrubs out NOx and other

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[30] Formaldehyde emissions are 0.013 kg/tonne.

harmful substances, does not operate as efficiently at higher temperatures. Thus, use of ethanol blends higher than E10 can lead to increased NOx emissions compared with those from pure gasoline or very low ethanol blends of E5-E10 (Searle et al., 2014).

In post-2001 vehicles, combustion of ethanol blends generally do not result in higher Nox emissions than when combusting gasoline alone (Searle et al., 2014). Newer vehicles are able to detect enleanment and can adjust the performance of the fuel injector to decrease the air:fuel ratio relatively quickly and thus enable proper operation of emissions controls. When higher blends of ethanol are consumed in flex-fuel vehicles (FFVs) designed for ethanol blends higher than 10%, NOx emissions are significantly lower than with gasoline. FFVs detect the ethanol concentration in the fuel and adjust the amount of fuel injected into the cylinder accordingly, and so do not experience enleanment (U.S. EPA, 2010). Table 4.5 below presents emissions from ethanol combustion in an E85 blend.

Table 4.5. Emissions from the combustion of E85 relative to gasoline

Pollutant	Per cent Decrease (Relative to Gasoline)	Gasoline Emissions (g/MJ)	E85 Emissions (g/MJ)	Emissions per Tonne of Feedstock (kg/tonne)
VOC	87%	0.0042	0.0079	0.114
NO_x	-42%	0.0123	0.0071	0.102
CO	-15%	0.1998	0.1699	2.432
PM	-100%	0.0004	0.0000	0.000

Note: Emissions per tonne of feedstock in the final column assign the entire emissions from the MJ of mixed fuel to the ethanol feedstock.

Source: Adapted from ICCT Roadmap Model and U.S. EPA, 2010

Renewable synthetic diesel, which is produced via pyrolysis and Fischer-Tropsch, has a chemical composition that resembles petrodiesel more than current commercial biodiesels, which are derived via trans-esterification. While renewable diesel has several properties similar to petrodiesel, its combustion emissions are generally expected to be lower, as shown in Table 4.6. A vehicle consuming R100 (100% renewable diesel fuel) emits less VOCs, NOx, CO and PM. Unlike with ethanol, enleanment does not occur when renewable diesel is combusted in a standard engine, and thus NOx emissions decrease relative to petrodiesel.

Table 4.6. Emissions from the combustion of R100 relative to petrodiesel

Pollutant	Per cent Decrease (Relative to PetroDiesel)	PetroDiesel Emissions (g/MJ)	R100 Emissions (g/MJ)	Emissions per Tonne of Feedstock (kg/tonne)
VOC	-5%	0.0056	0.0053	0.047
NO_x	-10%	0.0757	0.0681	0.602
CO	-10%	0.0501	0.0450	0.398
PM	-30%	0.0005	0.0003	0.003

Source: Adapted from ICCT's Roadmap Model and ARB (2012)

Because liquid fuels are less energy-dense than the fossil fuels they are replacing, in Table 4.6 the emissions impacts are normalized in units of grams per MJ of energy delivered for comparison purposes. Furthermore, to provide a basis for comparison against other biomass pathways, the emissions are also normalized in terms of emissions per tonne of biomass feedstock.[31]

Biomass power plants convert biomass to electricity via either direct combustion or gasification. Biomass may be combusted in biomass-only facilities, or co-fired with coal. Direct combustion typically occurs in stoker boilers or fluidized bed combustors (FBCs). Gasification entails a process wherein biomass is converted to syngas (a mixture of hydrogen, carbon monoxide and other gases) by reacting the biomass at high temperatures without combustion with a controlled amount of oxygen.

A 2003 NREL study (Bain et al., 2003) compares the measured emissions from a variety of California biomass power plants (23 stokers and 11 FBCs) and a planned power plant to existing coal and natural gas power plants. Figure 4.1 provides a comparison of the air emissions from a variety of biomass and fossil fuel power plants. Table 4.7 compares the emissions from fluidized bed biomass combustion power plants and wood gasification power plants to those from similar fossil fuel power plants. The fluidized bed biomass plant outperforms the coal power plant in every emissions category, particularly in reducing SOx emissions. The wood gasification plant has lower emissions for PM, CO, and NOx than the natural gas turbine, but it has significantly higher levels of SOx. Neverthless, in absolute terms, both the natural gas turbine and wood gasifier have lower SOx emissions than coal combustion facilities.

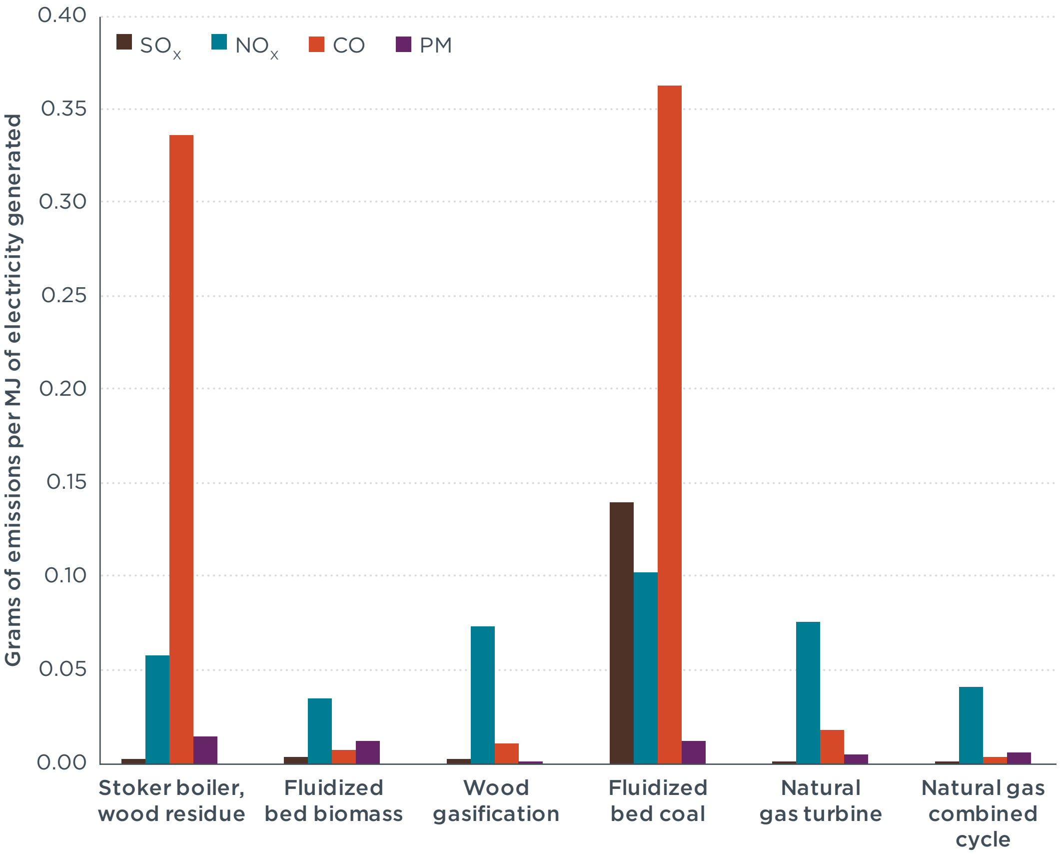

Figure 4.1. Comparison of combustion emissions from biomass and fossil fuel electricity generation

Source: Adapted from Bain et al., 2003

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[31] This analysis assumes a biomass conversion rate to ethanol of 0.3 tonnes of ethanol per tonne of feedstock, per the carbon intensity analysis. The conversion rate for diesel is calculated from the ethanol conversion rate on a per-unit energy basis.

Table 4.7. Comparison of Similar Biomass and Fossil Fuel Power Plants

Boiler Type	Emissions (g/MJ Electricity Delivered)			
	PM	SO_x	NO_x	CO
Biomass fluidized bed	0.011	0.003	0.034	0.006
Vs. coal fluidized bed	0.0%	-97.8%	-66.7%	-98.2%
Wood gasification	<0.001	0.002	0.073	0.010
Vs. natural gas turbine	-88.9%	5555.6%	-4.1%	-42.5%

Source: Adapted from Bain et al. 2003

The NREL study shows that biomass combustion for heat and power results in lower conventional pollutant emissions than coal, but not necessarily than natural gas. Because biomass as a feedstock contains less nitrogen and sulfur than coal, when it is combusted less NOx and SOx are produced (Bain et al. 2003). Biomass power also produces less CO than coal. Biomass combustion doesn't compare as favorably to natural gas, which already burns relatively cleanly. Biomass combusted in a fluidized bed boiler actually tends to emit more NOx, SOx, and CO than a natural gas turbine on an energy equivalent basis. Particulate matter emissions are in a similar range for biomass and coal and lower for natural gas. Combusting syngas derived from gasification is a cleaner process than combusting biomass directly, and gasified biomass power results in lower emissions of PM, CO, and NO_x compared with natural gas.

Waste incineration, which is common in the EU, can potentially emit harmful pollutants, including NOx and SOx but also heavy metals and potentially biohazardous emissions. The most harmful emissions—which may include heavy metals, dioxins, and furans—from waste incineration are not from the cellulosic biomass sources we are considering for biofuel and biomass power in this study. In fact, the Waste Incineration Directive of 2000 explicitly exempts incineration plants that treat vegetable waste from agriculture or forestry, vegetable waste from food processing and paper production, and wood waste because of their relatively low emissions of the most harmful pollutants.[32] Thus, directing biomass waste towards power would not affect the most harmful emissions from waste incineration plants, and so this issue is not within the scope of this analysis.

Bio-Based Materials

Due to the relative lack of data on the processing of biomass for heat and power, it is more difficult to draw conclusions on how it compares to manufacturing bio-based materials. Compared to both liquid biofuels, the manufacturing phase of polylactic acid (LCA) life cycle emits a lower magnitude of air pollutants. Manufacturing emissions for bio-based materials as a broad category would likely vary based on the type of material. The use phase of bio-based materials does not include combustion, therefore reducing emissions of air pollutants relative to bioenergy pathways.

PLA, a biodegradable plastic derived from plant starch, is the second-most common bioplastic sold worldwide, and can be considered to be somewhat representative of bio-plastic production processes. Vink et al. (2007) developed an eco-profile of PLA production using contemporary and near-future production processes in the United States. The eco-profiles are assembled using a full life-cycle assessment for PLA production in 2006 from cradle to grave, and separate out the air emissions impacts by

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[32] See the directive at: http://europa.eu/legislation_summaries/environment/waste_management/l28072_en.htm

life-cycle phase. The manufacturing phase of the PLA life cycle is directly responsible for 100% of life-cycle emissions of VOCs, 50% of NOx, and 40% of CO. Other air pollutants are more prominent in the upstream emissions of input fuels used to produce PLA. Table 4.8 provides a summary of the relevant air emissions from PLA manufacturing for comparison to liquid biofuel and biomass energy processes.

Table 4.8. PLA bio-plastic manufacturing emissions

Process	Emissions (kg/tonne feedstock)				
	PM_{10}	SO_x	NO_x	CO	VOCs
PLA production	0.03	0.16	3.83	2.30	0.08

Source: Adapted from Vink et al., 2007.

Comparison to regulatory pollutant limits

The results above indicate that using biomass for energy decreases emissions of non-GHG air pollutants in a variety of categories. The greatest emissions reductions in the literature were from liquid biofuel displacement of gasoline and biomass displacement of coal-derived electricity. However, these results must be contextualized by comparing them to the regulatory limits for pollutants in the transportation and electricity sectors. Figure 4.2 compares the emissions from liquid fuels and biomass combustion to emissions limits established by the Euro 6 standard and the proposed Industrial Emissions Directive.[33] The emissions from biomass are therefore presented as a share of the overall limit. This approach assumes that regulators have set limits on vehicle and power plant emissions in a way that is similarly protective of human health. The comparison to the limits is then used here as an approximate measure of impact on human health. Note that limits for heat and power emissions are likely higher than those for vehicle emissions because pollutants from centralized combustion facilities are generally emitted from smokestacks and are more dispersed before reaching ground level than vehicle emissions.

As shown in Figure 4.2, displacing coal has the highest impact on emissions, with significant reductions in NOx, SOx and CO emissions. It should be noted that the NOx and SOx reduction for biomass boilers compared to coal boilers shown here is greater than the regulatory limit for these pollutants. This is because the newest regulations were used here for the comparison whereas older data were used to estimate emissions; for power plants this is the Industrial Emissions Directive proposal, which is scheduled to go into effect in 2016.[34]

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[33] European Comission, 2007. Directive on Industrial Emissions (Integrated Pollution Prevention and Control). Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52007PC0844&from=EN

[34] See the proposal at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52007PC0844&from=EN

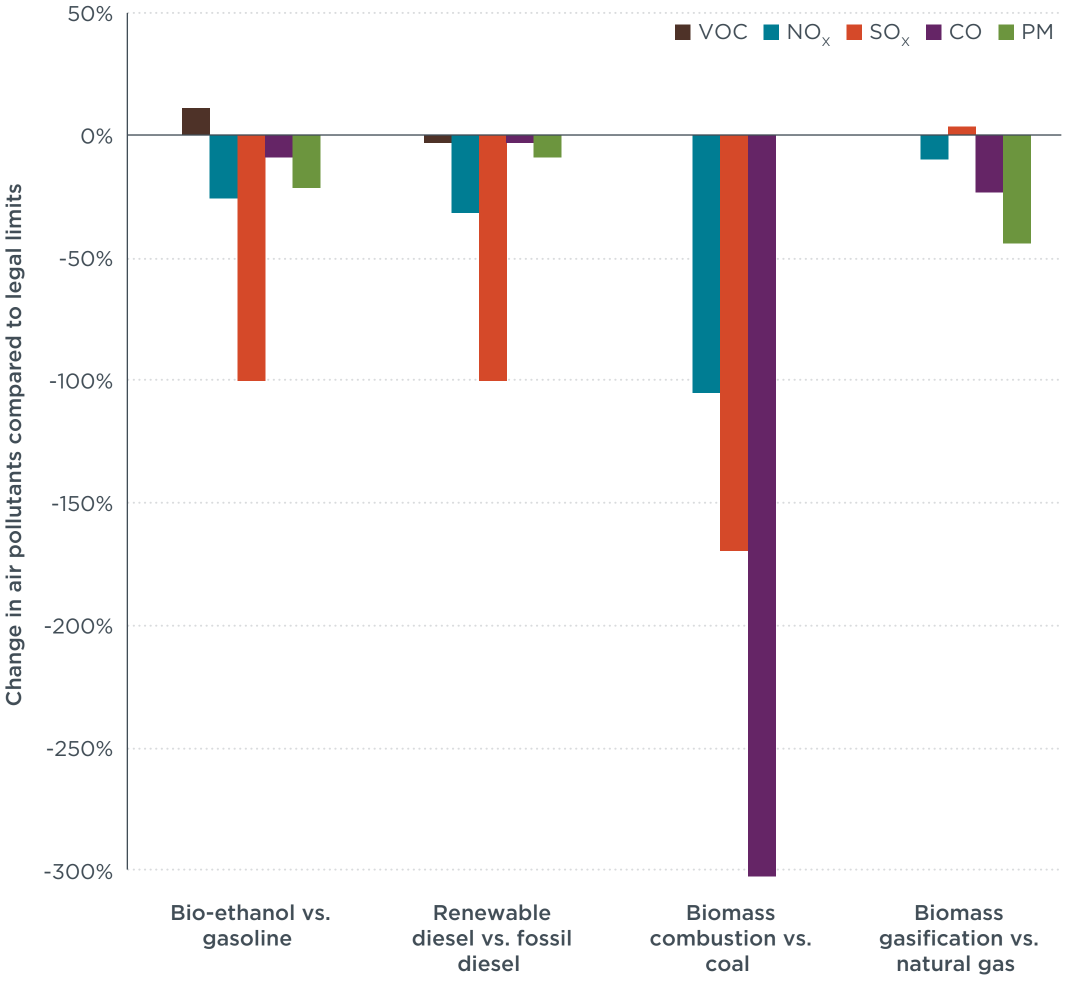

Figure 4.2. Change in emissions of conventional pollutants with four different biomass to energy pathways compared to the regulatory limit

4.2.2. Water Impact

The water use and pollution associated with feedstock production are considered outside of the scope of this analysis, because we are concerned with differing uses of biomass that has already been produced. Consequently, the water impact of biomass use in this section is limited to that used in the processing, production and use of biomass energy or bio-materials. For energy cropping in particular, the water impact of cultivation may be much higher than impacts related to processing.

Cellulosic ethanol production requires greater inputs of fresh water than starch-based ethanol production. On the lower end, Wu et al. (2008) estimate that a commercial ethanol conversion process uses on average 3.0 liters of water per liter of ethanol produced from starchy biomass, with a steep decline in water usage over the past 10 years. For cellulosic conversion, Wu et al. suggest that the process chosen impacts the water consumption, with pyrolysis and gasification using significantly less water (as little as 1.9 liters per liter) than biochemical conversion using enzymes (as much as 9.8 liters per liter). Ramchandran et al. (2013) suggest that ethanol production uses as much as 6 to 10 liters of water per liter ethanol produced—and generates more wastewater than ethanol.

Depending on the site of a given biorefinery, this may put a strain on local water supplies. Recent studies have indicated that the use of filtered wastewater as an input produces similar quality ethanol to that produced using fresh water, though this research is ongoing and has yet to be implemented at most refineries (Ramchandran et al., 2013). The wastewater generated from the cellulosic ethanol conversion processes comes primarily from the distillation process and has several qualities that discourage its reuse and necessitate treatment, including: high acidity, high biochemical oxygen demand (BOD), furan compounds, and phenol content Palmqvist et al. 2000). Some integrated refineries remediate wastewater from the distillation process using anaerobic digestion, which can support generation of energy to power the refinery and offset grid electricity (Kumar and Murthy, 2011; Humbird et al., 2011).

Fast pyrolysis, a method of producing bio-oil, does not consume significant amounts of water directly. Jones et al. (2009) presents a design case study for production of gasoline and diesel via pyrolysis that uses 3 liters of water per liter of product, which is lower than the amount of water used for petroleum refining. Jones et al. (2009) estimate that fast pyrolysis of wood residue consumes just 2.3 liters of water per liter of fuel—though this value may be reduced further as technology matures. However, in order to convert bio-oil into usable biodiesel and renewable gasoline, wastewater is generated as water is separated out from the hydrocarbon components of the bio-oil. CARB (2012) suggests that renewable diesel refining is similar to the process for standard petrodiesel already in use, concluding that any possible additional risks posed to water resources by renewable diesel were minimal.

The water impacts of biomass conversion may vary significantly depending on the exact feedstock or conversion process chosen, but ultimately are small relative to the water use necessary to grow biomass. While the amount of fresh water needed to manufacture biofuels described above is generally less than 10 liters of fresh water per liter of product, a crop such as corn can take from 10 to 324 liters of water to produce 1 liter of ethanol, depending on irrigation conditions (Wu et al., 2008). By comparison, petroleum refining uses from 3.4 to 6.6 liters of water per liter of diesel produced, putting it in a similar range as the ethanol conversion process itself (Wu et al., 2008). Even at the maximum estimate for cellulosic ethanol production (10 liters of water per liter of fuel produced, as shown above), the water use for fuel conversion is relatively small and unlikely to factor into the decision-making process.

The impact of heat and power pathways on water use is more difficult to assess, as water is not consumed directly for biomass processing. However, water consumption does occur during combustion, as thermoelectric power plants heat water to create steam to drive a turbine generator. While most of this water is ostensibly returned after entering the system, open-loop systems often consume a small amount of the water withdrawn. Recirculating systems, which keep water within the system, offer a closed-loop alternative. In contrast to open-loop systems, recirculating systems have a higher rate of water consumption. NETL projects that future biomass power plants are more likely to use recirculating systems (NETL, 2011).

Direct combustion of biomass using a steam turbine has a relatively large consumption factor for water—2.3 liters per kWh of energy produced (DeMeo and Galdo, 1997). This value is comparable to the water consumption for a conventional pulverized coal power plant with recirculating cooling, which ranges from 1.48 to 3.94 liters/kWh (Wu and Peng, 2010). Gasification power plants require substantially less water, with a consumption factor of only 0.15 liters/kWh (DeMeo and Galdo, 1997). Wu and Peng (2010) suggest that the upstream water use from irrigated crops would far outweigh the water consumed during combustion. Therefore, the choice of feedstock would have a far larger impact on water use than the combustion process.

Normalizing the results in terms of energy delivered, we find that the water consumed per MJ of energy delivered for liquid biofuels is comparable with petroleum refining, with pyrolysis consuming less fuel on average than cellulosic ethanol conversion. The biomass combustion pathway was similar to standard pulverized coal combustion, though it consumed less water per MJ of electricity generated. Figure 4.3 presents a comparison of the water consumption across pathways.

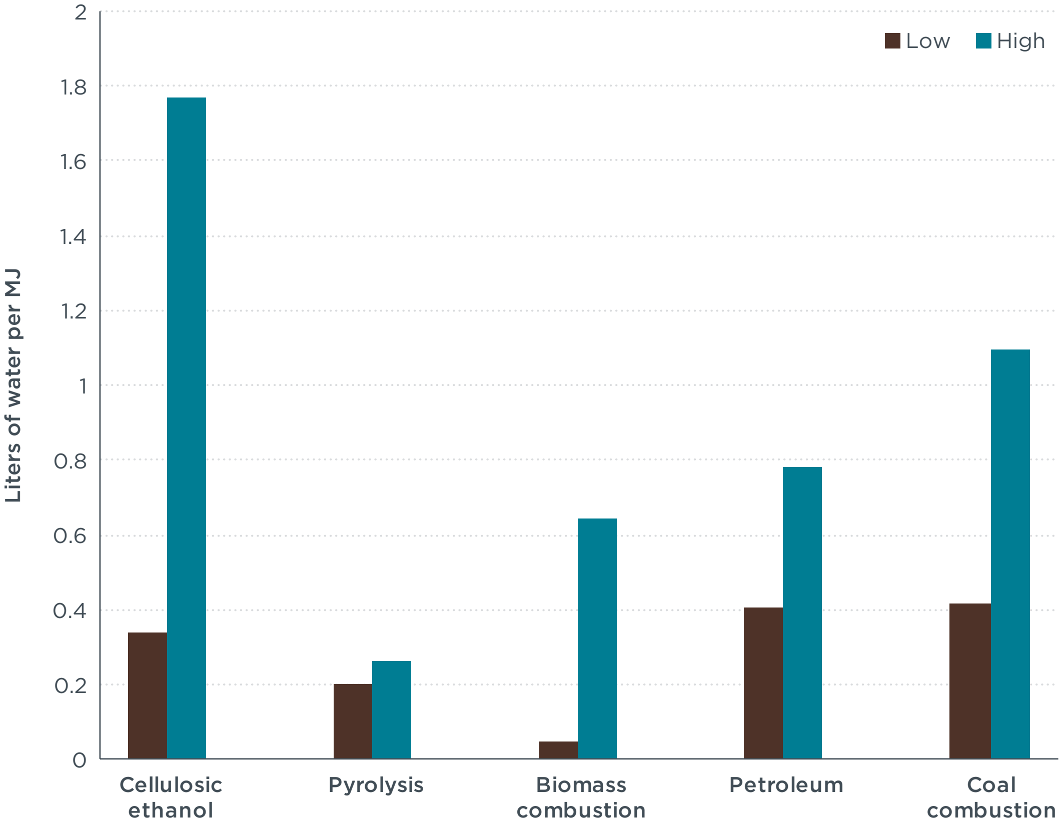

Figure 4.3. Water consumption for biomass and fossil fuel energy pathways

4.3. INDIRECT IMPACTS FROM WASTE AND BYPRODUCTS OF BIOMASS USE

This analysis considers adverse or beneficial environmental effects that occur outside of the immediate manufacture or use phases of a given biomass-derived product. Although the majority of pathways reviewed seek to efficiently convert biomass into energy, they also produce a variety of wastes and/or byproducts that can affect the environment both positively and negatively.

4.3.1. Liquid Biofuels

The production of liquid biofuels results in different types of byproducts depending on the conversion method. Some of these byproducts, which can include other types of fuel, may have direct energy and GHG impacts (see the GHG Impacts section), while others have non-climate implications for nutrient cycling.

The manufacture of cellulosic ethanol via biochemical processing disrupts tough lignin walls found in cellulose-based biomass in order to facilitate the fermentation of the internal cellulose and hemicellulose fibers within into ethanol. In addition to effluent, cellulosic ethanol production leaves a significant portion of the feedstock input as unfermented lignin—as much as 24% of the biomass input by mass (DoE, 2009). The development of integrated bio-refineries has encouraged the reuse of this leftover lignin by encouraging the combustion of the lignin on-site to generate energy. On-site combustion of lignin at cellulosic ethanol facilities could result in the displacement of electricity from the grid in exchange for additional PM emissions, as described in 4.2.1 above.

In the pyrolysis process, after the produced gas is captured and the bio-oil is separated out the remaining byproduct of the reaction is biochar (or char), a solid organic residue consisting of ash and carbon. Depending on the mode of the pyrolysis reaction, differing ratios of bio-oil, gas and char are produced (see Figure 4.4); for the purposes of producing liquid fuel, fast pyrolysis is the most typical (Jones et al., 2009).

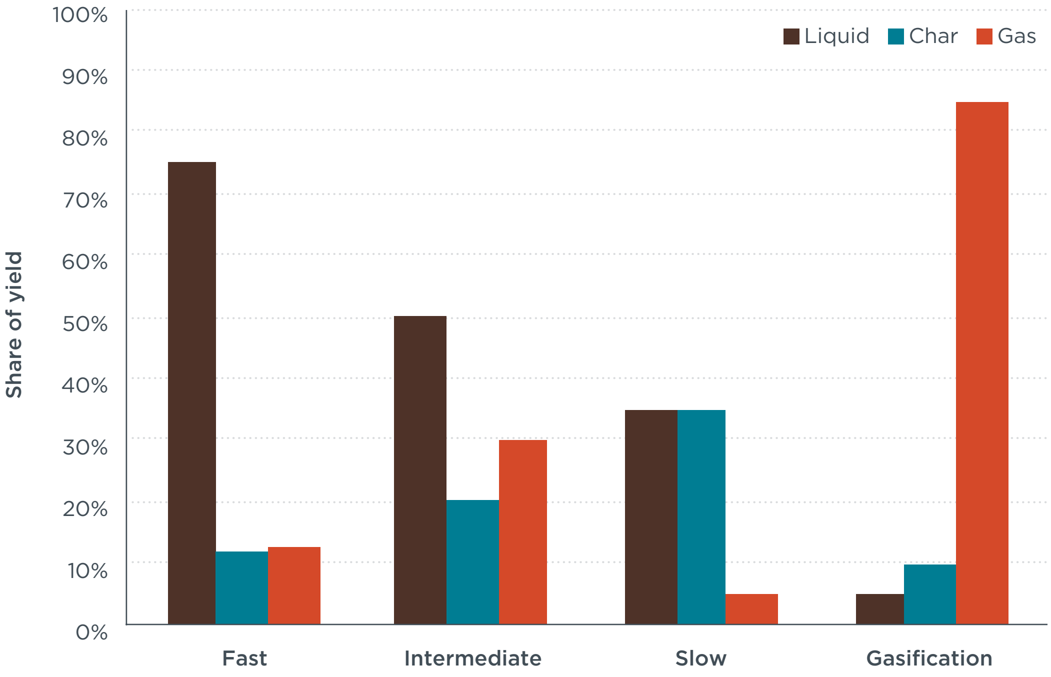

Figure 4.4. Yield ratios of products across pyrolysis modes

Source: Adapted from Jones et al., 2009

Pyrolysis gas and bio-oil, both of which are produced via pyrolysis, have direct uses as energy sources. These energy uses of these by-products are factored into the carbon intensity analysis as carbon offsets (See the GHG Impacts section). Biochar from pyrolysis may be directly combusted as an energy source (this use is considered in the GHG Impacts Section), but can also be used as a soil amendment. The extent of biochar's carbon fraction largely depends on reaction conditions (i.e., the rate and oxygen level of pyrolysis), whereas the remaining components of the biochar (i.e., mineral content) depend more on the biomass feedstock. Because of the low rate of carbon degradation in biochar, it could provide carbon sequestration if it is not combusted. Bio-char retained from pyrolysis production could provide as much as 112 kg of CO_2e sequestration per GJ of energy produced (Lehmann et al., 2006). Furthermore, the addition of biochar to agricultural soil results in greater water retention capacity, increased soil pH, and higher bioavailability of nutrients (Brewer, 2012). Literature and field trials on the use of biochar as a soil amendment have so far been mixed; the final result on crop yield and soil quality is highly dependent on the biochar source, quantity applied, soil type, and crop type (Zheng et al., 2010).

The Fischer-Tropsch process converts biomass into liquid fuels by first gasifying the feedstocks into syngas, then applying catalysts under high heat and pressure to convert the gas into liquid hydrocarbons. Similar to pyrolysis, once the liquids and gas are extracted, the solid fraction remains as a byproduct of the process. The remaining slag and ash is classified as non-hazardous, but is not considered economically valuable and would therefore likely be disposed of (Van Bibber, 2007).

4.3.2. Heat and Power

The direct combustion of biomass to generate heat and power generates ash as a byproduct of combustion. Ash consists of the solid residues remaining after combustion and contains a variety of nutrients and other inorganics that are resistant to the high temperatures of a boiler. The exact chemical composition of a given ash varies greatly depending on the feedstock chosen as well as the operating conditions of the combustion system. Types of ash collected from a heat and power system include coarse bottom ash collected from the combustion chamber and fly ash (both coarse and fine), which is typically collected from filters, precipitators or the boiler. These ashes have somewhat differing chemical properties but are referred to collectively for the purposes of this analysis. Ashes generated from the co-firing of biomass in conjunction with coal share many of the same physical and chemical characteristics of fly and bottom ash generated from coal combustion.

Existing uses for co-firing ash resemble those for coal-derived fly ash: low-grade construction or road material, concrete fillers, and cement additives (Van Eijk et. al., 2012). The EN-450 European standard for fly ash includes a provision for the inclusion of up to 20% biomass-based co-firing material with no performance losses. In these uses, ashes can be considered to displace the beneficial reuse of coal-derived fly ash, which in turn would have displaced either gravel or virgin cement.

Fly ash from co-firing biomass with coal could have superior environmental performance than coal-derived fly ash, which has several qualities that can adversely affect human health and the environment. The qualities of chief concern in fly ash from coal are the concentrations of heavy metals, particularly arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), and selenium (Se). The exact toxicity and risk to human health associated with coal-derived fly ash is still a contested issue, with much recent research indicating that the leaching of heavy metals can be mitigated in most uses. However, as biomass displaces coal in the heat and power sector, it would still reduce the concentrations of heavy metals in the coal combustion product waste stream and therefore further reduce the overall risk.

Currently, the utilization of biomass combustion ashes in Europe is technically feasible, but is constrained by the amount of biomass ash available and existing supply chains (Van Eijk et al., 2012). This could change if biomass combustion for heat and power were to expand in Europe. Ashes derived from biomass that is combusted without coal offers more promising opportunities for beneficial reuse because it does not contain many of the toxic materials commonly found in coal by-products. Biomass-derived ashes have a slightly different nutrient profile from coal ashes and have significantly fewer heavy metals (Van Eijk et. al. 2012). These differences make biomass-derived ashes unsuitable for use in some of the more common reuse pathways for coal or co-firing ashes, including cement and concrete. However, because they lack heavy metal contaminants, biomass ashes may instead be used as a soil additive on agricultural or forest soils to restore nutrients or act as a liming agent. However, some European countries classify ashes on a feedstock-by-feedstock basis and do not permit all biomass-derived ashes as acceptable for use as an agricultural soil amendment (Van Eijk et al., 2012).

Fly ashes from biomass gasification can be more challenging to beneficially reuse, due to their fineness, high proportion of unburned carbon, and high calorific value. Furthermore, the inert carbon matrix reduces nutrient value and is hydrophobic, making this type of ash poorly suited for use as a soil amendment (Van Eijk et al., 2012). Uses for these ashes are emerging, such as direct use as a fuel or as a cement binder, and may be viable in the near future (Pels et al., 2005).

4.3.3. Bio-Based Materials

For bio-based ethylene, which is derived from ethanol, the upstream generation of lignin waste discussed above would be applicable if the ethanol were generated from cellulosic biomass. For the conversion process between ethanol and bio-ethylene, IRENA (2013) reports that conversion yields of 97 to 99% have already been achieved. Thus, this stage is unlikely to generate significant waste. A 2007 life-cycle inventory of PLA production in the United States found that the two co-products from the PLA production process were gypsum and assorted landfilled waste. Part of the gypsum is sold for land application, while the remaining portion is stored in a dedicated landfill. PLA that is disposed of in a large-scale composting facility will also biodegrade, reducing the landfilling impacts of this pathway relative to other plastics. Some types of bioplastics are able to degrade during anaerobic digestion, but there is considerable variation depending on the type of bioplastic, pretreatment level, and the anaerobic digester conditions (European Bioplastics, 2015a).

For both bio-ethylene and PLA production, it is likely that byproducts from manufacture would be comparable to those from petroleum-derived materials. Therefore, they would not generate a sufficient impact to be a deciding factor. It is difficult to draw wide-ranging conclusions about the by-products of bio-based material production because of the heterogeneity of the industry. The manufacturing process for one material is not necessarily reflective of others. We recommend that regulators consider the byproducts generated by new bio-based materials, and that they constitute a portion of future environmental impact assessments for those materials.

4.4. OTHER USES OF BIOMASS

4.4.1. Compost

When biomass is used for energy or for the bio-based materials industry, it is unavailable to any alternative uses. This biomass diversion could create competition with existing uses of waste biomass and thus carry an opportunity cost. Harrison et al. (2014) identify that the sustainably available waste biomass in Europe has a variety of potential non-energy uses, and thus a cascade approach that prioritizes recycling and reuse would be appropriate.

The European Union's Waste Framework Directive (WFD) establishes a waste hierarchy of waste prevention and management that generally prioritizes reuse and recycling (including compost) over energy recovery.[35] The "gasification and pyrolysis using the components as chemicals" is explicitly defined as "recycling" under Annex II of the WFD. This places the use of waste in manufacturing bio-based materials at the same level as composting and above the use of waste for biofuels, heat, and power.[36] However, the WFD allows waste streams to deviate from the hierarchy if resulting in the best environmental outcome where this is "justified by life-cycle thinking on the overall impacts of the generation and management of such waste." It may thus be possible to make an argument that in appropriate cases the use of waste for biofuel should be prioritized over composting because of its comparatively greater life-cycle carbon reductions, and given the limits on demand for biomass resources for composting—though this may need to be evaluated on a case-by-case basis.

Composting is an environmentally beneficial alternative to landfilling organic waste, which uses up land and produces methane. Most organic waste is not a preferred feedstock for incineration (for energy recovery or otherwise) because of its high water content. It is not ideal to compost food waste on its own because of the high nitrogen content of these feedstocks. Conversely, green waste (e.g., leaves, woody residue) alone is not well suited for composting either—it must be combined with other types of waste. The composting process is most efficient at a carbon-to-nitrogen (C:N) ratio of about 30 to 1. For perspective, food waste typically has a C:N ratio of about 10:1. It is necessary to mix food waste with low-nitrogen biomass such as straw, sawdust, or autumn leaves at a ratio approximating 1:1 food waste to low-nitrogen biomass. Green compost, which has been made primarily from biomass residue, has a relatively low amount of readily available nitrogen compared to mixed waste compost (WRAP UK, 2015). Diverting sustainably available biomass—much of which consists of biomass residues—in large quantities to composting could pose difficulties because it would necessitate the use of a complimentary amount of diverted food waste.

Many of the feedstocks for large-scale composting as it is currently practiced in Europe, such as domestic yard waste and food waste, are unsuitable for energy recovery because of supply chain constraints or physical properties, and therefore would be likely to continue to be used for composting even in the context of an expansion of biomass use for energy. Composting has already been commercialized in Europe and is cost-effective where it is practiced. A key consideration for the diversion of additional material to composting is whether or not existing markets would match demand to increased supply. Diverting all sustainably available biomass to composting would be very likely to increase the supply of compost far past the point of market saturation—i.e., in the short to medium term, there may be no necessary competition for biomass resource between compost and other uses.

4.4.2. Anaerobic Digestion

Anaerobic digestion refers to the facilitated digestion of organic matter by microorganisms in an anoxic environment, which generates combustible biogas

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[35] Fuels are specifically excluded from the definition of "recycling" and are categorized as "other recovery."

[36] Including RDF.

for energy, as well as digestate, a nutrient-rich residue that can be used as a soil amendment. Anaerobic digestion produced 12.1 Mtoe of energy throughout the EU-27 in 2012, potentially displacing significant amounts of fossil fuel-derived electricity (European Biomass Industry Association, 2015). Anaerobic digestion is well suited for materials that have high moisture levels, such as household waste, as well as materials unsuitable for composting or energy recovery such as dairy waste and wastewater. Feedstocks high in lignin, such as woody residues and other sustainably available biomass, do not biodegrade to the same extent as other waste materials in an anaerobic digestion system because they have poorly accessible molecular structures (Montgomery and Bochmann, 2014). As described in Section 2.3.5 above, anaerobic digestion produces less energy and displaces fewer fossil fuels than dedicated energy conversion pathways.

The digestate produced by anaerobic digestion systems typically has significantly less odor than the inputs and is easier to apply than other soil amendments because it is a liquid. Digestate has a significantly higher amount of readily available nutrients than compost, with food-based digestates offering the greatest amounts of readily available nutrients (WRAP UK, 2011). However, it is unlikely that the nutrient content of digestate is sufficiently high to completely displace synthetic fertilizer.

4.5. RESULTS AND DISCUSSION

The non-GHG impacts of different biomass pathways are highly dependent on both the feedstock input and the specific conversion technology, but we can draw several broad conclusions about the general pathways based on our findings. In terms of air pollution, the use phase (i.e., combustion) is the largest contributor to air pollution, eclipsing the production emissions for both liquid fuels and heat and power. As bio-based materials do not incorporate combustion into their useful lifetimes, they compare favorably to bioenergy pathways on this metric. However, the manufacture of bio-based materials is an emerging technology and future developments could alter this result. The production emissions for all three pathways are relatively small, and in the case of bioenergy are significantly smaller than the emissions from combustion.

Indirect impacts from byproducts and wastes present a mix of outcomes, both positive and negative, depending once again on the technology in question. In general, heat and power pathways tend to create more byproducts in the form of ashes and residues. Similarly, pyrolysis technologies produce biochar. Many of these byproducts can restore nutrients to soils. Co-firing of biomass with coal reduces the heavy metal content of fly ashes relative to fly ash from the combustion of coal on its own, thus reducing the risks of heavy metal leaching in outdoor uses.

Putting the environmental impacts into context, the pollution from biomass energy pathways is generally less than those of petroleum-derived fuels. For bio-based materials, it is difficult to draw a conclusion due to the scarcity of data and multitude of technologies. With the exception of VOCs and NOx in several cases, biomass energy pathways emit fewer criteria air pollutants than comparable fossil fuels. In particular, biomass heat and power pathways offer optimal performance relative to regulations governing stationary combustion when the biomass is displacing coal. However, biomass displacement of natural gas combustion offers similar performance to liquid fuel use. Water consumption for biomass energy pathways is comparable to fossil fuel production and use.

Alternative uses of biomass, such as composting and anaerobic digestion, offer positive benefits in the form of nutrient cycling and reduced landfill demand. However, composting does not offset fossil fuel use, and the energy balance of anaerobic digestion is less than that of dedicated energy conversion pathways. As demonstrated in Section 2.3.5 above, anaerobic digestion of corn silage can generate 760 kWh (2,736 MJ) per wet tonne of waste (Böhni Energie and Umwelt, 1999). Assuming that the corn silage has a 15% moisture value, this equates to 3,219 MJ of electricity and heat. This is less than the amount of power generated in the least-efficient of any of the eight biopower pathways assessed in the LCA model—and about 30% of the heat and electricity generated from an equivalent amount of biomass in a CHP power plant. Furthermore, those processes are reliant on a mix of feedstocks and are not necessarily fully competitive with the competing uses highlighted in this report. So long as the GHG benefits of energy recovery pathways are demonstrated to be superior to those of composting and anaerobic digestion, an argument can be made that those pathways are justified within the framework of the WFD.

5. THE ROLE OF BIOMASS IN LONG-TERM DECARBONIZATION

5.1. INTRODUCTION

In 2009, the European Council established a goal of reducing GHG emissions in the European Union (the EU-27) by at least 80% from 1990 levels by 2050 following a 2009 agreement between the EU and the G8. The aim of this target is to limit global temperature increase to 2°C (relative to pre-industrial levels), thus mitigating the most damaging impacts of climate change. This target necessitates a reduction in emissions to only 1.2 $GtCO_2e$ annually—nearly a 75% reduction from the 2012 EU-28 emissions of 4.5 $GtCO_2e$ (see Figure 5.1 for a representative illustration of this reduction). To achieve these goals, wide-ranging changes must be implemented in the power and transportation sectors, facilitating a transition away from GHG-intensive fossil fuels to a variety of cleaner energy sources, including biomass energy.

Existing biomass conversion technologies, where implemented sustainability, may already mitigate climate change by reducing GHG emissions in the present day. The growing portfolio of biomass energy technologies could also play a valuable, longer-term role in meeting the European Union's 2050 decarbonization goals. A variety of roadmaps and projections envision biomass taking on a larger role in Europe's heat, power, and transport systems, though they differ about the extent of biomass energy deployment and its allocation between sectors. Furthermore, different projections of Europe's decarbonization in 2050 offer competing visions of technology deployment and thus leave different roles open for future biomass use.

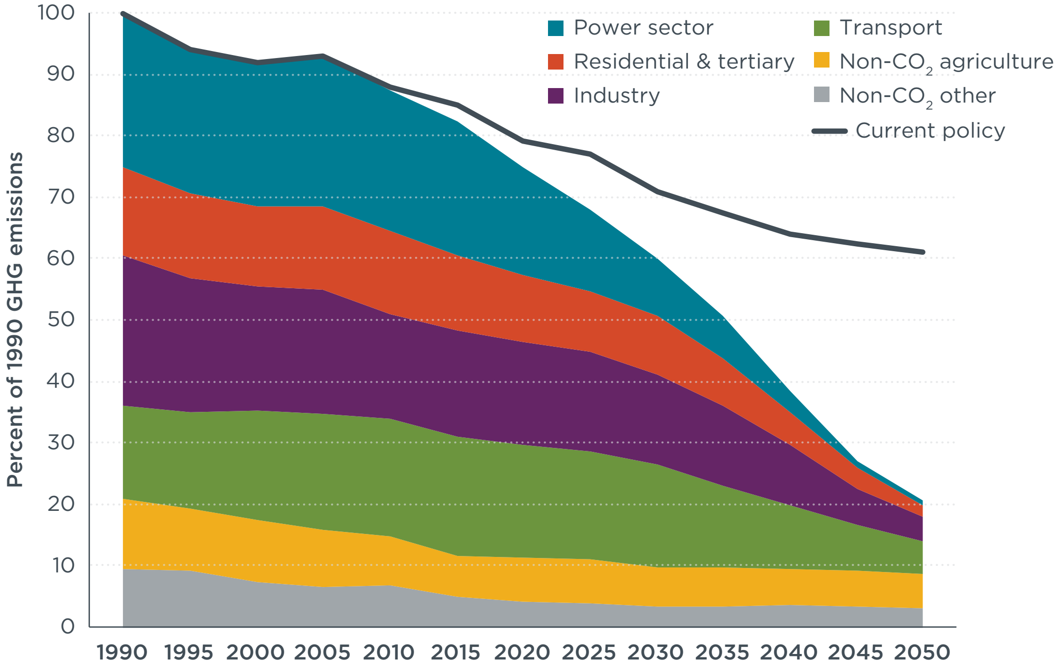

Figure 5.1. An example of EU GHG emissions reductions toward an 80% reduction

Source: Adapted from EC, 2013, Trends to 2050

The potential for rapid technological change and the uncertainty of the rate of deployment of new technologies mean that the biomass uses that offer the greatest short-term GHG reductions today may not always support development of the technology options required to meet 2050 goals. As technology improves, some sectors may develop low carbon alternatives that offer better value for money than biomass options, while other sectors could lag behind relying still on fossil fuels. Regulatory action now should therefore be attentive not only to the GHG, economic, and environmental impacts of short-term biomass use, but should consider the trajectories that will be needed to deliver the decarbonization agenda.

5.2. SCOPE OF ANALYSIS

This analysis considers several roadmaps and projections prepared by the European Commission (EC), intergovernmental organizations, and nongovernmental organizations (NGOs) that depict European energy consumption and technology deployment in 2050. Each roadmap takes a different set of assumptions about the role of given technologies in meeting Europe's decarbonization needs in 2050. The analysis compares a reference case assuming no major policy or economic shifts with a variety of roadmaps that model more vigorous policy intervention to meet climate goals.

The review of each roadmap will consider the following factors:

1. **Energy Supply:** This factor considers the distribution of energy sources that are projected to comprise the European energy mix (for heat, power, and transportation) and the extent to which the distribution of each source will change from the present.
2. **Technological Change:** Technological change is likely necessary to meet the EU's 2050 decarbonization targets, and new technologies may greatly affect one sector's energy needs without affecting the carbon intensity of others.

After assessing each roadmap's approach to 80% lower EU emissions in 2050, we assess the role of biomass energy within them to determine how projections view the availability, the likelihood of technology deployment, and, most importantly, the extent to which it competes with or displaces other sources of energy. Additionally, we review a set of studies that discuss the likelihood of vehicle electrification by 2050 in order to address the uncertainty on this topic within the various roadmaps assessed. Based on this, we consider the necessary direction that may need to be set out in biomass energy policy in the near term in order to facilitate these developments in the long term.

5.3. REFERENCE CASE

The EC's Trends to 2050 report (finalized in 2013) provides a reference scenario to 2050 for policymakers by extrapolating current EU-28 economic and population trends to 2050 in conjunction with the assumption that the EU's legally binding GHG and RES targets for 2020 will be met. The report makes several assumptions about technological change but does not consider additional large-scale climate policy commitments. This reference case shows the extent to which technology change and existing policy commitments affect the deployment of various biomass conversion technologies in the absence of a 2050 decarbonization commitment. It was intended to serve as a benchmark for assessing the impacts of future climate policy initiatives at the EU level.

The Trends to 2050 report uses the general-equilibrium PRIMES model to simulate an EU-28 energy market wherein energy demand is met at the lowest cost from each possible energy source, with consideration of supply technologies and environmental policies. The report's assumptions about biomass consumption were developed with the PRIMES biomass supply mode. New technologies included in the reference case include improved efficiency (e.g., vehicle engines, end-use energy efficiency, smart grid), improvements in centralized power generation (e.g., carbon capture and storage, supercritical coal plants), and cost reductions for renewables such as solar photovoltaics (PVs) and offshore wind.

With existing policy commitments, the reference case projects that the EU energy system reaches 20% deployment of renewable energy sources as a share of gross energy consumption by 2020, with 10% deployment occurring within the transportation sector.[37] By 2050, renewable energy sources accounts for 29% of EU gross energy consumption—50% within the power sector and 14% within the transport sector. The growth of renewable energy sources post-2020 is influenced by the European emissions trading system (ETS), ongoing technological progress, and RES-enabling policies (e.g., direct subsidies).

On the supply side, the Trends to 2050 Report projects biomass demand to exceed EU production levels until 2020, due to existing policy obligations. Only after 2020 does biomass production in the EU meet demand, thus driving down the need for biomass imports. Until 2020, however, the report projects that demand will need to be met with imported biomass. In the reference case, PRIMES modeling suggests that short rotation tree plantations and lignocellulosic energy crops will expand over the time series in order to meet biomass demand in conjunction with the expansion of advanced biofuel pathways—perennial crops are projected to occupy 9% of available cropland by 2050.

Though the reference case projects that the share of renewable energy rises from 12.5% in 2010 to 29% in 2050, biomass-derived energy does not contribute significantly to that growth beyond 2020. As shown in Figure 5.2, without further policy intervention beyond the requirements of the RED in 2020, biomass energy peaks at less than 10% of transport energy demand, whereas fossil fuel energy still comprises a large majority of overall demand. The projected growth of the liquid biofuels sector continues beyond 2020 because of a combination of high fossil fuel prices and reduced costs of biomass production and collection. Similarly, the net electricity generation from biomass is only projected to contribute 8% of total electricity generation and 35% of on-site CHP steam generation by 2050. Figure 5.3 shows that after 2020, the majority of growth in renewable energy comes from wind power, while the share of biomass remains relatively constant.

The reference scenario, as shown in more detail within the DG Clima Roadmap (EC, 2011a), projects that biomass production would more than double from 2005 levels, reaching 9,546 PJ based on current trajectories by 2050, of which 2,512 PJ and 1,507 PJ would come from waste products and agricultural residues, respectively. From 2030 to 2050, biomass production growth is projected to remain fairly stable (peaking at 9,672 PJ in 2030), with the relative distribution shifting towards 2050 as lignocellulosic crops are produced in greater quantities to replace first-generation biomass feedstocks (EC 2011a). The bulk of this increase would come from the period 2010 to 2020 in order to fulfill the EU's 10% renewable energy sources target for the transportation sector.

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[37] Renewable energy sources are defined by the EC here as "energy resources which are naturally replenishing but flow-limited." These sources include biomass, waste energy, hydropower, wind, geothermal, solar, wave, and tidal energy.

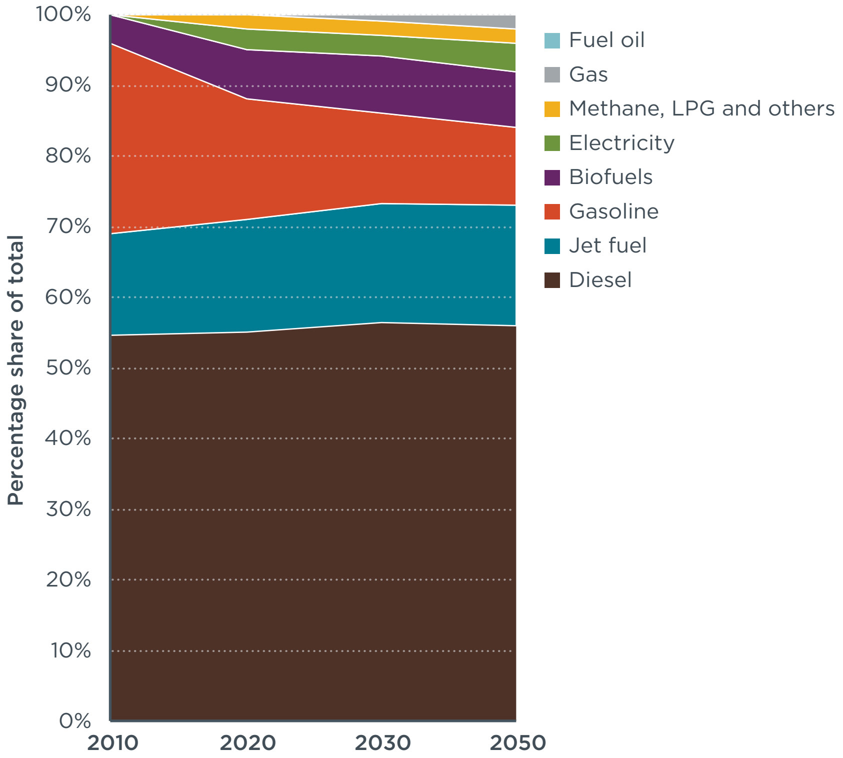

Figure 5.2. Reference case growth of transport energy demand in Europe to 2050

Source: Adapted from EC (2013)

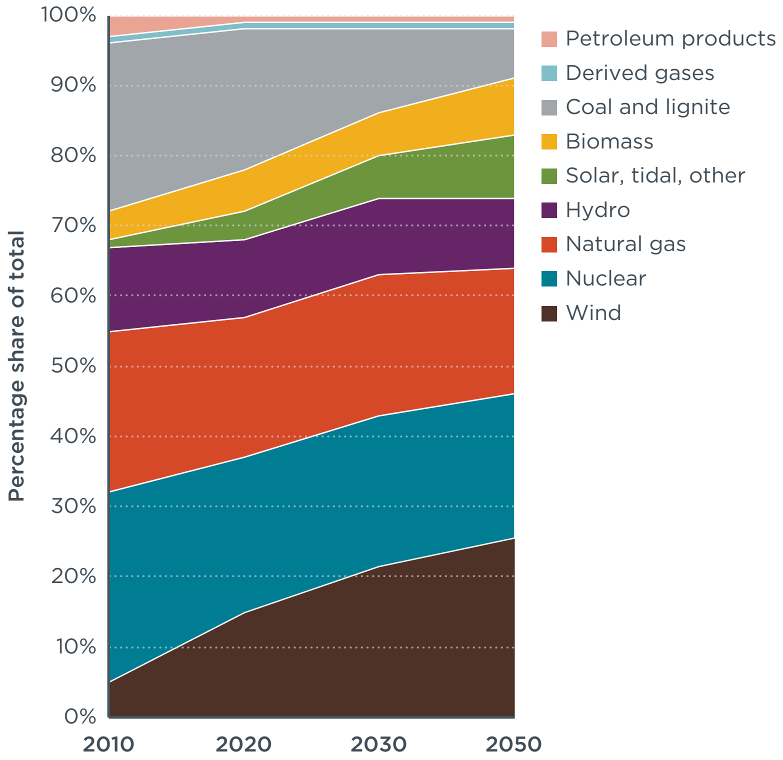

Figure 5.3. Reference case growth of electricity energy demand in Europe to 2050

Source: Adapted from EC (2013)

The reference case projects that without further policy intervention, the penetration of electric vehicles will be restricted to niche markets, such as urban areas and municipal fleets, with total penetration limited to 8% in Europe (EC, 2013). Of that total, two-thirds would consist of PHEVs still partially reliant on liquid fuel. The report also projects that biofuel consumption within the aviation sector would only slowly begin after 2035, driven by high ETS prices. Trends to 2050 projects that power plant technologies will improve significantly to increase the relative contribution of biomass to heat and power. Co-firing rates with fossil fuels are projected to increase up to 26% (as a total share of thermal fuel). Additionally, biogas use is projected to increase to 25% of biomass power by 2025 and then plateau.

Overall, the Trends to 2050 report projects that without additional policy commitments, the EU will reduce GHG emissions by 44% in 2050, relative to 1990 levels. While this is a sizeable reduction, it does not sufficiently reduce the EU's GHG emissions to meet the 80% reduction and thereby mitigate the worst potential climate impacts.

5.4. EU ROADMAPS

The reference case explored above suggests that absent further policy intervention, the current trajectory of energy use and emissions in the EU will be incompatible with the EU's decarbonization goals. Consequently, the EC has produced several roadmaps that depict alternative policy and technology scenarios for the EU that result in steeper emissions reductions by 2050. The three roadmaps explored in this section include DG Clima's roadmap for moving to a competitive low-carbon economy in 2050 (2011a), DG Mobility and Transport's "Roadmap to a Single European Transport Area" white paper (2011c), and DG Energy's "Energy Roadmap to 2050" (2011b).

The overwhelming majority of the EU's emissions in 2013—nearly 80 percent—came from energy generation (i.e., all combustion activities for heat, power, and transportation), ensuring that the energy sector will be the primary target for decarbonization efforts in order to reach the EU's 2050 goal (EEA, 2013). Europe's heat, power and transportation sectors contribute such a high proportion of total emissions that together they must likely undertake the steepest emissions reductions in order to reduce the overall economy's emissions by 80% (ECF, 2010). The DG Mobility and Transport Roadmap claims that transport sector GHG emissions will need to be cut by 60% with respect to 1990 to meet the 2050 goal (EC, 2011c). Efforts to reduce the carbon intensity of energy generation will likely involve both increased deployment of low-carbon energy sources (i.e., renewable energy) and improving the efficiency of existing, fossil fuel–based technologies. The energy sector, which relies on high-capital infrastructure investment, requires near-term policy direction in order to reduce emissions in the long-term.

The DG Clima roadmap (2011a) presents a scenario analysis of how the EU can shift to a low-carbon economy by 2050 through sectoral milestones for GHG emissions reductions for 2030 and 2040. This roadmap seeks to provide a general cost-effective approach for meeting the EU's decarbonization target while also serving as the basis for the DG Energy 2050 Energy Roadmap as well as DG Mobility and Transport's white paper, which explore their respective sectors in more detail.

The 2011 DG Clima roadmap projects that electricity consumption will increase at historical rates as the effects of efficiency in stationery electricity consumption and growing electric vehicle penetration cancel each other out. The share of "low-carbon technologies" in the EU's electricity mix increases from around 45% today to around

60% in 2020, 75–80% in 2030, and nearly 100% in 2050.[38] The relative deployment of each type of low-carbon technology varies depending on the scenario. The DG Clima roadmap suggests that until 2025, the primary GHG emissions reductions from transport would come from efficiency improvements; only after 2025 would fuel switching accelerate.

The DG Clima roadmap estimates that biomass production would need to increase by 56% relative to the reference case by 2050—reaching 14,905 PJ of energy. This total significantly exceeds the roughly 1,500 PJ of energy sustainably available from wastes and residues in Europe, indicating that the shortfall may need to be met with energy crops (Harrison et al. 2014). The majority of the expansion would occur from 2030 to 2050, with lignocellulosic crops growing to account for more than a third of the entire sector on an energy basis. Waste products and agricultural residues would generate 3,643 PJ and 2,051 PJ, respectively, by 2050.

The report anticipates a long-term role for biofuels in both the heavy-duty and aviation sectors, but notes that in the event of slower-than-projected passenger vehicle electrification biofuels would likely have a role in the light-duty vehicle sector as well. Of the 14,905 PJ of biomass energy available in 2050, DG Clima projects that 1,926 PJ (46 Mtoe) of liquid biofuels would be used for road transport; if vehicle electrification is delayed, that number could reach 3,852 PJ (92 Mtoe) in 2050. In the standard decarbonization scenario, biofuels would comprise 25% of the energy mix for road transport (of the 175 Mtoe total road transport energy demand); in the case of delayed electrification, this total could rise to 43% of the energy mix for road transport (of the 214 Mtoe total road transport energy demand). The residual petroleum demand in these scenarios is 36% (63 Mtoe) and 34% (94 Mtoe) of road transport energy, respectively. In all decarbonization scenarios, aviation biofuel use reaches 1,048 PJ (25 Mtoe) in 2050 out of a total aviation energy demand of approximately 50 mtoe.

The 2011 DG Clima roadmap envisions a long-term role for fossil fuels using carbon capture and storage (CCS), wherein GHG emissions from centralized combustion are sequestered instead of released into the atmosphere. The different scenarios in the roadmap explore various levels of CCS deployment, ranging from cases where it plays an integral role in mitigating GHG emissions to scenarios where commercialization of CCS technology lags behind other alternatives. The roadmap estimates that the EU has a total of 250 Gtonnes of CO_2 storage capacity, sufficient to sequester power sector GHG emissions to 2050. The global action scenario estimates that 76% of power sector emissions would be sequestered.

While the roadmap doesn't differentiate between the different sources of emissions sequestered with CCS, it is reasonable to speculate that some CCS technology would be used to sequester emissions from stationary biomass combustion. While biomass combustion offers carbon savings relative to the use of fossil fuels, it still emits an absolute amount of GHGs. Capturing carbon from biomass combustion would therefore provide net carbon reductions. As the role of fossil fuels within the power sector declines, CCS for stationary biomass combustion could thus offer GHG sequestration to complement other, higher-emitting sectors of the economy.

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[38] In the roadmap, low-carbon technologies are defined as 1) renewable energy sources, 2) nuclear power, and 3) carbon-capture and sequestration-equipped fossil fuel plants.

The DG Clima roadmap mentions the possibility of manufacturing biomass-based materials to displace more GHG-intensive products, but does not include this option in any of the scenarios modeled. Synergy between liquid fuels and the biochemical industry could lead to complementary growth in the coming decades. As ethanol conversion technology improves, however, this could increase the commercial viability of pathways such as bio-ethylene production from cellulosic ethanol (as discussed in Section 2.3.5 above). Likewise, improvements in the biochemicals sector could be harnessed to increase yields within the liquid fuel conversion process.

The white paper from DG Mobility and Transport also envisions an important role for liquid biofuels in sectors where electrification is more difficult, anticipating that by 2050 as much as 40% of energy consumption for long-distance freight hauling may be met using liquid biofuels. Similarly, low-GHG biofuels could also increase to up to 40% of the bunker fuel used by the marine sector by 2050. Depending on the extent of electrification within the light-duty vehicle sector, biofuels would only provide up to 15–25% of energy demand (not including any biomass-derived electricity from the grid).

The white paper notes uncertainty in the extent to which the European passenger vehicle sector could be electrified, with a range of 20 to 60% depending on the policy option taken. This leaves a modest role for liquid biofuels to contribute to the passenger and light-duty vehicle sector. Due to the difficulty of electrifying the aviation sector, the white paper highlights the role that technology innovation could play in improving fuel efficiency for liquid fuels—as much as 60% by 2050. Remaining energy needs could then be met by drop-in biofuels.

The 2011 DG Energy roadmap depicts a varied set of scenarios, ranging from a business-as-usual reference scenario similar to the Trends to 2050 report described above, to a “High RES” scenario with significant renewable energy deployment. The roadmap suggests an overall shift to electricity in 2050, with an increase in heating and cooling demand as well as 65% of passenger vehicles relying on the electricity grid (EC, 2011b). The roadmap projects that as electricity consumption increases to 2050 (to 17,751 PJ annually in the reference case), the share of renewables could substantially increase in action scenarios, growing to a range of 55% to 97% of gross energy consumption in Europe.

Biomass energy in the DG Energy roadmap is projected to provide a large contribution to centralized power and heating, as well as transportation sectors for which electrification would be more difficult, namely aviation, long-distance road transport (i.e., heavy-duty vehicles) and rail. In the reference scenario, the DG Energy roadmap projects that liquid biofuels use increases by more than a factor of 10 to reach 37-39 Mtoe (Million tonnes oil equivalent) in 2050, out of domestic biomass production of 186 to 189 Mtoe. This would constitute roughly 10% of the projected 383 Mtoe of energy consumption in the transport sector in 2050. In contrast, the decarbonization scenarios in the DG Energy roadmap project that liquid biofuels could provide from 68 to 72 Mtoe of energy in 2050, falling between the two values projected in the 2011 DG Clima Roadmap. This range is approximately a quarter of the total domestic biomass production in the decarbonization scenarios (241 to 302 Mtoe). In the decarbonization scenarios, the projected increase in the biomass share of energy occurs in conjunction with a decrease in transport sector energy demand (to a range of 229 to 238 Mtoe in 2050), so that biofuel use would account for approximately 30% of transportation energy use.

5.5. OTHER ROADMAPS

Beyond the roadmaps produced by the EC itself, several NGOs have developed their own possible pathways for Europe to meet the decarbonization goals. The roadmaps assessed here include studies by the European Climate Foundation (ECF), the International Energy Agency (IEA), the World Wildlife Federation (WWF), and the Sustainable Development Solutions Network (SDSN).

The ECF developed a decarbonization roadmap for the EU-27 (along with Norway and Switzerland) that describes a range of scenarios with renewable energy deployment ranging from 40% to 80% throughout the region. Working backwards from the emissions reductions necessitated by the 2050 goal, the ECF roadmap develops a prediction using a technology-agnostic approach that incorporates existing or near-term technologies. A key element of the roadmap's assumptions is the implementation of a rising carbon price in the EU (plateauing at a price of €110/ton by 2030) and the use of GDP and energy demand data from the International Energy Agency's "450 Scenario."[39] Europe's energy demand is assumed to increase 12% from 2010 to 2050.

To meet increased European power demand while simultaneously lowering carbon intensity, ECF projects that Europe would rely on a mix of intermittent and non-intermittent renewable energy sources (RES) as well as the deployment of CCS systems for fossil fuel power plants. Using the McKinsey Power Generation Model, biomass availability in Europe is constrained to 16,200–18,000 PJ/yr, after accounting for imports, water use and competition with food. As with the DG Clima (2011) roadmap, this estimate exceeds the roughly 1,500 PJ of energy sustainably available from wastes and residues in Europe cited in Harrison et al. (2014), thus implying that the production of energy crops would be needed in order to meet the projections. The ECF roadmap assumes that some biomass demand will be met by using energy crops instead of biomass waste, which increases overall supply at the risk of competing with food demand. The extent of this competition in the ECF roadmap is not discussed further.

Of the total biomass energy use envisioned in 2050 by ECF, just over half (9,000 PJ) is allocated to the transport sector, mostly to meet demand for liquid fuels for heavy-duty vehicles, marine transport and aviation. ECF projects that 55% of road transport fuel demand would be met by liquid biofuels, predominantly in the heavy-duty sector, along with 30% of the marine and aviation sectors. The residual petroleum demand in the transport sector is projected to range from 78 to 146 Mtoe in 2050, depending on the scenario. After transport, the remaining 7,560 PJ of projected biomass capacity is used in the heat and power sector to provide baseload power in support of intermittent renewables—this would increase dedicated biomass power generation to 12% of the power sector by 2050. However, it is important to note that ECF expects that in future years, the grid power demand for the road transport sector will increase by nearly 1,500% (from 180 PJ to 2,600 PJ) as vehicle electrification increases.[40]

The International Energy Agency (IEA) presents two projections of future energy demand to 2035 in its World Energy Outlook, the baseline "New Policies Scenario," which incorporates expected future policy commitments, and the "450 Scenario," which depicts energy demand consistent with the goal of limiting the global increase in

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[39] The 450 Scenario describes a global effort to reduce GHG emissions, first from the deployment of renewable technologies globally and then via an international policy framework targeting climate change.

[40] Additionally, ECF expects that 20% of electric vehicle energy would come from biomass power.

temperature to 2°C by limiting atmospheric GHGs to 450 parts per million (ppm) of CO_2. The scope of the 450 Scenario aligns more closely with the 2050 decarbonization goals for the EU.

The IEA analysis models energy use in the European Union from 2020 to 2040. The New Policies Scenario projects increased use of biomass in all sectors to 2040, with the majority of the increase in bioenergy occurring within the heat and power sector—rising to 11% of power generation by 2040. In the New Policies Scenario, the contribution of biofuels to transportation reaches 14% in 2040. In contrast, the more aggressive 450 Scenario expands the role of bioenergy within transportation, with an increase to 27% of total transportation energy demand by 2040.

The WWF's 2011 Energy Report advocates for a large role for biomass in a global effort to switch to 100% renewable energy deployment. Unlike several of the other roadmaps assessed, it has a global focus instead of a strictly EU focus. The roadmap calls for a global total of 105 EJ (105,000 PJ) of sustainably available biomass to be used annually. This suggestion is approximately three times higher than the current biomass use of 35,000 PJ (WWF, 2011). The report projects a fairly even split between biomass used in the heat and power sector and biomass used for transport, with 54,200 PJ and 50,800 PJ used in each sector by 2050, respectively (of the heat and power total, 16,200 PJ would be used for electricity). In percentage terms, this is 100% of the transportation sector and 25.7% of the heat and power sector.

An important point in the WWF projections is the role of biomass energy for heat and power, particularly in industrial applications. In some cases, solar heating would provide insufficient high temperatures, or alternately, a gaseous or solid feedstock would be necessary (e.g., in steel-making).

The WWF roadmap mentions the opportunity for bio-based materials to displace existing materials, though this possibility is not factored into the report's calculations. It does note, however, that extrapolating from current trends, there would be 66,000 PJ of demand for petrochemical feedstocks in 2050 that could be met with biomass feedstocks; furthermore, this demand could be met in addition to the demand for biomass for energy. The report also describes the possibility for bio-based materials to be combusted for energy at the end of their usable lifetimes.

The Sustainable Development Solutions Network produced a 2014 report, "Pathways to Deep Decarbonization," which assesses how an 80% GHG emissions reduction can be accomplished on a nation-by-nation basis. For several of the largest EU nations, such as Germany and France, the total biomass share of energy is projected to grow to approximately 600 PJ and 680 PJ, respectively. In France, SDSN projects that liquid fuel use will decrease significantly due to increased fuel efficiency, decreased freight volumes and vehicle electrification. Thus, SDSN suggests that only 22% of liquid fuels used in France will be biofuels. In Germany, the projected share of biofuels in the transportation sector is higher, but still not a majority of the liquid fuel used.

5.6. VEHICLE ELECTRIFICATION

As the mix of technologies changes, so do the optimal uses of biomass—a present-day use with high GHG reductions may be rendered obsolete or crowded out by technology shifts prior to 2050. A key technological uncertainty relevant to biomass is the extent of vehicle electrification by 2050—if vehicles as a whole become more reliant on the electricity grid, this could crowd out opportunities for liquid biofuels. This section considers a variety of projections from the literature on the extent to which electrification takes hold for passenger vehicles, heavy-duty vehicles, and the aviation sector.

The ECF's roadmap uses a technology-agnostic approach that does not place big bets on any single technology, instead assuming that 2050 GHG emissions reductions will be made via a mix of available technologies. Using the McKinsey Global GHG Abatement Cost Curve, ECF calculates the maximum abatement potential until 2030 and identifies the extent to which various sectors must implement efficiency improvements and then shift energy sources in order to meet emissions targets.

From 2010 to 2050, ECF projects that approximately half (0.8 $GtCO_2e$) of GHG reductions for transport can be met with efficiency improvements; however, the subsequent necessary reductions (0.8 $GtCO_2e$) must be met by fuel shifting. This necessitates a mix of vehicle electrification and fuel shifting in the following sectors:

- **Light and Medium-Duty Vehicles:** ECF assumes that vehicle electrification will reach 100% for light and medium-duty vehicles by 2050, with 80% of vehicles being full battery-electric vehicles (BEVs) and the remaining 20% Plug-In Hybrid Electric Vehicles (PHEVs).
- **Heavy-Duty Vehicles:** A mix of technology deployment, including 45% use of liquid biofuels and a 45% use of hydrogen fuel cells.
- **Marine and Aviation:** Biofuel use increases to 30% of fuel demand, but further deployment is constrained by biofuel availability.

A key assumption in the ECF roadmap is the complete penetration of electric vehicle technologies and the light and medium-duty vehicle markets by 2050, which is based on economic modeling showing that the total cost of ownership for the average passenger vehicle will be cheaper for electric vehicles relative to internal-combustion engine (ICE) vehicles in the 2020s.

Despite optimistic projections in some roadmaps, the extent of passenger vehicle electrification is highly uncertain by 2050. A 2013 study by the U.S. National Research Council (NRC) uses a cost model which inputs changes in gasoline prices, electricity prices, and the expected decreases in alternative vehicle technologies to project the sales of vehicles to 2050 in the United States across a variety of scenarios. The alternative vehicle technologies assessed in the report include: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). The scenarios included a baseline scenario and different levels of feebates applied to each of the above alternative technologies.

Only three of the NRC scenarios were able to achieve electric vehicle deployment over 80%. Each of the high-deployment scenarios used a feebate system that provided subsidies of $20,500 for BEVs, $27,500 for FCEVs, $13,000 for PHEVs in 2015, decreasing over time. This level of subsidy is massive; it is about double the highest combined fiscal incentive that has been available in Europe (Norway[41]) and would cover almost the entire purchase cost of some of the cheaper available BEV models. Even in these optimistic cases, there appeared to be a "floor" for ICE sales, attributed

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[41] Estimated for the Renault Zoe, a typical, non-luxury BEV. The incentives are no longer available.

to the inability of BEVs to satisfy the demands for driving range and short refueling time of all drivers. The fuel source for ICEs in these scenarios was assumed to be 100% liquid biofuel.

A 2015 study by the Electric Power Research Institute (EPRI) assesses the extent to which vehicle electrification would impact GHG emissions and power demand for the U.S. electricity grid. The study looks at a timeline from 2015 to 2050 by using an EPRI market-adoption tool to evaluate the shifts in market share for different vehicle types for the entire on-road fleet over the time series. This model uses a cohort model to simulate vehicle aging and replacement over time, in conjunction with projected improvements and adoption of new technologies. Using that modeling approach, EPRI projects that in an aggressive electrification scenario, 67% of new vehicles sold would be PEVs by 2050 (of which the majority would be BEVs). Of the total vehicle-miles travelled in 2050, EPRI projects that 53% would be travelled by PEVs in an aggressive electrification scenario.

Electrification of the heavy-duty vehicle sector is substantially less certain than for passenger vehicles, making this sector much more reliant on liquid fuels or fuel cells. As of 2013, only 1,000 battery electric trucks were operating worldwide, though significant performance improvements are expected within the next five years (Den Boer et al., 2013). Den Boer et al. (2013) model a GHG reduction scenario wherein 90% of the heavy-duty fleet is powered either by electric or fuel cell trucks. This “Ambitious Alternative” scenario considers a case where overhead catenary grid-integrated vehicles (OC-GIV) and fuel cell hybrid-electric vehicles (FCHEV) achieve cost-competitiveness within the long haul sector in 2025 and achieve 90% penetration by 2050; for shorter distances, the breakdown is half FCHEV and half BEV trucks. This scenario was developed in the absence of cost modeling and thus has explorative value for evaluating possible GHG reductions from the heavy-duty sector instead of offering a prediction of 2050 technology deployment. However, the scenario does provide insight on how heavy-duty vehicle electrification and decarbonization can plausibly occur.

Due to the more efficient drivetrains of electric vehicles, it is likely that a vehicle powered by biomass-derived electricity would generate lower emissions per gallon-gasoline equivalent (GGE) than vehicles combusting liquid biofuels. However, this should not impact the policy focus for biomass to mitigate climate change. Even as electric vehicles achieve greater market penetration, there is no certainty that the grid electricity supplying them would necessarily come from biomass energy. Furthermore, as demonstrated above, even with the most optimistic projections of EV penetration, there would be substantial demand for liquid fuels in the heavy-duty, marine, and aviation sectors. Thus, the continued use of liquid biofuels would not crowd out the growing EV market.

Despite the vastly different assumptions about the future of vehicle technologies in the roadmaps and studies assessed in this chapter, the transportation sector is still likely to consume a substantial amount of liquid fuels in 2050. For the purposes of shaping future policy, this result is significant because it indicates that even in the “best-case” scenarios, which include 100% vehicle electrification, there is sufficient demand in certain “inflexible” sectors such as heavy-duty vehicles, marine transport and aviation to still consume a large share of biomass energy. The anticipated reliance of the transport sector on liquid fuels—even at high levels of electrification technology penetration for passenger vehicles—means that current or near-term investment and policy focus on biofuels would not be crowded out by competing technologies in the long-term. The various electrification scenarios indicate that there is likely sufficient demand for all types of liquid fuels that there is no need to prioritize gasoline or diesel substitutes over the other. Even if the full supply of sustainably available biomass feedstocks were converted to gasoline substitutes because it is most-cost effective or for any other reason, there would likely still be some amount of additional liquid fuel that would need to be met with gasoline.

5.7. RESULTS AND DISCUSSION

All of the roadmaps reviewed, including the baseline Trends report, envision a substantial role for biomass in 2050 as a means of reducing GHG emissions within the EU. The various roadmaps which envision an 80% reduction in GHG emissions all expand the role of biomass energy beyond that of the reference case developed in the EC's Trends to 2050 report, underscoring the potential for sustainable biomass to reduce GHG emissions. An overview of the roadmaps' projections of relative energy contributions to the electricity and transport sectors is depicted in Figure 5.4 below. While bio-based materials are another potential pathway for biomass feedstocks to 2050, projections of the growth and development of this sector are less certain than energy pathways.

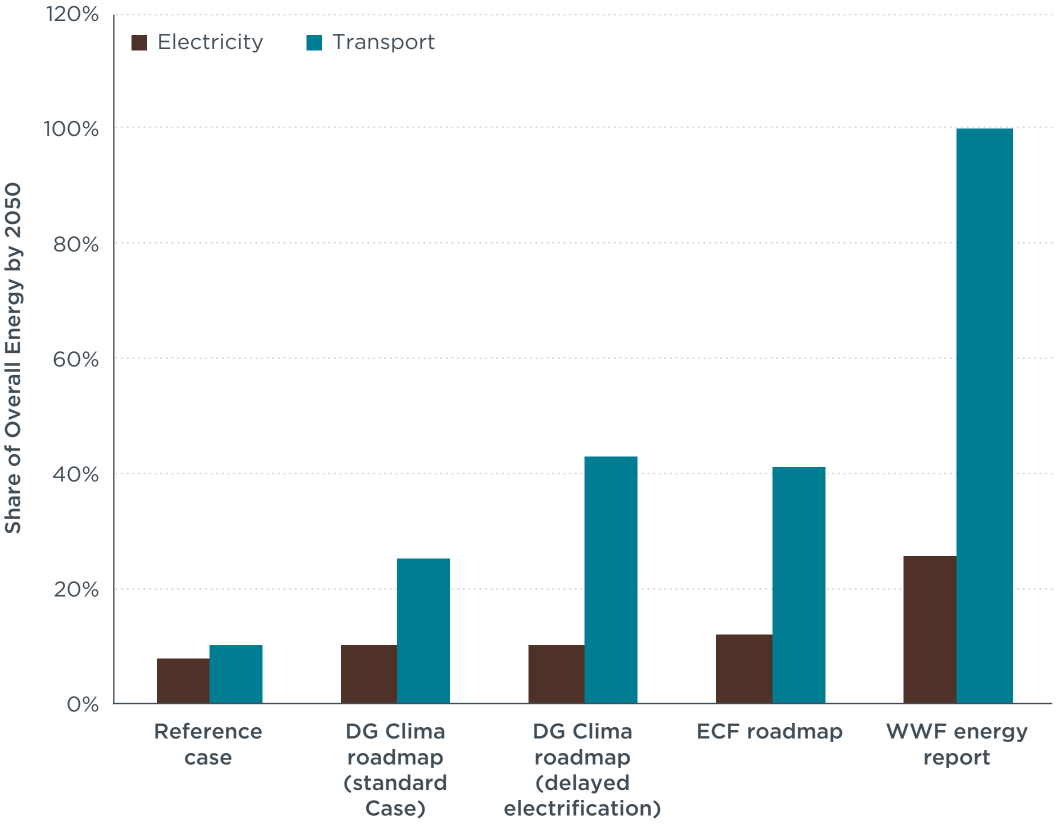

Figure 5.4. Biomass contribution to electricity and transport sectors in 2050, by roadmap

Note: WWF Energy Report provides projections for global electricity and transport energy demand.

The extent of biomass combustion in the various roadmaps varies widely, with biomass contributing from 10 to 25% of electricity generation by 2050. This range would represent a marginal increase to over double of the projected biomass use in the Trends to 2050 baseline projection. This is likely due to the important role of biomass as a baseload source of power that could complement other, intermittent renewable energy sources. As biomass combustion increases, the use of coal declines to near zero in decarbonization scenarios (against a reference case value of 15 percent), while natural gas would decline to 30% of the heat and power sector. Furthermore, CCS deployment for stationary combustion would mitigate GHG emissions from both biomass and natural gas.

Projections of biomass use vary considerably within the transportation sector, in part due to uncertainty over the extent of vehicle electrification, with projections ranging from 25% to 100% of vehicle fuel demand. If vehicle electrification develops more slowly than anticipated or at the lower end of this range, biofuels would likely take on a larger role in the passenger vehicle sector. Even in the most optimistic projections of vehicle electrification, there remains a substantial role for liquid fuels within the heavy-duty, aviation, and marine sectors, and thus an opportunity for biofuels to deliver emissions reductions.

We can conclude from this analysis that decarbonization would likely increase the demand for biomass in both the heat and power and transportation sectors relative to baseline trends. The forecast for bio-based materials is less certain, as the industry is further from commercialization, though biopolymers have the opportunity carve out an increasing share of the growing global plastics industry as their conversion technologies mature. Structural considerations, such as complementarity between baseload biomass combustion and intermittent renewables, help to ensure the continued demand for biomass through the timeline assessed. While limited stocks of sustainably available biomass could limit the use of biomass in 2050 and generate competition between pathways, in the immediate future the various uses of biomass are more complementary than competitive. Increasing demand for biomass for a given use, alongside policy certainty for renewable energy demand, could enhance sustainable residue collection and supply chains. For example, near-term use of biomass in the heating sector could improve residue collection and waste recovery technologies and supply chains to facilitate the deployment of liquid fuel conversion in the longer term. Therefore, it is unlikely that policy support for a given biomass pathway in the near future would generate demand within a sector for which there will not be sufficient demand in 2050.

Through the review of various pathways for the EU to meet its decarbonization obligations, it grows clear that the projected biomass needs of the EU far exceed its supply of sustainably available biomass from wastes and residues, as identified by Harrison et al. (2014). Addressing the gap between projected biomass needs and the limited supply of wastes and residues should be a priority for policymakers moving forward, and should prompt the development of improved supply chains for wastes and low-impact energy crops in order to meet that demand. As the needs of the EU move beyond the energy provided by wastes and residues, the future of biomass deployment could be increasingly affected by whichever pathways offer the greatest value-added use and thus support higher costs for energy cropping. This development could tilt future biomass use away from lower-value heat and power applications and increasingly towards liquid biofuels and bio-based materials.

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