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SYSTEMS PERSPECTIVES ON BIOREFINERIES

CHALMERS

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PREFACE

Replacing fossil fuels with biomass in the production of energy carriers, materials and specialty chemicals is a challenge that now confronts humanity. Numerous questions demand an answer: in which applications we shall use the limited biomass resource; how the raw materials are best refined; if biorefineries can be integrated in existing industries; and what policy instruments are required to realise the biorefineries of the future.

There is not one final answer to questions like these. However, different systems studies can provide us with complementary pieces of the puzzle. These can be valuable by themselves, or be brought together into a larger and more complex picture. *Systems Perspectives on Biorefineries 2014* contains twelve chapters that address different topics related to the immensely important issue of how the world's biomass resources can, or should, be converted into the goods we need and desire.

Systems Perspectives on Biorefineries is an evolving ebook with annual updates. You may also want to read *Systems perspectives on Renewable Power* and *Systems Perspectives on Electromobility*.

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1

ASSESSING BIOREFINERIES

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INTRODUCTION

Biomass, a product of the solar energy influx and the synthesis of carbon dioxide and water, has been used since the dawn of humanity, always as a source of food and as a source of energy and materials since the invention of controlled fire and simple tools some hundred thousand years ago. The transition from hunting and gathering to agriculture has over the last five millennia led to a rapid increase of world population and a human dominance over the Earth's land surface and biota.

When wood was becoming scarce in the 18th century, fossil fuels, i.e. old biomass transformed into coal, oil and natural gas over millions of years, provided an alternative source of energy and carbon, and formed the basis of a second grand transition, industrialisation. Fossil fuels enabled an expansion of energy use by two orders of magnitude, and spurred mass consumption of products made of convenient materials, such as plastics. However, at current extraction rates many deposits will dry up in the coming decades, and, in parallel, the extraction, transport and combustion of fossil fuels create a host of local and global environmental problems, most notably climate change due to emissions of carbon dioxide. A transition to a climate neutral society that is less dependent on finite resources will require a massive shift from fossil to renewable sources of energy and materials.

Energy can be harnessed from many renewable sources.¹ However, photosynthesis in plants, i.e. biomass, is currently the only economically viable option to capture the carbon atoms in the atmosphere for use in materials and convenient energy carriers.² Hence an immense demand for biomass feedstock refined to fit a range of applications currently dependent on coal, oil and natural gas can be

1 See Chapter 3 and 4 in *Systems Perspectives on Renewable Power* (2014) Chalmers University of Technology, Göteborg, Sweden.

2 See Chapter 12 in *Systems Perspectives on Renewable Power* (2014) on the potential to capture carbon from air and water to produce so called 'electrofuels'.

foreseen. Chapter 3 in this book provides an overview of biobased products that can substitute for fossil fuel based alternatives. In addition, new uses of carbon may emerge or increase in importance such as carbon fibres in light weight materials and carbon nanotubes and graphene in applications yet to be explored. Given the already significant scale of human appropriation of biomass and the scale of fossil fuel use such a transition is challenging, to say the least. Chapter 4, that provides a review of assessments of global biomass resources, concludes that the gap between high and low estimates of resource availability is staggering and that increased supply of biomass involves potential benefits as well as significant risks. Chapter 5 further elaborates on socio-economic consequences of increased biomass demand.

Clearly there is a need to convert primary biomass into a wide range of final goods in resource efficient ways. This requires that new processes are developed and deployed on a large scale. The refining of biomass into multiple products can be captured by the term 'biorefining'. Biorefining takes place in a 'biorefinery', a concept analogous to an oil refinery, which converts crude oil into a range of products. In Chapter 2, we conclude that there is not yet a stabilised definition of the concept. Since we might be in the beginning of a large scale industrial transformation that will continue for decades we don't know what type of biorefineries that eventually will emerge. Therefore, we will stay with an inclusive broad definition, and allow us to shift focus between chapters.

Nevertheless, given the observations above it is difficult not to view biorefining and biorefineries as a potentially crucial part of a sustainable industrial society, not without serious challenges and possible drawbacks, and therefore a very interesting and important object of study.

Development of biorefineries will not start from a blank page. They will be developed in complex industrial and cultural settings. Chapters 2 and 6-8 provide examples of how new biorefinery concepts can be integrated in the processing industry and Chapters 9-11 discuss how economic and environmental performance of different technical designs depend on the character of larger surrounding technical systems. They conclude that the best choice of product portfolio will depend on many, uncertain but identifiable parameters related to both technology and system context. Chapters 9-11 use different but related methodologies to assess the performance of biorefineries; they all highlight the critical impact of system environment and conclude that it is crucial to be transparent about assumptions.

The huge, but uncertain, demand for a range of new biobased products, the limitations on resource availability and the constraints given by existing infrastructure bring many questions to the fore. In which applications would it be most beneficial to use biomass?³ How can a biorefinery be made as efficient as possible to save resources? Which configurations can maximise reduction of greenhouse gases and other environmental impact? How can new processes be integrated in existing industrial facilities? Is there a risk that optimisation in the short term lock out better long term options? Is it at all possible to compare different options? Which options should be compared?

³ On the relative efficiency and competitiveness of biofuels in the transport sector, see also Chapter 5 and 8 in *Systems Perspectives on Electromobility* (2014) 2nd. ed. Chalmers University of Technology, Göteborg, Sweden.

All these questions belong to the area of technology assessment and aim at informing decisions related to technology choice at different levels in society. In this book we apply various types of systems analysis to address some of these questions. Chapters [9-11](#) provide examples of assessments of energy efficiency, profitability and reduction of greenhouse gas (GHG) emissions. In the next sections of this chapter we will outline a typology of assessment methods to guide the reader and also indicate what type of questions that may be addressed in coming editions of this evolving ebook.

The issue of which technology to select is related to how new technologies actually are selected and allowed to develop from idea to full blown industrial systems. A different set of questions then needs to be addressed. How can technical change processes be conceptualised to inform action? How can different stakeholders such as policy makers, firms, consumers, academia and media stimulate innovation, guide technological trajectories and enable large industrial transformation?

Chapter [12](#) discusses which policy instruments that could be effective in taking biomass gasification and synthetic biofuels from the demonstration stage to commercial production. The chapter concludes that the materialisation of novel biorefinery concepts will require brave and cleverly designed technology specific governmental policies to attract investors.

ASSESSMENTS AND DECISION CONTEXT

Firms routinely assess technological options. The goodness measure used is typically profitability under current, or expected, market conditions and regulatory framework.

One reason why other societal actors (such as academics or public authorities) should be involved in technology assessment is that the objectives of other social groups or governments may differ from that of firms. Due to insufficient environmental regulation, skewed power distribution and the short sightedness and bounded rationality of individual actors there is a need for alternative views on the desirability of different technological options. Also the firms themselves may benefit from considering viewpoints of outsiders, not only to anticipate future regulation, but also to enhance their own imagination and innovativeness.

For a government, that wants to assess technologies in order to support decisions on public investment or design of incentives and regulation, economic performance from a social long term perspective or environmental impact could be appropriate measures of goodness. For longer term decisions, complex and aggregated parameters such as costs and profitability tend to be less relevant due to the ever ongoing structural change in the economy, and hence simpler physical measures of efficiency may also be of use. (In Chapter [9](#), we apply physical measures of performance, i.e. energy efficiency, and in Chapters [10](#) and [11](#) we use environmental and economic parameters.)

No technology assessment can provide an answer to the question if a technology is good in general. There is no scientific definition of a 'good' technology and the

measure of performance is ultimately a normative matter. Moreover, even if we agree at a general normative level, different measures of performance will be more or less relevant in different decision contexts. Also the relevant time frame and geographical scope and how wide group of technologies you want to make claims about (the desired balance between technological universality and particularity) are affected by what type of decision one seeks to inform.

In many decision contexts more than one type of study could be of relevance. If you own a biorefinery plant and need to make decisions on near term investments, you might want to assess some specific options that marginally change the processes in your existing factory located in a well defined system environment. However, you might also be interested in the best long term options in your industry (e.g. pulp production) and related industries (e.g. motor fuel production) and whether your best short term options in fact could turn out to be sub-optimisations leading into a dead end. If you are a policymaker with a wide geographical jurisdiction, technological universality could be more important than a precise fit to a particular industrial setting and the relevant measure of performance could differ from that of the factory owner, but you might also be interested in short term implications for specific firms or social groups (Chapter 5).

A TYPOLOGY OF ASSESSMENTS BASED ON TWO TYPES OF SYSTEM DELINEATION

From the above it is clear that different types of assessments fulfil different functions. One way to create a general typology of assessments is to distinguish between studies with narrower and wider system boundaries. The ‘technology’ or ‘technical system’ we assess can be more or less inclusive, ranging from a focus on one specific product or process to society at large.

We suggest that there are two fundamental ways to extend or contract the system boundary. We here use the term *vertical system boundary* for extensions along value chains, while we use the term *horizontal system boundary* for the inclusion of many or few value chains, i.e. the number of inputs or outputs. A wide system boundary in the vertical direction then allow for many alternative value chains,⁴ while a wide system boundary in the horizontal direction includes many complementary value chains.

An example of vertical system expansion is when you shift from a well-to-tank to a well-to-wheel study. In the former you only consider how a resource such as biomass is turned into fuel, while in the latter you compare alternative pathways for turning the biomass into transport allowing also for alternative drive trains such as electric propulsion⁵. An example of a horizontal system expansion is when you consider that the fuel production process also have other outputs such as electricity and heat or other inputs besides biomass.

⁴ Why a wide vertical system boundary implies the inclusion of many alternative value chains. In short, with a longer value chain there are more alternative pathways from input to output

⁵ See Chapters 5 and 6 in *Systems Perspectives on Electromobility* (2014) 2nd. ed. Chalmers University of Technology, Göteborg, Sweden.

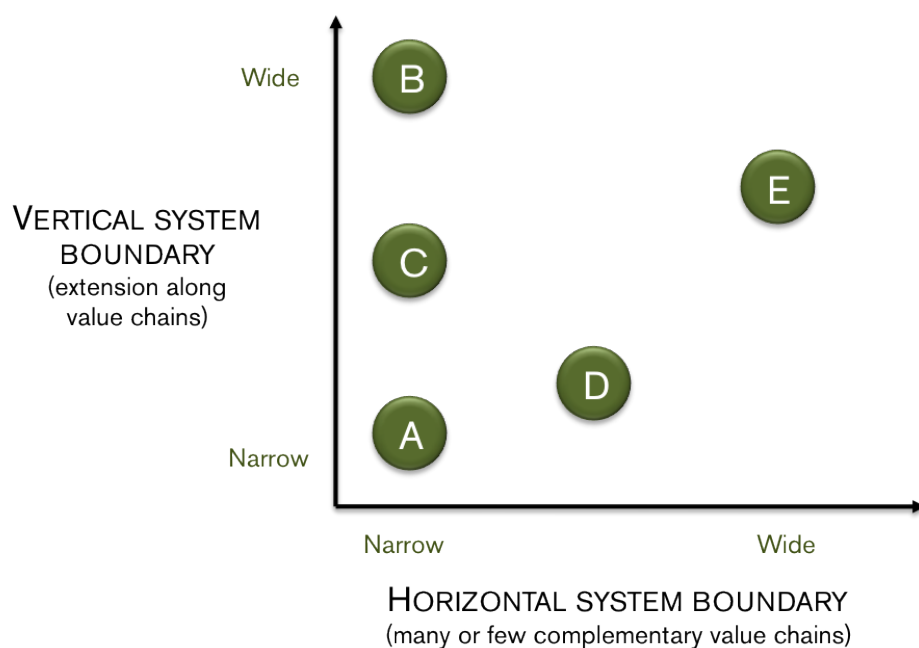


Figure 1.1 Different studies, as well as different standard methodologies, apply different system boundaries. A modelled system can encompass many or few value chains (horizontal system boundary) and smaller or larger parts of these value chains (vertical system boundary). The methodological positions A-E are explained and exemplified in the text.

In Figure 1.1 it is indicated that the degree of vertical and horizontal system expansion can be used to differentiate between different types of assessments (A-E). In the following two sections we elaborate on the vertical and horizontal dimensions, respectively, and return to what could be meant by e.g. position B or E.

VERTICAL SYSTEM BOUNDARIES AND MEASURES OF PERFORMANCE

Every value chain extends in two directions. There is an input side, i.e. resources, and an output side, i.e. products or services. However, of special relevance for technological assessments is to note that there are also outputs, or side effects, of negative value. Since these have a negative value they could also be considered as inputs (like resources they are associated with a cost). Due to this ambiguous nature we treat it as a separate category. Inputs, outputs and negative side effects are visualised in Figure 1.2. The system boundary can be more or less vertically extended in all of the three dimensions in this figure. (Note that movements along all of these three axes correspond to movements along the vertical dimension in Figure 1.1.)

The choice of vertical system boundary depends on desired performance measure which in turn depends on decision context. A simple and general measure of performance can be captured by the term 'efficiency' which compares inputs and outputs, how much that is produced compared to how much resources that is used in a part of a value chain. To give an example, for processing plants where wheat is used to produce a specific liquid biofuel, say ethanol, one can measure the efficiency of converting grain (MJ_{grain}) to ethanol ($\text{MJ}_{\text{ethanol}}$) (position A in Figure 1.1 and Figure 1.2).

However, this process is part of a value chain ranging from primary resources to final end uses. Taking one step towards more primary resources we can observe that the grain is produced on a piece of farmland. A more general study could include other ways to use that farmland, e.g. salix cultivation, or include other types of bioproductive land and compare a larger set of options from biomass to ethanol. On the output side it is not really ethanol that is the final good. It might be transportation fuel (MJ_{fuel}) or vehicle propulsion (vehicle-kilometer), or rather passenger transport (person-kilometer) or even communication that should be viewed as the final output. And on the input side, bioenergy is not the primary input either. The solar energy influx on a piece of land could be used in ways to provide transport or communication not involving bioenergy at all.⁶

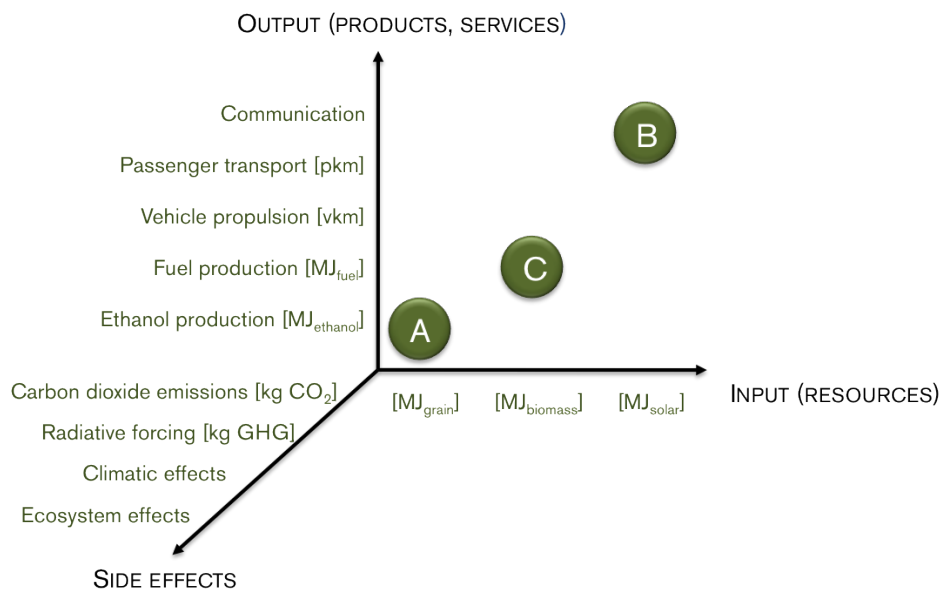


Figure 1.2 A system boundary can be more or less vertically extended towards final end use in the output dimension, towards primary resources and towards final side effects, depending on which performance measure that is relevant for the decision context at hand. The figure illustrates the example of ethanol production from grain taking (A). This is one possibility out of many to convert biomass into fuel (C) which in turn is one of many ways to use solar irradiation to provide communication (B). The side effect dimension is exemplified with CO_2 emissions.

For some decisions by some stakeholders (typically with a more narrow timeframe and limited decision domain) it might be most appropriate to select a system boundary around the ethanol processing plant and evaluate different pathways from grain to ethanol (position A in Figure 1.1 and Figure 1.2), while for other decisions (typically more long term, society wide and strategic) it might be more relevant to evaluate different options for converting solar energy to personal transport, or even communication (position B). Chapter 9 takes an intermediate position and assess the conversion efficiency from biomass to transportation fuels (position C).

Unwanted side effects make up the third dimension. Technology assessments are often used to estimate the magnitude of environmental impact, but social consequences could be included as well. Also in this dimension vertical expansion can

⁶ See Chapters 5 in *Systems Perspectives on Electromobility* (2014) 2nd. ed. Chalmers University of Technology, Göteborg, Sweden.

be made as there is a hierarchy from direct effects of a process to the final effects we really care about. We can estimate the emissions of CO₂. But CO₂ concentration in itself is not an endpoint, more generally we might be interested in radiative forcing from greenhouse gases (GHG), or rather, the contribution of increased radiative forcing to climatic change or even the impact of climatic change on human health or ecosystems. Chapters 10 and 11 discuss CO₂ balances of different system configurations, but also include some aspects at the GHG level, e.g. the effect of emissions of methane from landfills (Chapter 11). While climate change, is the most popular impact category at present, there are also numerous other environmental and social categories that could be considered (see e.g. Chapter 5).

In this three dimensional performance space we can fit a broad range of assessments from narrow technical studies (narrow vertical system boundaries) that focus on the efficiency and direct effects of a specific process to philosophical speculations (wide vertical system boundaries in all three dimensions) on how to design societies where the primary resources on Earth are used to meet our final needs and desires while minimizing the negative effects on Nature and Humanity.⁷

HORIZONTAL SYSTEM BOUNDARIES: MULTIPLE INPUTS AND OUTPUTS

Assessment studies do not only apply different vertical system boundaries but also different horizontal system boundaries. While some studies are focused on how efficiently one input is converted into one output, others include multiple inputs, multiple outputs or multiple side effects.

One example of horizontal system extension relates to the negative side effects. While a typical life cycle assessment (LCA) focuses on the production of one product, it normally takes into account multiple emissions and impact categories such as acidification, ecotoxicity and climate change. However, some LCAs focus on only one impact category, e.g. GHG as in Chapter 10 (sometimes referred to as carbon footprint). When technologies have different impact on different categories one runs into the classical problem of comparing apples and oranges.

Of special relevance for assessments of biorefineries is the simultaneous production of many products. Chapters 9 and 10 discuss the simultaneous production of fuel and electricity, and Chapters 9 and 11 assess different implications of considering heat as byproduct. There is not one correct answer how to compare different processes with non-identical sets of products or how to decide how much of the total emissions and resource use caused by a multiple output process that should be allocated to one of the products. For plants that could produce a wide range of very different products, sometimes including materials with unique properties it

⁷ The ambition to develop very high level assessments, some kind of 'world assessment' was probably higher in the early days of systems analysis. See for example Boulding (1956) General systems theory – the skeleton of science. *Management Science* 2:197 and Meadows, et al. (1972) *The limits to growth*. New York, NY, USA: Universe Books. For the reader skilled in Swedish, Ingelstam (2012) *System – att tänka över samhälle och teknik*. 2nd. ed. Eskilstuna, Sweden: Swedish Energy Agency, provides an accessible discussion on the development of systems analysis. More recently, the International Panel for Climate Change (IPCC) have made less comprehensive but more detailed attempts in this direction. Rockström, et al. (2009) A safe operating space for humanity. *Nature* 461(7263):472-475, have opened a discussion on planetary boundaries and there are signs of that the discussion on environmental macro economics is being revitalized, see e.g. Jackson, T. (2009) *Prosperity without growth : economics for a finite planet*. London, UK: Earthscan. Other contributions may be found in various qualitative scenarios and fiction novels.

becomes exceedingly difficult to construct relevant comparisons (see for example the multitude of possible biorefinery products listed in Chapters 3 and 6).

To compare systems that are horizontally extended, and loaded with 'apples and oranges', one needs to apply some kind of multi-criteria analysis. In the end this implies that someone, be it a panel of experts, the analyst herself or the decision maker, more or less explicitly need to translate different resources, products or negative side effects to a common metric. Money is one general and commonly used metric. In a sense this could be viewed as a vertical system expansion if the monetary value is assumed to capture some universal value of the primary resources, final goods or negative effects. Such a proposition is intellectually hard to defend but is nevertheless used in a range of system models and cost benefit analyses, and due to the importance of monetary metrics in society such exercises can have a great pedagogical value if used with care. There also exist other metrics that can be applied in special cases, such as energy (Chapter 9), exergy and mass or specific valuation scales used in some LCA frameworks.

Studies that are horizontally extended include those that are less vertically extended, such as assessment of individual processing plants with multiple inputs and outputs (position D in Figure 1.1) and system models that are both horizontally and vertically extended and thus include large parts of society's industrial system (position E). These are typically used to analyse questions of how to best make use of a set of resources, for example limited supplies of oil and biomass, to serve a set of demand categories⁸.

CHANGING SYSTEM CONTEXT AND CONTENT: ON THE UNIVERSALITY AND VALIDITY OF CLAIMS

In all studies there is a trade-off between producing more universally applicable results and results of significant value for a unique situation. If the place is specified and the time frame short you can be detailed about technological performance, physical infrastructure and institutional setting. If you want to capture some general features that are relevant in many places or in a more distant future you need to take into account variation and change of technology performance and system environment.

Studies with wider and narrower system boundaries differ in one important aspect. If the system boundary is narrow, one has to make simplified assumptions about the system environment. On the other hand, if the boundaries are wide one has to make simplified assumptions about the system content. For instance, if you study one industrial process you may be very specific about that process, whereas you make a simple representation of how electricity and fuels are produced in society. On the other hand, if you would like to study many different processes, and how they interact, the system boundaries becomes wider, but at the same time the level of technical detail will be lower.

To make claims with broad temporal and spatial applicability based on studies with narrow system boundaries, one has to test how the investigated technologies

⁸ See for example the global energy system model [GETOnline](#) and Chapter 8 in *Systems Perspectives on Electromobility* (2014) 2nd. ed. Chalmers University of Technology, Göteborg, Sweden.

perform in a wide range of contexts. For example, the carbon dioxide intensity of electricity production and transport could vary between countries and change over time. An example of how the ranking of two alternatives are sensitive to such contextual changes is provided in Chapter [10](#).

With wider system boundaries the technological content cannot be specified to any greater extent. In this case one should be aware of that not only the performance of known technological components change over space and time, but also that the set of available technologies and structural relations are continuously transformed. Over longer time scales the co-evolution of technologies, knowledge fields, physical infrastructures, economic organisation and culture radically change the appropriateness and fitness of technological components.

Imagine that someone in 1910 would have made a model of the future development of short distance transport based on a cost comparison between horses, trams, bikes and cars. Such a study would probably have failed to consider the role of suburbs, highways, changing life styles and new materials and maybe even had overlooked the role of cheap oil. If the same study had been made ten or twenty years earlier the automobile as an option might have been neglected altogether.

ASSESSING TECHNOLOGIES OR CONSEQUENCES OF INTERVENTIONS

One recurring debate in the assessment community is if one should investigate the performance of a technology as part of a given system or how the addition of a technology changes a given system on the margin.⁹ Typically this boils down to the question if one should use average or marginal data, e.g. if one should use the carbon dioxide intensity of the average electricity production or of the electricity production that needs to be added on the margin. In the LCA community, the latter is called a consequential perspective, and the former an attributional (or state-oriented) perspective. For studies with a consequential perspective the inclusion or exclusion of so called 'indirect effects' causes additional discussion.

The more straight-forward method for technology assessment is the attributional, or state-oriented, perspective. Commonly, this perspective is used to compare the environmental performance of different options in the current industrial context, e.g. what is required (in terms of resource use and emissions) to produce one tonne of bioplastics in present day Sweden? However, this perspective could as well be used to assess the performance of technologies in hypothetical future systems, e.g. assessing the performance of a novel technology in a future situation when the technology is mature and deployed at a large scale. It might even be the most suitable method for exploring and comparing the potential impact of emerging technologies.

Even if a technology seems to perform well in a future state, the consequences of an individual investment in a technology today may have other consequences.

⁹ A full treatment of this issue is beyond the scope of this introductory chapter. For a more comprehensive discussion see Sandén (2008) Standing the test of time: Signals and noise from environmental assessments of energy technologies. *Materials Research Society Symposium Proceedings* 1041:183-189 and Sandén and Karlström (2007) Positive and negative feedback in consequential life-cycle assessment. *Journal of Cleaner Production* 15(15):1469-1481.

For instance, electric cars seem to be a more environmentally friendly option than gasoline, or ethanol, cars in a future system dominated by renewable electricity supply. However, the consequence of driving an electric car today may be that electricity production from coal increases¹⁰. Thus a consequential perspective tries to establish the effects of an investment in a certain technology (or more generally, the effects of a system intervention).

Then a key question is which effects to include. Some effects are direct and linear involving only physical interaction (similar to the state-oriented perspective), while others propagate through economic and social systems, so called indirect effects. Some of these indirect effects lead to a new stable state, or equilibrium, through the force of stabilising negative feedback, e.g. due to scarcity driven price increases. It is not clear how many steps one should follow these indirect effects. If wood is used in Sweden, is then more wood produced somewhere else in the world? Or does it lead to a price increase that lowers the demand, or does the increased demand for wood increase the demand for land and thereby raises agricultural costs and the price of food? And if food prices go up... etc. Chapter 11 includes a discussion on what the actual marginal effect is if excess heat from a biorefinery is supplied to a district heating system and thereby substitute for biomass combined heat and power production.

A second type of effects, driven by positive feedback, makes life even harder for the analyst. Positive feedback can result in 'butterfly effects' and radical structural change due to mechanisms such as economies of scale, learning by doing, imitation and institutional adaptation.

Of these many possible cause-effect chains only rudimentary equilibrium-thinking, leading to suggestions to use data for some marginal change of the current system, has penetrated the assessment community. Contribution to radical system change is much harder to assess numerically and is almost always neglected even if these effects in many cases are more important (see references in Footnote 3).

From the perspective of the analyst, assessments based on a state-oriented perspective are more straight-forward and require fewer uncertain assumptions. On the other hand, such studies say little about the actual consequences of specific interventions and leave to the decision maker to find answers on how to realise the options that are found preferable. The consequential approach implies that the analyst takes on some of the responsibility of the decision maker and analyse the effects of an action. However, the analyst will soon run into consequences that are hard, or even impossible, to assess and quantify. Some issues will always be left to the judgement of the decision maker, and there exists no established rule where the analyst should stop and the decision maker should continue. There is always a risk that the analyst includes, not the consequences of greatest importance, but those that can be quantified.

¹⁰ See Chapter 6 in *Systems Perspectives on Electromobility* (2014) 2nd. ed. Chalmers University of Technology, Göteborg, Sweden.

ASSESSING PROSPECTS AND REQUIREMENTS FOR TECHNICAL CHANGE

From the previous section we find that there is no sharp dividing line between technology assessments and studies that analyse change mechanism and how system intervention can affect the realisation of different options. However, we also noticed that assessment can be stripped from the question of realisation (state-oriented analysis). Similarly, the question of realisation can be stripped from the normative question of which technology that is preferable. What system change is at all possible, and what is likely within a certain timeframe? What is the likely impact of a system intervention such as the implementation of a certain policy instrument? Or, what system intervention is required to realise a certain option and reach a specific outcome?

In previous sections we made a classification of assessment studies based on the extension of the system boundary. A similar strategy can be applied to methodologies and disciplines that study change mechanism. Management studies typically draw the system boundary around one individual firm. Questions about what measures that can be taken by a firm are in focus. Technological innovation system (TIS) studies focus on the processes in society that leads to the realisation of one technological option, while sectoral and national systems of innovation put the innovative capacity of industries and nations central stage. Chapter 12 takes a technology-centred perspective and provides an example of an investigation of what policies (governmental intervention) that would be required to take biomass gasification from experiment to market.

The essence of what has been termed the multi-level perspective (MLP) is that transformations of large socio-technical systems and transitions from one system to another depend on interlinked dynamics at several system levels. Such studies typically describe how a stable socio-technical regime, e.g. the pulp and paper industry, its customers and related regulation and norms, is transformed due to forces at a higher societal 'landscape' level that open windows of opportunity for novel technologies that grows in niches of the old system.

Another basis for classification is what types of mechanisms that are taken into account (compare the discussion in the previous section). While a few formal models include learning, or experience curves, which internalise some positive feedback mechanisms, the main mechanisms in most engineering models and models based on neoclassical economics are optimisation based on cost minimisation and stabilising negative feedback leading to market equilibrium. In the often more qualitative models stemming from evolutionary economics, economics of innovation, management, sociology and history of technology, learning and institutional change are given a central role and the description of radical change stemming from positive feedback in a transformative process is a key objective.

BIOREFINERIES AND GUIDANCE SYSTEMS IN THE DARK

Which is the best biorefinery? What is the optimal allocation of scarce biomass resources to different markets? How is the most advantageous portfolio of policy instruments designed to realise the biorefinery of the future?

There is not one answer and there is not one best methodology to search for answers either. We take an eclectic standpoint. Different types of studies provide us with different pieces of understanding that can be valuable by themselves or be brought together into a larger and more complex picture. We see no role for a 'super model' in which one tries to include all mechanisms at all system levels. Different methods provide different arguments that are more or less relevant in different decision contexts.

However, different methods and results need to be compared. The relevance of different approaches needs to be discussed and the numbers need to be put side by side.

It is worth observing that systems analysis does not only take on the role of bureaucratic investigation, the somewhat dry and objective assessment of options. It is also a creative art that can extend the imagination of people, the space of plausible ideas. And, it may be used for criticism of prevailing presumptions in hegemonic discourses, or in the service of lobby groups. Finally, we have also found that systems analysis can be used as a neutral meeting place where stakeholders are allowed to interact and the analyst becomes a mediator.¹¹

While we admit that we do not have any final answers, that we all are in the dark, we boldly claim that we have some torches that can shed light upon aspects and provide credible arguments for decisions that ultimately are taken by the members of society, the voters, the consumers, the managers, the policy-makers, the designers, the engineers...

¹¹ For some further thoughts on the use of systems analysis see e.g. Sandén and Harvey (2008) *Systems analysis for energy transition: A mapping of methodologies, co-operation and critical issues in energy systems studies at Chalmers*. CEC, Chalmers University of Technology, Göteborg, Sweden.

2

WHAT IS A BIOREFINERY?

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INTRODUCTION

The term “biorefinery” appeared in the 1990’s in response to a least four industry trends. First, there was an increased awareness in industry of the need to use biomass resources in a more rational way both economically and environmentally. The environmental issue was both policy and consumer driven. Second, there was a growing interest in upgrading more low-quality lignocellulosic biomass to valuable products. Third, there was an increased attention to the production of starch for energy applications. Finally, there was a perceived need to develop more high-value products and diversify the product mix in order to meet global competition and, in some cases, utilise an excess of biomass (especially in the pulp and paper industry).

In a biorefinery, biomass is upgraded to one or more valuable products such as transport fuels, materials, chemicals, electricity and, as byproduct, heat (Chapter 3). In principle all types of biomass can be used, e.g. wood, straw, starch, sugars, waste and algae (Chapter 4). But there is more to it than that. The aim of this chapter is to explain in some more detail what a biorefinery is or could be.

There have been many attempts to determine what should be meant by a “biorefinery” and in the next section we provide some of the definitions and additional meaning that has been attached to the concept. To give a more in-depth understanding of what a biorefinery might be, the following sections describe process technologies that are often considered as key constituent parts of biorefineries and some opportunities for integration in existing processing industry that also can be viewed as biorefining.

DEFINITIONS AND CONNOTATIONS

There exist several definitions of a biorefinery and biorefining. The preference for one over the other often depends on context. Two widely used definitions are formulated by IEA and NREL, respectively:

*"Biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy."*¹

*"A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass."*²

Two definitions related specifically to biorefineries in the forest industry add the requirement of economic optimisation:

*"Full utilization of the incoming biomass and other raw materials for simultaneous and economically optimized production of fibres, chemicals and energy."*³

*"Maximising the economic value from trees," which requires "an improved business model and corporate transformation".*⁴

In his speech on the Biorefinery Joint Call Info Day (Brussels, 16 September 2008), the European commissioner for environment Janez Potočnik defined sustainable biorefineries as:

*"Facilities that can combine biomass conversion processes and equipment to generate fuels, power and new materials ... in an economically, socially and environmentally sustainable way."*⁵

All definitions include biomass upgrading. The incentives for upgrading differ, for some the sustainability of the system and of the biomass use is enough, for some the combination of sustainability and high-value products (economic incentive or optimisation) is included. The use of "system" only means the biorefinery system itself, not necessarily any integration with a process industry or other large energy system (e.g. district heating). Furthermore, a biorefinery can be a "polygeneration plant" that produces many products simultaneously, but not necessarily so. With the definitions available, a biorefinery can be anything from one single machine for conversion of biomass up to a complex, polygeneration plant integrated with other industries and energy systems.

Since the concept of a biorefinery can cover a broad range of technical systems, there are several "grey zones" with configurations that some would consider to be biorefineries while others would not.

¹ IEA (International Energy Agency) (2008) *Bioenergy Task 42 on Biorefineries. Minutes of the third Task meeting*. Copenhagen, Denmark, Mar. 25-26.

² NREL Biomass Research (2009) [accessed 2014-07-28].

³ Swedish Energy Agency (2008) *Swedish Pulp Mill Biorefineries*. Eskilstuna, Sweden: Swedish Energy Agency. (ER 2008:269)

⁴ Paul Stuart (2011) *Biorefinery 101: Maximizing Benefits and Minimizing Risks Associated with Implementing the Forest Biorefinery*. Smithers PIRA e-Learning [webinar 2011-04-13].

⁵ Janez Potočnik (2008) *Biorefineries – new generation*. Presented at the *Info Day on the Biorefinery Joint Call*, Brussels, Belgium, Sep. 16.

A biorefinery can produce traditional products from biomass, e.g. electricity and heat. Some would not consider a plant that only produces electricity and heat to be a biorefinery. If these traditional products are produced with a higher efficiency or if the system for some other reason is considerably improved through a non-traditional upgrading of the biomass (e.g. via gasification), more people would probably accept the biorefinery label. Thus, the biorefinery concept also connotes novelty, something “non-traditional” or even something more “efficient” or “better”.

In contrast, some technologies are so novel that they for this reason are excluded from lists of biorefinery concepts. One example of a new technology under development is biodiesel from algal production and fermentation. This technology is still at the research stage but can be an alternative to other vegetable as well as fossil oils. There is still a lack of knowledge about possible plant configurations and their technical and economic characteristics.

Most definitions allude to processes that upgrade biomass all the way to some type of end product (see Chapter 1 for discussion of end products and system delineation). In some industrial applications, however, upgraded biomass is used as an energy carrier or in an intermediate process and is not a part of the end product. Obvious examples are from the iron and steel industry, in which biomass in the future could be used for chemical reduction instead of coal. Is this a biorefinery? As discussed below, in order to use biomass it must first be upgraded to e.g. “bio-coke” or gas. This means that “biorefining” is needed, and this refining can be integrated with subsequent processes. Hence one can argue that this type of system should be included in a complete list of biorefinery concepts.

Is Carbon Capture and Storage (CCS) a biorefinery technology? As is discussed in more detail below, a CCS plant can be combined with or compete with an integrated biorefinery. In both cases CCS can be considered and assessed as an alternative option in various biorefinery configurations.

To sum up, biorefineries constitute a broad class of processes that refine different forms of biomass into one or many products. Additional meaning attached to the concept could be production of “novel products” in “novel ways”, “more efficient”, “more environmental friendly” or “more integrated with other systems”. Here, we refrain from taking an absolute stand on these conceptual matters. Instead we continue by explaining some processes that have been considered to be key elements of various biorefining systems.

TWO KEY CONVERSION PROCESSES

A common delineation between different types of biorefineries is the one between thermochemical and biochemical pathways. The dominant processes within these classes are gasification and fermentation. However, also several other processes for conversion and upgrading exist as separate processes or as parts of other conversion pathways (see sections below, Figure 3.1 in Chapter 3, and Chapter 6).

The most important types of biomass feedstock for use in biorefineries are sugar, starch and lignocellulosic materials (woody biomass). There is an interaction

between feedstock, process and end product. It is relatively easy to ferment sugar and starch and only the cellulose and hemicelluloses parts of wood (Figure 2.1) can be processed and made available for fermentation, while all parts, including lignin, can be gasified. An important end product of fermentation is ethanol while a range of other substances, such as hydrogen, methanol, methane and dimethyl ether (DME) are typical end products of the gasification pathway.

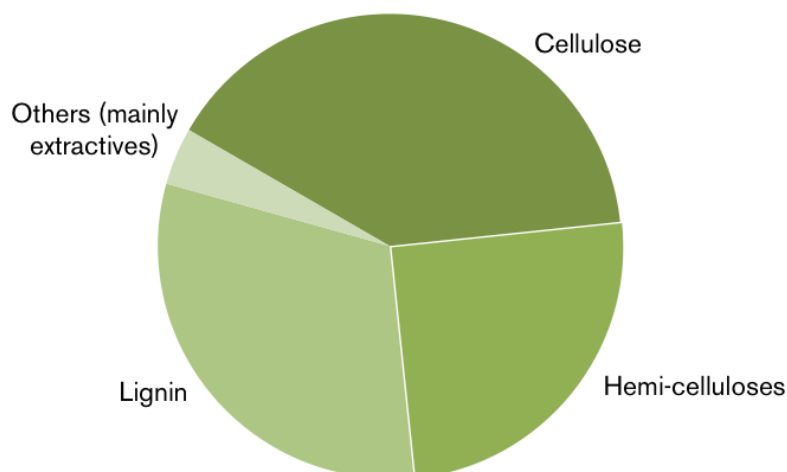


Figure 2.1 Example of wood component distribution (softwood).

Lignocellulosic material is the most important feedstock in the Scandinavian system; it represents the largest global potential in terms of mass and energy and may display less direct competition with land use for food production (Chapter 4). For this reason, there is some focus on woody biomass in the following sections, while sugar and starch based processes are included in the section on fermentation below and further discussed in Chapter 3.

GASIFICATION PATHWAY

Gasification involves heating a material using a gasification agent such as oxygen, steam or air. The feedstock is broken down to a mix of small molecules, mainly carbon monoxide and hydrogen, known as synthesis gas or syngas. This is then used for building new more complex molecules for use as fuels, chemicals or materials. The syngas can also be used in a combined cycle for producing electricity with high efficiency.

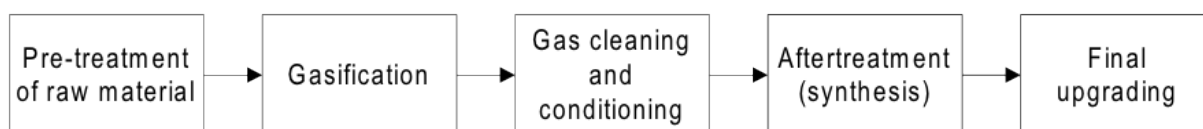


Figure 2.2 Schematic description of the gasification chain.

The biomass often needs some pre-treatment before it is gasified and the product gas needs cleaning and conditioning before synthesis. A simple block diagram illustrating the different sub processes is shown in Figure 2.2 (see also Figure 12.1 in Chapter 12). There is a dependency between the different sub processes. The type of final product dictates which type of synthesis that is required, which in turn

dictates necessary syngas properties (cleaning and conditioning) and so forth. The different sub processes are briefly discussed below.

The most common way to classify gasifiers is according to fluid dynamics. There are three main types. In fixed bed (or moving bed) gasifiers the gasifying agent passes through a fixed bed of biomass feedstock at a relatively low velocity. Usually this type of gasifier is used in small scale applications and the gasifying agent is typically air. With co-current design, the high exit gas temperature lowers the problem with tars and the product gas can after filtration directly be feed to an internal combustion engine.

In fluidised bed (FB) gasifiers the gasifying agent has a velocity high enough to fluidise a bed containing a small fraction of biomass. Biomass is continuously added to the bed. Two types of FB-gasifiers exist: bubbling and circulation fluidised beds. FB-systems are used in medium to large scale applications. The gasifying agent can be air, oxygen or steam.

In entrained (or suspension) flow gasifiers, small particles of feedstock are entrained in a gasifying agent, normally oxygen or steam. This type of gasifier is used in large scale applications.

As mentioned earlier, there is a dependency between sub processes in the gasification chain. One example is that different gasifier types require different feedstock quality with respect to moisture and particle size. A dry fuel is always advantageous from an efficiency point of view (Chapter 9), but is not always required from a practical perspective.

The fixed bed gasifier requires a coarse biomass feed. Particle diameters in the range 3-50 mm are preferred. Some biomass material needs to be pelletised before use. Moisture in the fuel can be handled although, according to some sources, the moisture content should not exceed 40% for optimal performance.

In fluidised bed gasifiers, the particle diameter is normally in the range 0.1- 5 mm. Moisture is normally not a practical problem although high moisture content leads to lower process efficiencies. Dried biomass is therefore preferred.

Entrained flow gasifiers normally require dried material. It is not primarily the gasifier that sets the drying requirements, but the crushers, conveyors and gasifier charging systems that needs a dry fuel to maintain a continuous flow of biomass to the gasifier. The particles must be small, typically diameters below 0.1 mm for coal. However, since biomass is more reactive than coal there are studies indicating that particle sizes up to 1 mm, or even 2 mm, can be accepted.

Hence, depending on the type of gasifier, different pre-treatment methods are required such as drying, crushing and grinding. It could be noted that disintegration of wood into small particles by crushing and grinding⁶ requires substantially more power than disintegration of coal to the same particle size.

⁶ Comminution is the professional term for this operation.

Another factor to consider is logistics. Untreated biomass is a bulky material and expensive to transport. Therefore, decentralised energy densification could be advantageous when transportation distances are long, which is not unlikely considering the size required to enable good economies of scale in gasification. Technologies for energy densification include pyrolysis, liquefaction and torrefaction.

Pyrolysis is a conversion process that produces a liquid oil and char. The oil can be used for electricity or heat production or can be processed further into transportation fuels or chemicals. Fast pyrolysis is a process where biomass is heated rapidly to around 500°C in the absence of oxygen, thereby forming bio-oil, char and some gas. The total energy losses in this process are approximately 20%. Pyrolysis can be of interest in connection with large gasification plants, since converting biomass into a liquid could be a way to reduce transportation costs of feedstock to gasification plants not located close to harbours. It could also facilitate feeding in pressurised (especially entrained flow) gasification plants. Pyrolysis as a biorefining technology is also of interest for other reasons in process industries. For example, the pulp and paper industry can use pyrolysis to convert by-products into bio-oil. The oil refining industry can use it to produce biobased diesel through hydrotreating or cracking and the iron and steel industry can use the pyrolysis products, both the oil and the char, as reducing agents in the blast furnace.

Liquefaction is another technology which, like pyrolysis, converts solid biomass feedstock into a liquid. The difference is that liquefaction occurs under high pressure at a lower temperature and in the presence of hydrogen and a catalyst. This technology has a higher reactor complexity, which makes it more expensive and the technology is not as developed as pyrolysis. Torrefaction is a slow thermal degradation of biomass at low temperatures in the absence of oxygen. During the process about 70% of the mass is retained as a solid product resulting in a stable coal-like material and the rest is obtained as gases. About 90% of the energy content is retained in the solid product.

The cleaning and conditioning requirements depend on the type of gasifier used and on downstream processing. Both simple filters and chemical reactors (e.g. water gas shift reactors) are included in this category. Low temperature gasifiers (below 1000°C) often need some kind of tar conversion process. Besides carbon monoxide and hydrogen, the product gas contains water, methane and higher hydrocarbons. If the final product is not substitute natural gas (SNG), a reformer is often included to reduce the amount of methane and increase the amount of hydrogen in the syngas. Catalysts in the synthesis are often sensitive for impurities like sulphur and for some synthesis reactions it is also necessary to remove carbon dioxide. This necessitates the inclusion of absorption processes like Rectisol or Selexol. The carbon dioxide from these processes could be sent to storage (CCS).

FERMENTATION PATHWAY

The fermentation pathway in a biorefinery concept offers a versatile possibility to convert the sugar-containing polymers, cellulose and hemicellulose, to a range of

products. The lignin part of the biomass cannot be converted via the fermentation route.

The core in the fermentation pathway is the fermentation step in which microorganisms are used to convert the sugar to a specific product. One of the benefits of microbial sugar conversion is that the microorganisms act as specific catalysts that can produce a range of products. The metabolic capacity of the cell enables microorganisms to produce compounds that cannot be produced, or can be produced only with difficulty, via chemical routes. There are also examples where biochemical and chemical routes are close competitors.

Fermentation processes are traditional processes, for thousands of years used to preserve food. Since the World War I, fermentation processes have been used for industrial production of energy carriers and chemicals. The last years' development in life science has further advanced the possibility to design microorganisms for production of selected chemicals that cannot be produced efficiently by microorganisms found in nature.

From a biorefinery perspective, it is of particular interest to use microorganisms to produce chemicals and energy carriers. Examples of fermentation products produced today at an industrial scale are ethanol, lactate, amino acids and citric acid. Several studies show the potential to produce a large range of chemicals in fermentation processes, pointing to the possibility to produce all necessary platform chemicals by a fermentation route (see also Chapter 3).

Sugar and starch can easily be fermented with traditional methods. However, also lignocellulosic feedstock can be used in more advanced biorefinery concepts, including different waste streams and plants and trees grown especially for this purpose (see Chapter 4). Before such raw material streams can be fermented they need to be converted to a monosaccharide solution.

Major efforts have been made in developing bioethanol production via the fermentation route. Different process concepts have been developed. Below we discuss how such a process may look like as a show-case for how a number of other fermentation products can be produced. The experience from developing the bioethanol process will be very important for the further development of different fermentation pathways and biorefinery concepts.

The lignocellulosic material is first mechanically degraded, i.e. chipped, grinded or milled in order to increase the surface area. Over the years, a number of different methods have been proposed for hydrolysis of the lignocellulosic material. Generally, two routes are employed to hydrolyse the lignocellulosic material. The first route is the use of acid hydrolysis and the second is the use of a pretreatment process prior to enzymatic hydrolysis. In both cases, there are several possible methods or operation modes and the choice of method has to be based on a number of considerations, e.g., type of feedstock, organism used for fermentation of the released sugars, process integration and overall economics.

Figure 2.3 depicts three different configurations of the enzymatic route: (i) SHF, separate hydrolysis and fermentation (ii) SSF, simultaneous saccharification and fermentation, and (iii) CBP, consolidated bioprocessing. A requisite process step for SHF and SSF is the production of cellulytic and hemicellulytic enzymes (either on-site or in specialised production plants located elsewhere). In SHF, the stream from pretreatment is completely hydrolysed enzymatically before fermentation. SHF offers the opportunity of choosing operating conditions optimised for each step. In SSF, hydrolysis and fermentation occur at the same time. SSF confers a lesser product inhibition in the hydrolysis than SHF does, because of concurrent sugar consumption in the fermentation.⁷ CBP is the most elegant and efficient way of producing ethanol since production of cellulytic and hemicellulytic enzymes, complete hydrolysis and fermentation only demand one process step.

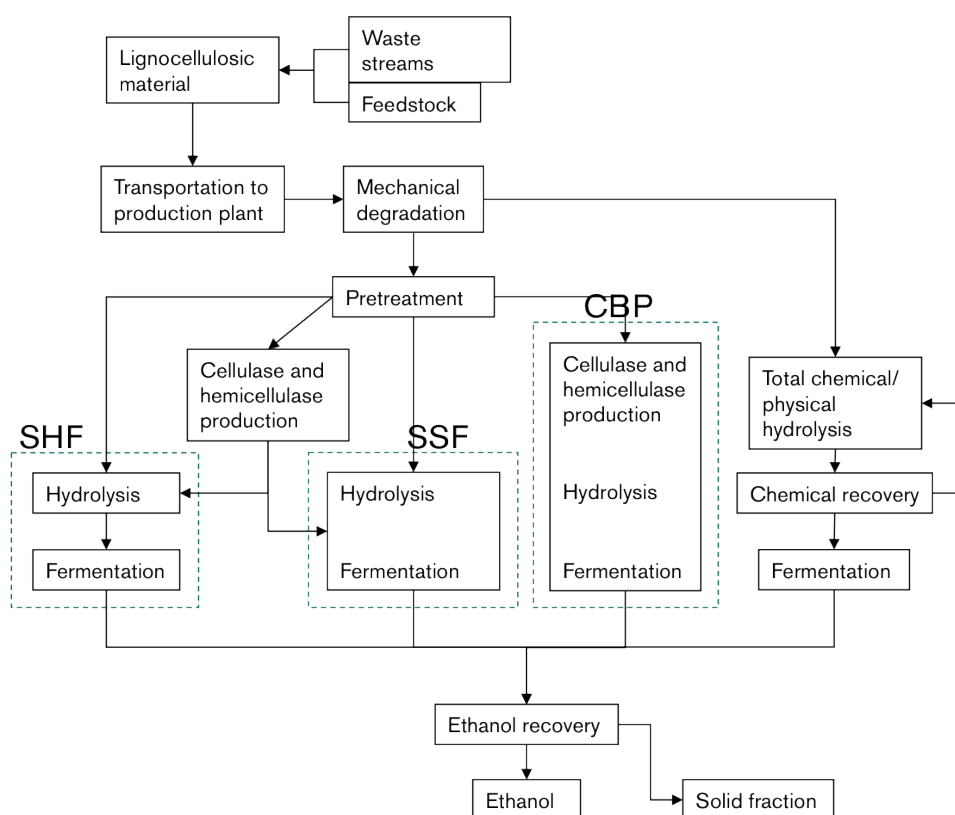


Figure 2.3 Examples of fermentation routes for producing bioethanol from lignocellulosic materials. SHF =Separate hydrolysis and fermentation, SSF=Simultaneous saccharification and fermentation and CPB=Consolidated bioprocessing. Source: Olsson L., H. Jørgensen, K. Krogh and C. Roca (2005).⁸

In all fermentation routes, it is of utmost importance that all sugar residues are fermented with high product yield in order to use resources efficiently and reach good economic performance. Consequently, the fermentation microorganism must be able to convert all monosaccharides present in the stream to the wanted product with high efficiency. An additional challenge is that the streams are not streams of only monosaccharides, but different by-products have accumulated during the processing, including acids (released from the raw material, added as process chemicals or stemming from the sugar degradation), furans (sugar

⁷ "Product inhibition" means that the product of an enzyme reaction binds to the enzyme and inhibits its activity.

⁸ Olsson L., H. Jørgensen, K. Krogh and C. Roca (2005) Bioethanol production from lignocellulosic material. In *Polysaccharides: structural diversity and functional versatility*. 2nd. ed. (ed. S. Dumitriu), 957-993. New York, NY, USA: Marcel Dekker, Inc.

degradation product) and phenolics (lignin degradation products). These compounds influence the cellular metabolism and may hamper efficient fermentation. Solutions to this challenge may either be addressed by optimising the processing steps to decrease the release and production of these compounds or by adapting the microorganism to the fermentation media. A strong research effort is taking place to design microorganisms at the genetic level.

After the fermentation step, the ethanol is recovered in a distillation step. The solid fraction containing lignin and other components can be used to either produce heat and electricity for the production plant or for external energy use, or alternatively be converted to high value co-products (see Chapter 9 for a discussion on how the valuation of byproducts affect the energy conversion efficiency of the process and Chapter 11 for the value of heat).

INTEGRATION OF BIOREFINING IN THE PROCESSING INDUSTRY

In many cases biorefining would benefit from being integrated with a processing industry. This may be crucial in order to achieve reasonable energy efficiency and economy. With the exception of some concepts for producing specialty chemicals in certain pulp mills (Chapter 6), implemented biorefineries in process industries are very rare. This section therefore provides an overview of suggested or planned biorefinery concepts in some process industries.

The pulp and paper industry is, for obvious reasons, a key industry when it comes to biorefinery integration. There are several ongoing and planned projects for implementation of biorefinery options in this industry. Examples are extraction of hemicelluloses and lignin in the pulping process, black liquor gasification, biomass gasification and ethanol production as a part of the pulping process. This is further discussed in Chapter 6.

Most of the metallurgical processes of iron and steel-making industry are energy intensive and are conducted at temperatures above 1,000°C. Steel can be produced from scrap in an electric arc furnace while steel production from iron ore is often carried out in a blast furnace. Raw material in the form of iron ore pellets, coke and limestone are charged into the blast furnace. Ore is converted into iron by heating whereby the carbon atoms from coke and coal powder combine with the oxygen atoms in the ore. The liquid iron is then transported to a converter where the carbon content is reduced to below 2% and the iron is turned into steel.

Due to the magnitude of the energy use, large amounts of biomass could be used in the iron and steel industry. However, the variety of options for increased use and refining of biomass in the iron and steel industry are limited. One way is to replace fossil carbon with carbon from biomass, either as a reducing agent in the blast furnace or as a fuel in heating furnaces. Another possibility is to develop an industrial symbiosis together with a stand-alone biorefinery where excess heat from the iron and steel industry can be used in processes at the biorefinery.⁹

⁹ There are also some other processes being proposed, e.g. using biomass for syngas production in so called molten iron-bath reactors. This technique is yet at an early stage of development.

Alternative biobased reducing agents include methane, carbon monoxide, hydrogen, ethanol and methanol. To give an example, approximately one-third of the injection coal can be replaced with methane. Using solid biomass as an alternative reducing agent would probably create practical problems due to the lower heating value. An alternative is carbonisation of biomass to enrich the carbon content and remove oxygen. The resulting biomass charcoal can then be injected into the blast furnace.

The crude oil refining process is very complex and includes many conversion units in order to keep pace with market demand. Approximately 7- 15% of the crude oil feedstock is used as fuel in the refinery. The refinery process converts the crude oil using a number of different processes depending on which products that are to be produced. The more light products that are produced and the less heavy residues that are left the more conversion units are included in the process and the more complex is the refinery. A simplified flow chart of an oil refinery is provided in Figure 2.4.

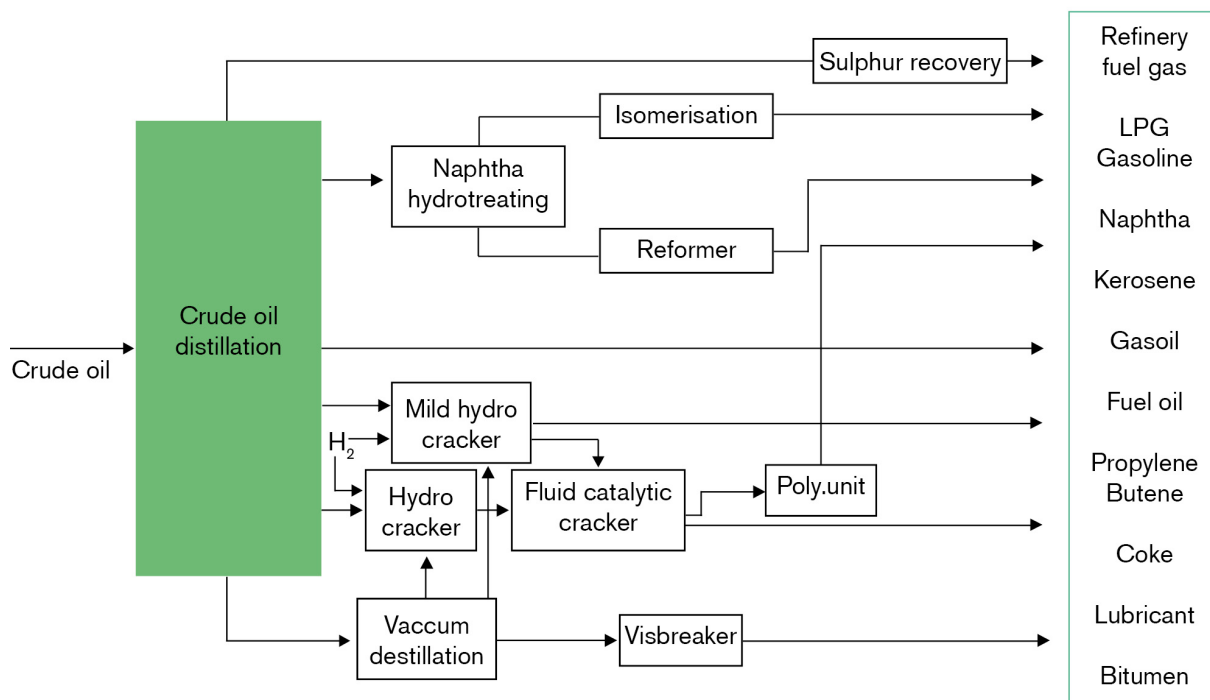


Figure 2.4 Schematic process flow chart for an oil refinery.

Oil refineries have the opportunity to integrate biorefinery options in many ways. Biofuels can be upgraded to meet existing fuel standards by using catalytic cracking to reduce oxygen content and molecular size and improve thermal stability. The catalytic cracking process is still under development. A driving force for this technology is that no hydrogen is needed, which is beneficial for the energy economy of the oil refinery. Another opportunity is hydro-treating of liquids, e.g. pyrolysis oil). In this way biobased diesel can be produced.

Transesterification is a process for converting vegetable oils into biodiesel. This process is interesting for industries that have oil residues that can be converted

into a biodiesel, such as raw tall oil in the pulp and paper industry, or for industries interested in using biodiesel to blend into petroleum products, such as the oil refining industry.

To meet the increasing demand for hydrogen and at the same time introduce biomass into the petroleum processes, one option could be to produce hydrogen through on-site gasification of biomass. One such pathway could be to co-feed byproducts from the oil refinery, such as coke, with biomass, or biobased energy commodities, into a gasification plant for hydrogen production. Another option is gasification followed by Fischer-Tropsch synthesis of the syngas. Products from the Fischer Tropsch process are naphtha, diesel and wax. To maximise the amount of diesel the wax can be cracked at the refinery. The naphtha fraction can be converted into gasoline through isomerisation to improve the octane number.

There are large amounts of excess heat at relatively high temperature levels in an oil refinery. If there is no district heating system (Chapter 11) or other heat-consuming industry in the vicinity and no planned internal novel use, the heat can be used for biomass drying (to be shipped and finally used elsewhere) or for desorption in a CCS unit (see below).

There are at least two existing biorefinery concepts in the oil refinery industry. In 2010, Preem started producing diesel with a 30% renewable content in a modified mild hydrocracker unit. This unit has a capacity of 330,000 m³ diesel per year (11 PJ per year). The renewable feedstock is raw tall oil, which is a by-product from kraft pulp mills (Chapter 6). Neste Oil in Finland is another oil refining company that produces diesel from biobased feedstock (NExBTL) by modifying an existing hydrotreater. NExBTL is to 100% based on palm oil.

CCS AND BIOREFINERIES

CCS (Carbon Capture and Storage) means that CO₂ in e.g. flue gases from an industry is captured in an absorption medium and then desorbed in a separate vessel, pressurised and transported to an onshore or offshore storage. To reach very low CO₂ emission levels, or even negative emissions, such processes can become important components in future biorefineries and complement or compete with other biorefinery processes (see Chapter 7 for perspectives on the potential for CCS in general and especially in the pulp and paper industry).

Currently four CO₂ capture processes are developed: post-combustion, pre-combustion, oxy-combustion and chemical looping. All four processes can be of interest in different types of industrial plants. The post-combustion is most commonly discussed for industrial applications and is therefore presented here in some more detail.

Separating CO₂ after combustion implies that the CO₂ is removed from the flue gases. Several methods are available and the composition and properties of the flue gas decides which method to select. These parameters are in turn dependent on the fuel and combustion process used. The post-combustion process can be applied to all combustion plants and is the only method available for retrofit.

The most common method for post-combustion is chemical absorption, since it can handle low partial pressures of CO₂. Other methods for post-combustion capture include cryogen and membrane technologies. In chemical absorption, the separation efficiency is relatively high, above 85 %, and an almost pure CO₂ stream is produced. The CO₂ is then compressed and cooled to liquid state. The process requires large amounts of energy for the regeneration of the absorbent. There are many absorbents being discussed. The two most common ones are MEA (monoethanolamine) and ammonia.

Several studies have shown that the most expensive part is the heating for desorption of the CO₂. In many industrial applications, this heat could be supplied from available excess heat (temperature levels of 90-120 °C are needed), thereby considerably decreasing the total cost for the whole CCS system. This is a reason why CCS in industry sometimes could achieve the same economy as in coal condensing plants, despite the smaller sizes. On the other hand, the use of excess heat for CCS may compete with other ways of using excess heat in a biorefinery (see Chapters 6, 7 and 11).

CONCLUDING REMARKS

Different definitions of “biorefinery” have been suggested. We can conclude that “biorefineries” is a concept that represents a broad class of processes that refine different forms of biomass into one or many products or services. Additional meaning attached to the concept could be production of “novel products” in “novel ways”, “more efficient”, “more environmental friendly”, “sustainable” or “more integrated with other systems”. In this book we embrace this somewhat vague and open umbrella definition.

The biorefinery concept can be filled with real world examples of processes that make use of biomass to produce useful products and services. In this chapter we have discussed gasification and fermentation pathways and a range of possibilities to integrate biorefining in the processing industry to fill the concept with some meaning. In other chapters more content will be added to the concept.

3

MARKET POTENTIAL OF BIOREFINERY PRODUCTS

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INTRODUCTION

The call for products based on renewable resources has grown louder in recent years because of the increasing awareness of the public about environmental problems that are caused by the society's dependence on fossil resources. As a result, the petrochemical industry has been looking for feedstock alternatives and accompanying technologies (see also Chapter 8). For instance, Chevron formed a joint-venture with Weyerhaeuser (a forest products company), in order to produce fuels, and Royal Dutch Shell is a long-time partner of Iogen, a company that is developing technology for producing second generation bioethanol.

Table 3.1 Estimated annual growth rate and value of a set of promising products based on wood fibre. Source: FPAC & FPIInnovations (2011)¹.

Products	Annual growth rate 2009-2015 (%)	Global value 2015 (billion USD)
Green chemicals	5.3	62.3
Alcohols	5.3	62.0
Bioplastic and plastic resins	23.7	3.6
Platform chemicals	12.6	4.0
Wood fibre composites	10.0	35.0
Glass fibre market	6.3	8.4
Carbon fibre	9.5	18.6

Moreover, biobased industries like the pulp and paper industry are looking for opportunities to revive their commodity-based business by considering the

¹ FPAC & FPIInnovations (2011) *The New Face of the Canadian Forest Industry - The Emerging Bio-revolution*. [accessed 2014-07-28].

expansion of their product portfolios with added-value products (see also Chapter 6). For instance, a recent study that focused on the Canadian forestry industry identified several products that can be manufactured from wood fibre and have an interesting projected annual growth rate and value (Table 3.1). The goal of this expansion is to increase companies' profit margins and to make efficient use of the renewable resources that they have traditionally been using.

The biorefinery is a process concept that is a means to produce biobased products that are both economically and environmentally beneficial. The biorefinery includes the use of many kinds of biobased feedstocks and makes use of several technological concepts that are based on chemical, biochemical and thermochemical transformations (Figure 3.1).² (See Chapter 2 for alternative definitions and Chapters 2 and 6 for process descriptions.)

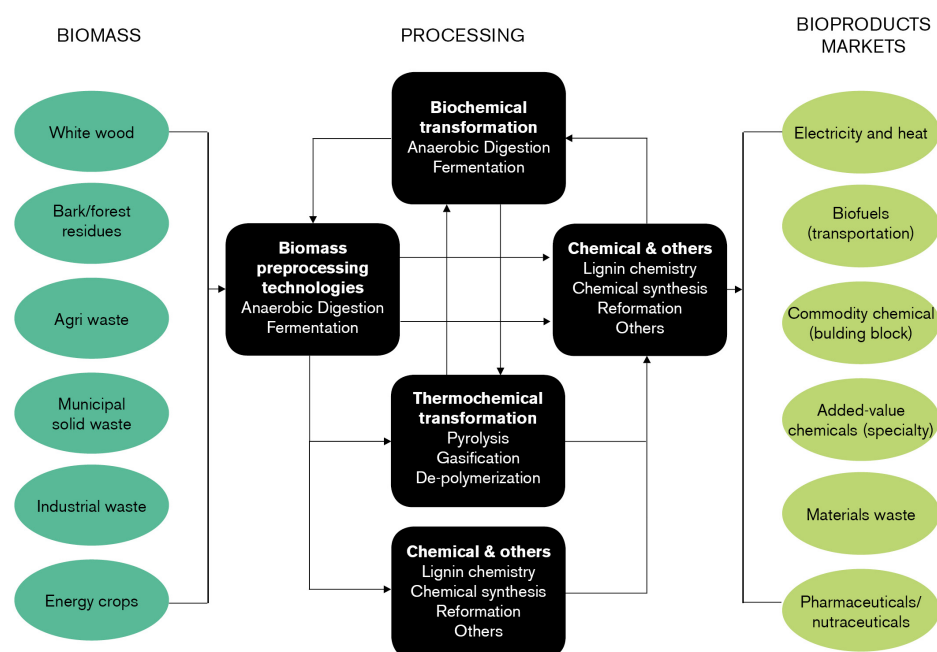


Figure 3.1 Biorefinery feedstocks, technologies and product markets (see also Chapter 2).

The purpose of this chapter is to give an overview of some of the products that can be manufactured using biorefinery concepts. First, the biorefinery product platform is discussed. This is followed by a discussion of the products that can be manufactured. A distinction will be made between platform chemicals, added-value chemicals, materials and bioenergy. This chapter will be concluded with some thoughts on how to decide which biorefinery products are feasible for production.

2 Janssen, M. et al. (2008) Successful partnerships for the forest biorefinery. *Industrial Biotechnology* 4(4):352–362.

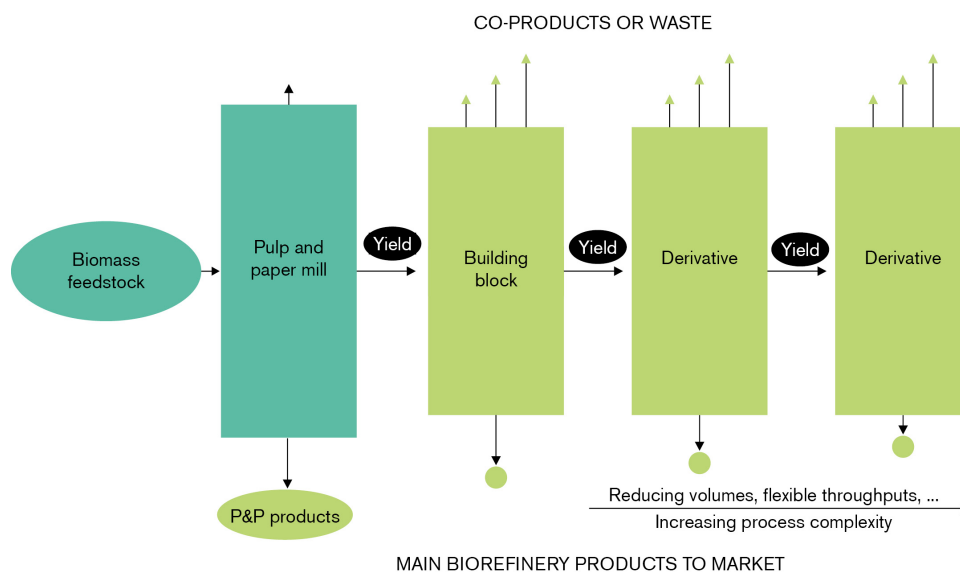


Figure 3.2 Forestry company product portfolio including a biorefinery product platform.

BIOREFINERY PRODUCT PLATFORM

A product platform-based approach can be applied to explore the opportunities for manufacturing biorefinery products. A product platform is “the common technological base from which a product family is derived through modification and instantiation of the product platform to target specific market niches”.³ The biorefinery platform-based approach involves the production of a chemical building block or intermediate product and this intermediate product is subsequently converted to a larger number of products. Such a product platform can e.g. be added to an existing pulp and paper mill product portfolio (Chapter 6), resulting in a new company product portfolio (Figure 3.2). This approach has successfully been used by the petrochemical industry.

Biomass-based products can substitute for fossil fuel based products. A distinction can be made between replacement and substitution products: replacement products are identical in chemical composition to existing products, but are based on renewable resources, e.g. bioethanol; substitution products have a different chemical composition to existing products, but have a similar functionality, e.g. PLA (polylactic acid) which would substitute PET (polyethylene terephthalate) in the production of e.g. plastic bottles.⁴

³ T. Simpson, J. Maier and F. Mistree (2001) Product platform design: method and application. *Research in Engineering Design* 13:2–22.

⁴ V. Chambost, J. McNutt and P. Stuart (2008) Guided tour: Implementing the forest biorefinery (FBR) at existing pulp and paper mills. *Pulp and Paper Canada* 109.7–8:19–27. In other contexts these concepts might have a slightly different meaning.

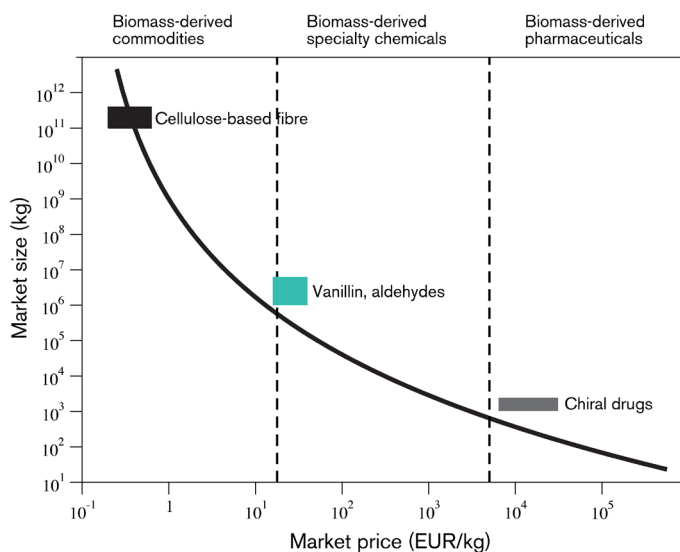


Figure 3.3 Illustration of price-market size relationship for biobased products The squares indicate ranges regarding market volume and price.

The value of biorefinery products is strongly dependent on the volume that is produced (Figure 3.3): commodities (e.g. cellulose-based fibre, ethanol) will typically have low prices, whereas added-value chemicals (e.g. vanillin, aldehydes) and pharmaceuticals (e.g. chiral drugs) will typically have a significantly higher price.⁵ Table 3.2 gives examples of the current production volume, and the potential market volume and value of some biorefinery products. This price-volume relationship may have an impact on the choice of the products that a company wants to produce: high-volume commodities with a low profit margin, or specialty chemicals with a small market but high profit margin.

Table 3.2 Production and market potential for some promising biorefinery products.

Biorefinery Products	Biorefinery production (ktonnes/year)	Year	Market potential (ktonnes/year)*	Potential value (billion EUR)
Platform chemicals				
Lactic acid	350	n/a	54 000	8.1
Succinic acid	15	n/a	245	1.4
Added-value chemicals				
Ethylene	200	2008	130 000	130
Xylitol	45	n/a	75	0.34
Astaxanthin	0.004	n/a	0.13	0.20
Materials				
Polylactic acid (PLA)	230	2008	54 000	90
TPS/PLA blend	330	2008	14 000	30
Viscose	3 500	2005	60 000	120
Transportation fuels	88 000	2008	2 500 000	1200

*The potential market volume is defined as the market volume of the fossil fuel alternative of a given product in the given year (if available).

Making a decision on this trade-off between profit margins and production volumes needs to be based on a market analysis while taking into account the technical feasibility of product manufacturing and the identification of business partners for securing the value chain. As well, the biorefinery product portfolio may be established while taking into account manufacturing flexibility (i.e. to adjust

⁵ C. Cobden (2011) *Integrating Bioenergy with Forest Sector Facilities*. Presentation at CanBio/CRIBE Bioenergy Conference Thunder Bay, ON, Canada, Apr. 26.

product volumes) and supply chain network design.⁶ Furthermore, the product platform approach will increase the flexibility of the operations because it is relatively easy to switch to the production of a different chemical. (See also Chapter 6 for a discussion on factors that influence process choice in pulp mills, Chapter 11 on the value of heat as a byproduct and Chapter 12 on technical and market risks.)

PLATFORM CHEMICALS

There are several chemicals that are considered for production of biobased products. The US Department of Energy made an assessment of the most important biobased chemicals based on, among others, market data, properties and the technical complexity of the synthesis pathways.⁷ This list of chemicals was recently updated based on the progress that has been made with regard to the production of these chemicals (Table 3.3).⁸ Well-known examples in this list are ethanol, lactic acid and succinic acid.

Table 3.3 US Department of Energy “Top 10” biobased chemicals. The table is arranged such that the similarities and differences between the two lists become apparent.

Year 2004	Year 2010
	Biohydrocarbons (isoprene, other)
	Lactic acid
	Ethanol
Succinic, fumaric and malic acids	Succinic acid
2,5-Furan dicarboxylic acid	Furans (furfural, HMF, FDCA)
3-Hydroxypropionic acid	Hydroxypropionic acid/aldehyde
Levulinic acid	Levulinic acid
Glycerol	Glycerol and derivatives
Sorbitol	Sorbitol
Xylitol/arabinitol	Xylitol
Aspartic, glucaric, glutamic, itaconic acid	
3-Hydroxybutyrolactone	

Global fuel ethanol production was about 70 million tonnes (Mt), or 2 EJ, in 2010 and almost entirely produced by means of fermentation.⁹ Not only is bioethanol used as a fuel (see section on bioenergy later in this chapter), it can also be used as a precursor for the production of ethylene which is a petrochemical with one of the highest production volumes (see also example in Chapter 8). Ethylene can be produced at an extremely high conversion rate (99.5%) from ethanol by means of vapour phase dehydration.¹⁰ It is an intermediate product that can be used for the production of many consecutive intermediates and final products. About 80% of the ethylene consumed in the United States, Western Europe and Japan is used for production of ethylene oxide, ethylene dichloride, and linear Low- and High-Density Poly-Ethylene (LDPE and HDPE). Ethylene is also used to make

6 Mansoornejad, B., Chambost, V. and Stuart, P. (2010) Integrating product portfolio design and supply chain design for the forest biorefinery. *Computers & Chemical Engineering* 34(9):1497–1506.

7 Werpy, T. and Petersen, G. (2004) *Top value-added chemicals from biomass, Volume I: Results of screening for potential candidates from sugars and synthetic gas*. Springfield, VA, USA:U.S. Department of Energy/Pacific Northwest National Laboratory (Tech. rep. PNNL-14808).

8 Bozell, J.J. and Petersen, G.R. (2010) Technology development for the production of biobased products from biorefinery carbohydrates – the US Department of Energy’s “Top 10” revisited. *Green Chemistry* 12(4):539–554.

9 Renewable fuels association (2013) *World Fuel Ethanol Production*. [accessed 2014-07-28].

10 Bozell, J.J. and Petersen, G.R. (2010).

ethyl-benzene, alcohols, olefins, acetaldehyde and vinylacetate. The global production capacity for ethylene was 140 Mt per year in 2011 and continues to grow.¹¹ This means that half of the current global ethylene production, in principle, could be derived from bioethanol. Furthermore, ethanol can be used for the production of ethyl esters such as ethyl acrylate (for polymer production) and ethyl acetate (used as a solvent in industry), and ethylamines that are used in the synthesis of pharmaceuticals, surfactants and agricultural chemicals.

Lactic acid is commercially produced mainly by the fermentation of glucose. The production of biobased lactic acid is about 350 thousand tonnes per year. The conventional process is not optimal; for every tonne of lactic acid that is produced, one tonne of gypsum is produced. Furthermore, the separation and purification steps are expensive. Recent advances in membrane-based technologies have however resulted in more cost efficient processes.¹²

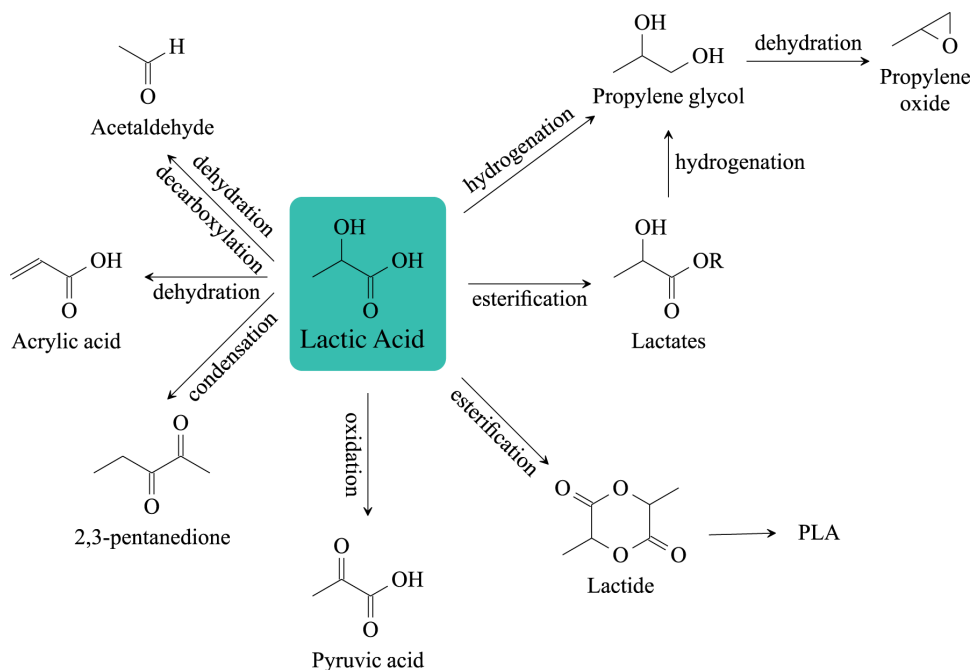


Figure 3.4 Lactic acid as a platform chemical.

Lactic acid can be used as a platform chemical for the production of a wide range of chemicals (Figure 3.4). It is currently mostly used for the production of polylactic acid (PLA). The increased demand for PLA is the main driver for the increasing production of lactic acid. PLA is a replacement product for polyethylene terephthalate (PET) and thus can be used for the production of e.g. plastic bottles. Furthermore, it can be applied in textiles, films and foams. Lactic acid can also be used for the production of propylene oxide (via the formation of propylene glycol) which has an important role in the production of polyurethanes (and thus has a large industrial application, e.g. as foam for insulation in buildings). Another high-volume derivative from lactic acid is acrylic acid. This is the primary building block for the formation of acrylate polymers which have numerous applications e.g. in surface coatings and adhesives.

¹¹ True, W. (2011) Global ethylene producers add record capacity in 2010. *Oil & Gas Journal* 109(14):100–104.

¹² Corma, A. et al. (2007) Chemical Routes for the Transformation of Biomass into Chemicals. *Chemical & Engineering News* 107(6):2411–2502.

Succinic acid is considered an important platform chemical that can be produced from renewable resources and its market size has been projected to be about 250 kt per year. Production has recently started at a scale of a few thousand tonnes per year but new larger production plants are planned.¹³

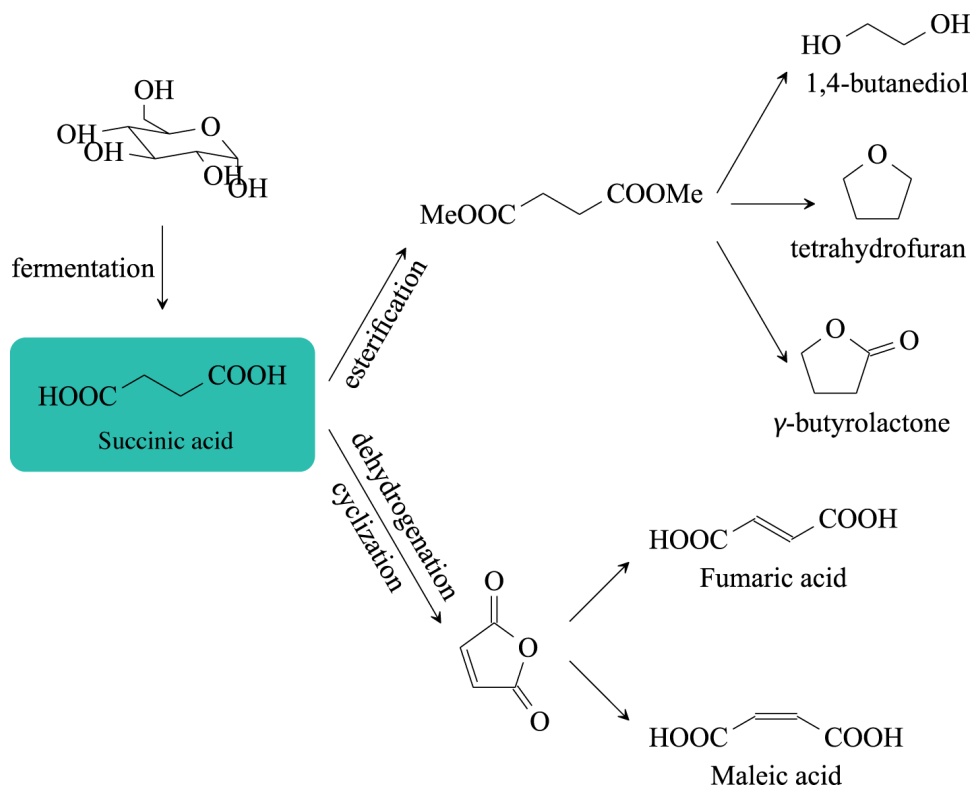


Figure 3.5 Succinic acid as a platform chemical. Source: Corma A. et al (2007).¹⁴

Succinic acid can be produced by the fermentation of glucose and used as a precursor for a range of products (Figure 3.5). For instance, succinate esters are intermediates for the production of 1,4-butanediol, tetrahydrofuran and γ-butyrolactone: 1,4-butanediol is an important building block for the production of polyesters, polyethers and polyurethanes; tetrahydrofuran is used as an industrial solvent for PVC and can be polymerised to form poly (tetramethylene ether) glycol (PTMEG); γ-butyrolactone is another industrial solvent and is an intermediate for the production of agrochemicals and pharmaceuticals. Fumaric acid is currently under investigation for treatment of multiple sclerosis.

ADDED-VALUE CHEMICALS

Platform chemicals can be used to produce added-value chemicals which themselves are precursors of even more valuable applications as shown in the preceding section (e.g. bioethylene for the production of bio-PE). This section will highlight some examples of the production of pharmaceuticals and nutraceuticals based on renewable resources.

¹³ McCoy, M. (2009) Big Plans For Succinic Acid. *Chem. Eng. News* 87(50):23–25.

¹⁴ Corma, A. et al. (2007) Chemical Routes for the Transformation of Biomass into Chemicals. *Chemical & Engineering News* 107(6):2411–2502.

Platform chemicals can be used to produce precursors for the production of pharmaceuticals. Examples that were given in the preceding section were ethylamines (from ethanol) and γ -butyrolactone (from succinic acid). Biologically active compounds can also be extracted from biomass, which has been done for a long time already. One example is betulin, which can be found in high concentrations in birch bark and the Chaga mushroom. Betulin can then be transformed into betulinic acid which has anti-retroviral, anti-malarial and anti-inflammatory properties, as well as a potential as an anti-cancer agent.¹⁵

Nutraceuticals (products that promote health) may be extracted from biomass as well. One well-known example is astaxanthin which is produced naturally by micro-algae. Astaxanthin has a strong anti-oxidant character and may prevent some cancers. Plant cell cultures can also be used for the production of nutraceuticals. An issue that needs to be addressed is the efficient extraction of the relevant metabolites. Solvent-based extraction has several drawbacks such as low yield and long extraction times. Enzyme-based extraction is an alternative to such conventional extraction methods. For example, the extraction of stevioside, a high intensity non-nutritive sweetener, has been improved by applying an enzyme-based method.¹⁶ Another prominent nutraceutical is xylitol, which is applied as a natural sweetener in mouthwashes, toothpastes or chewing gums. The global consumption of xylitol was about 45 kt in 2005 (Table 3.2).¹⁷ Xylitol is produced by the hydrogenation of xylose, which itself is the product of the decomposition of xylan. Xylan is a hemicellulose and thus can be found in lignocellulosic biomass (see Chapter 6).

MATERIALS

The global production capacity of emerging bioplastics has been estimated at 0.4 Mt in 2007, with projected growth to 4 Mt in 2020.¹⁸ The most important emerging bioplastics in 2007 were PLA (polylactic acid) and starch plastics. PLA, starch plastics, biobased PE and PHAs (polyhydroxy alkanoates) were projected to be the most important ones in 2020. As discussed above, PLA and PE can be produced from lactic acid and ethanol, respectively. In contrast to these two plastics, PHAs are produced directly via fermentation within the microorganism and are stored in granules in the cell cytoplasm. Carbon sources for the production of PHAs include carbohydrates, alcohols, alkanes and organic acids, depending on the type of PHA wanted and the microorganism used in the fermentation. Other emerging biobased plastics include polytrimethylene terephthalate (PTT), polyamides (nylon), polyurethane and thermosets like epoxy resins.

Besides these emerging bioplastics, there is a range of established biopolymers which include non-food starch (without starch for fuel ethanol), cellulosic polymers and alkyd resins. These polymers comprise a volume of 20 Mt per year. There are several types of starch plastics including thermoplastic starch (TPS). TPS is produced by the extrusion of native starch. However, it is of somewhat limited

15 Mullauer, F. B. et al. (2009) Betulin Is a Potent Anti-Tumor Agent that Is Enhanced by Cholesterol. *PLoS ONE* 4(4):e1.

16 Puri, M. et al. (2012) Enzyme-assisted extraction of bioactives from plants. *Trends in Biotechnology* 30(1):37–44.

17 Kadam, K. et al. (2008) Flexible biorefinery for producing fermentation sugars, lignin and pulp from corn stover. *Journal of Industrial Microbiology & Biotechnology* 35(5):331–341.

18 L. Shen, J. Haufe and M. K. Patel (2009) *Product overview and market projection of emerging bio-based plastics*. Copernicus Institute for Sustainable Development and Innovation, Utrecht University.

usefulness due to its hydrophilicity and inferior mechanical properties compared to conventional polymers. Cellulosic polymers include organic cellulose esters and cellulose ethers. Organic cellulose esters replaced cellulose nitrate because of the latter's flammability. Cellulose esters have been widely applied in packaging films, cigarette filters and textile fibres; cellulose ethers however have only been used in non-plastic applications. Alkyd resins are made from glycol or glycerol, fatty acids or triglyceride oils. The major part of manufactured alkyd resins is used for the coating of industrial goods and infrastructure.

One major application of natural fibres can be found in the production of paper products (380 Mt of paper and paperboard in 2009).¹⁹ Lignocellulosic (woody) biomass is mostly used as the source of fibre. The processing of the wood for producing pulp has a large impact on the application and the properties of the paper: mechanical pulping retains all of the wood components in the pulp and is used mostly for the production of newsprint; chemical pulping (e.g. the kraft pulping process, see Chapter 6) on the other hand strives for the separation of lignin, hemicellulose and other compounds in order to free the cellulose fibres for the production of e.g. uncoated free sheet. Besides these conventional types of paper, new applications of paper that are currently in the R&D stage are bioactive paper and "intelligent" paper.

The textile industry also makes extensive use of natural fibres, e.g. wool, cotton and silk. However, textile fibre can also be produced from (wood) pulp (dissolving pulp, see Chapter 6). This type of fibre is called man-made or regenerated cellulose fibres, and in 2005 the annual production was approximately 3.5 Mt.²⁰ Examples of this type of fibre, which differ from each other in terms of physical properties, are viscose, modal and lyocell. One can note that also PLA (discussed above) can be used for the fabrication of fibre used in textiles.

Biobased composites have already been used in the past. For instance, in 1941, Henry Ford unveiled the "soybean car", but it was suspended due to the outbreak of World War II. The car had a tubular steel frame with 14 plastic panels attached to it. These panels consisted of soybean fibre in a phenolic resin.²¹

Biocomposites can be made by mixing plastics and fibres. Examples are a composite from L-poly lactide and jute fibre mats, and composites composed of regenerated cellulose fabric and biodegradable polyesters. Other types of green composites are based on fibre and soy, and fibre and natural rubber. Textile composites have been developed that have superior mechanical properties. For instance, phenolic composites reinforced with jute and cotton woven fabrics have been found to be suitable for the production of lightweight structural applications. Fibre-reinforced biocomposites have been applied extensively. Roof structures have been successfully fabricated from soy oil-based resin and cellulose fibres in the form of paper sheets made from recycled cardboard boxes. Plastic and wood fibre composites are being used in decks, docks, window frames and molded panel components. As well, a wood fibre was found to be the best replacement

¹⁹ FAO Statistics (2012).

²⁰ Shen, L. and M. K. Patel (2010) Life cycle assessment of man-made cellulose fibres. *Lenzinger Berichte* 88:1–59.

²¹ See "The Soybean Car" thehenryford.org.

of asbestos in fibre cement products. Lastly, almost all German car manufacturers now use biocomposites in various applications such as dashboards and door panels (polypropylene and natural fibres) and asbestos has been replaced by flax fibres in disk brakes.²²

BIOENERGY

Biofuels used as transportation fuels are currently the most prominent products that are produced in biorefineries, bioethanol being the best known. The production of bioethanol (for use as a transportation fuel) is mandated to be 110 Mt per year (3.2 EJ per year) in 2022 in the United States, of which 62 Mt per year (1.8 EJ per year) should be bioethanol from lignocellulosic feedstock.^{23,24} Currently, the major part of the bioethanol produced in the United States is based on corn. Brazil also is a major producer of bioethanol and uses sugarcane as feedstock. The Brazilian production of fuel ethanol was nearly 21 Mt (0.6 EJ) in 2010. Since 1975, a fuel ethanol programme has been in place in Brazil which mandates that the content of ethanol in car fuel is at least 25% (E25).

Biodiesel can be produced from vegetable oils (jatropha, micro-algae) or animal fat feedstocks. The biodiesel is formed via the transesterification of these feedstocks into methyl or ethyl esters. The world-wide production of biodiesel was 16 Mt (0.6 EJ) in 2010, which was a significant increase from less than 4 Mt in 2005.²⁵ Biodiesel can be used as a car fuel, as a heating oil, and has been tested for railway and aircraft usage.

Other examples of proposed transportation fuels based on renewable resources are butanol, Fischer-Tropsch diesel (FT diesel), methanol, dimethyl ether (DME) and hydrogen. Hydrocarbons can be produced by converting plant-based sugars using catalytic chemistry. Butanol is proposed as a substitute for gasoline due to its energy content (higher than ethanol) and ability to mix with gasoline in high proportions. Biobutanol is typically produced using ABE (acetone, butanol, ethanol) fermentation. However, the current ABE technology is not mature enough yet to be able to compete with conventional ethanol technology.²⁶ There are several pilot and demonstration plants that aim at producing FT diesel, methanol, DME or hydrogen from gasified biomass or black liquor (see Chapters 2, 6 and 12). Gasification enables that more of the energy content in the biomass feedstock can be converted to the targeted fuel as compared to pathways based on fermentation (see Chapters 2 and 9).

Other bioenergy products are mostly used for generation of heat and electricity. Examples of such products are wood pellets, bio-oil and lignin. Wood pellets have gained popularity in Europe as a means to reduce CO₂ emissions of heat and electricity generation. In Canada, the amount of deadwood suitable for pellet production has increased significantly due to the pine beetle infestation. Even if

22 John, M.J. & Thomas, S. (2008) Biofibres and biocomposites. *Carbohydrate Polymers* 71:343-364.

23 Energy Independence and Security Act of 2007.

24 The realism of this goal for ethanol from woody biomass can be put into question. See discussion on scale-up of the production of other types of fuels based on woody biomass in Chapter 12.

25 Carriquiry, M. A. et al. (2011) Second generation biofuels: Economics and policies. *Energy Policy* 39(7):4222-4234.

26 Pfromm, P. H. et al (2010) Bio-butanol vs. bio-ethanol: A technical and economic assessment for corn and switch- grass fermented by yeast or *Clostridium acetobutylicum*. *Biomass & Bioenergy* 34(4):515-524.

the transportation of wood pellets from the west coast of Canada to Europe is taken into account, environmental benefits are expected.²⁷

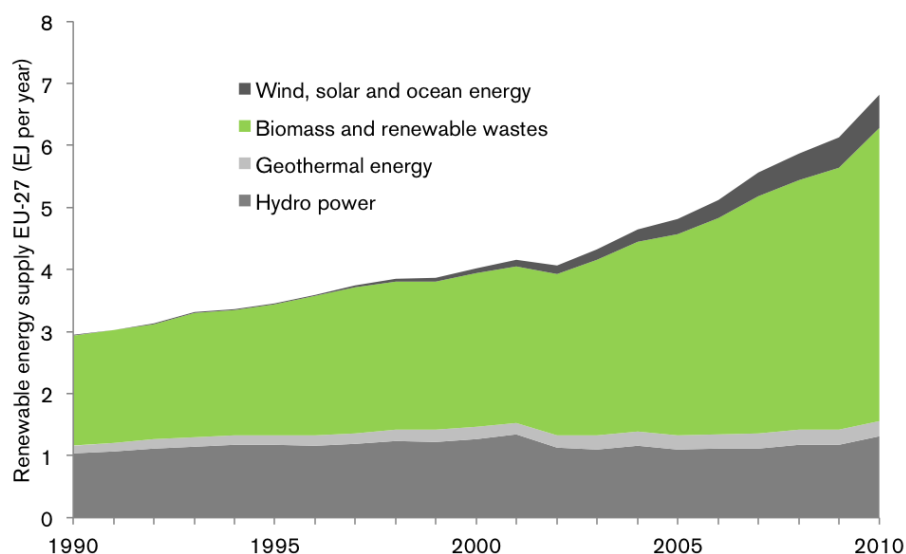


Figure 3.6 Supply of renewable energy in Europe. Source: Eurostat (2012).

Pyrolysis is a means to produce bio-oil, which can be used as an energy resource or as a feedstock for chemicals production. Besides the bio-oil, a pyrolysis process typically also yields char and gas.²⁸ Lastly, lignin can be separated in pulp mills and used as a fuel (Chapter 6). Lignin has a higher heating value than wood and can either be burned as such or co-fired with other (fossil-based) fuels.

The interest in using biomass, or more generally, renewable resources for energy generation has increased more recently due to environmental concerns. On the one hand, the share of bioenergy is small when compared to energy that is generated from fossil fuels (6% vs. 77% in the EU-27 in 2009, respectively). On the other hand, among renewable energy sources (biomass, hydro, geothermal, wind and solar), biomass supply is dominant accounting for 68% in 2010. In absolute terms bioenergy supply in EU-27 increased from 1.7 EJ in 1990 to 4.7 EJ in 2010 (Figure 3.6).

Sweden has a significantly different energy mix (Figure 3.7). The share of biomass in the energy mix has increased from about 10% in the 1980s to 23% in 2010. The growth in biomass use for energy purposes is largely responsible for the increase of the share of renewable energy in the Swedish energy mix during this period.

27 F. Magelli et al. (2009) An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass & Bioenergy* 33(3):434–441.

28 Mohan, D. et al. (2006) Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review. *Energy & Fuels* 20(3):848–889.

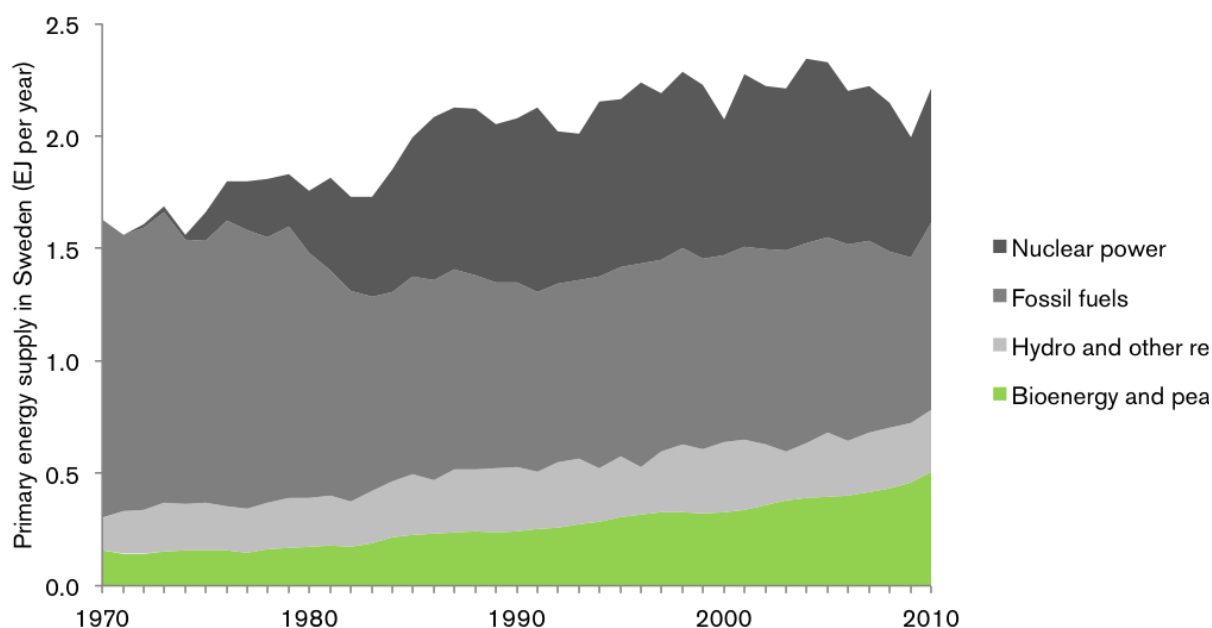


Figure 3.7 Resource mix of energy supply in Sweden. Source: The Swedish Energy Agency (2012).

The examples of the EU and Sweden show that the share of bioenergy (heat and electricity) has been growing steadily in recent years, and that there can be large differences between countries to what extent biomass is used as an energy source.

CONCLUDING REMARKS

There is a plethora of potential biobased products and many have a significant growth potential. Biobased products can be classified in different ways, and no matter which classification that is selected there will remain ambiguities. For example, when considering platform chemicals such as ethanol, a relevant question becomes whether or not to consider it as the final (ethanol as fuel) or as an intermediate product (ethanol as a precursor for ethylene and PE production). Nevertheless, it is apparent from this chapter that the portfolio of possible products includes a wide range from high volume low price commodities, such as biofuel and bioplastics, to low volume high price substances, such as specialty chemicals for the pharmaceutical industry.

The successful commercialisation and diffusion of these products do not depend on technical issues only. For instance, the forestry products industry will have a challenge in introducing wood-based biofuel on the market because corn-based ethanol is currently produced at lower cost partly due to sheer production volume. Besides production costs, market size and competition, also policy instruments affect the competitiveness of different products. For example, in many countries there are currently subsidies when biomass is used for biofuels and bioelectricity production, while this is not the case for the production of green chemicals and materials. Moreover, the environmental impact of the production of biobased products needs to be taken into account, when assessing the future desirability of individual products. It is not guaranteed that all biobased products are more environmentally friendly than their fossil-based counterparts.

4

HOW MUCH BIOMASS IS AVAILABLE?

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INTRODUCTION

Human beings have always influenced their habitats and the conversion of natural ecosystems to anthropogenic landscapes is perhaps the most evident alteration of the Earth. Human societies have put almost half of the world's land surface to their service, and human land use has caused extensive land degradation and biodiversity loss, and also emissions to air and water contributing to impacts such as eutrophication, acidification, stratospheric ozone depletion and climate change. The substitution of biomass with fossil resources has – together with the intensification of agriculture – saved large areas from deforestation and conversion to agricultural land. However, intensified land management and the use of oil, coal and natural gas cause many of the environmental impacts we see today. Societies therefore take measures to reduce the dependence on fossil resources and return to relying more on biomass and other renewable resources.

Besides that demand for food and conventional forest products such as paper and sawnwood grows around the world, the ambition to replace fossil-based products (especially fuels) with biobased products presents considerable opportunities as well as challenges for agriculture and forestry. Figure 4.1 illustrates this by presenting a magnitude comparison of biomass output in forestry and agriculture with prospective biomass demand for energy (see figure caption for more detailed description). One immediate conclusion from this comparison is that the biomass extraction in agriculture and forestry will have to increase substantially in order to provide feedstock for a bioenergy sector large enough to make a significant contribution to the future energy supply. Biomass will also be required as feedstock for the production of new types of biomaterials displacing their fossil based alternatives (e.g., plastics, rubber and bulk chemicals, see Chapter 3), but this materials production only uses on the order 10% of total annual petroleum and gas production.¹ It is the use of fossil fuels in the energy sector that is the main source of society's exploitation of fossil resources and the displacement of fossil fuels with biomass consequently represents the largest prospective use.

¹ Some 10% of the coal is used in steel production.

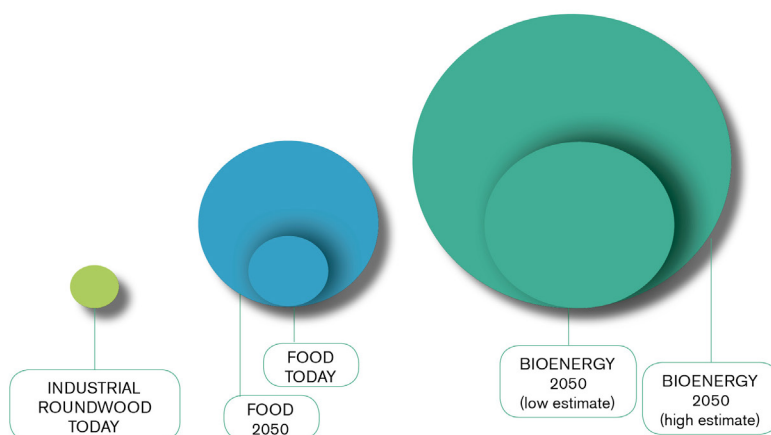


Figure 4.1 Comparison of the food and agriculture sector with a prospective bioenergy sector. The energy content in today's global industrial roundwood production is about 15-20 EJ per year, and the global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) corresponds to about 60 EJ per year². The large green circles show the range (25th and 75th percentiles) in biomass demand for energy found in a recent review by the IPCC of 164 long-term energy scenarios meeting <440 ppm CO_{2eq} concentration targets (118 to 190 EJ per year of primary biomass). Source: IPCC (2011)³.

A first quantitative understanding of prospects for meeting future biomass demands can be gained from considering the total annual aboveground net primary production (NPP: the net amount of carbon assimilated in a time period by vegetation) on the Earth's terrestrial surface. NPP is estimated to correspond to about 35 billion ton of carbon, or 1260 EJ⁴, per year (Haberl et al., 2007), which can be compared to the current world energy use of about 500 EJ per year and the present and prospective biomass demands shown in Figure 4.1. (see numbers in figure caption). This comparison shows that the present and prospective biomass demand is clearly significant compared to global NPP. Establishing bioenergy as a major future contributor to energy supply requires that a significant part of global terrestrial NPP takes place within production systems that provide bioenergy feedstocks. Total terrestrial NPP may also have to be increased through fertilizer, irrigation and other inputs on lands managed for food, fibre and bioenergy production.

Biomass production, to provide feedstocks for bioenergy and new types of biobased products, interacts in complex ways with the production of food and other conventional biobased products. Some biomass flows that earlier were considered to be waste products can find new economic uses, and opportunities for cultivating new types of crops and integrating new biomass production with food and forestry production can help improve overall resource management. However, the growing biomass demand also means increased competition for land, water and other production factors, and can result in overexploitation and degradation of resources.

² Statistics from FAO (2011)

³ IPCC (2011) *Special Report on Renewable Energy Sources and Climate Change Mitigation*. United Kingdom and New York, NY, USA: Cambridge University Press

⁴ Assuming an average carbon content in biomass of 50% and 18 GJ/ton (dry biomass and average lower heating value, see Chapter 9 for a discussion on heating values and water content of biomass feedstock).

This chapter discusses long-term biomass resource potentials and how these have been estimated based on considerations of the Earth's biophysical resources (ultimately net primary production, NPP) and restrictions on their use arising from competing requirements, including non-extractive requirements such as soil quality maintenance or improvement and biodiversity protection. The focus is on assessments that are concerned with biomass supply for energy but these are relevant also for those thinking about the prospects for a biobased economy in general. Approaches to assessing biomass potentials – and results from selected studies – are presented with an account of the main determining factors. An account is also given of possible consequences that can follow from a substantially increased use of biomass as feedstock for bioenergy and other bioproducts – and how these consequences can be addressed.

METHODOLOGIES FOR ASSESSING BIOMASS SUPPLY POTENTIALS

Studies have used different approaches to assess how biophysical conditions influence the biomass supply potential. Studies also differ in whether – and how – they consider important additional factors, such as socioeconomic considerations (see Chapter 5), the character and development of agriculture and forestry, and factors connected to nature conservation and preservation of soil, water and biodiversity.⁵ Assessments that only consider biophysical conditions produce so-called *theoretical potentials*. If also limitations imposed by the employed production practices, and the competing demand from other biomass end uses (e.g., food), are considered one commonly refers to *technical potentials*. The term *sustainable potential* is sometimes used when also various limitations connected to nature conservation and soil, water and biodiversity preservation are considered.

There are also studies that quantify *market potentials*, which might be done from both the supply side and the demand side (Figure 4.1 showed results of demand side assessments). Supply side assessments of market potentials aim at estimating how much biomass that can be produced below a given cost limit. They combine data on land availability, yield levels, and production costs to obtain plant- and region-specific cost-supply curves. These are based on projections or scenarios for the development of cost factors, including opportunity cost of land, and can be produced for different contexts (including different policy regimes) and scales. Examples include feasibility studies of supplying individual bioenergy plants, sector-focusing studies, and studies producing comprehensive multi-sector cost-supply curves for countries, larger regions, or for the entire world.⁶ The biomass production costs can be combined with technological and economic data for related logistic systems and conversion technologies to derive market potentials for secondary energy carriers such as bioelectricity and biofuels for transport. The cost limits used to derive market potentials are also dependent on policy regime as well as on costs for competing energy technologies and development of the overall energy system.

5 See, e.g., the overview of 17 studies in Berndes et al. (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy* 25(1):1-28.

6 See, e.g., Hoogwijk et al. (2009) Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass and Bioenergy* 33(1):26- 43.

Most assessments of the biomass resource potential considered in this section are variants of technical and market potentials that employ a “food and fibre first principle” with the objective of quantifying biomass resource potentials under the condition that global requirements of food and conventional forest products such as sawnwood and paper are met with priority. Studies that start out from such principles should not be understood as providing guarantees that a certain level of biomass can be supplied for energy purposes without competing with food or fibre production. They quantify how much bioenergy could be produced at a certain future year based on using resources not required for meeting food and fibre demands, given a specified development in the world or in a region. But they do not analyze how bioenergy expansion towards such a future level of production would – or should – interact with food and fibre production.

RANGES OF ESTIMATED BIOMASS POTENTIALS

Table 4.1 shows ranges in the assessed technical potential for the year 2050 for various biomass categories. The wide ranges shown in Table 4.1 are due to the variety of methodological approaches applied and diverging assumptions about critical factors such as economic and technology development, population growth, dietary changes, nature protection requirements and effects of climate change on agriculture and forestry production. Some studies exclude areas where attainable yields are below a certain minimum level. Other studies exclude biomass resources judged as being too expensive to mobilise, given a certain biomass price level, even if assessment of economic potentials is not the stated aim of the study.

Figure 4.2(a) shows – as an example – estimates of European supply potentials corresponding to certain food sector scenarios for 2030 considering also nature protection requirements and infrastructure development. The cost supply curves shown in Figure 4.2(b) were subsequently produced including biomass plantations and residues from forestry and agriculture. The key factor determining the size of the potential in this case was the pace of land productivity development in pasture production, i.e., the amount of meat and milk that could be produced per unit of pasture land.

Studies that quantify the biomass resource potential consider a range of factors that reduce the potential to lower levels than if they are not included. These factors are also connected to impacts arising from the exploitation of biomass resources. Despite that assessments employing improved data and modelling capacity have not succeeded in narrowing down the uncertainty range of potential future biomass supply, they do indicate the most influential factors that affect the potential. The following sections briefly describe how the potentials of the different categories of biomass in Table 4.1 are estimated and elaborate on the impact of important factors.

Table 4.1 Overview of global technical potential of land-based bioenergy supply for a number of categories (primary energy, rounded numbers). The total assessed technical potential can be lower than the present bioenergy supply of about 50 EJ/year in the case of high future food and fiber demand in combination with slow productivity development in land use, leading to strong declines in biomass availability for energetic purposes. Source: IPCC (2011).

Biomass category	Comment	2050 technical potential (EJ/year)
Organic waste	A heterogeneous category that can include, e.g., organic waste from households and restaurants, and discarded wood products such as paper and demolition wood. The availability depends on future consumption patterns, competing uses and implementation of collection systems.	5 – 50
Residue flows in agriculture	By-products associated with food/fodder production and processing, both primary (e.g., cereal straw from harvesting) and secondary residues (e.g., rice husks from rice milling).	15 – 70
Dung	Population development, diets, and the character of livestock production systems are critical determinants: usually only dung from confined livestock production is assumed to be available.	5 – 50
Forest biomass	Biomass from silvicultural thinning and logging, and wood processing residues such as sawdust and bark. Dead wood from natural disturbances, such as fires and insect outbreaks, represents a second category. Some studies estimate the size of available forest growth that is not required for industrial roundwood production to meet projected demand for conventional forest products such as sawnwood and pulp. "Available forest growth" here refers to growth occurring on lands judged as being available for wood extraction. High forest biomass potentials correspond to a much larger forest biomass extraction for energy than what is presently achieved in industrial wood production. Zero potential indicates that forest biomass requirement to meet the demand for conventional forest products can become larger than the estimated forest supply capacity.	0 – 110
Dedicated biomass production on surplus agricultural land	Includes conventional agriculture crops, tree species (e.g., eucalyptus, and pine) grown in plantations providing pulpwood and other conventional forest products, and new types of plants suitable as feedstock for bioenergy or new types of biomaterials. "Surplus agriculture land" refers to former agriculture land no longer used for food production, but availability of such land needs not imply that less land is needed for food in the future compared to today: land may become excluded from agriculture use in modeling runs due to land degradation processes or climate change making them non-suitable for food crops and food production may then have expanded elsewhere, for instance by converting forests to croplands. Large potential requires global development towards high-yielding agricultural production and low demand for grazing land, making very large areas (similar scale as present global cropland area) available for biomass plantations. Zero potential reflects that studies report that food sector development can be such that no surplus agricultural land will be available.	0 – 700
Dedicated biomass production on marginal lands	Some studies specifically assess the extent of marginally productive land or land that has become degraded due to unsustainable use, but that still could be suitable for some bioenergy schemes, for instance via reforestation. There is no globally established definition of degraded/marginal land and not all studies make a distinction between such land and other land judged as suitable for bioenergy. Adding an estimate of potential biomass supplies from surplus agriculture lands with another estimate of potential biomass supplies from degraded lands may therefore lead to double counting since the studies may actually refer to partly the same land areas. Low potential for this category indicate competing land demand for, e.g., extensive grazing management and/or subsistence agriculture, or that the biomass production on the land is judged to not be viable.	0 – 110
Total		<50 – >1000

The total assessed technical potential can be lower than the present bioenergy supply of about 50 EJ/year in the case of high future food and fiber demand in combination with slow productivity development in land use, leading to strong declines in biomass availability for energetic purposes. Source: IPCC (2011).

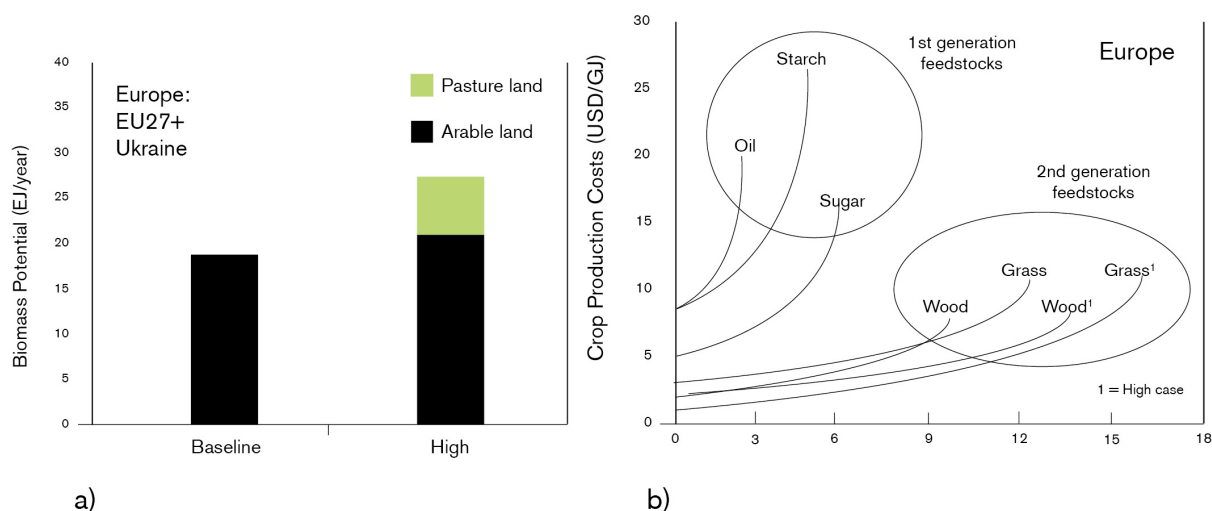


Figure 4.2 Examples of modelled biomass resource potentials in Europe year 2030 (a) based on food sector scenarios and consideration of nature protection requirements and infrastructure development. The cost supply curves (b) were produced based on data in (a) and projections of production cost development for various agricultural biomass production systems up to 2030. Sources: (a): Fischer et al., (2010)⁷; (b): de Wit and Faaij (2010)⁸.

ORGANIC WASTE AND RESIDUE FLOWS IN AGRICULTURE

Many factors determine how much organic waste that is produced in society or how much residues that are generated in agriculture and forestry – and also how much of this that can be extracted.

First of all, the future volumes of post-consumer organic waste as well as residues in agriculture and forestry production are determined by the future demand for agriculture and forestry products. Assumptions about population growth, economic development, dietary changes and consumption patterns in general thus influence the outcome in studies that quantify the future potential of residues. The way studies characterise materials management strategies (including recycling and cascading use of materials) is also important since it influences how the demand for different types of products translates into demand for basic food commodities and industrial roundwood.

Organic waste is a heterogeneous category that can include, e.g., organic waste from households and restaurants, and discarded wood products such as paper and demolition wood. The availability depends on many factors including consumption patterns, competing uses and implementation of collection systems. Studies use similar approaches for quantification as when assessing primary residue volumes in agriculture and forestry, i.e., production or consumption data are combined with factors that reflect the amount of organic waste that is produced per unit of product output. More rough estimates may simply combine information about per capita production of organic waste with population projections. As there is no global set of agreed definitions of different organic waste and residue categories available, it is important to make sure that double counting is avoided if assessments of residue and waste flows are made based on combining results

⁷ Fischer et al. (2010) Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. *Biomass and Bioenergy* 34(2):173-187.

⁸ de Wit and Faaij (2010) European biomass resource potential and costs. *Biomass and Bioenergy*. 34(2):188–202.

from studies that themselves focus on only one or a few waste streams. Different studies might also be more or less incompatible in the sense that the quantifications are made based on diverging assumptions about population growth, economic development, consumption patterns and character of production systems. This is a challenge also when other biomass categories are studied.⁹

Assessments of the potential contribution of *agricultural residue flows* to the future biomass supply combine data on future production of agriculture products obtained from food sector scenarios with so-called “residue factors” that account for the amount of residues generated per unit of primary product produced. For example, harvest residue generation in agricultural crops cultivation is commonly estimated based on the harvest index of respective crops, i.e., the ratio of harvested product to total aboveground biomass.¹⁰ The shares of these biomass flows that are available for energy (“recoverability fractions”) are then estimated based on consideration of other extractive uses (e.g., animal feeding or bedding) and other requirements such as the need to leave residues on the ground for the purposes of soil conservation. Other recoverable biomass flows in the food sector can be estimated in a similar way. For example, recoverability fractions for dung are set based on the structure of the animal production sector (confined production vs. free grazing) and then used to quantify the bioenergy potential associated with dung management.

Changes in the food industry influence the residue generation per unit product output in different ways: crop breeding leads to improved harvest index reducing residue generation rates; implementation of no-till, or conservation, agriculture requires that harvest residues are left on the fields to maintain soil cover and increase organic matter in soils; shift in livestock production to more confined and intensive systems can increase recoverability of dung but reduce overall dung production at a given level of livestock product output.

In agriculture, overexploitation of harvest residues is one important cause of soil degradation in many places of the world.¹¹ Fertilizer inputs can compensate for nutrient removals connected to harvest and residue extraction, but maintenance or improvement of soil fertility, structural stability and water holding capacity requires recirculation of organic matter to the soil.¹² Residue recirculation leading to nutrient replenishment and storage of carbon in soils and dead biomass contributes positively to climate change mitigation by withdrawing carbon from the atmosphere and by reducing soil degradation and improving soil productivity leading to less need to convert land to cropland and thereby lowering GHG emissions arising from vegetation removal and ploughing of soils.

9 See also Chapter 9 for a discussion on the problems and risks of mixing results from studies that use different definitions and incompatible assumptions.

10 See, e.g., Krausmann et al. (2008) Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecological Economics* 65(3):471-487.

11 Blanco-Canqui, H., and R. Lal (2009) Corn stover removal for expanded uses reduces soil fertility and structural stability. *Soil Science Society of America Journal* 73(2):418-426.

12 Wilhelm, W.W. et al. (2007) Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal* 99:1665-1667.

RESIDUES AND UNUSED GROWTH IN FORESTS

The generation of logging residues in forestry, and of additional biomass flows such as thinning wood and process by-products, is estimated using similar methods as when residue flows in agriculture are quantified. Again, recoverability fractions are estimated based on consideration of other extractive uses (e.g., fibre board production in the forest sector) and other requirements such as the need to leave dead wood in the forest to promote biodiversity. Changes in the forest industry influence the residue generation per unit product output, e.g. increased occurrence of silvicultural treatments such as early thinning to improve stand growth will lead to increased availability of small roundwood suitable for energy uses.¹³

Studies indicate that the cost of soil productivity loss may restrict residue removal intensity to much lower levels than the quantity of biomass physically available in forestry.¹⁴ However, the combination of residue harvest and nutrient (including wood ash) input can avoid nutrient depletion and acidification and can in some areas improve environmental conditions due to reduced nutrient leaching from forests.¹⁵ Development of technologies for stump harvesting after felling increases the availability of residues during logging. It can also reduce the cost of site preparation for replanting and reduce damage from insects and spreading of root rot fungus.¹⁶ Yet, again, it can also lead to negative effects including reduced forest soil carbon and nutrient stocks, increased soil erosion and soil compaction.¹⁷ Besides soil sustainability, additional aspects (e.g., biodiversity and water quality) need to be considered. Organic matter at different stages of decay plays an important ecological role in conserving soil quality as well as for promoting biodiversity and thresholds for desirable amounts of dead wood in forest stands are difficult to set.

In addition to the residue flows that are linked to industrial roundwood production and processing to produce conventional forest products, forest growth above what is currently harvested is considered a source of forest wood in some studies. Figure 4.3 shows an example for the case of Europe, where both current wood removals and the unused forest growth are compared to the current gross energy use in order to place the forest wood flows in the context of energy systems. The potential of unused forest growth is quantified based on estimating the net annual increment (NAI) of biomass in the parts of forests that are assessed as being available for wood supply and deducting the present biomass removals on the same land.¹⁸ Countries close to the dotted diagonal have a non-used NAI that is roughly

¹³ See Chapter 6 for an outline of current and potential utilization of residue flows in pulp mills.

¹⁴ Gan, J. and Smith, C. (2010) Integrating biomass and carbon values with soil productivity loss in determining forest residue removals. *Biofuels* 1(4):539-546; Titus, B.D. et al (2009) Wood energy: Protect local ecosystems. *Science* 324(5933):1389-1390.

¹⁵ Börjesson, P. (2000) Economic valuation of the environmental impact of logging residue recovery and nutrient compensation. *Biomass and Bioenergy* 19(3):137-152; Eisenbies, M., E. Vance, W. Aust, and J. Seiler (2009) Intensive utilization of harvest residues in southern pine plantations: Quantities available and implications for nutrient budgets and sustainable site productivity. *BioEnergy Research* 2(3):90-98.

¹⁶ Saarinen, V.-M. (2006) The effects of slash and stump removal on productivity and quality of forest regeneration operations – preliminary results. *Biomass and Bioenergy* 30(4):349-356.

¹⁷ Walmsley, J.D., and Godbold, D.L. (2010) Stump harvesting for bioenergy - A review of the environmental impacts. *Forestry* 83(1):17-38.

¹⁸ NAI minus current removals is a rough indication of how much removals can increase in a given country. NAI refers to the average annual volume of increment of all trees, with no minimum diameter, minus the natural losses. Thus, it is equivalent to natural forest growth in a year (minus the natural losses).

equal to the current removals or, in other words, the total NAI is twice as large as the current removals. The further up a country is in the diagram, the larger is the non-used NAI compared to the country's gross energy consumption. A special case that can play a role is forest growth that becomes available after extensive tree mortality from insect outbreaks or fires.¹⁹

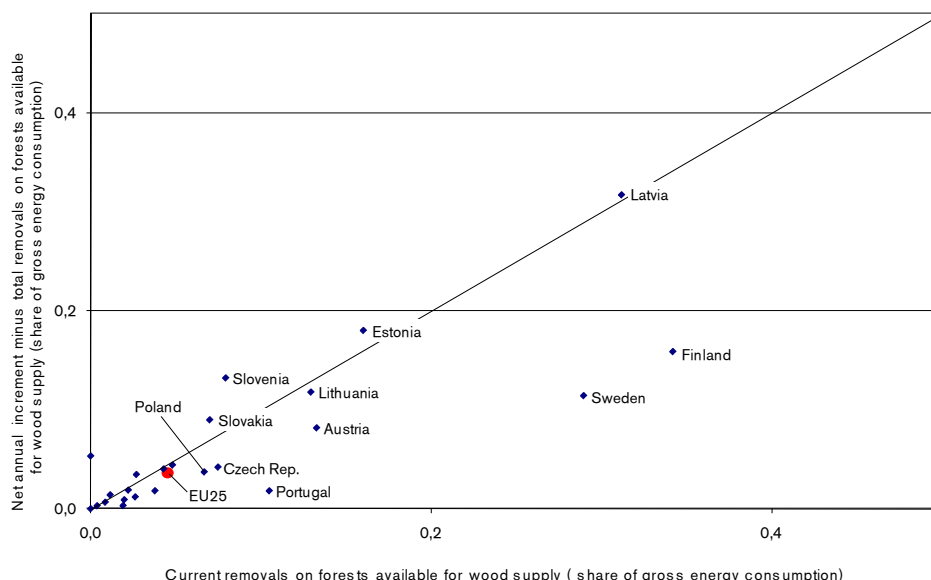


Figure 4.3 Relationships between current gross energy consumption and wood removals from forests available for wood supply (x-axis) and the balance between net annual increment and current removals in the respective countries (y-axis). The forest extraction levels and balance are converted to energy units based on an assumed energy content of 10 GJ/m³ of wood and then divided by each country's gross energy consumption. Source: Berndes (2010)²⁰.

Studies that consider the possibility to exploit unused forestry growth as a feedstock source do not commonly account for the possibilities to intensify conventional long-rotation forestry to increase forest growth over time. Yet, many studies indicate significant potential for intensifying conventional long-rotation forestry to increase forest growth and total biomass output – for instance by fertilizing selected stands and using shorter rotations– especially in regions of the world with large forest areas that currently practice extensive forest management.²¹ However, concerns about biodiversity and other undesirable effects might restrict productivity-enhancing measures.

There is also the need to consider the net outcome in relation to climate change mitigation, one primary objective of using more biomass as feedstock for fuels and other products. Changed forest management in response to bioenergy demand influences forest carbon flows and can lead to increased or decreased forest carbon stocks.²² Shortening forest rotation length in order to obtain increased output of timber and biomass fuels leads to decreased carbon stock in living biomass (other things being equal). Intensified biomass extraction in forests, for instance

19 Dymond, C.C. et al. (2010). Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. *Forest Ecology and Management*, 260(2), pp. 181-192.

20 Berndes (2010) Strategies for 2nd generation biofuels in EU – Co-firing to stimulate feedstock supply development and process integration to improve energy efficiency and economic competitiveness. *Biomass and Bioenergy* 34(2):227-236.

21 Berndes, G et al. (2011) *Bioenergy, land use change and climate change mitigation*. Background Technical Report. IEA Bioenergy. (ExCo:2011:04).

22 Berndes, G et al. (2011).

for bioenergy, can lead to a decrease in soil carbon or the dead wood carbon pool compared to existing practice. Conversely, if changed forest management employing intensified extraction also involves growth-enhancing measures, forest carbon stocks may increase. Finally, increasing CO₂ concentrations²³ and associated climate change influence future forest productivity and the potential of utilizing unused forest growth is sensitive to technical and economic aspects of biomass extraction in areas with limited infrastructure and other constraints on access.

PLANTATIONS DEDICATED TO BIOENERGY

The category biomass plantations include many different types of biomass production systems, ranging from the cultivation of conventional food crops to management of tree plantations that are grown in rotations up to several decades. The category differs from the forest category in that the production commonly uses agricultural practices, i.e., employing even aged monocultural stands that are subject to fertilizer, pesticide and other inputs. Certain boreal forest stands might share some of these features but are despite of this usually included in the forest category. The potential biomass supply from dedicated biomass plantations is estimated based on assessments of the availability of land that is suitable for such plantation, and the biomass yields that can be obtained on the available lands. Given that surplus agricultural land is commonly identified as the major land resource for the biomass plantations, food sector development is critical. The rate of intensification in agriculture is consequently a key aspect because it influences both land availability for biomass plantations (indirectly by determining the land requirements in the food sector) and the biomass yield levels obtained. Studies also point to the importance of diets and the food sector's biomass use efficiency in determining land requirements (both cropland and grazing land) for food.²⁴

Most earlier assessments of biomass resource potentials used rather simplistic approaches to estimate the technical potential of biomass plantations, but the continuous development of modelling tools that combine databases containing biophysical information (soil, topography, climate) with analytical representations of relevant crops and agronomic systems and the use of economic and full biogeochemical vegetation models has resulted in improvements over time.²⁵

As an example, Figure 4.4. shows the modelled global land suitability for both lignocellulosic plants and conventional food and feed crops that are suitable as biofuel or biomaterials feedstock (see caption to Figure 4.4 for information about plants included). By overlaying spatial data on global land cover derived from best available remote sensing data combined with statistical information and data on protected areas, it is possible to quantify the extent of suitable land for different land cover types. A suitability index has been used in order to represent both yield potentials²⁶ and suitability (see caption to Figure 4.4).

23 Elevated CO₂ levels in the ambient air stimulate plant growth. However, plants grown in conditions where other factors (e.g. limitations of rooting volume, light, temperature) restrict growth may not show a sustained response to elevated CO₂.

24 See, e.g., Wirsenius et al. (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems* 103(9):621-638.

25 See, e.g., Beringer et al. (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Global Change Biology Bioenergy*; Fischer et al. (2009) *Biofuels and Food Security*. Vienna, Austria: The OPEC Fund for International Development (OFID) and International Institute of Applied Systems Analysis (IIASA).

26 Yield potential is the yield obtained when an adapted cultivar (cultivated variety of a plant) is grown with the minimal possible stress that can be achieved with best management practices.

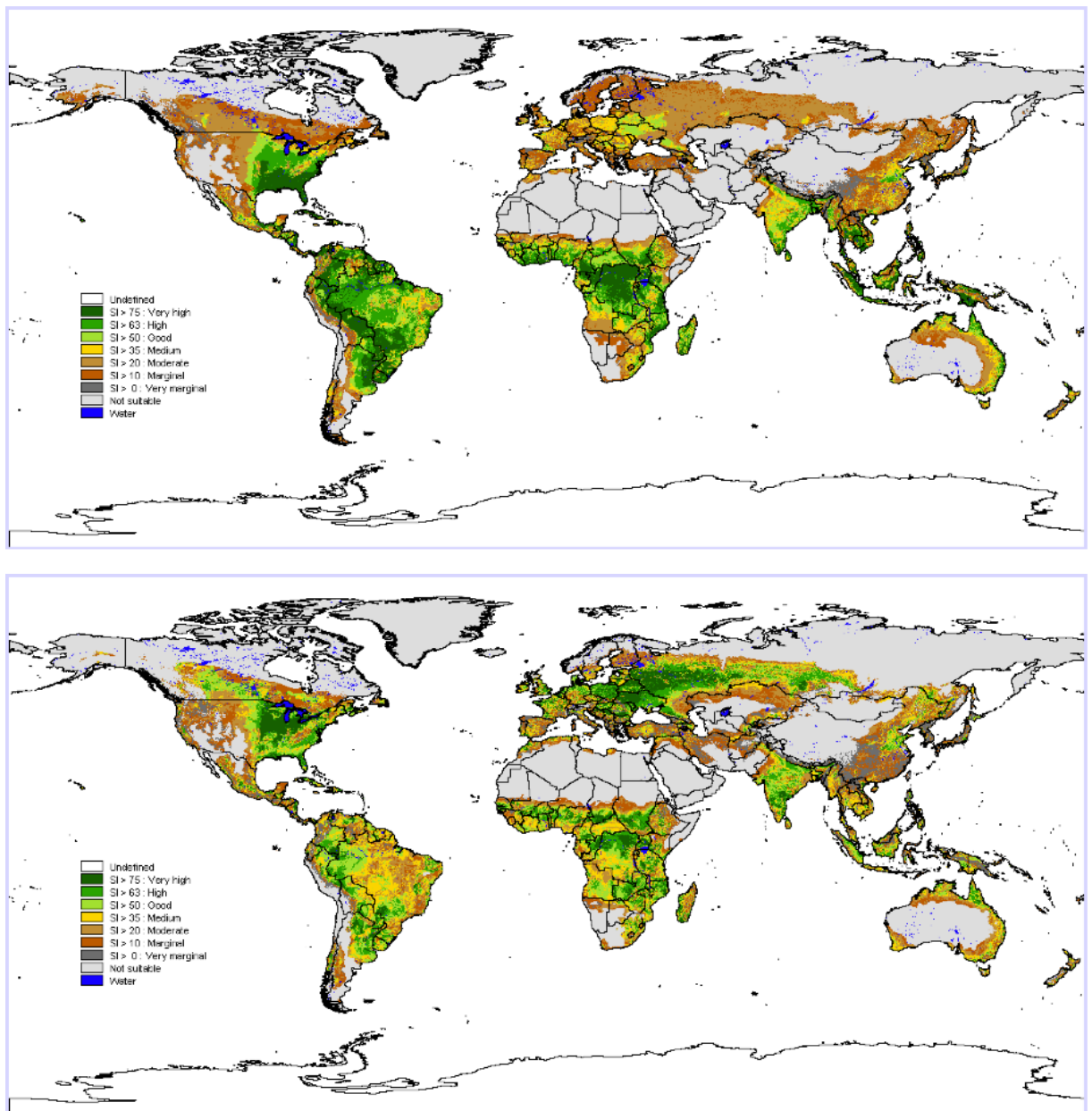


Figure 4.4 Global land suitability for bioenergy plantations. The upper map shows suitability for herbaceous and woody lignocellulosic plants (*Miscanthus*, switchgrass, reed canary grass, poplar, willow, eucalypt) and the lower map shows suitability for first generation biofuel feedstocks (sugarcane, maize, cassava, rapeseed, soybean, palm oil, jatropha). The suitability index SI describes the spatial suitability of each pixel and reflects the match between crop requirements and prevailing climate, soil and terrain conditions. The map shows suitability under rain-fed cultivation and advanced management systems, which assume availability of sufficient nutrients, adequate pest control and mechanization, and other practices. Results for irrigated conditions or low input management systems would result in different pictures (Fischer et al., 2009)²⁷.

Considerations concerning biodiversity can limit both intensification and expansion of the agricultural land area. The common way of considering biodiversity requirements as a constraint is by including requirements on land reservation for biodiversity protection. However, the focus is as a rule on forest ecosystems and takes the present level of protection as a basis. Other natural ecosystems also require

²⁷ Fischer, G. et al. (2009) *Biofuels and Food Security*. Vienna, Austria: The OPEC Fund for International Development (OFID) and International Institute of Applied Systems Analysis (IIASA).

protection – not least grassland ecosystems – and the present status of nature protection for biodiversity may not be sufficient. Bioenergy plantations can support biodiversity conservation in human-dominated landscapes, particularly when multiple species (e.g., agroforestry systems) are planted and mosaic landscapes are established in uniform agriculture landscapes and in some currently poor or degraded areas. Biomass resource potential assessments, however, as a rule assume yield levels corresponding to what is achieved in monoculture plantations and therefore provide little insight into how much biomass could be produced if a significant part of the biomass plantation were shaped to contribute to biodiversity preservation.

It is notable that several studies of agricultural development²⁸ show lower expected yield growth than studies of the biomass resource potential that report very high potentials for biomass plantations.²⁹ Some observations indicate that it can be a challenge to maintain yield growth in several main producer countries due to land degradation as a consequence of improper land use.³⁰ Water scarcity can limit both intensification possibilities and the prospects for expansion of bioenergy plantations.³¹ There can also be limitations and negative aspects of further intensification aiming at farm yield increases; high crop yields depending on large inputs of nutrients, fresh water, and pesticides can contribute to negative ecosystem effects, such as changes in species composition in the surrounding ecosystems, groundwater contamination and eutrophication with harmful algal bloom, oxygen depletion and anoxic “dead” zones in oceans being examples of resulting negative impacts.³² However, agricultural productivity can be increased in many regions and systems with conventional or organic farming methods.³³

Conversely, there are also reasons to look positively at the potential of biomass plantations. Studies reaching high potential for biomass plantations points primarily to tropical developing countries as major contributors and in these countries there are still substantial yield gaps to exploit and large opportunities for productivity growth – not the least in livestock production.³⁴ The low productivity of rain-fed agriculture that prevails in many regions can be improved through improved soil and water management, fertilizer use and crop selection.³⁵ Advances in plant breeding and genetic modification of plants not only raise the genetic yield potential but also may adapt plants to more challenging environmental conditions,

28 E.g. Alexandratos, N. (2009) World food and agriculture to 2030/50: highlights and views from mid- 2009. In: *Proceedings of the Expert Meeting on How to Feed the World in 2050*. Rome, Italy, Jun. 24-26. Economic and Social Development Department, Food and Agriculture Organization of the United Nations.

29 Johnston, M. et al. (2009) Resetting global expectations from agricultural biofuels. *Environmental Research Letters* 4(1):014004

30 IAASTD (2009) *Agriculture at a Crossroads. International Assessment of Agricultural Knowledge Science and Technology for Development*. Washington, DC, USA: UNEP/DEWA.

31 Berndes, G. (2008) *Water Demand for Global Bioenergy Production: Trends, Risks and Opportunities*. Report commissioned by the German Advisory Council on Global Change. Berlin, Germany: Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen.

32 Donner, S.D. and C.J. Kucharik (2008) Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proceedings of the National Academy of Sciences* 105(11):4513-4518.

33 Badgley, C. J. et al. (2007) Organic agriculture and the global food supply. *Renewable Agriculture and Food Systems* 22(02): 86-86.

34 Wirsén, S. et al. (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems* 103(9):621-638.

35 Lal, R. (2003) Offsetting global CO₂ emissions by restoration of degraded soils and intensification of world agriculture and forestry. *Land Degradation & Development* 14(3):309-322.; Rost, S. et al. (2009) Global potential to increase crop production through water management in rainfed agriculture. *Environmental Research Letters* 4(4):044002.

such as on marginal or degraded soils. Improved drought tolerance can improve average yields in drier areas and in rain-fed systems in general by reducing the effects of sporadic drought and can also reduce water requirements in irrigated systems. Selection and development of suitable plant species and genotypes for given locations to match specific soil types, climate, and conversion technology is possible, but is at an early stage of understanding for some energy plants.³⁶ Thus, there is a large yield growth potential for dedicated biomass plants that have not been subject to the same breeding efforts as the major food crops.

Besides reducing land requirements for meeting food and materials demand by increasing yields, plant breeding and genetic modification could make lands initially considered unsuitable available for rain-fed or irrigated production. Landscape approaches that integrate bioenergy production into agriculture and forestry systems to form multi-functional land use systems producing multiple (bioenergy, food and fiber) products could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity and that also help restore and maintain soil productivity and healthy ecosystems.³⁷ Conservation agriculture and mixed production systems (double-cropping, crop with livestock and/or crop with forestry) hold potential to sustainably increase land and water productivity and improve food security and efficiency in the use of limited resources such as phosphorous.³⁸ Integration can also be based on integrating feedstock production with conversion – typically producing animal feed that can replace cultivated feed such as soy and corn and also reduce grazing requirement.³⁹

CONCLUDING REMARKS

To sum up, the size of the future biomass potential is dependent on a number of factors that are inherently uncertain and will continue to make long-term potentials unclear. Important factors are population and economic and technology development and how these translate into fibre, fodder and food demand (especially share and type of animal food products in diets) and the development in agriculture and forestry. Additional factors include climate change impacts on biological productivity and future land use including its adaptation capability; considerations set by biodiversity and nature conservation requirements; and consequences of land degradation and water scarcity. Nevertheless, it can be concluded that it might be possible to produce several hundred exajoules (EJ) per year of biomass as feedstock for bioenergy and other bioproducts – if developments are favourable. This can be compared with the present biomass use for energy at about 50 EJ per year.

36 See e.g. Chapple, C., Ladisch, M. and Meilan, R. (2007) Loosening lignin's grip on biofuel production. *Nature Biotechnology* 25(7):746-748; Karp, A., and I. Shield (2008) Bioenergy from plants and the sustainable yield challenge. *New Phytologist* 179(1):15-32; Lawrence, C.J., and Walbot, V. (2007) Translational genomics for bioenergy production from fuelstock grasses: Maize as the model species. *Plant Cell* 19(7):2091-2094.

37 Note that such multiple output systems could be regarded as biorefineries depending on definition and system boundary (compare definitions in Chapter 2).

38 Heggenstaller, A.H. et al. (2008) Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agronomy Journal* 100(6):1740-1748; Herrero, M. et al. (2010) Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. *Science* 327(5967):822-825.

39 Dale, B.E. et al. (2010) Biofuels done right: Land efficient animal feeds enable large environmental and energy benefits. *Environmental Science & Technology* 44(22):8385-8389.

Organic waste and residue flows in agriculture and forestry represent important sources of biomass, but consideration of biodiversity and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set bounds on residue extraction in agriculture and forestry. It is clear that high biomass potentials require that biomass plantations become established on a large scale and that these achieve high yield levels. Thus, agriculture development and increased land use productivity are prerequisites for reaching high biomass supply potentials. Grasslands and marginal, or degraded, land have potential for supporting substantial biomass production, but biodiversity considerations, water shortages, and the difficulty of establishing viable production on such lands may limit this potential.

At the same time, the development of suitable biomass production systems, using also new types of plants, may make it possible to produce biomass on lands less suited for conventional food crops and integrated (bioenergy, food, fiber) production systems can promote higher efficiency in the use of land, water and other resources.

While recent assessments employing improved data and modelling capacity have not succeeded in providing narrow, distinct estimates of the biomass resource potential, they have advanced the understanding of how influential various factors are on the resource potential and that both positive and negative effects may follow from increased biomass use for energy and biomaterials. The insights from resource assessments can in this way improve the prospects for expanding the use of biomass for energy and for other purposes by pointing out the areas where development is most crucial and where research is needed. Studies using integrated energy industry and land use cover models⁴⁰ can provide further insights into how an expanding bioenergy sector interacts with other sectors in society including land use and management of biospheric carbon stocks. Such insights are essential when contemplating the prospects for displacing fossil resources with biomass.

40 See, e.g., Melillo et al. (2009) Indirect emissions from biofuels: How important? *Science* 326(5958):1397-1399.; Strengers, B. et al. (2004) The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. *GeoJournal* 61(4):381-393; Wise et al. (2009) Implications of limiting CO₂ concentrations for land use and energy. *Science* 324(5931):1183-1186.

5

SOCIO-ECONOMIC CONSEQUENCES OF INCREASED BIOMASS DEMAND

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INTRODUCTION

A large-scale expansion of the use of biomass for energy and raw materials¹ is likely to have substantial repercussions on social and economical conditions from the local to the global level.² These impacts can be both positive (e.g. job creation, increased energy security, and improved health conditions) and negative (e.g. higher food prices leading to increased poverty and food insecurity). Whether deliberate or unintended, these socioeconomic consequences of increased demand for biomass and bioenergy need to be accounted for in a comprehensive assessment of biomass technologies (see Chapter 1).

The aim of this chapter is not to provide a comprehensive overview of the full set of socio-economic effects of increased biomass use, given the multitude of existing bioenergy systems and the many ways in which they interact with and effect human welfare.³ Rather, the aim is to cast some light over some of the most frequent claimed and debated benefits and detriments of a large scale employment of bioenergy technologies: (1) its potential to increase employment and promote development, especially in rural areas, (2) the impact on agricultural commodity prices and the effect this in turn has on food security and poverty, mainly in developing countries, and (3) the extent to which increased bioenergy demand has contributed to a global rush for land, having a negative impact on local livelihoods.

¹ In the following text I will simply refer to bioenergy demand, but the consequences of increased demand for biomass are the same whether used for energy purposes or as a raw material feedstock.

² Chum, H. et al. (2011) Bioenergy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. (eds. O. Edenhofer, et al.) Cambridge, UK and New York, NY, USA:Cambridge University Press, pp. 209-332.

³ The interested reader is referred to Chapter 2 and 9 of IPCC (2011) *Special Report on Renewable Energy Sources and Climate Change Mitigation*. (eds. O. Edenhofer, et al.) Cambridge, UK and New York, NY, USA:Cambridge University Press.

A key conclusion emerging from this chapter is that the socio-economic consequences differ widely between bioenergy systems that are land intensive (e.g. crop-based biofuels) and those that are not (e.g. systems based on residue flows from agriculture and forestry), since increased demand for land is what drives the negative impacts on poverty, malnutrition and land rights. Formulating policies that account for this distinction is key if we are to realize the climate mitigation potential offered by bioenergy without concomitant adverse impacts on socio-economic development.

THE IMPACTS OF BIOENERGY ON EMPLOYMENT

A key argument for public policies aimed at supporting the use of biomass for the production of heat, electricity, and liquid biofuels—apart from climate mitigation and security of supply—has been the notion that it will increase employment and foster rural development. Especially in developed countries, where intensification of agriculture and land abandonment has led to unemployment and outmigration in rural areas, this argument has carried weight.

To understand the impacts increased bioenergy demand has on employment it is instructive to divide it into those resulting directly from the increased biomass utilization and secondary effects arising from market adjustments (*equilibrium effects*). The former includes the labour needed to produce the bioenergy and run bioenergy facilities (*direct effects*), increased employment generated through increased demand for goods and services in the bioenergy supply chain (*indirect effects*), and additional jobs generated by the consumption by those directly and indirectly employed in the bioenergy system (*induced effects*).⁴ These impacts will by definition be positive and can be substantial, especially in rural areas where the primary biomass production takes place.⁵

These positive effects tend, however, to be offset by market equilibrium effects. These occur primarily as increased bioenergy production crowds out other consumption or divert capital, labour, and land away from other uses. To illustrate this point, consider the example of corn ethanol production in the US, which according to some industry estimates would generate 1 000 jobs for each 100 million gallons of production capacity. However, the estimate falls to 250 jobs if one accounts for the fact that the corn demanded for ethanol production will not come from additional production, but partly come from production that would have occurred anyway (and is merely diverted from other consumers) and partly from cropland already in production that is shifted from planting soy to corn.⁶

Four important determinants of the direction and magnitude of the equilibrium effects are (1) the economic competitiveness and (2) the relative labour intensity of a given bioenergy system, and the effect increased bioenergy demand has on (3) rural wages and (4) terms of trade.

4 Domac, J. et al. (2005) Socio-economic drivers in implementing bioenergy projects. *Biomass and Bioenergy* 28(2):97-106.

5 Berndes, G. and Hansson, J. (2007) Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. *Energy Policy* 35(12):5965-5979.

6 Low, S.A. and Isserman, A.M. (2009) Ethanol and the Local Economy: Industry Trends, Location Factors, Economic Impacts, and Risks. *Economic Development Quarterly* 23(1):71-88.

If bioenergy is more costly than its alternatives and is increased through subsidies, this will shift government spending away from more labour intensive consumption (e.g. health, education and other social services), leading to negative employment effects.⁷ The same can be said if costlier bioenergy is introduced through, e.g. mandates, leading to higher energy costs for consumers and reductions real incomes and consumption. If, on the other hand, the bioenergy system in question is profitable, it will lead to overall savings and free up incomes for consumption of other goods, leading to general positive effects on incomes and employment.

Similarly, within the agricultural sector increased bioenergy production will have a negative employment effect if it is relatively land intensive compared to other agricultural production and cropland is scarce, as bioenergy production then will crowd out other more labour intensive production (e.g. livestock production).⁸

The two final factors that will be important in determining the overall employment effect of increased bioenergy demand both relate to the fact that increased demand for bioenergy will push up agricultural commodity prices (an issue we will examine in more detail below). If agricultural wages rise in response to higher profits in agriculture the positive employment effects tend to disappear.⁹ Changes in prices also affect a country's terms-of-trade; if a country is a net exporter of agricultural goods (the price of which is increasing) or if increased bioenergy leads to a reduction of energy imports and an increase in domestic production, employment (and overall welfare effects) tend to be positive.¹⁰

There are two reasons to believe that most bioenergy systems are more likely to generate positive employment effects than other renewable energy technologies (e.g. solar photovoltaics): (1) the fact that many bioenergy technologies are relatively close to being economically competitive (especially at high fossil fuel prices), implying that the effects from crowding out other consumption (whether private or public) will be small, and (2) that the direct jobs created by bioenergy systems to a larger extent are for unskilled labour and in areas where unemployment often is higher.

In line with this, most studies that include the general equilibrium effects on employment still finds positive employment impacts of most bioenergy technologies, albeit smaller than those studies that only include direct and indirect effects.¹¹ However, given the importance of, *inter alia*, costs and labour and land intensity, forestry- and residue-based bioenergy systems are likely to have larger positive impacts given that they do not compete for land resources in the same way as cropland-based bioenergy systems.

7 Trink, T. et al. (2010) Regional economic impacts of biomass based energy service use: A comparison across crops and technologies for East Styria, Austria. *Energy Policy* 38(10):5912-5926.

8 Trink, T. et al. (2010).

9 Trink, T. et al. (2010).

10 Trink, T. et al. (2010); Steininger, K. and Wojan, T. (2011) Economic Impact of Bioenergy Development: Some evidence from Europe and the US. *Eurochoices* 10(3):31-37.

11 Steininger, K. and Wojan, T. (2011).

THE EFFECT OF BIOENERGY DEMAND ON AGRICULTURAL COMMODITY PRICES, POVERTY AND MALNUTRITION

Against a backdrop of nearly three decades of declining or stable food prices, the world saw a sudden and sharp increase in the price of basic agricultural commodities in the years of 2007-2008, ranging from 60% (wheat and corn) to over 120% (rice), see Figure 5.1. Taking the world by surprise, the 2007-2008 food price crisis sparked both public upheavals across the world and an intense—and sometime heated—debate on the role played by biofuel mandates in developed countries.

While the United Nation's special rapporteur on the right to food, Jean Ziegler, went as far as describing the diversion food for the production of biofuel as a “crime against humanity” and calling for a five-year ban on biofuel production, the US and EU tried to downplay the role of biofuels, with the European Commission arguing that its modest use of cereal for the production of ethanol was a “drop in the ocean” and “not something to shake the markets”.¹² And although world prices dropped back to lower levels after 2008 spike, they did so to levels that were higher than those prevailing prior to the crisis, and 2011 again saw increases in agricultural commodity prices and a renewed debate about the role of biofuels in pushing up food prices.

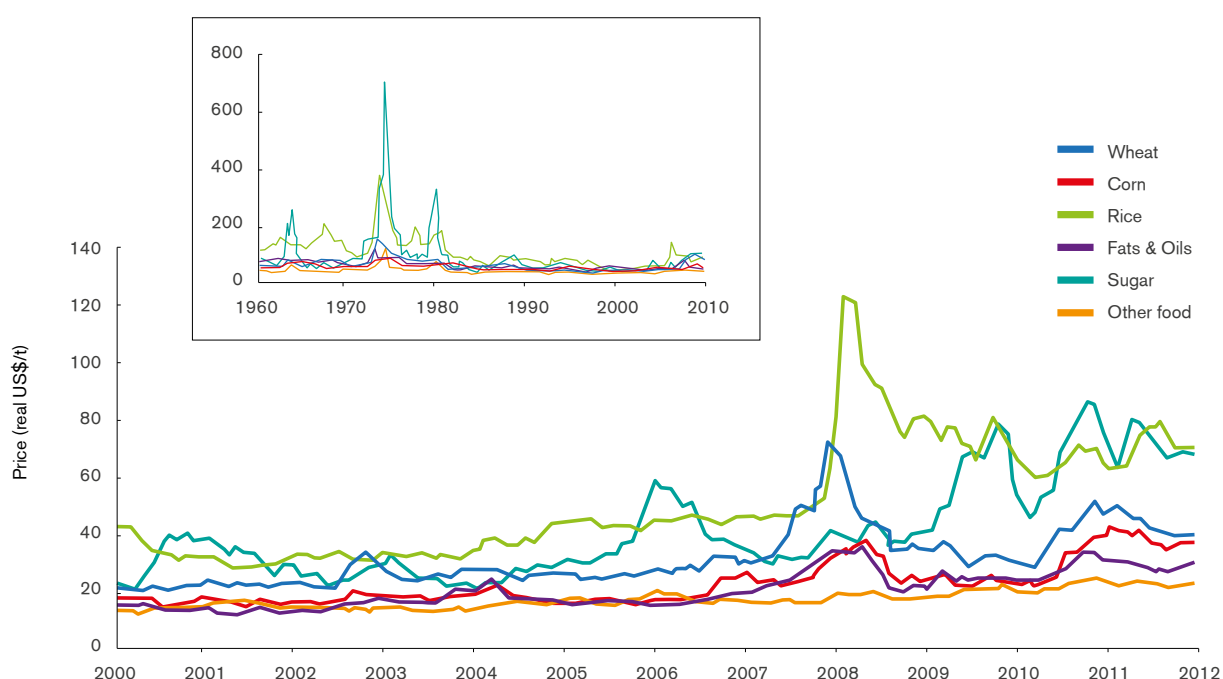


Figure 5.1 Monthly world market prices for major agricultural and food commodities in the period January 2000 to March 2012 (and in the inset from 1960-2012). Source: World Bank (2014)¹³.

Several studies have shown how the increased demand for biofuels has strengthened the integration between energy and agricultural markets, and hence the effect bioenergy demand can have on the latter.¹⁴ The basic mechanism through

¹² Ciaian, P. and Kancs, d.A. (2011) Interdependencies in the energy–bioenergy–food price systems: A cointegration analysis. *Resource and Energy Economics* 33(1):326-348.

¹³ World Bank (2014) *World Bank Commodity Price Data (The Pink Sheet) Historical Data*. Featured product to the World Bank Commodity Market Outlook.

¹⁴ See, e.g. Ciaian, P. and Kancs, d.A. (2011); Tyner, W.E. (2010) The integration of energy and agricultural markets. *Agricultural Economics* 41:193-201.

which this new linkage is established is by competition for arable land; if agricultural land resources were unlimited, increased demand for biofuels would have little effect on food prices. In the biofuels debate it is sometimes argued that the problem is that we use food (e.g. corn or wheat) to produce biofuels, and not non-food feedstocks such as cellulose. However, as long as the production of feedstock requires agricultural land higher demand for biofuels will tend to drive up food prices, whether the actual feedstock can be eaten or not.¹⁵

While the basic causality from increased biofuel use to welfare effects for the world's poor is relatively straightforward—i.e. higher demand for biofuels leads to agricultural land being diverted to produce biofuel feedstock, leading to lower food production and higher food prices, in turn affecting malnutrition and poverty—the are many real world complexities involved in tracing each step in this chain.¹⁶

Starting with the first step, the impact of bioenergy demand on agricultural commodity prices will depend on the responsiveness of supply and demand, such as the possibility to increase cropland area or increase agricultural yields or substitute feedstock crops in consumption.¹⁷ There is a broad consensus that biofuel demand was a major, though not the sole, contributor to the 2007-2008 prices increases¹⁸, with quantitative estimates suggesting that 30-50% of the price spike was due to increased demand for biofuels.¹⁹

Prices increases due to higher biofuel demand can generally be expected to be highest for the crops used directly as biofuel feedstock (e.g. corn and vegetable oils) and in the regions where the increased production of biofuel occurs. The reason for the former is that there is imperfect substitutability both for supply and demand of biofuel feedstocks. For instance, rice production in the US compete relatively little for land with other crops and therefore experience very small increases in price due to increases in demand for corn ethanol.²⁰

The reason for price increases being largest where increased production takes place is that, e.g. trade barriers, transaction and transportation costs imply that prices are not perfectly transmitted to international markets. This could help shelter low- and middle-income countries from price increases due to increased biofuel production in high-income countries (e.g. EU and the US). However, agricultural markets in Latin America and Asia were generally well integrated in world markets even prior to the 2007-2008 food crisis, and although African agricultural markets historically have exhibited less than perfect integration, price transmission from world market prices during the 2007-2008 food crisis was high also in many parts

15 Though, if the yield of second generation feedstocks are higher, this will lessen the competition for land and hence the effect on food prices.

16 Headey, D. and Fan, S. (2008) Anatomy of a crisis: the causes and consequences of surging food prices. *Agricultural Economics* 39:375-391

17 Naylor, R.L. et al. (2008) The ripple effect: biofuels, food security, and the environment. *The Environment* 49(9):30-43.

18 Other important factors identified are declining stock-to-utilization ratios, depreciation of the dollar, rising oil prices, and—in the case of rice—export policies.

19 See a summary of studies in Höglund, J. et. al. (2013) *Biofuels and land use in Sweden – An overview of land use change effects*. Stockholm and Gothenburg, Sweden: f3 The Swedish Knowledge Centre for Renewable Transportation Fuels and Foundation. (Report No 2013:7)

20 Babcock, B.A. (2011) *The Impact of US Biofuel Policies on Agricultural Price Levels and Volatility*. Geneva, Switzerland: International Centre for Trade and Sustainable Development (ICTSD). (Issue Paper No. 35).

of this continent.²¹ Moreover, market integration is higher for widely traded cereals (i.e. wheat, maize, rice)—i.e. exactly the commodities for which prices rose most in 2007-2008—than for locally produced staples (e.g. cassava, plantains, beans), oilseeds, and livestock.

How will developing countries faced with higher world prices for basic agricultural commodities fare? A first indication to the answer to that question is provided by the fact that the majority of low-income countries are net importers of food and have seen deteriorating terms of trade in food up until recently, and would thus most likely stand to lose from further food price increases.²² Despite a downward trend, the FAO still lists 66 countries as low-income and food-deficit (i.e. being net-importers of food), the majority of which are in Africa, see Figure 5.2. Consistent with this most studies analyzing the welfare implications of biofuel mandates have found that low- and middle-income countries experiences losses from higher food prices, with the exception of prospective biofuels exporters such as Brazil and Thailand.²³

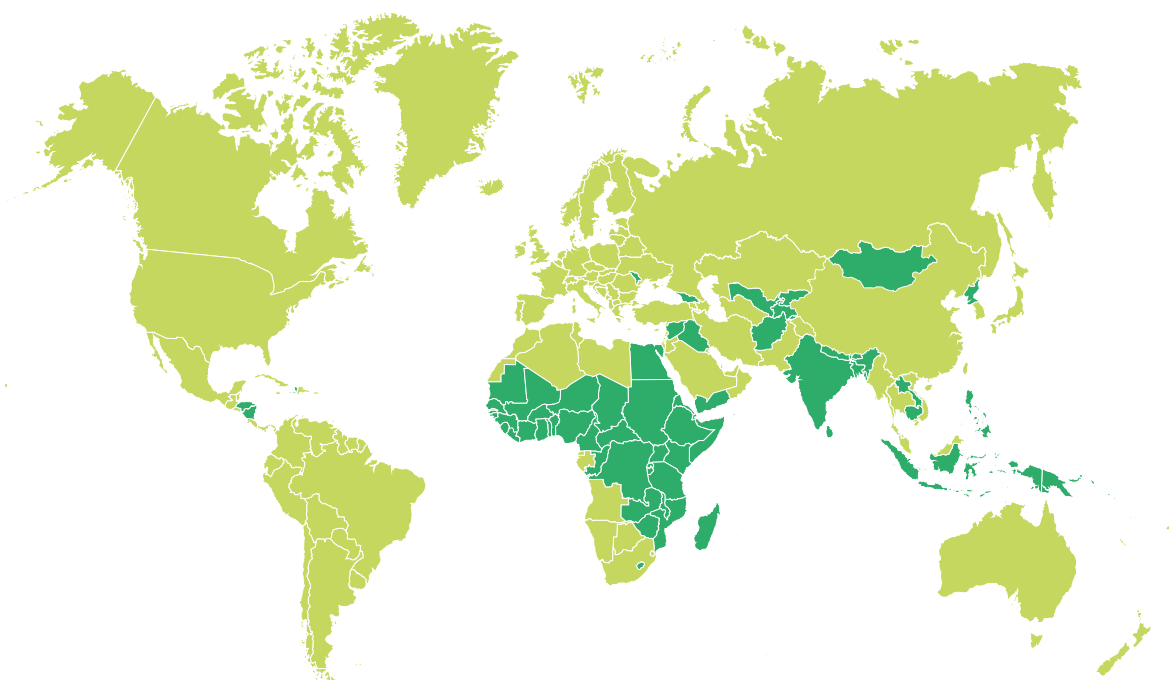


Figure 5.2 Countries in shaded dark are those defined as low-income, food deficit (LIFC). Source: FAO (2012).

And just as countries who are net importers of food will tend to lose from higher prices, so will households in those countries that are net consumers of food. That this is the case for the vast majority of urban households is hardly surprising, but

21 See, e.g., Brown, M.E. et al. (2012) Country and regional staple food price indices for improved identification of food insecurity. *Global Environmental Change* 22(3):784-794.; Minot, N. (2011) *Transmission of World Food Price Changes to Markets in Sub-Saharan Africa*. Washington, D.C., USA: International Food Policy Research Institute (IFPRI).

22 Ng, F. and Aksoy, M.A. (2008) Food price increases and net food importing countries: lessons from the recent past. *Agricultural Economics* 39:443-452.; Schmidhuber, J. (2007) *Biofuels: An emerging threat to Europe's Food Security? Impact of an Increased biomass use on agricultural markets, prices and food security: A longer-term perspective*. Notre Europe.

23 See, e.g., de Hoyos, R.E. and Medvedev, D. (2011) Poverty Effects of Higher Food Prices: A Global Perspective. *Review of Development Economics* 15(3):387-402.; Timilsina, G.R. et al. (2010) *The Impacts of Biofuel Targets on Land-Use Change and Food Supply: A Global CGE Assessment*. Washington, D.C., USA: The World Bank. (Public Research Working Paper 5513).

the fact is that household surveys from developing countries consistently find that the major share of the population even in rural areas are net consumers of food and would lose from higher food prices, at least in the short run.²⁴ In the longer run wages for rural labor and crop yields may increase in response to higher prices, reducing the negative impacts, though the limited empirical evidence there is these effects suggest that they are rather modest.²⁵

There are two reasons why consumers in developing countries are more vulnerable to increases in agricultural commodity prices. The first is that food expenditures make up a larger share of the total household budget in developing countries. For instance, in Sri Lanka and Bangladesh food accounts for over 60% of total consumption; the corresponding figures for Swedish and American households are 13% and 10%, respectively.²⁶ The second is that a larger share of the average food basket in developing countries is made up of basic agricultural commodities (e.g. grains). This implies that a given increase in the price of these commodities will have larger impact on food inflation in developing countries than in high-income countries where the cost for the basic commodities accounts for only 20-35% of the final retail price of food (due to a larger share of processed food whose price is determined to larger extent by other inputs such as wages, energy, transport, and storage).²⁷

Poor households can respond to higher food prices in three main ways: by reducing the amount of food purchased, by switching to cheaper but less nutritious food, and by reducing other consumption, in all cases reducing welfare. Evidence from a number of developing countries collected by the World Food Programme (WFP) during the 2007-2008 food crisis show widespread evidence of reductions in both the quality and quantity of food consumed (having a direct impact on hunger and malnutrition), as well as weak evidence of household coping by reducing expenditures on health and education, or sale of economic assets (having long-term impacts on poverty).²⁸

Different studies have tried to quantify the effect of the 2007-2008 food price hike on poverty, using both simulation models and survey data, most of them indicating that in the order of a 100-200 million people would have been lifted out of poverty and food insecurity if prices had remained stable.²⁹ However, measuring the effect of the food crisis solely in terms of number of people pushed below a given

24 See, e.g., Bryngelsson, D.K. et al. (2012) The effect of food-price movements on African households. *International Journal of Agricultural Resources, Governance and Ecology* 9:121:146.; Jayne, T.S. et al. (2010) Principal Challenges Confronting Smallholder Agriculture in Sub-Saharan Africa. *World Development* 38(10):1384-1398.

25 See, e.g., Ravallion, M. (1990) Rural Welfare Effects of Food Price Changes under Induced Wage Responses: Theory and Evidence for Bangladesh. *Oxford Economic Papers* 42(3):574-585.; Thiele, R. (2003) Price Incentives, Non-price Factors and Agricultural Production in Sub-Saharan Africa: A Cointegration Analysis. *African Development Review* 15(2-3):425-438.

26 OECD/FAO (2008) *OECD-FAO Agricultural Outlook 2008-2017*. Paris, France: OECD Publications.

27 Dewbre, J. et al. (2008) High food commodity prices: will they stay? who will pay? *Agricultural Economics* 39:393-403.

28 Brinkman, H.-J. et al. (2010) High Food Prices and the Global Financial Crisis Have Reduced Access to Nutritious Food and Worsened Nutritional Status and Health. *The Journal of Nutrition* 140(1):153S-161S.

29 de Hoyos, R.E. and Medvedev, D. (2011) Poverty Effects of Higher Food Prices: A Global Perspective. *Review of Development Economics* 15(3):387-402.; B Headey, D. (2011) *Was the Global Food Crisis Really a Crisis? Simulations versus Self-Reporting*. Washington, DC, USA: International Food Policy Research Institute.; Ivanic, M. and Martin, W. (2008) Implications of higher global food prices for poverty in low-income countries. *Agricultural Economics* 39:405-416.; Shapouri, S. et al. (2009) *Food security assessment, 2008-2009*. Washington, D.C., USA: Economic Research Service, United States Department of Agriculture.; Tiwari, S. and Zaman, H. (2010) *The Impact of Economic Shocks on Global Undernourishment*. Washington, D.C., USA: The World Bank.

poverty or hunger threshold reduces the welfare impact to single dimension. For instance, studies also show that higher food prices tend to increase the poverty gap, pushing the already poor deeper into poverty.³⁰ Some also argue that biofuel mandates have contributed to increases in price volatility, which also can have large welfare implications, especially for the poorest.³¹

HIGHER AGRICULTURAL COMMODITY PRICES AND THE GLOBAL RUSH FOR LAND

In the late 19th century USA experienced a boom of land acquisitions as settlements expanded west, fuelled by a newly constructed transcontinental railway and prospects of economic riches, displacing Native American populations and causing author and humorist Mark Twain to famously exclaim “Buy land, they’re not making it anymore!”. In much the same way, the first decade of the 21st century saw a global rush for land, with deals for the outright purchase, lease, or concessions of land in developing countries totalling over 200 million hectares (Mha) worldwide, or close to five times the area of Sweden.³² Over half of this area was in Sub-Saharan Africa.

The increased global demand for bioenergy (primarily biofuels) has contributed to this development, both directly and indirectly. Directly, as the production of biofuel feedstocks accounts for the largest share of land acquisitions—40% of the area for deals where the purpose of the land use is known—see Figure 5.3. Indirectly, as the underlying driver of the land rush has been an expectation that a tightening global market for agricultural commodities—driven by increasing populations, incomes, and biofuels demand—will drive up future returns from arable land. Symptomatically, between October 2008 and August 2009 alone—in the wake of the global food crisis—close to 50 Mha of large-scale land acquisition deals were struck.³³

The changing outlook for agricultural markets has had implications not only for governments that seeks to safeguard the food security of their populations, but also for global agribusiness. Falling agricultural prices throughout much of the 20th century squeezed economic margins in farming and caused agribusiness to focus on upstream (i.e. fertilizer, seeds, machinery) and downstream (i.e. processing and distribution) markets. As higher, and more volatile, agricultural commodity prices have increased the risks for downstream processors and distributors and boosted farm incomes, agribusiness has shifted back to a greater involvement in primary production.³⁴

30 de Hoyos, R.E. and Medvedev, D. (2011) Poverty Effects of Higher Food Prices: A Global Perspective. *Review of Development Economics* 15(3):387-402.; Ivanic, M. and Martin, W. (2008) Implications of higher global food prices for poverty in low-income countries. *Agricultural Economics* 39:405-416.

31 Babcock, B.A. (2011) *The Impact of US Biofuel Policies on Agricultural Price Levels and Volatility*. Geneva, Switzerland: International Centre for Trade and Sustainable Development (ICTSD). (Issue Paper No. 35).; FAO/OECD (2011) *Price Volatility in Food and Agricultural Markets: Policy Responses*. Washington, D.C., USA: The World Bank.

32 Due to the lack of transparency the exact scale of this phenomenon is difficult to gauge. This number, which refers to deals reported in media or research reports and compiled by the Land Matrix project up until November 2011, is likely to be an underestimate. Anseeuw, W. et al. (2012) *Land Rights and the Rush for Land: Findings of the Global Commercial Pressures on Land Research Project*. Rome, Italy: The International Land Coalition.

33 Deininger, K. et al. (2011) *Rising global interest in farmland: Can it yield Sustainable and equitable benefits?* Washington, D.C., USA: The World Bank.

34 Cotula, L. (2012) The international political economy of the global land rush: A critical appraisal of trends, scale, geography and drivers. *Journal of Peasant Studies* 39(3-4):649-680.

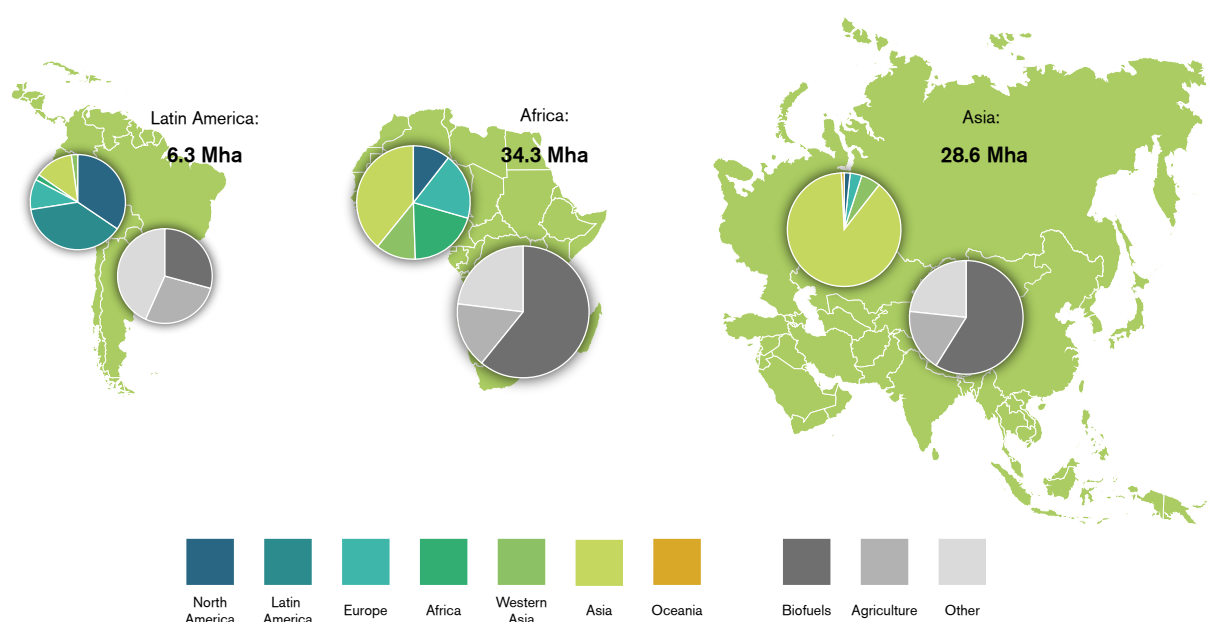


Figure 5.3 Distribution of land acquisitions between different investor regions and between different planned uses of the land (other includes forestry, industry, mining, tourism and other). The data present here pertain to a subset of all reported large-scale land deals, not solely relying on media reports but cross-referenced from different sources. Source: Anseeuw et al. (2012).³⁵

Consequently, while much media attention has focused on large-scale acquisitions by land (or water) scarce countries like South Korea or Saudi Arabia or emerging economies like China and India, reality is more nuanced. Private entities (companies and investment funds) account for the major share of land deals and national elites (politicians, civil servants, local business people) making investments targeted at domestic, rather than export, markets plays an important role (see also Figure 5.3).³⁶

Given the urgent need for investment in agriculture in many developing countries, notably in Sub-Saharan Africa, if well managed these investments presents an opportunity to instigate broad-based rural development by creating employment opportunities, providing smallholders access to technology and markets, and providing funds for public goods (e.g. infrastructure) and social services (through revenues from leasing or selling land, as well as from increased tax revenues).³⁷

However, there is overwhelming evidence that these positive effects have failed to materialise, and instead the recent race for land has lead to widespread loss of access to land and other vital resources (e.g. water and housing) for local

³⁵ Anseeuw, W. et al. (2012) *Land Rights and the Rush for Land: Findings of the Global Commercial Pressures on Land Research Project*. Rome, Italy: The International Land Coalition.

³⁶ Cotula, L. (2012) The international political economy of the global land rush: A critical appraisal of trends, scale, geography and drivers. *Journal of Peasant Studies* 39(3-4):649-680.

³⁷ Deininger, K. et al. (2011) *Rising global interest in farmland: Can it yield Sustainable and equitable benefits?* Washington, D.C., USA: The World Bank.

communities, with insufficient or non-existent compensation, and with women being disproportionately hard hit.³⁸

There are a number of reasons for this. First, acquisitions often claim to target “marginal” or “unused” land, but in reality not much land fits that description and for obvious economic reasons most acquirers have prioritised land that is highly suitable for agriculture (i.e. fertile, well-watered or with good rainfall) with access to infrastructure and consumer markets (see Chapter 4 regarding assessments of potential for biomass production on marginal lands). Even in the cases when such land is not already under cultivation, it is likely to be collectively owned and used by local communities for grazing, hunting, shifting cultivation, harvesting of forest products, or shifting cultivation. Such lands often constitute the major asset of rural communities and its appropriation can have seriously adverse impacts on livelihoods, especially for the poorest households, pastoralists and forest dependent communities.³⁹

Second, many planned investments were not technically viable or investors lacked sufficient expertise, leading to many projects failing or falling far behind schedule. As a consequence “local people had often suffered asset losses but received few or none of the promised benefits”.⁴⁰ In yet other cases, e.g. in Nepal and Uruguay, acquisitions were purely speculative and solely served to fuel land price inflation.⁴¹

Finally, developing country governments were either incapable or unwilling of harnessing the potential positive force of investments to further strategic development plans and instead have offered acquirers land for little or no rent in an ad hoc manner, largely bowing for investor interests.⁴²

The underlying reason why the renewed interest in developing country agriculture has failed to translate into long term investments benefiting rural communities and instead resulting in wholesale land grab can be found in the existing power structure and lack of functioning institutions in many host countries. Weak democratic governance and legislative frameworks at both national and international level that favours investor interests and large-scale commercial agriculture enterprises, has contributed to the neglect of land rights of rural poor and a sidelining of small-holder involvement in agricultural development.⁴³

38 See, e.g. Anseeuw, W. et al. (2012) *Land Rights and the Rush for Land: Findings of the Global Commercial Pressures on Land Research Project*. Rome, Italy: The International Land Coalition.; Deininger, K. et al. (2011) *Rising global interest in farmland: Can it yield Sustainable and equitable benefits?* Washington, D.C., USA: The World Bank.; German, L. et al. (2011) *Contemporary processes of large-scale land acquisition by investors. Case studies from sub-Saharan Africa*. Occasional Paper. Bogor Barat, Indonesia: CIFOR.

39 Anseeuw, W. et al. (2012).

40 Deininger, K. et al. (2011) p. xxxiii.

41 Anseeuw, W. et al. (2012).

42 Anseeuw, W. et al. (2012).; Deininger, K. et al. (2011).

43 Anseeuw, W. et al. (2012).; Deininger, K. et al. (2011).

DISCUSSION

Judging from the above overview of the main socio-economic consequences of expanded use of bioenergy to date, it seems obvious that the scales tip heavily towards the negative side; while positive employment effects have not been as large as anticipated, increases in food prices, and the associated impacts on poverty, malnutrition and the land access for the rural poor, that can be tied to increased bioenergy demand have been substantial. And this as the result of a relatively modest increase in demand for bioenergy; biofuel feedstock production today accounts for roughly one percent of global cropland, but future projections for bioenergy plantations put the figure between 20-60% of global cropland area (see Chapter 4).⁴⁴

Does this mean that we should abandon the endeavour to substitute fossil fuels for biobased energy and raw materials? No, not necessarily. It does, however, have some important implications for how to manage that transition in order to minimise negative socio-economic consequences.

Firstly, as is evident from the discussion in this chapter, the socio-economic consequences from different bioenergy sources and technologies can differ widely. Directing the short-term expansion of biomass use primarily towards the utilization of residues streams from agriculture, forestry, and municipal waste offers a win-win situation as it has been shown to have the largest positive local employment benefits while at the same time avoids the indirect, negative global impacts on poverty, malnutrition, and land rights.

Secondly, while bioenergy has been a major contributor to increased demand for land and the concomitant negative consequences, the other factors (increased populations, income induced diet shifts, other land demands, and a shrinking resource base due to cropland degradation) implies that the negative effects of higher demand and prices for land will not disappear even if we abandoned biomass-based energy and raw materials completely. We still need legislative and institutional reforms that support the rural poor and harness the positive development potential that bioenergy proponents, correctly, have identified could arise from the increasing value of arable land. This implies strengthening the resource rights of rural people (e.g. through legal recognition of land rights, including over common lands), empowerment of smallholder producers (e.g. through contract farming arrangements with land investors), and by making land use decision making more transparent, inclusive and accountable.⁴⁵

Until there is considerable progress on these issues we should be very cautious about expanding the use of land-based biomass for energy and materials. Note that this may entail introducing policies that restrict or discourage the demand for land-based biomass, as higher fossil energy prices in conjunction with pricing of

44 Berndes, G. and Hansson, J. (2007) Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. *Energy Policy* 35(12):5965-5979.

45 Anseeuw, W. et al. (2012) *Land Rights and the Rush for Land: Findings of the Global Commercial Pressures on Land Research Project*. Rome, Italy: The International Land Coalition.; Deininger, K. et al. (2011) *Rising global interest in farmland: Can it yield Sustainable and equitable benefits?* Washington, D.C., USA: The World Bank.; Jayne, T.S. et al. (2010) Principal Challenges Confronting Smallholder Agriculture in Sub-Saharan Africa. *World Development* 38(10):1384-1398.

carbon emissions is poised to make bioenergy increasingly profitable.⁴⁶ The recent reversal of the EU position on the issue of crop-based biofuels is an example of a step in this direction. We also need to consider other options for curbing the global demand for land; for instance by increasing agricultural productivity in many developing countries (closing the yield gap), by reducing food wastage that currently leads to losses of more than a third of global agricultural production, and by shifting diets away from land-intensive meat consumption (e.g. through pricing the greenhouse gas emissions from production).⁴⁷

46 Azar, C. (2011) Biomass for energy: a dream come true... or a nightmare? *Wiley Interdisciplinary Reviews: Climate Change* 2(3):309-323.

47 See, e.g., Foley, J.A. et al. (2011) Solutions for a cultivated planet. *Nature* 478(7369):337-342.; Godfray (2010) Food Security: The Challenge of Feeding 9 Billion People. *Science* 327(5967):812-818.; Wirsenius, S. et al. (2011) Greenhouse gas taxes on animal food products: rationale, tax scheme and climate mitigation effects. *Climatic Change* 108(1):159-184.

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OPPORTUNITIES FOR BIOREFINERIES IN THE PULPING INDUSTRY

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INTRODUCTION

Increased energy and raw material prices along with tougher competition and contracting markets for pulp products have highlighted the need for the pulp industry to enlarge their traditional product portfolio with new value-added products. There is also a strong growing interest from society to replace petroleum-based products with products from renewable sources. The spent cooking liquor in a kraft pulp mill, called black liquor, is today used for electricity and steam production, but it could partly be converted into other valuable products, making use of the chemical structures of complex organic compounds derived from the wood components. Moreover, the cellulose fraction which is currently used for paper products can be used for other purposes, such as production of biofuels or specialty cellulose products. In addition, there are new possibilities to make use of low quality biomass, for example forest residues.

The pulp mills have good prerequisites to become the future biorefineries. Firstly, the scale of the industry means both large volumes of biomass feedstock in large production sites permitting economies of scale. Secondly, some by-product streams, e.g. black liquor, are already partly processed in pulp production and can be more suitable for further refining than wood waste, agro fibres or other natural-fibre feedstock. Biomass is a more complex raw material than petroleum and utilizing partly processed streams permits a very efficient resource use. Thirdly, location of the new industries at the pulp mill means excellent process integration opportunities (access to heat sources and heat sinks, waste and effluent handling, water, general infrastructure and logistics).

The size of the global pulp production implies that only parts of the biomass-containing process streams could be used for production of chemicals and materials, unless the market for the products increases considerably. Nevertheless, the value of these products could be significant (see Chapter 3). In contrast, there is one product category with virtually no demand limit. For electricity and biofuels, the market exceeds the possible production capacity, even if all the biomass currently processed in pulp mills would be used (see Chapter 4, Figure 4.1).

All these factors contribute to a strong driving force to develop pulp mills into biorefineries that convert biomass into a wide range of products. However, how to best balance the selection of outputs and combine different processes is a very complex issue. This chapter, therefore, aims to present possible pulp mill biorefinery pathways and related processes, focusing on the kraft pulp industry, and discusses factors influencing the optimal design of a pulp mill biorefinery.

PULP PRODUCTION

There are two principle ways to produce pulp, by chemical or mechanical separation of the cellulose fibres (see also Chapter 3). In Sweden, for example, about two thirds of the pulp is produced by chemical separation, with the kraft (sulphate) process as the predominant method.¹ This chapter will focus on chemical pulp production, in particular kraft mills, since the opportunities for these mills to be developed into biorefineries are larger than for mechanical mills. The remaining part of chemical pulp production is mainly done using the sulphite process, which has many similarities with the kraft process and therefore also similar opportunities. The production of chemical pulp is dominated by relatively few countries including USA, Canada, Japan, Sweden, Finland and Brazil.

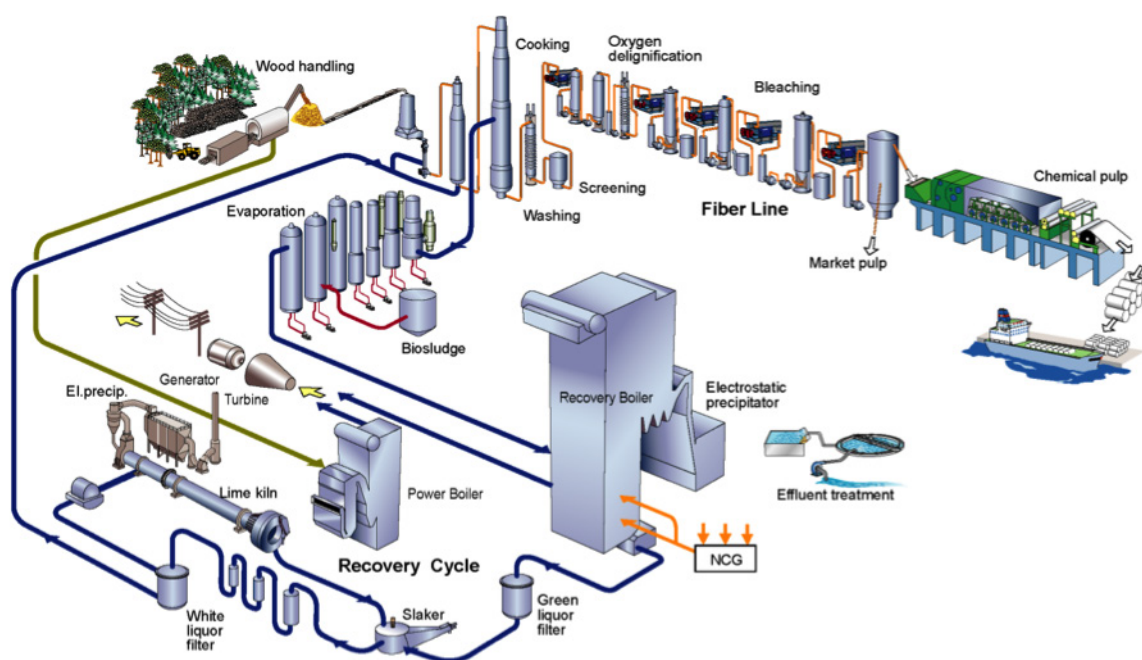


Figure 6.1 Overview of a conventional kraft pulp mill. © 2008 Kvaerner Pulping.

¹ Swedish Forest Industries (2009) *Bruk 2009*. Skogsindustriernas miljödatabas.

Figure 6.1 shows an overview of a conventional kraft pulp mill. After the pulp wood has been debarked and cut into wood chips, it is added to the digester where it is mixed with cooking liquor, known as white liquor, containing the cooking chemicals (NaOH and Na₂S) and water. Cellulose fibres in the wood chips are then separated from lignin (which acts as a glue between the fibres) because lignin reacts with the chemicals in the white liquor. The chemicals and lignin form so called black liquor. The black liquor also contains other substances, mainly hemicellulose (a part of the hemicellulose remains in the pulp however) but also extractives (fat and resinous acids), aliphatic acids and inorganics like Na₂CO₃ and Na₂SO₄. The fibres are separated from the black liquor in a washing step and are then screened and possibly bleached before pulp is obtained. The pulp is either dried and transported to a paper mill (this is called a market pulp mill), or processed further to paper at the mill (called an integrated pulp and paper mill).

The black liquor, which contains large amounts of water, is evaporated before it is burned in a special boiler, called a recovery boiler. In the recovery boiler, combustion of the organic compounds releases heat that is used for production of steam. The remainder of the liquor can be found at the bottom of the boiler in the form of a smelt. The smelt is dissolved to form green liquor, which is sent to the chemical preparation where white liquor for the digester is produced. Thus, the recovery boiler functions both as an energy and chemical recovery unit. In the lime kiln, which is part of the white liquor preparation, fuel oil and natural gas are the most commonly used fuels today.

The steam produced in the recovery boiler is used in a back-pressure steam turbine for electricity generation. The steam is then used to satisfy the heating requirements in the pulping process, such as in the digestion, evaporation and drying stages. In cases where the steam from the recovery boiler is not sufficient to satisfy the mill steam demand, an additional boiler is used to produce steam for the back-pressure turbine. The fuel in this boiler is often bark from the debarking of the logs, possibly supplemented by purchased forest residues, fuel oil or natural gas. A surplus of steam can also occur, that is, more steam is produced by the recovery boiler than is needed at the mill. This steam could for example be used to produce additional electricity in a condensing steam turbine. A surplus of electricity from the mill could be exported to the grid. If located within reasonable distance from a district heating network, excess steam or heat from the mill could also be used to supply district heating demand (see Chapter 11). Several mills also produce tall oil, which is derived from extractives in the black liquor and can be separated into different fractions that can be used as fuel or be further processed to other products.

BIOREFINERY TECHNOLOGIES IN THE PULPING INDUSTRY

In a sense, biorefineries already exist. From the description in the previous section it is apparent that conventional kraft pulp mills can be regarded as biorefineries, since, apart from the pulp, electricity and possibly district heating and chemicals from tall oil are produced. In addition, implementing non-conventional alternative biorefinery concepts in pulp mills is not a new subject. Already in the 1940s attempts were made to produce pure lignin from pulp mills.²

2 Tomlinson G.H. and Tomlinson G.H. Jr. (1946) *Method for treating lignocellulosic material*. US Patent, US 2406867.

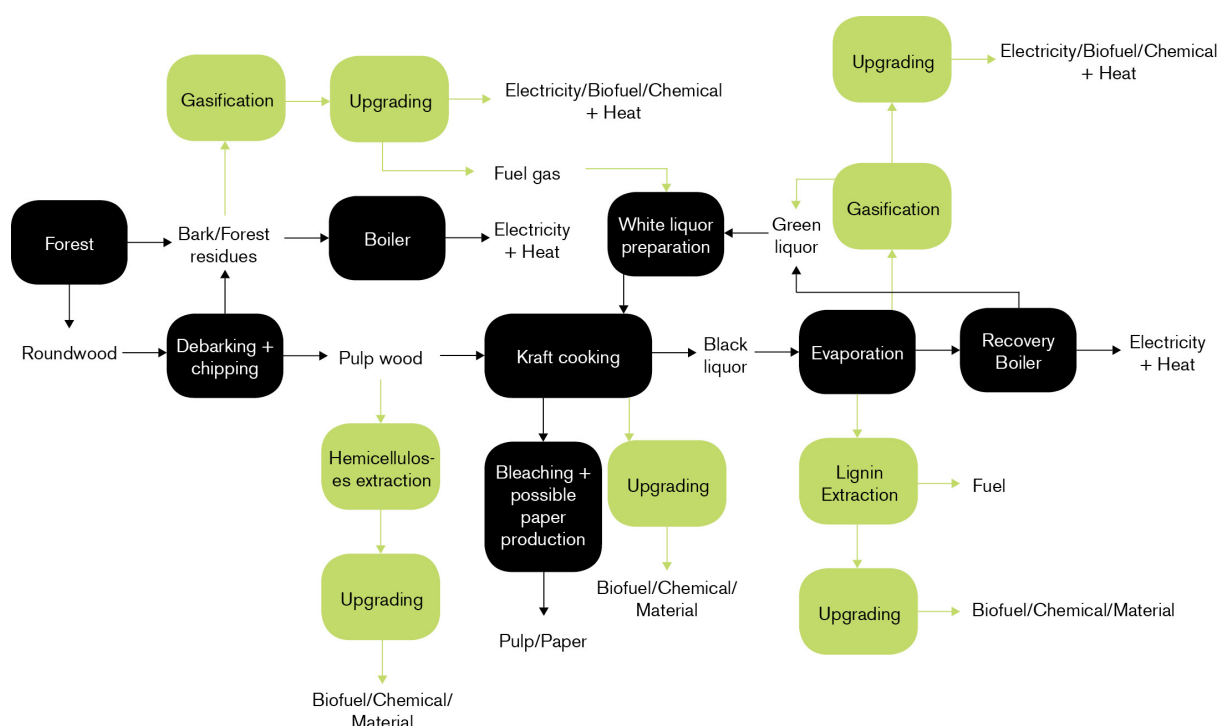


Figure 6.2 Example of biorefinery concepts and products (green process units) that could be implemented at a kraft pulp mill (conventional process units are black).

In Sweden, Domsjö Fabriker in Örnsköldsvik, owned by Aditya Birla Group, is an example of a mill that has taken steps towards a more complex biorefinery. It has a sulphite-based process and produces specialty cellulose (used e.g. as textile), ethanol, lignin, carbonic acid and biogas. Another example of an existing biorefinery is Borregards facility in Sarpsborg in Norway. It has also a sulphite-based process and produces specialty cellulose used e.g. in celluloses ethers. It is also a leading global supplier of lignin-based binding and dispersing agents. Other products from Borregard are vanillin and fine chemicals for the pharmaceutical industry.

Figure 6.2 gives an overview with examples of possible kraft pulp mill biorefinery concepts and end-products. Pulping biorefineries can be categorised in different ways, for example with respect to end-product, i.e. energy, materials or chemicals, or with respect to processes, where one mainly can see two pathways; thermo-chemical processes and processes for separation and refining (often bio-chemical processes). Another important distinction is between processes that are based on process streams from the kraft process, e.g. extraction of hemicelluloses from the wood, lignin from the black liquor and gasification of black liquor, and processes that could be integrated to a pulp mill, for example gasification of solid biomass or other types of biomass upgrading such as torrefaction and pyrolysis, using forest residues or falling bark from the mill (see also Chapter 2). In the following sections we will take a closer look at some of these options.

In addition to processes and products included in Figure 6.2, there are other examples of biorefinery concepts that could be implemented at pulp mills, such as separation and refining of extractives from wood and bark for production of

tailored polymers, coating agents, antioxidants, etc. Another interesting future opportunity for pulp and paper mills is CO₂ capture and storage (see Chapter 7). It could potentially contribute to large reductions of CO₂ emissions as well as high profits for large mills at future high costs for CO₂ emissions.³

HEMICELLULOSES EXTRACTION

Hemicelluloses consist mainly of macro-molecular sugars with different characteristics, such as glucuronoxylans and galactoglucomannans oligomers, from which a wide range of value-added products can be produced, e.g. ethanol, butanol, xylitol, lactic acid, fiber additives and hydrogels (see Chapter 3 for more information about e.g. ethanol, xylitol and lactic acid).

In a conventional kraft mill, most of the hemicelluloses end up in the black liquor. Hemicelluloses can be extracted from black liquor via different methods such as heat treatment, ultrafiltration and a combination of ultrafiltration and nano-filtration. Extraction of hemicellulose from black liquor has caught the interest in particular when lignin extraction from black liquor is targeted, because a lower content of hemicelluloses in the black liquor would facilitate the extraction of lignin as well as increase the purity of final lignin product, e.g. less ash content in separated lignin.^{4,5}

The hemicelluloses could also partially be extracted prior to pulping (Figure 6.2). In dissolving pulp processes, hemicelluloses should be removed prior to pulping since a pure cellulose-based product is to be produced (these processes will be discussed in a coming section).⁶ There has also been an interest in extracting hemicellulose prior to pulp production in kraft pulp mills and thermomechanical pulp mills.⁷ Several hemicelluloses pre-extraction methods can be found in the literature e.g. dilute acid hydrolysis, steam explosion, hot-water extraction, pre-extraction using organic solvents, alkaline extraction and near-neutral extraction using green liquor as extracting solvent. These methods differ in extraction yield, chemicals used and steam demand and in to what extent they affect the quality and quantity of the pulp.

LIGNIN EXTRACTION

Extracted lignin from the black liquor can be used either within the mill, e.g. by replacing fossil fuel oil in the lime kiln, or externally e.g. in CHP plants. Lignin can also be used as a raw material for the production of chemicals and materials, e.g. carbon fibers, activated carbon or phenols.

3 Hektor E. (2008) *Post-combustion CO₂ capture in kraft pulp and paper mills – Technical, economic and systems aspects*. Doctoral thesis, Chalmers University of Technology.; Jönsson, J., and Berntsson, T. (2012) Analysing the potential for implementation of CCS within the European pulp and paper industry. *Energy* 44(1):641-648.; Pettersson, K. (2011) *Black Liquor Gasification-Based Biorefineries – Determining Factors for Economic Performance and CO₂ Emission Balances*. Doctoral Thesis, Chalmers University of Technology.

4 Wallmo H. et al. (2009) The influence of hemicelluloses during the precipitation of lignin in kraft black liquor. *Nordic Pulp & Paper Res. J.* 24(2):165-171.

5 Lundqvist F. et al (2009) Separation of lignin and hemicelluloses from alkaline process liquors. In *Proceedings of NWBC*, Helsinki, Finland, Sep. 2-4.

6 Liu Z. et al. (2011) Application of hemicelluloses precipitated via ethanol treatment of pre-hydrolysis liquor in high-yield pulp. *Bioresource Technology* 102 (20):9613-9618.

7 Bilek, E.M. et al. (2011) Evaluation of a value prior to pulping - thermomechanical pulp business concept, part 2. *TAPPI Journal* 10(5):31- 38.

When lignin is extracted, the steam production in the recovery boiler decreases due to reduction of organic content in the black liquor. In many pulp mills the recovery boiler is the bottleneck when an increase in the production capacity is planned. Lignin extraction can therefore remove the need for increased recovery boiler capacity (so called “debottlenecking”). This can also be accomplished by extraction of hemicelluloses (see previous section), however not to the same extent, because lignin is the main organic component in the black liquor and it has a higher heating value. However, there is a limit to how much lignin that can be extracted without affecting the combustion properties in the recovery boiler.

A commercially available technology for lignin extraction is LignoBoost, developed by Chalmers University of Technology and Innventia AB and today owned by Metso. The technology is based on addition of CO₂ to a black liquor side stream that is diverted from the evaporation plant, which results in lignin precipitation. The precipitated lignin is then filtered and washed.⁸

GASIFICATION OF BLACK LIQUOR

Black liquor gasification (BLG) is currently being developed as an alternative technology for energy and chemical recovery. In the gasification process the main fraction of the organic content in the black liquor is converted to a synthesis gas (syngas) and the pulping chemicals are recovered and returned to the pulping process, similar to the recovery boiler process. The syngas can be used as a feedstock for production of biofuels such as DME (dimethyl ether), methanol, FT (Fisher-Tropsch) fuels or hydrogen, or as a fuel for electricity generation in a combined cycle cogeneration unit (see Chapter 2 for a general description of gasification processes). Several BLG technologies have been under development during the past 30 years. In recent years, the major developer of BLG technology has been the Swedish company Chemrec. Their technology is based on pressurised, high-temperature (950-1000°C), oxygen-blown, entrained-flow gasification.⁹ (See Chapter 12 for a discussion on prerequisites for a future development of this and other gasification technologies in Europe.)

Replacing the recovery boiler with a BLG plant will change the mill's energy balance. Excess heat at suitable temperature levels from the BLG plant can be used to generate steam. Some steam is used internally at the BLG plant, but there is a significant surplus that can be used in the mill processes. However, it should be noted that less steam is produced compared to the conventional recovery boiler powerhouse configuration, since either motor fuels or more electricity are produced in the case of BLG. Even highly energy-efficient market pulp mills will have a significant need for external wood fuel if black liquor gasification with motor fuel production is to be implemented.¹⁰

ALTERNATIVE PRODUCTS FROM CELLULOSE

8 FRAM (2005) *FRAM Final report Application area: Model mills and system analysis*. Stockholm, Sweden: STFIPackforsk, (FRAM Report No 70)

9 See e.g. Chemrec (2011) and Ekbohm T et al (2005) *Black Liquor Gasification with Motor Fuel Production – BLGMF II*. Stockholm, Sweden: Nykomb Synergetics. (P21384-1)

10 Pettersson, K. (2011) *Black Liquor Gasification-Based Biorefineries – Determining Factors for Economic Performance and CO₂ Emission Balances*. Doctoral Thesis, Chalmers University of Technology.

Changed consumers' habits, resulting in lowered consumption of paper, along with a growing market for other high-value products from the cellulose, makes it interesting for kraft pulp mills to partly, or fully, convert their production to e.g. dissolving pulp. As it has been mentioned, in dissolving pulp production hemicelluloses are removed prior to cooking. There are two chemical processes for production of dissolving pulp, the modified sulfite process and the pre-hydrolysis kraft process. The dissolving pulp is currently used either for specialty products, e.g. rayon yarn for industrial products such as tire cord or for viscose staple fibers, e.g. rayon for textile and disposable wipes (see also Chapter 3).

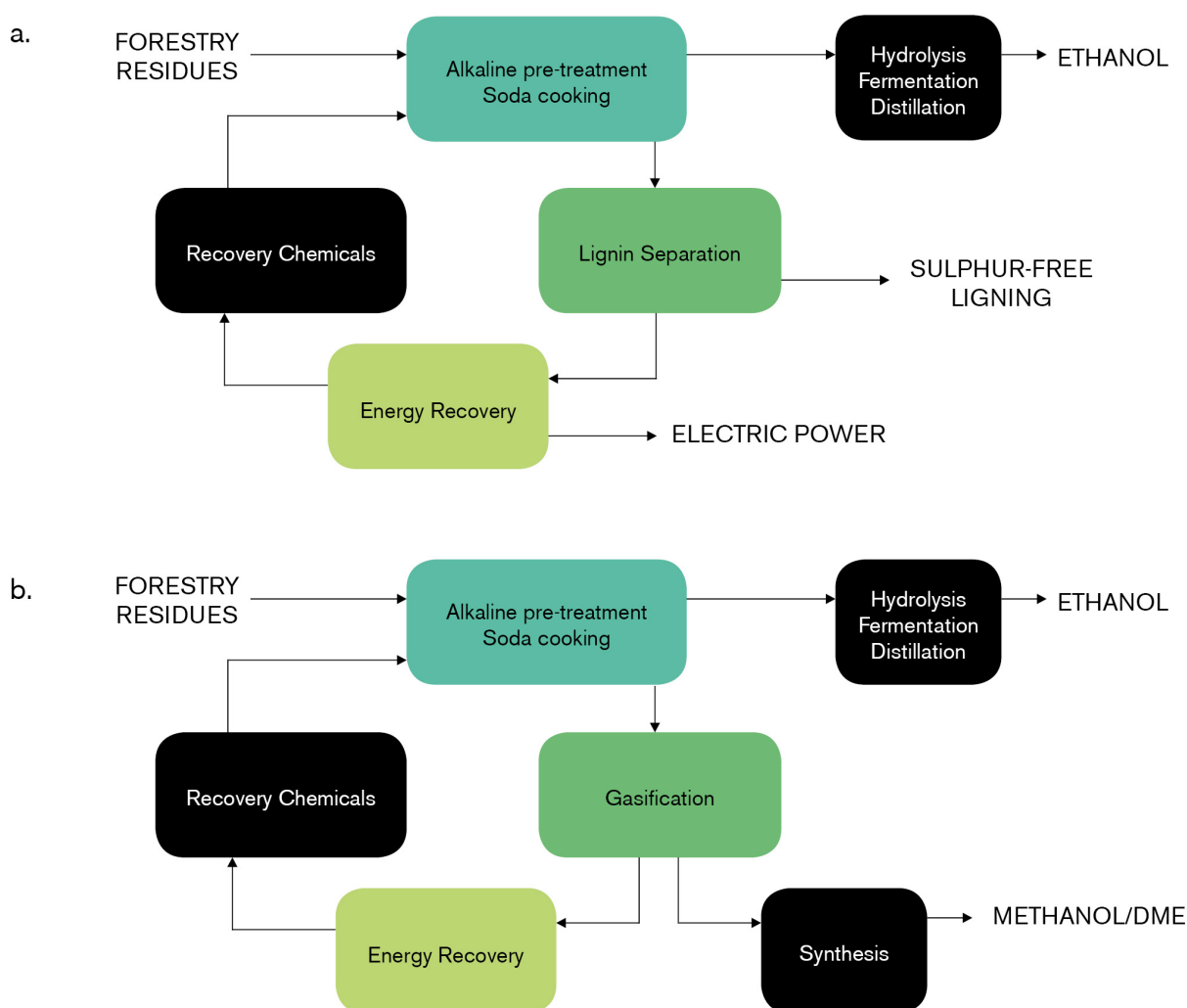


Figure 6.3 Conceptual designs of a pulp mill converted to an ethanol production plant. (a) – Option with lignin separation and (b) – Option with methanol/DME production. The black liquor could of course also go directly to the recovery boiler. Source: Olm L. et al (2007). Ethanol from Swedish wood raw material by simplified alkline cooking process. STFI-Packforsk report no. 291, August 2007.

Converting an existing pulp mill or one of the fibre lines, to an ethanol production plant is another alternative for utilizing cellulose. The ethanol production plant may have a potential of enabling largescale production of ethanol with relatively low investment costs as many of the process units required for ethanol production already exist in a kraft pulp mill.¹¹ A process suitable for integration in a pulp mill

¹¹ Jansson, M. et al. (2010) Second-generation ethanol through alkaline fractionation of pine and aspen wood. *Cellulose Chem. Technol.* 44(1-3):47-52.

is alkaline and sulphur-free pretreatment of lignocellulosic material.¹² The process starts with rather pure cellulose in the hydrolysis stage, which makes it unique from other processes that aim to produce ethanol from lignocellulose. Figure 6.3 suggests two conceptual designs for a pulp mill converted to an ethanol production plant.

ENERGY COMBINES

Another type of biorefinery, not directly utilizing the process streams from the kraft process, can be created when a mill and another consumer, or producer, of heat are integrated to achieve synergistic effects such as heat cascading. This can be called an “energy combine” (or e.g. industrial symbiosis as mentioned in Chapter 2). In this concept, mills with a heat surplus can be integrated with processes such as lignocellulosic ethanol production¹³ or different types of biomass upgrading, for example drying, torrefaction or pyrolysis that require heat (see Chapter 2). For mills with a heat deficit, integration with for example solid biomass gasification with production of motor fuels and/or electricity, which in total has a heat surplus, could be an option.

Since there is a substantial heat surplus from gasification processes, integration with other industrial processes or district heating systems can improve both the economic performance and the GHG emission balances of the process (see Chapter 11). There are a limited number of heat sinks that are large enough and that are able to accept excess heat all year round. In countries like Sweden and Finland, the pulp and paper industry constitutes a significant integration potential for solid biomass gasification concepts (see also Chapter 12 for a discussion on the potential for integration in the Nordic countries in relation to the size of the European fuel markets).

FACTORS INFLUENCING THE OPTIMAL DESIGN OF A PULPING BIOREFINERY

What is the optimal design of a biorefinery in the pulping industry? The optimal design of a pulp mill biorefinery is dependent on a number of characteristics of the mill such as type of mill, steam (heat) balance, size, need for investments, available investment capital, and geographical location. It also depends on a range of external factors such as prices of energy carriers, chemicals and materials and the presence of policy instruments. In order to discuss the different process options presented in this chapter in relation to these factors, the presented processes are summarised, structured and commented further in Table 6.1. Table 6.1 also includes the level of investment and operating and maintenance costs for the different processes, as well as examples of possible contributions of the processes in a Swedish perspective. Ethanol is used as an example of a potential alternative product derived from the cellulose fraction instead of pulp. Since energy combines do not refer to a specific process, they are not included in Table 6.1.

¹² von Schenck A. et al (2011) Ethanol from Nordic wood raw material by alkaline simplified sodacooking pretreatment. In *Proceedings of the XIX International Symposium on Alcohol Fuels - ISAF*. Verona, Italy, Oct. 10-14.

¹³ As described in the previous section, where one of the pulp lines can be converted for ethanol production using the existing process equipment, but also exchanging heat with the remaining pulp lines, or integration of other types of lignocellulosic ethanol production that only exchanges heat with the pulp mill processes.

The *type of mill* is the main factor influencing its *steam balance*, which determines the applicability and performance of different biorefinery concepts. For example, as discussed, implementation of solid biomass gasification is suitable at mills with a steam deficit, while torrefaction is suitable to implement at mills with a steam surplus.

The energy efficiency of pulp mills is increasing and already today many market pulp mills have a steam surplus. In the future, the steam surplus is expected to increase further, making it possible to e.g. extract large amounts of lignin or hemicelluloses without creating a steam deficit and making the plant dependent on external fuel. However, at integrated pulp and paper mills the steam surplus will be small or non-existent, even at future mills with higher energy efficiency. Thus, implementation of biorefinery concepts that partly utilise the organic content in the black liquor will create a steam deficit, or increase the existing steam deficit, and thus increase the need for external fuel, e.g. wood fuel, at the mill.

Consequently the profitability of an investment in e.g. lignin extraction in market pulp mills and in integrated pulp and paper mills depends on the development on two different energy markets (compare the discussion on reference systems in Chapter 10). At the market mills the electricity price is influencing the profitability (assuming that the alternative use of existing steam surplus is electricity production) while at integrated mills the wood fuel price is influencing the profitability (assuming that the steam deficit is covered by a conventional biomass CHP plant).¹⁴

Previous studies show that the economic performance, as well as the potential to reduce global CO₂ emissions, is generally better for biorefinery processes such as lignin extraction and black liquor gasification at mills with a significant steam surplus.¹⁵ This emphasises the importance of considering different steam saving measures such as increased heat integration and investments in new energy-efficient equipment at a pulp mill. The lower steam demand a mill has, the greater the part of the organic content in the black liquor can be used for production of more valuable products instead of steam (assuming constant usage of external wood fuel). For example, lowering the steam demand at a market pulp mill enables the mill to extract more lignin or hemicelluloses without making the mill dependent on external wood fuel. Several studies have shown that these types of energy efficiency measures generally are both profitable and lead to decreased global GHG emissions.¹⁶

The influence on the steam balance of producing other products than pulp from the cellulose is dependent on the type of product produced. Ethanol production, for example, leads to slightly lower steam usage, as indicated in Table 6.1. Another important factor influencing the steam balance, not just for the cellulose-based processes but also for the other biorefinery concepts described here, is how much

14 In the latter case the electricity production is practically unaffected, since the decreased electricity production in the recovery boiler's steam turbine is compensated by the electricity production in the biomass CHP.

15 See e.g. Pettersson, K. (2011) *Black Liquor Gasification-Based Biorefineries – Determining Factors for Economic Performance and CO₂ Emission Balances*. Doctoral Thesis, Chalmers University of Technology.

16 See e.g. Jönsson J and Algehed J (2010) Pathways to a sustainable European kraft pulp industry: Trade-offs between economy and CO₂ emissions for different technologies and system solutions. *Applied Thermal Engineering* 30(16):2315-2325.

of the refining that takes place at the mill. Extracted lignin, for example, could be sold directly to replace oil as a feedstock in an industrial process located elsewhere or be refined to products such as carbon fibers or phenols at the mill. As mentioned above, the mill could provide excellent integration opportunities regarding for example heat exchanging and general infrastructure and logistics.

Generally, most processes benefit, to some extent, from economies of scale. Therefore, the size of the mills and its streams such as raw material, black liquor and steam surplus or deficit influence the specific investment cost of biorefinery concepts. For example, the minimum capacity of gasification plants in order to be competitive is about 200 MW of fuel input (corresponding to 6 PJ, or 2 TWh, per year).¹⁷ Thus, the steam deficit of a mill has to be of a certain size if integration with solid biomass gasification is to be considered. Studies indicate that the size of a possible ethanol production plant using extracted hemicelluloses as feedstock is too small to be economically feasible at a normally sized mill.¹⁸ However, the upgrading of the hemicelluloses to specific chemicals and materials with higher market value can make an operation economically feasible also at lower volumes. There is also a possibility to refine a stream to intermediate products at the mill, which are sent to a larger plant elsewhere. One example could be to produce FT liquor from gasified black liquor at the mill and then sent it to an oil refinery for final upgrading to diesel and gasoline.

The mill's need for investments is also an important factor. For example, the recovery boiler has to have reached the end of its technical lifetime before it makes economic sense to consider implementation of full-scale BLG plants. As has been discussed, investment in lignin extraction, or to some extent hemicelluloses extraction, is a way to "debottleneck" the recovery boiler when increasing the production capacity at a mill. A smaller BLG plant could also be an option for this. Previous studies show that both investment in lignin extraction or a small BLG plant are more cost-efficient ways to achieve a capacity increase than rebuilding the existing recovery boiler.¹⁹

The extent to which a biorefinery process is a part of the actual pulping process is also a factor that will determine the desirability of implementation, i.e. if an interruption of a novel process will interrupt the pulp production? Black liquor gasification is maybe the technology with the highest level of integration with the pulping process. It needs to continuously process pulping chemicals to provide the mill with green liquor. This makes heavy demands on the technology when it comes to achieving stable and continues operation, which is currently the greatest challenge for BLG technology development.

In principal, several different biorefinery concepts could be combined. For example, a mill can extract hemicelluloses from the wood and lignin from the black

17 McKeough P and Kurkela E (2008) *Process evaluations and designs in the UCG project 2004-2007*. Espoo, Finland: VTT Technical Research Centre of Finland. (VTT RESEARCH NOTES 2434)

18 Frederick et al. (2008) Co-production of ethanol and cellulose fiber from Southern Pine: A technical and economic assessment. *Biomass and Bioenergy* 32:1293-1302.

19 See e.g. Jönsson, J. et al. (2012) Comparison of options for debottlenecking the recovery boiler at kraft pulp mills – Economic performance and CO₂ emissions. *Proceedings of ECOS 2012 – The 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. Perugia, Italy, Jun. 26-29.

liquor, gasify the black liquor and at the same time also gasify solid biomass in order to maintain the steam balance. However, one can question whether it is realistic for a mill to implement several new processes, at least in a short-term perspective. In addition, the steam deficit and thus also the need for additional wood fuel could become very large. One also has to consider economies of scale, where for example the black liquor gasification plant would have a much smaller size if hemicelluloses and lignin are extracted and thus also a higher specific investment cost. However, there are processes that can benefit from being combined. For example, as mentioned earlier, studies indicate that extraction of hemicelluloses makes it easier to extract lignin. The amount of available investment capital is often also limited, and mills cannot make all desired, i.e. profitable, investments; they have to prioritise. The level of the investment costs for the different biorefinery concepts are indicated in Table 6.1. The level varies from relatively low to very high. (See also Chapter 12 for a discussion on technical and market risks associated with such investments.)

The *geographical location* of the mill is an important factor affecting the possibilities for implementation of different biorefinery concepts as it influences access to forest biomass, availability of infrastructures and distance to markets of final and intermediate goods (see Chapter 8).

The development of *prices* of different energy carriers (wood fuel, electricity, heat, motor fuels, etc.), chemicals and materials, and the presence of different policy instruments promoting production of renewable alternatives or policy instruments that put a price on CO₂ emissions, will to a large extent determine the future economic performance, and indirectly, the CO₂ emission balances of different biorefineries.

To give an idea of what impact the different biorefinery configurations may have on the energy system, their potential contributions in Sweden are given in Table 6.1. For example, the possible contribution from black liquor gasification is large compared to the potential of hemicellulose and lignin extraction. However, this is related to how much raw material (black liquor) the technology uses, and thus also to how much less steam that is produced.

In Table 6.1 it has been assumed that extracted hemicelluloses and lignin, as well as the cellulose, are used for energy purposes. This has been done in order to facilitate a comparison with biofuels produced via black liquor gasification. In addition, data concerning possible upgrading of hemicelluloses and lignin to different chemicals or materials are very scarce. Some chemicals and materials could have a much higher market value but also a much smaller market size (e.g. lignin-based carbon fibres), than energy commodities (Chapter 3). In some cases implementation of a technology in one mill might be enough to satisfy the entire world market. This could lead to a situation where different mills specialise on different products, in contrast to today's situation where most kraft pulp mills are quite similar.

There are large uncertainties regarding future prices of energy carriers and policy instruments promoting production of renewable energy commodities such as electricity and motor fuels. Therefore, it is difficult to estimate the future profitability

of, for example, black liquor gasification (see Chapter 12 and Figure 12.3). When it comes to estimation of the future profitability of extraction and further upgrading of lignin or hemicelluloses to chemicals or materials, the uncertainties are even higher. This is both due to the uncertainty regarding which products could be produced and the markets for them, but also the uncertainty regarding if there will be any policy instruments promoting production of biomass-based chemicals or materials. Today, only policy instruments for biomass-based energy products, not biomass-based chemicals and materials, exist. Since there are such large uncertainties regarding future prices and policy instruments, it is critical that technology assessments that compare different biorefinery concepts show the economic performance under different future conditions that include different levels of prices and policy instruments (see also Chapter 1 for a discussion on changing system contexts).

Finally it should be emphasised that neither production of biofuels via black liquor gasification, nor production of materials and chemicals from extracted lignin or hemicelluloses are yet fully developed and commercial processes. Technical uncertainties still make it unclear when different biorefinery alternatives could be realised on a commercial scale.

Table 6.1 Characteristics of different pulping biorefinery technologies.

Pulping biorefinery technology	Examples of products	Main influences on existing process ¹	Example of potential energy contribution in Sweden ²	Economic aspects	Technology development status and challenges	Additional comments
Hemicelluloses extraction	Ethanol, butanol, acetic acid, xylitol, fiber additives, hydrogels	-Decreased electricity and steam production in the recovery boiler	-Ca 7 PJ (2 TWh) ethanol/year ^{3,4} -Represents ca 2 % of the Swedish motor fuel use -Will result in lower electricity production and increased use of wood fuel	-Low investment cost for the extraction process -Low/medium operating and maintenance costs for the extraction process -The total investment and operating and maintenance costs depends on the downstream processing of the extracted hemicelluloses	-Extraction prior to dissolving pulp production is commercialized and implemented -Extraction prior to kraft pulping is under development -The main challenge is to minimize the impact on the quality and quantity of the pulp -Several processes for upgrading the extracted hemicelluloses are under development	-Releasing capacity in the recovery boiler, thus enabling a mill capacity increase -Studies indicate that the scale of a possible ethanol production plant will be too small to be economically competitive (assuming Scandinavian sized mills) -Extraction of hemicelluloses makes it easier to extract a more pure lignin product
Lignin extraction	Fuel, carbon fibres, activated carbon, phenols	-Decreased electricity and steam production in the recovery boiler	-Ca 30 PJ (8 TWh) lignin/year -Represents ca 30 % of the Swedish fuel oil use -Will result in lower electricity production and increased use of wood fuel ⁵	-Low/medium investment cost for the extraction process -Medium operating and maintenance costs for the extraction process -The total investment and operating and maintenance costs depend on the downstream processing of the extracted lignin	-There is a commercial technology available for lignin extraction -Several processes for upgrading the extracted lignin are under development -A demonstration plant exists for the LignoBoost technology and the EU has approved a 90 MSEK R&D grant awarded by the Swedish Energy Agency towards the industrial scale demonstration plant	-Releasing capacity in the recovery boiler, thus enabling a mill capacity increase -Some lignin extraction processes require CO ₂ and they could therefore be interesting to combine with separation of CO ₂ from flue gases or from the lime kiln
Black liquor gasification	Methanol, DME, FTD, hydrogen, electricity	-Replaces existing system for energy and chemical recovery -Biofuels: decreased electricity and steam production -Electricity: increased electricity and decreased steam production -Increased lime kiln load, thus increased need for lime kiln fuel	-Ca 70 PJ (20 TWh) methanol/year -Represents ca 25 % of the Swedish motor fuel use -Will result in lower electricity production and increased use of wood fuel	Biofuels: -Very high investment cost -Medium operating and maintenance costs Electricity: -High investment cost -Medium operating and maintenance costs	-The technology is under development -Production of fuels from syngas are commercial processes, however not for biomass based syngas -The main challenge is to show that the technology can achieve stable and continuous operation -A development plant exists for the Chemrec technology and the EU has approved a 500 MSEK R&D grant awarded by the Swedish Energy Agency towards the industrial scale demonstration plant	-Enables increased pulp yield -The recovery boiler has to be in the end of its technical lifetime in order for a full-scale BLG plant to be implemented -BLG is a part of the existing process to a larger extent than extraction of lignin and hemicelluloses, required to continuously process pulping chemicals and provide the mill with green liquor -When producing biofuels from the syngas, CO ₂ is separated as part of the process -Investment in a smaller BLG unit (working in parallel with the recovery boiler) enables a mill capacity increase
Ethanol production	Ethanol	-Ethanol production instead of pulp production (partly or fully converted mill) -Usage of raw material of lower quality and a lower price than wood for the pulp process -Decreased steam use	-Ca 55 PJ (15 TWh) ethanol/year ⁶ -Represents ca 15 % of the Swedish motor fuel use -Will be produced on the expense kraft pulp ⁷	-Low/medium investment cost -Medium operating and maintenance costs	-Already established technology from the soda pulping process and the first generation ethanol production -Low theoretical yield of ethanol from lignocellulosic biomass so the lignin must give a valuable contribution as a by product	-Possible to extract sulphur-free lignin -A stream of almost pure CO ₂ is produced in the ethanol fermentation step, that could e.g. be used if lignin is extracted

¹ The influences for the hemicelluloses extraction and the lignin extraction are the influences resulting from only the extraction processes, not from possible following upgrading of the extracted material.

² Assuming full implementation at all Swedish kraft pulp mills (market kraft pulp mills and integrated kraft pulp and paper mills).

³ Acetic acid is produced in almost the same quantities as ethanol, and also with a higher market value.

⁴ If the kraft pulp mills are converted for production of dissolving pulp, about three times more hemicelluloses can potentially be extracted.

⁵ If lignin is assumed to be used as a fuel, it makes no sense to extract lignin from a mill without a steam surplus, since this has to be compensated by increased use of wood fuel, excepted to have the same price as the extracted lignin.

⁶ Can also contribute to increased extraction of lignin or increased electricity production, since the steam use decrease when the pulp production is changed to ethanol production.

⁷ It is of course not realistic that all kraft pulp mills should be converted to ethanol production plants, this is however just to give an idea about the possible contribution of the biorefinery technology.

CONCLUDING REMARKS

With increasing energy and raw material prices, tougher competition and contracting markets for pulp products, development of biorefineries is a possible way for companies in the pulp and paper industry to remain competitive. There are several biorefinery pathways enabling production of value-added products such as biofuels, electricity, chemicals and materials in addition to pulp. These biomass-based products could replace products produced from fossil fuels. This chapter has presented pulp mill biorefinery processes, with a focus on the kraft pulp industry, and discussed factors influencing the optimal design of a pulp mill biorefinery.

Examples of pulp mill biorefinery options that utilise process streams from the kraft process are extraction of hemicelluloses from wood or lignin from the black liquor, and gasification of black liquor. In addition, there are processes that could be beneficially integrated with a pulp mill, for example gasification or other types of biomass upgrading such as torrefaction and pyrolysis, using purchased forest residues and bark from the mill. Finally, the cellulose fraction which is currently used for paper products can be used for other purposes, such as textile or ethanol production.

The optimal design of a pulp mill biorefinery is dependent on a number of characteristics of the mill such as type of mill, steam balance, size, need for investments, available investment capital, and geographical location. It also depends on a range of external factors such as prices of energy carriers, chemicals and materials and the presence of policy instruments. Thus, even for a given mill with known characteristics there are large uncertainties regarding both the absolute and relative future performance of the different biorefinery concepts. Furthermore, due to, limited, but yet attractive markets for many chemicals and materials, it is possible that future kraft pulp mills will need to specialise on different products, and hence display a greater variety as compared to the more homogenous industry of today.

7

PERSPECTIVES ON THE POTENTIAL FOR CCS IN THE EUROPEAN PULP AND PAPER INDUSTRY

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INTRODUCTION

The Pulp and Paper Industry (PPI), like other energy-intensive industry branches, is suitable for implementation of carbon capture and storage (CCS) since they have large on-site emissions of CO₂ and usually also excess heat available which can be utilised in the capture process. Further, since a large share of the CO₂ emissions associated with the European PPI originates from biomass, if CCS is implemented the levels of CO₂ in the atmosphere can be further reduced in comparison to implementing CCS only on fossil emission sources, i.e. provided the biomass is grown in a sustainable way. This fact makes CCS within the European PPI an interesting alternative.¹ This chapter assumes that world governments adopt policy measures that stimulate significant CO₂ reductions and the purpose of this chapter is to discuss CCS as an option for the PPI to significantly reduce its CO₂ emissions. The chapter gives an introduction to CCS in general and CCS in the PPI in particular. Some main opportunities and challenges are presented and discussed and an example of the potential for CCS in the European PPI is

¹ See for instance ZEP (2012) *Biomass with CO₂ capture and storage (Bio-CCS) - The way forward for Europe*. European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP).

presented. The chapter ends with a list of main conclusions. This chapter is partly based on Johnsson et al. (2012)² and Jönsson and Berntsson (2012)³.

A SUMMARY ON CCS TECHNOLOGY

The capture and storage of CO₂ (often referred to as “carbon capture and storage”, CCS) involves four major steps: (1) capture of CO₂ from large point sources, such as power plants or industrial processes, (2) treatment of the CO₂ for transport (compression and/or liquefaction), (3) transport of the captured CO₂ to a storage site, and (4) injection of the CO₂ into the storage site, typically a geological formation located deep underground. Current research and development includes all four aspects of CCS. However, most emphasis so far has been on the capture processes (1) due to capture being the most expensive part of the CCS chain. The additional expense of applying CCS on a power plant or industrial process originates from increased investment and operation and maintenance costs (capture technology) and costs for transportation and storage of captured CO₂. In addition, the capture of CO₂ is in most cases energy demanding, which is normally considered as an energy penalty compared to the process without capture. The energy demand can, however, be reduced if the capture process is efficiently integrated, something which can be analysed using different process integration tools (see Chapter 8). The costs discussed today are at least 50-60 EUR/ton CO₂ for the whole CCS chain. However, the aim is to achieve future costs for capture and storage as low as about 25 EUR/ton CO₂. This cost estimation is very sensitive to assumptions and to the nature of the host process which explains the substantial spread of estimates that can be found in the literature. For CCS to be an alternative, the cost of capture, transport and storage need to be lower than the cost for emitting the CO₂.

The actual capture technology is by no means one single technology, rather, several options and possibilities exist. For integration of CO₂ capture in the PPI, the currently most significant technologies are post-combustion capture by solvents and possibly the oxy-fuel process.⁴ In addition, there are other important capture technologies such as Chemical-Looping-Combustion. However, this capture technology is less mature and would require reconstruction of the boilers, making it less significant within the next 10-20 years. Post-combustion capture essentially uses a solvent to absorb the CO₂ from the flue gases in a scrubber, which is then stripped by boiling off the CO₂, which is captured, including regeneration of the solvent. The boiling off and regeneration requires heat and the captured CO₂ requires compression work, which result in the above-mentioned energy penalty. Examples of solvents that can be used include amines and chilled ammonia. An advantage for post-combustion capture using solvents is that it can be implemented for retrofit of existing plants. Pre-combustion capture by the oxy-fuel method can simply be described as performing the combustion in a controlled atmosphere consisting of pure oxygen and re-circulated flue gases. Here, the energy penalty stems from operation of the air separation unit required to obtain the oxygen.

² Johnsson, F. et al. (2012) The importance of CO₂ capture and storage – a geopolitical discussion. *Thermal Science* 16(3):655-668.

³ Jönsson, J., and Berntsson, T. (2012) Analysing the potential for implementation of CCS within the European pulp and paper industry. *Energy* 44(1):641-648.

⁴ Introducing the oxy-fuel process would, however, demand much more reconstruction of the boilers compared to post-combustion capture.

Based on a review of recent studies (IASKS 2012⁵, GeoCapacity⁶, NPD 2012⁷, EC 2012⁸, Kjærstad et al.^{9, 10, 11}) some conclusions can be drawn regarding the current stage CCS technology, opportunities and challenges. First, there is probably more than sufficient storage capacity in Europe to store most of the emissions from large-scale sources for several decades. There is now an urgent need to gain experience in CO₂ injection and CO₂ storage. However, most CCS projects in Europe with storage in onshore reservoirs have been abandoned due to fierce local opposition. At the same time, projects with offshore storage have met little or no opposition. By far most of the identified offshore storage capacity in Europe is located in the North Sea. It is clear that CCS requires political commitment and a renewed willingness to go forward with research, development and demonstration. Since no emitters are willing to invest billions in developing a technology that only might be useful after 2020, investors will require financial security and possibly even full funding of the first large-scale demo-projects. Finally, failure to implement CCS will require close to complete phase-out of fossil fuels if stringent CO₂-emission reduction targets are to be met.

CCS PLANTS – GLOBALLY, WITHIN THE EU AND IN THE SWEDISH PPI

Large-scale CCS is already taking place at some sites in the world; in Norway more than 13 million tonnes (Mt) of CO₂ has been injected into an aquifer in the North Sea (Utsira) while injection into the Tubåen formation in the Barents Sea has been stopped due to rapid pressure build-up around the injection well. The projects in Norway separate CO₂ from natural gas so that the natural gas can be marketed, i.e. the cost of capture would have had to be carried anyway and since Norway has a substantial tax on CO₂-emissions from the offshore industry, it is more cost efficient to store the CO₂ than to emit it. Also, since 2004 0.6 Mt of CO₂ per year has been stripped from natural gas produced from the In Salah gas field in Algeria followed by injection into an aquifer. In the US, CO₂ has been injected into oil fields to enhance recovery (so-called EOR – Enhanced Oil Recovery) for several decades and in 2010, there were more than 120 CO₂ EOR projects injecting more than 60 Mt CO₂ annually of which 13 Mt from anthropogenic sources. The by far largest CO₂ project in the world, the Gorgon project in Australia, is under construction and is projected to separate between 3.4 and 4.0 Mt of CO₂ per year from natural gas and inject it into an aquifer.

However, within the European Union several CCS projects under development have been abandoned during the last few years. In particular, out of the six CCS projects receiving a combined financial support of one billion euro from the EU under the EEPR (European Energy Program for Recovery), at least two projects

5 IASKS (2012) Fossil Fuels: Climate Change and Security of Supply. *International Journal of Sustainable Water and Environmental Systems* 4(1):79-87.

6 [Geocapacity Project](#).

7 NPD (2012) Norwegian Petroleum Directorate.

8 European Commission (2012) *Energy Roadmap 2050*. Luxembourg: Publications Office of the European Union.

9 Kjærstad, J. et al. (2011) Establishing an integrated CCS transport infrastructure in northern Europe - Challenges and Possibilities. *10th International Conference on Greenhouse Gas Control Technologies (GHGT10)*. Amsterdam, Netherlands, Sep. 19-23.

10 Kjærstad, J., et al. (2011) CCS in the Skagerrak-Kattegat-region - Assessment of an intraregional CCS infrastructure and legal framework. *10th International Conference on Greenhouse Gas Control Technologies (GHGT10)*. Amsterdam, Netherlands, Sep. 19-23.

11 Kjærstad, J., et al. (2012) Modelling large-scale CCS development in Europe – linking techno-economic modelling to transport infrastructure. *11th International Conference on Greenhouse Gas Control Technologies (GHGT11)*. Kyoto, Japan, Nov. 18-22.

have either been shelved or deferred indefinitely; the Hatfield IGCC in the UK and the Jämschwalde project in Germany. Since we are already in 2013, it appears likely that only a handful of the twelve targeted CCS plants in Europe will become operational in 2015 as envisioned by the European Commission.^{12,13} This is critical since there is an urgent need to move the development into demonstration of large-scale capture units so that these can be tested, further developed and improved in order to reduce cost.

Today, CO₂ is captured from the flue gases at two Swedish pulp and paper mills, M-real Husum and StoraEnso Nymölla. The captured CO₂ is, however, not transported and stored as pure CO₂ but chemically bound in the production of PCC (precipitated calcium carbonate).

DOES CAPTURING BIOGENIC CO₂ GENERATE NEGATIVE EMISSIONS?

CCS implemented on biomass fuelled (biogenic) processes (Bio Energy Carbon Capture and Storage, BECCS), e.g., sugar cane-based ethanol mills, chemical pulp mills and biomass-fired power plants, can provide the possibility to reduce atmospheric levels of CO₂. This is usually referred to as negative CO₂ emissions or as carbon negatives. However, there are several challenges for BECCS that remain to be resolved for it to play a major role in the energy system. For example, it is likely that capturing CO₂ from biomass fired processes will be more expensive compared to implementation in large scale coal fired power plants, due to economies of scale for biomass fired plant that are limited by biomass fuel logistics as well as technical aspects in the actual process design, e.g., the maximum steam temperature (determining the plant efficiency) may have to be limited to avoid alkali related high temperature corrosion on heat transfer surfaces. In addition, it should be noted that net negative emissions can only be achieved when more greenhouse gases are sequestered than are released into the atmosphere. Until CCS has been applied to all fossil fuelled power plants and all other CO₂ emissions have been curbed, the total net global CO₂ emissions will not be negative.

From the year 2013, (fossil) CO₂ capture, transport and storage installations will be incorporated in the European Union emission trading scheme (EU ETS). Capture and storage of CO₂ from combustion of biomass has not yet been incentivised through the ETS. However, it is expected that inclusion of the concept of carbon negatives will be required to meet the stringent long-term emission reductions proposed by for instance the EU. For the discussion of CCS in the PPI in this chapter it is assumed that in future policy schemes captured and stored CO₂ originating from sustainably produced biomass is granted the same economic compensation as CO₂ originating from fossil fuels.

CCS IN THE PULP AND PAPER INDUSTRY

The PPI is energy-intensive and has large on-site emissions of CO₂. Consequently, the CO₂ emissions in the PPI are associated with only a limited amount of geographical sites, i.e. mills. Furthermore, previous research has shown that for the chemical kraft PPI (sulphate process), there are many technologies and system

¹² Reuters (2012) *UK won't get EU cash for carbon storage: EU sources*. Press release. Nov. 11.

¹³ [NER300](#).

solutions which can reduce the process steam demand, yielding a heat surplus and thus enabling energy-efficient production of additional added-value products such as materials, chemicals, transport fuels, electricity or district heating. In this way the mill is transformed into a biorefinery (see e.g. descriptions of different biorefinery concepts in Chapters 2 and 6). Another alternative is to integrate carbon capture (CC) by utilising the heat surplus to (fully or partly) cover the heat demand in the carbon capture processes. This way the cost and energy efficiency of the concept is improved.¹⁴ Previous research has shown that compared to other options for using surplus steam, CCS gives much larger reductions of global CO₂ emissions and is economically comparable to more proven technology alternatives – such as increased electricity production in condensing turbines – if the economic value of capturing CO₂ is high.¹⁵ The potential for carbon capture and storage (CCS) in the industry sector and the potential for formation of industrial capture clusters have previously been discussed.¹⁶ However, analyses of the potential for CCS in the industrial sector usually do not include the PPI since the CO₂ emissions in this sector to a large extent are biogenic.

OPPORTUNITIES AND CHALLENGES FOR IMPLEMENTING CCS IN THE PULP AND PAPER INDUSTRY

CCS, being an emerging, capital intensive technology requiring large scale implementation, shares some of the policy challenges described for biomass gasification in Chapter 12. In addition, the following opportunities and challenges are important to take into account when discussing CCS in the PPI:

A significant part of the emissions in the PPI are biogenic. As previously mentioned, the fact that the CO₂ emissions in the PPI to a large extent are biogenic provides both an opportunity and a challenge. An opportunity since in the long term perspective if the addition of fossil CO₂ to the atmosphere is reduced (by e.g. CCS on fossil emission sources) implementing CCS also on biogenic sources could contribute to slowly “decarbonising” the atmosphere. However, it provides a challenge since all existing regulations and policy instruments (ETS etc.) in the area include only fossil CO₂, limiting the economic incentives for investments in capturing biogenic CO₂.

The development of the EU ETS. Presently the majority of CO₂ emissions from the stationary energy system in Europe are regulated in the EU ETS. The EU ETS has clearly defined emission targets to be achieved by the year 2020 and is believed to be a key instrument also after this year in forthcoming policy within the EU. However, emissions have been regulated in so called trading periods, where the first (2005-2008) and second have ended (2009-2012), to even out annual variations from for example temperature and hydro power generation fluctuations. In the beginning of the third trading period (2013-2020) price in the EU ETS is about ~8 EUR/ton CO₂, which is far too low to have an impact on the development of CCS. The reason for such a low price can partly be explained by over allocation

¹⁴ Also mills without a steam surplus can be transformed into a biorefinery and/or implement CCS but with weaker economic performance (see Chapter 6).

¹⁵ Jönsson, J., et al. (2012) Comparison of options for utilization of a potential steam surplus at kraft pulp mills—Economic performance and CO₂ emissions. *International Journal of Energy Research* 37(9):1017-1035.

¹⁶ See e.g. Rootzén, J., et al. (2011) Prospects for CO₂ capture in European industry. *Management of Environmental Quality* 22(1):18-32.

of emission permits as well as the possibility to use international credits in the EU ETS. The result is an excess of about 1-1.5 billion emission allowances, corresponding to 1-1.5 billion tonnes (Gt) of CO₂, in the beginning of trading period three.¹⁷ Thus, without further actions prices are expected to remain low until after 2020.

The EC communication “Energy Roadmap 2050” describes possible pathways for the EU energy system indicating almost full CO₂ emission reduction from the electricity generation sector, which at present is the majority of all emissions in the EU ETS. If put into practice, such a zero net CO₂ emission electricity system is estimated to correspond to CO₂ prices in the range of 100 EUR/ton CO₂ for the period 2030 and beyond.¹⁸ At these CO₂ price levels the PPI and other process industry sectors might very well become interested in CCS as CO₂ abatement technology.

Efficiency gains through potential heat integration and integration with other biorefinery concepts. The potential for heat integration of the capture process is one reason why CC is of interest for the PPI. Previous research has shown that process steam savings can be made with thermal integration of a CC unit. This way the capture cost is reduced and the CC-concept can become more profitable.¹⁹ Finally, it could be interesting to combine CC and lignin extraction at a mill since some of the captured CO₂ could then be used in the lignin separation process (see Chapter 6 for further reading on lignin extraction and other alternative biorefinery concepts in the PPI) and thus eliminate the need to buy more expensive CO₂ on the market.

The largest reductions of CO₂ emissions compared to other technologies for utilisation of mill excess heat. If the PPI is to contribute to significantly to reduction of global CO₂ emissions, CCS is the technology that by far provides the largest reductions compared to e.g. other possible technology options to utilise potential steam and heat surplus. However, even though the process can be efficiently integrated, the future economic performance of the technology is highly dependent on the development of the price for emitting CO₂ (including potential benefits received for capturing biogenic CO₂) as well as other energy market prices.

High investment costs. Investments in CO₂ capture technologies are associated with high capital costs. Since CCS is a non-commercial technology the estimated costs are highly uncertain. This contributes to making the future economic performance of the technology hard to predict. Furthermore, the energy cost for capture is also significant and can thus not be neglected. Hence, for CO₂ capture to be economically and technically realistic the source of CO₂ needs to be large enough and the energy heat demand of the capture process should preferably be possible to integrate with other processes at the capture site. As previously stated, when capturing CO₂ in the PPI the potential for heat integration gives a possibility

¹⁷ EC (2012) Commission Staff Working Document. Information provided on the functioning of the EU Emissions Trading System, the volumes of greenhouse gas emission allowances auctioned and freely allocated and the impact on the surplus of allowances in the period up to 2020. Brussels, Belgium: European Commission. (SWD(2012) 234).

¹⁸ Odenberger, M. et al. (2013) Prospects for CCS in the EU Energy Roadmap to 2050. *Energy Procedia* 37:7573:7581.

¹⁹ Hektor, E. and Berntsson, T. (2007) Future CO₂ removal from pulp mills - Process integration consequences. *Energy Conversion and Management* 48(11):3025-3033.

to reduce the heat demand that has to be provided by primary energy and thus improve the economic performance.

Potential storage locations and infrastructure for transport of emissions. Today, CCS is not a commercial technology and the necessary infrastructure for both transport and storage is neither in place nor definitely planned. The latest European wide assessment of storage capacity was completed in 2009 with the GeoCapacity project which, applying a conservative approach, estimated total storage capacity in 25 European countries to 117 Gt of which 96 Gt in aquifers, 20 Gt in oil and gas fields and 1 Gt in coal fields.²⁰ More than a third, almost 44 Gt, was assumed to be located in the Norwegian and UK part of the North Sea. It should, however, be noted that most estimates only are rough preliminary estimates, in particular with regard to capacity in aquifers. Sweden was not a part of the GeoCapacity project but the Swedish Geological Survey has done preliminary estimates of storage capacity in three aquifers in the Swedish part of the Baltic Sea. The most promising structure, Faludden, southeast of Gotland, may have a storage capacity ranging from 450 to 4,500 Mt. Two smaller and much more uncertain areas have also been identified; offshore southwest Skåne and in the southeastern part of the Kattegat Sea.²¹ For the pulp and paper mills located near harbors the buildup of transport infrastructure could be facilitated since ships could be used for transport before the total transported amounts could justify the establishment of pipe infrastructure.

AN EXAMPLE: POTENTIAL FOR CCS IN THE EUROPEAN PPI CONSIDERING THE GEOGRAPHICAL LOCATIONS OF THE MILLS

Here, the European pulp and paper industry is defined as mills located in the countries that are included in CEPI (Confederation of European Paper Industries), i.e. the countries in Europe with the highest density of pulp and paper industry. Today, the European PPI is transforming due to increased global competition and changing market demands. In this process many (small) less profitable mills are decommissioned and the remaining mills are increasing their production capacity, keeping the total pulp and paper production rather constant. This structural change implies that not all of the mills in production today will still be in production at the time when CCS will be commercially available. To account for this fact, the mills included to represent the European PPI have been chosen based on competitive strength and size; this gives a selection of 171 mills for this example.

The amounts of on-site CO₂ emissions from the pulp and paper mills included in this example are presented in Figure 7.1. For comparison, the total on-site emissions of CO₂ for all CEPI mills are also presented. As can be seen in the figure the kraft mills have much larger on-site emissions compared to the mechanical pulp and paper mills (using more electricity) and the pure paper mills (having a lower energy demand in total since no virgin fiber is processed).

²⁰ GeoCapacity (2009) *Assessing European Capacity for Geological Storage of Carbon Dioxide. Storage Capacity*. Copenhagen, Denmark: EU GeoCapacity consortium. (SES6-518318 D16 WP2).

²¹ Anthonsen, et al. (2012) CO₂ storage potential in the Nordic region. *11th International Conference on Greenhouse Gas Control Technologies (GHGT11)*. Kyoto, Japan, Nov. 18-22.

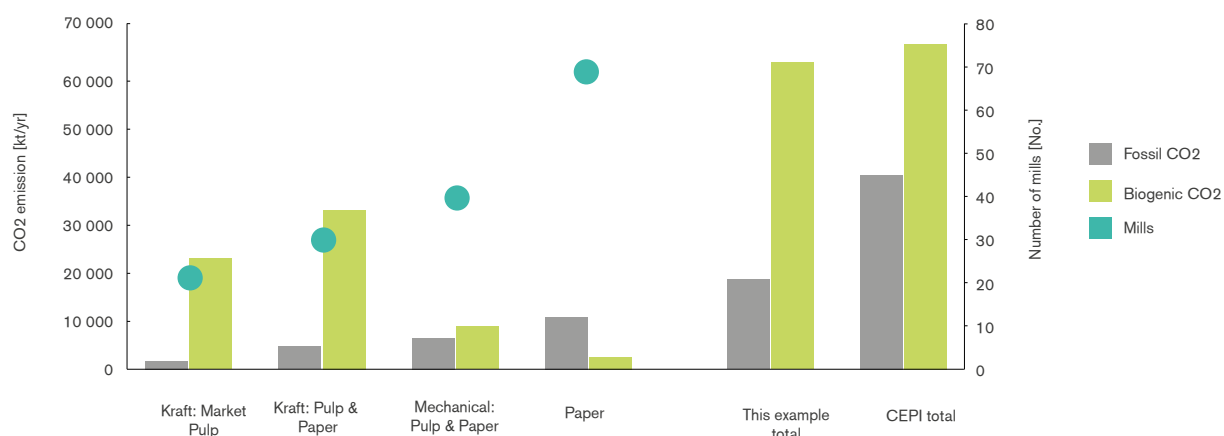


Figure 7.1 Fossil and biogenic emissions of CO₂ for the mills included in the example compared to CEPI total emissions.

The geographical distribution of these CO₂ emissions is shown in Figure 7.2 together with an overview of where different types of mills are located. As can be seen, the regions with the highest emissions are located around the Baltic Sea (in Sweden and Finland), in the south of Spain and in the middle of Portugal (the regions with most kraft pulp and kraft pulp and paper mills).

Today, CCS is not a commercial technology and the necessary infrastructure for both transport and storage is neither in place nor definitely planned, as described earlier in this chapter. It is thus hard to predict which plants will have the most favorable preconditions for implementing CCS. To address this task, a reasonable approach could be to assume the following:

- Infrastructure is most likely to be developed first in proximity to sites with many large point sources, hereafter denoted capture clusters.
- Depending on how the biomass-based CO₂ is viewed from a mitigation point of view, it can be assumed that infrastructure will first be built around large fossil point sources or around large point sources regardless of the origin of the emissions.
- It is reasonable to assume that mills with larger emissions will have a larger potential for profitable introduction of CCS compared to mills with small emissions.

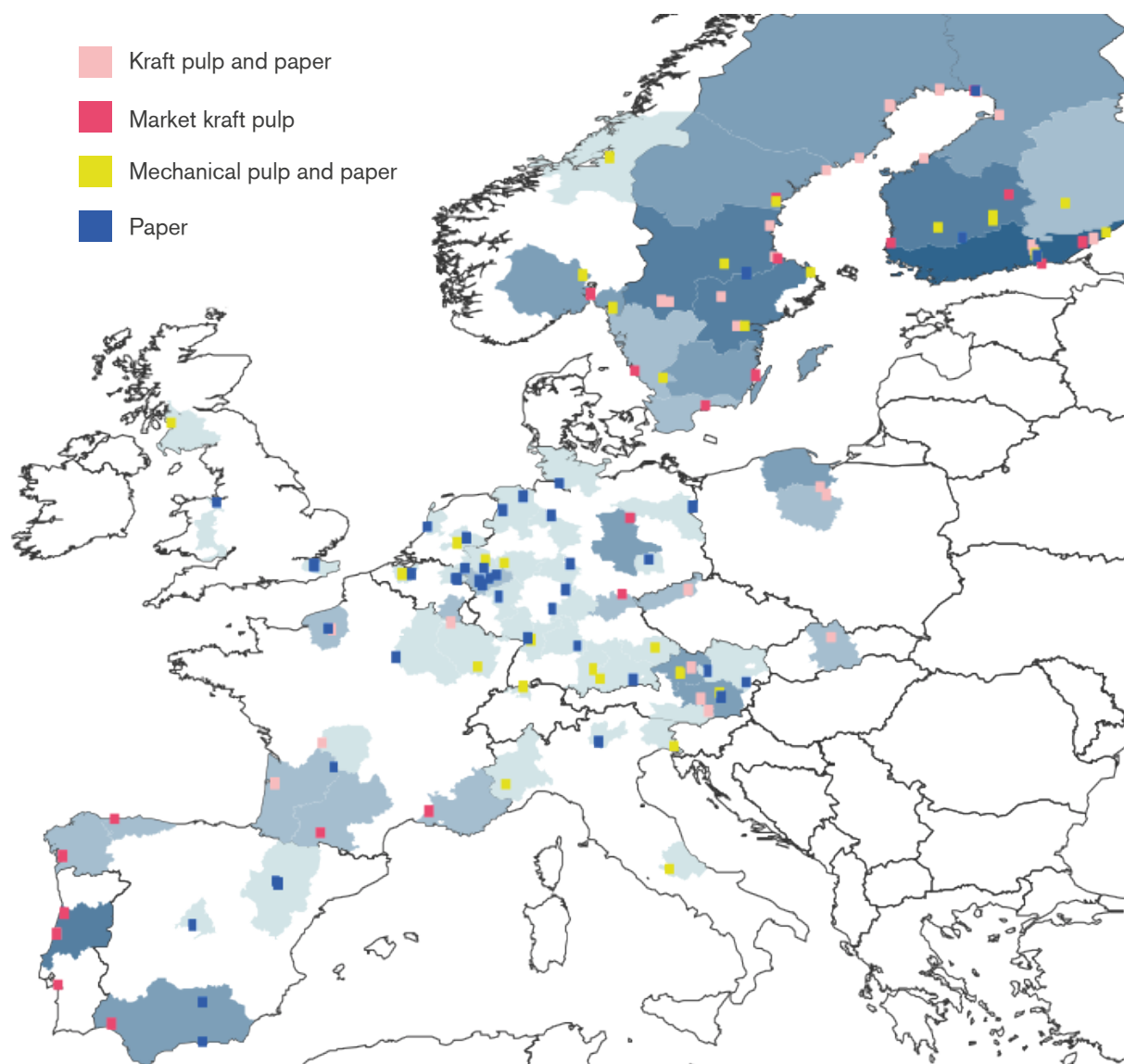


Figure 7.2 The geographical distribution of on-site CO₂ emissions from the European PPI. The colored squares represent individual mills (emitting >0.1 Mt CO₂/yr). Regions colored in blue have a high density of emissions; the darker the color, the higher the emissions. Figure originally presented by Jönsson and Berntsson (2012)²².

The geographical positioning of the pulp and paper mills included in the work on which this example is based in relation to the geographical positioning of other energy-intensive industries, power plants and capture clusters is displayed in Figure 7.3.f

²² Jönsson, J., and Berntsson, T. (2012) Analysing the potential for implementation of CCS within the European pulp and paper industry. *Energy* 44(1):641-648.

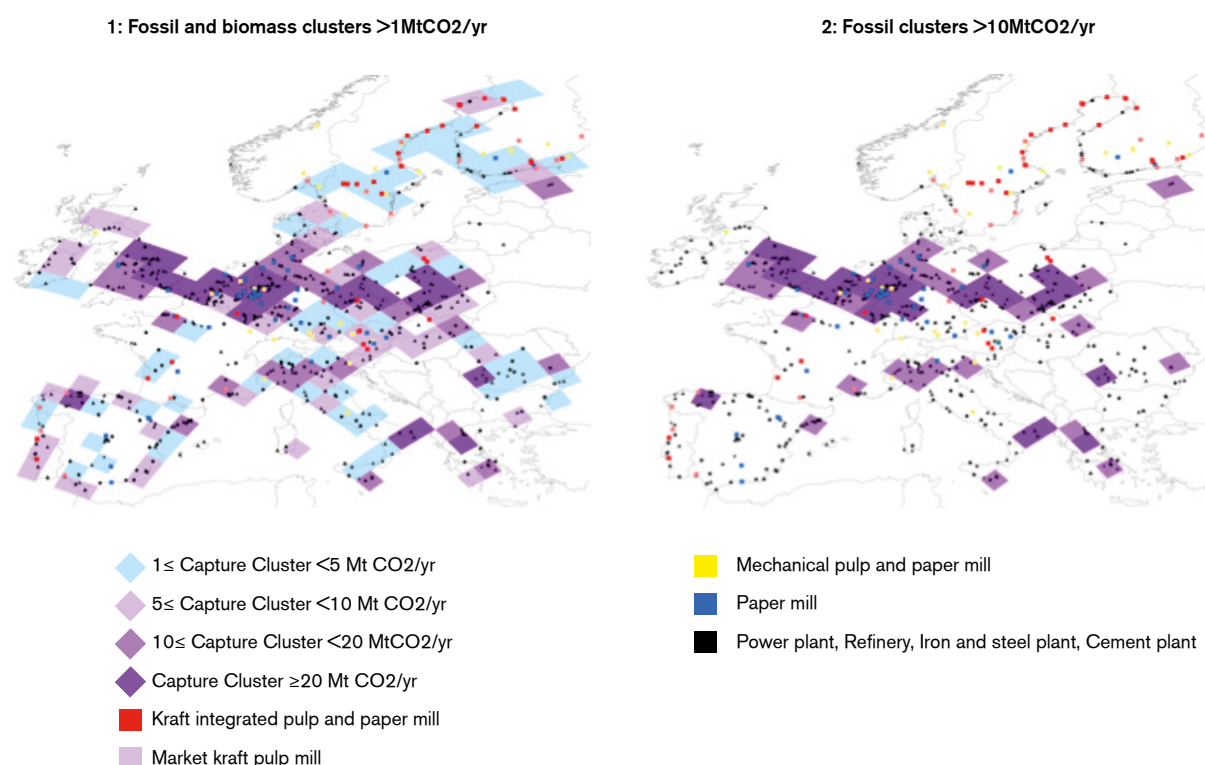


Figure 7.3 The geographical distribution of the European PPI in relation to other large industrial point sources and power plants emitting CO₂. Possible capture cluster areas are represented by colored squares (150 × 150 km). Adapted from figure first presented in Jönsson and Berntsson (2012).²³ The underlying map and the data for other heavy industries and power plants were compiled by Rootzén et al (2011).²⁴

As can be seen in Figures 7.2 and 7.3, most of the large emitting kraft pulp and paper mills are located on the eastern coast of Sweden and in Finland, far away from most of the largest fossil capture clusters created by other energy-intensive industries and power plants. The most beneficial geographical positions in terms of close proximity to potential capture clusters and potential storage sites in the North-Sea²⁵ are held by paper mills in central Europe. These mills have, however, much smaller on-site emissions compared to the kraft mills. On the other hand, it should also be noted that most Swedish and Finnish sources are located along the coast which will facilitate the build-up of a cost efficient CCS infrastructure with minimum impact on the environment since ships can be utilised to transport the CO₂ initially when volumes are on the rise. Also, a location close to the coast will provide easy access to cooling water for the capture and compression processes.

²³ Jönsson, J., and T. Berntsson (2012) Analysing the potential for implementation of CCS within the European pulp and paper industry. *Energy* 44(1):641-648.

²⁴ Rootzén, J., et al. (2011) Prospects for CO₂ capture in European industry. *Management of Environmental Quality* 22(1):18-32.

²⁵ Assuming storage in closed aquifers, mineralization of the CO₂ could be another option, however that technology need a major breakthrough before being possible to commercialise in large scale.

CONCLUDING REMARKS

Of the total on-site CO₂ emissions from the PPI a large part is biogenic. A third of the mills are responsible for about 75% of the emissions. Consequently, implementing CCS in the European PPI will lead to capture of mainly biogenic CO₂. To make CCS in the PPI a viable option it is therefore critical that capture of biogenic CO₂ is granted the same financial support as capture of fossil CO₂.

If CCS is to be introduced on a large scale in order to reach substantial CO₂ emission reductions within the European PPI, the emission intensive Scandinavian kraft PPI must be included. If this is done, up to around 60 Mt CO₂ per year could be captured. This is more than the total amount of fossil CO₂ emitted per year in Sweden (presently around 50 Mt CO₂ per year).

The amount of CO₂ that can be captured from the European PPI depends heavily on the expansion of transport infrastructure. While the Swedish and Finnish PPI's from one point of view have beneficial location along the coast which may facilitate the build-up of a CCS infrastructure, they are located far away from Europe's major emission clusters. The results from the example provided in this chapter show that when matching the PPI capture potential with the potential for CCS within other energy-intensive industries and the power and heat sector, the CO₂ emission intensive kraft PPI holds a very poor geographical position compared to potential large capture clusters and storage places. This is especially true if only the largest capture clusters are considered. Due to this poor matching between CO₂ sources and potential CO₂ sinks and transport infrastructure, it can be argued that for the European PPI, CCS has an up-hill road in order to be a viable, large scale alternative for reduction of CO₂ emissions.

8

OPTIMAL LOCATION OF BIOREFINERIES

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INTRODUCTION

Biorefineries can be built as stand-alone systems or co-located with existing systems such as industrial plants or district heating systems. There are different criteria for selecting a suitable location for a biorefinery, for example closeness to raw material, product markets and heat sinks and sources or existing experiences and know-how. Further, the entire upgrading process from raw material to end products does not necessarily have to be located at the same place. Intermediate products could be produced and transported to other sites for further upgrading. Thus, the suitable location for a biorefinery depends on a trade-off between different parameters. Since biorefineries are not implemented to a large extent today and new technologies are constantly being developed, there is a need for studies that address questions such as how different overall performance parameters (overall efficiency, economic performance and GHG emissions reduction potential) are affected by the choice of location of the different stages in the biomass upgrading process, the pros and cons of different location options and what is of specific importance to consider concerning the location of biorefineries. It is relatively easy to quantify the effect of parameters such as transportation distances for raw materials and products or the degree of heat integration. The effect of other parameters are more difficult to quantify, e.g. experience and know-how concerning handling of the raw material, the processes or the products.

This chapter describes different criteria for selecting the location of biorefineries. Examples of biorefinery concepts are presented together with a discussion of the pros and cons of different candidate locations. One important driving force for location of biorefineries which could improve the overall efficiency significantly is the opportunities for heat integration, which will be in special focus in the latter part of this chapter. A methodology for quantifying the possibilities for heat integration within and between different processes is described and an example that

illustrates the consequences of different locations with different possibilities for heat integration is presented.

CRITERIA FOR SELECTING A LOCATION FOR A BIOREFINERY

There are a range of factors that affect the suitable location of a biorefinery plant. *Closeness to raw material* shortens the transportation distances and thereby the emissions and costs associated with distribution of the raw material. Closeness to a harbour could be a way of enabling longer transportation distances at reasonable costs. Also *closeness to product markets and users* could shorten transportation costs. It should be emphasised that the energy density often is much higher for products than for raw materials, thereby enabling more efficient transportation. Possibilities to implement *large-scale production*, economies of scale, would benefit most processes. *Heat integration* of the biorefinery with an existing industrial process or a district heating system could enable excess heat to be used or delivered resulting in less fuel use and thereby reduced heating costs within or outside the biorefinery (see also Chapter 11). Opportunities for *re-use or co-use of existing process units* reduce the investment costs. In the long run, however, it might be better to adjust the processes to the new raw materials and products to achieve higher efficiency. Opportunities to *use existing infrastructures* such as raw material handling systems also reduce the investment cost. There is a significant difference in building an entirely new plant than to add a new process to an already existing plant.

To be able to use e.g. existing process units is not only a question of reduced investment costs. It could also lead to reduced technical risks of implementing biorefinery concepts since the experience and know-how concerning operation (of a part) of the process already exists. In the same way, there could be opportunities to *capitalize on experience and know-how* concerning the raw material and its supply and the products and their markets. Finally, the availability of *financial capital* and willingness to invest is a critical factor.

BIOREFINERY TECHNOLOGIES AND ASSOCIATED SUITABLE LOCATIONS

First we can start by making a distinction between biorefineries that can be located relatively freely and biorefineries that are a natural part or an extension of an existing process. Most biorefinery technologies belong to the first category. However, a number of the technologies that are described in Chapter 6 belong to the second category. These technologies extract valuable products from the material streams in a kraft pulping process, e.g. extraction of hemicelluloses from the wood, extraction of lignin from the black liquor and gasification of black liquor. Gasification (and a certain degree of raw gas cleaning) and extraction steps must take place at the pulp mill, but further upgrading of these components to valuable products such as biofuels, chemicals or materials could be carried out elsewhere. However, there are a number of significant benefits of locating upgrading of the syngas from black liquor gasification at the mill. For example, the gasification process including upgrading to biofuels has a steam surplus whereas the mill has a need for process steam and thereby efficient heat integration can be achieved.

We now return to the first category which includes most biorefinery technologies. For example, the two key conversion processes described in Chapter 2, i.e. gasification (excluding gasification of black liquor) and fermentation of lignocellulosic feedstock, can be located in many different places.

In total, gasification processes have a significant heat surplus. Therefore heat integration with other industrial processes or district heating systems can improve the economic performance as well as the GHG balances of the integrated system as a whole. However, for solid biomass gasification there is no natural integration with another process as in the case of black liquor gasification. Further, there are a limited number of heat sinks that are large enough and that are able to accept excess heat all year around. Several studies show the efficiency gains that can be achieved by integrating motor fuel production via gasification of solid biomass with pulp and paper mills rather than building them for stand-alone operation.¹ Furthermore, it has been shown that integration with a pulp and paper mill generally constitutes a more attractive option for solid biomass gasification plants compared to integration with a district heating system due to a longer operating time.² However, the excess heat from gasification processes generally has a very high temperature which makes it suitable for power generation or combined power and heat generation, and it is therefore also possible to make use of the excess heat of stand-alone plants.³

Production of ethanol, either as a biofuel or intermediate product, is the most discussed product of the fermentation pathway. Producing lignocellulosic ethanol requires steam. This steam demand could be satisfied by firing process by-products in a combined heat and power (CHP) plant, thereby achieving autonomous operation in stand-alone mode without the need for external fuel. However, these plants have a substantial excess of low temperature heat (below approximately 100°C) and therefore location close to a district heating network could be beneficial. If the plant is located close to a pulp mill with excess steam, the by-products from the ethanol process could be used for other purposes than heating. For example, the lignin could in the future perhaps be used for valuable materials. There is a lignocellulosic ethanol process developed that is similar to the kraft pulping process and that to a large extent can use existing equipment at a kraft pulp mill (see Chapter 6). This could be a way to e.g. introduce lignocellulosic ethanol production at a lower cost.

It is important to study if and how the design of different biorefinery process units could be changed in order to increase the internal heat integration and/or the opportunities for heat integration with different types of industrial processes. For example, the characteristics of the ethanol process may then be changed and the amount of low temperature excess heat could be reduced.

¹ See e.g. McKeough, P. and Kurkela, E. (2008) Process evaluations and designs in the UCG project 2004-2007. Espoo, Finland: VTT Technical Research Centre of Finland; Joelsson, J.M. et al. (2009) CO₂ balance and oil use reduction of syngas-derived motor fuels co-produced in pulp and paper mills. *17th European Biomass Conference & Exhibition*. Hamburg, Germany, Jun. 29 – Jul. 3.

² Wetterlund, E. et al. (2011) Systems analysis of integrating biomass gasification with pulp and paper production – Effects on economic performance, CO₂ emissions and energy use. *Energy* 36(2):932-941.

³ See e.g. Isaksson, J. et al. (2012) Integration Of Biomass Gasification With A Scandinavian Mechanical Pulp And Paper Mill - Consequences For Mass And Energy Balances And Global CO₂ Emissions. *Energy* 44(1):420-428.

CO-LOCATION OF BIOREFINERIES WITH THE PULP AND PAPER INDUSTRY

In a Swedish perspective the pulp and paper industry is a major industry (more than 10% of the export and approximately 50% of the industrial energy usage in Sweden) that accounts for a large share of potential sites for co-location of biorefineries. There are several reasons why the pulp and paper industry is especially interesting for co-location of biorefineries including closeness to biomass resources, long-term experience and well-developed infrastructure for handling large volumes of biomass, access to heat sinks and/or heat sources (depending on the type of mill) and, for some biorefinery technologies, existing process units and experience concerning their operation. Possible disadvantages of co-location with the pulping industry could be long distances to and lack of knowledge about the products and their markets, e.g. motor fuels or chemicals, as well as limited possibilities to deliver (more) low temperature excess heat to district heating networks. As described in the previous section and in Chapter 6, some biorefinery technologies utilise streams from pulp mill processes and must consequently be located at a mill (at least partly). Furthermore, for the reasons listed above, it may also be attractive to co-locate other biorefinery technologies, such as gasification of solid biomass or lignocellulosic ethanol production, at pulp and paper mills.

Another industry, closely related to the pulp and paper industry, is the saw mill industry. Existing saw mills are potential integration sites with e.g. closeness to and experience regarding handling of the raw material.

CO-LOCATION OF BIOREFINERIES WITH THE PETROCHEMICAL AND OIL REFINERY INDUSTRY

There are several examples of biorefinery technologies, mainly those involving gasification and fermentation pathways, which could be of interest for co-location with other large process industries (see also Chapter 2). Industries such as oil refineries and petrochemical complexes are today based on fossil feedstocks and are exploring options to integrate renewable feedstock into their operations. There are a number of advantages resulting from co-locating biorefineries at oil refinery and petrochemical cluster sites. In addition to general integration advantages such as making use of existing infrastructure, these industries can often use biorefinery products (intermediates) such as Fischer-Tropsch crude, syngas and ethanol directly as feedstocks in their production processes (see also Chapter 3). Furthermore, there are often substantial opportunities for heat integration with the biorefinery processes, and these industries have experience and know-how concerning the (final) products and their market. Possible disadvantages could be long distances to and lack of experience of handling large biomass resources. This could be managed by undertaking the first biomass upgrading stages at a pulp and paper mill. One example of this type of multi-location biorefinery could be production of Fischer-Tropsch crude from gasified black liquor or gasified woody biomass at a pulp and paper mill which is then transported for further upgrading to finished Fischer-Tropsch motor fuels (diesel and gasoline) at an oil refinery.⁴ The pulp and paper industry takes care of the initial handling of large volumes of biomass, while the oil refinery handles a feedstock that is relatively similar to crude

4 See e.g. Isaksson, J. et al. (2012) Integration Of Biomass Gasification With A Scandinavian Mechanical Pulp And Paper Mill - Consequences For Mass And Energy Balances And Global CO₂ Emissions. *Energy* 44(1):420-428.

oil implying that they can accomplish the final upgrading stages with relatively small changes to their existing process units. Thus, this type of cooperation uses existing infrastructure and process units, and builds upon decades of knowhow about the raw material and its supply, production processes and the products and their market. Furthermore, production of Fischer Tropsch fuels requires large scale in order to be profitable, and this can be accomplished at the oil refinery.

When co-locating biorefineries with these industries it is possible that existing processes are operated in almost the same ways as they are today but with a feedstock that is produced from biomass instead of from fossil fuels. However, it may also be that a different process is preferable if biomass is the raw material and that the existing process units are modified or used to a lesser extent and need to be complemented by other processes or process units. Consider for example a petrochemical plant that uses natural gas in order to produce syngas. Natural gas could be produced via gasification of biomass (so-called substitute natural gas, SNG) and could thereby replace a certain part of the fossil natural gas used.⁵ However, from an efficiency point of view it would be better to use the syngas produced from biomass gasification directly in the petrochemical plant and not take the route via SNG. Yet, for other reasons such as security of supply and minimising technical risks it could nevertheless be preferably to use SNG (which could be substituted with fossil natural gas if problems occur).

CO-LOCATION OF BIOREFINERIES WITH OTHER PROCESS INDUSTRIES OR DISTRICT HEATING SYSTEMS

The iron and steel industry is the third category of energy-intensive process industries in Sweden. The variety of options to use biomass in the iron and steel industry is limited, but very large amounts of biomass could be used due to the magnitude of the energy flows of the host process plant (see Chapter 2). All types of industrial processes could of course consider integration with a biorefinery for heat integration purposes only, i.e. without exchanging any material flows or using any existing process units. For biorefineries with large amounts of low temperature excess heat, the possibility for integration with a district heating system could be crucial in order to reach profitability. The possibilities for delivering industrial excess heat to a district heating system is limited, and it could be interesting to explore other options for usage of low temperature excess heat, such as electricity production using an organic Rankine cycle (ORC).

ESTIMATION OF HEAT INTEGRATION POTENTIAL THROUGH PINCH ANALYSIS

Through increased heat integration within and between different biorefinery processes, and between biorefinery processes and existing industrial process plants, biorefinery products can be produced with a lower usage of fuel for process heating purposes. This section gives an introduction to how heat integration potentials can be estimated using pinch analysis.

⁵ See e.g. Arvidsson, M. et al. (2012) Integration opportunities for substitute natural gas (SNG) production in an industrial process plant. *Chemical Engineering Transactions* 29:331-336.

Process integration refers to systematic methods for designing integrated production systems with a focus on efficient energy use and reducing the environmental load. Pinch analysis⁶ is the most frequently used process integration methodology and allows the user to set energy targets for an industrial process, i.e. the minimum amounts of heat that must be added and removed (i.e. cooled) in a process, as well as the maximum amount of heat that can be recovered internally through exchanging heat. Thereafter, pinch technology provides guidelines for designing heat exchanger network to maximise heat recovery, as well as guidelines for retrofitting existing heat exchanger networks. Pinch analysis is a methodology that is very useful when complex industrial processes are to be analysed in order to save energy and money. This technology came into use in the end of the 1970s and has since then been developed further into a useful tool for grass root design and retrofit of industrial processes.

The minimum temperature difference, DT_{min} , is the lowest temperature difference between the hot stream (a stream that requires cooling) and the cold stream (a stream that requires heating) that can be accepted in a heat exchanger and its value is determined by economic considerations.

Industrial processes are normally composed of many hot and cold streams. They can be represented graphically using composite curves. The hot and cold composite curve is constructed by calculating the heat content of all hot and cold streams respectively in the various temperature intervals. The goal is to establish energy targets (i.e. minimum heating and cooling demands as well as maximum possible internal heat recovery) for a given value of DT_{min} . Figure 8.1 presents an example of composite curves for a process with two different values of DT_{min} . Where the two curves overlap, internal heat exchanging is possible and heat can be transferred from the hot to the cold streams. Where the two curves do not overlap, external heating or cooling must be used. Note that although there are many streams in the system, in general the minimum allowable temperature difference between hot and cold streams (DT_{min}) occurs at one point only. This point is called the pinch.

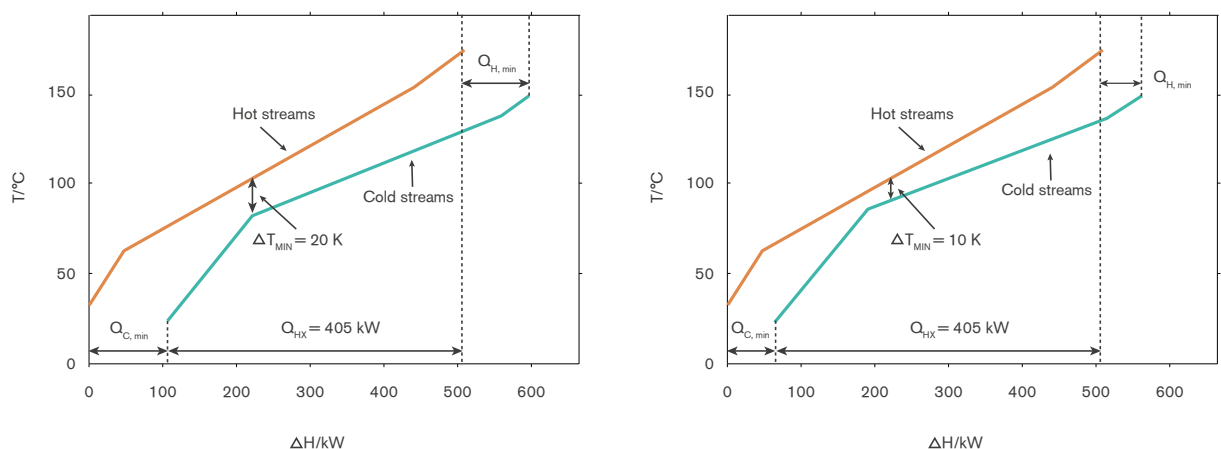


Figure 8.1 Examples of representations of composite curves for a process using two different values of the minimum temperature difference, DT_{min} .

⁶ For an extensive description of the pinch analysis methodology, see e.g. Kemp, I. (2007) *Pinch Analysis & Process Integration - A user guide on process integration for the efficient use of energy*. Oxford, UK: Butterworth-Heinemann.

From the figure we can see that for a DT_{min} of 20°C , the maximum possible internal heat recovery (heat exchange between hot and cool streams), Q_{HX} , is 405 kW, the minimum heating demand $Q_{H,min}$ is 80 kW and the minimum cooling demand $Q_{C,min}$ is 100 kW. When DT_{min} is decreased to 10°C the maximum possible internal heat recovery, Q_{HX} , is increased to 450 kW, thereby decreasing the minimum heating demand, $Q_{H,min}$, to 40 kW and the minimum cooling demand, $Q_{C,min}$, to 60 kW. Thus, by reducing DT_{min} we also reduce the energy utility costs, since we need less heating (typically steam) and cooling (typically water). On the other hand, we increase our capital costs, since the reduced driving force (DT_{min}) means that the necessary heat exchanger area increases. The DT_{min} value for which the sum of the energy and capital cost reaches its minimum is therefore the optimal value that should be chosen for the design. It should also be noted that flat behaviour is usually observed around the optimum value of DT_{min} , thus there are often a number of heat exchanger network solutions with costs close to the optimum value. This implies that there is often a significant degree of freedom available for the network designer.

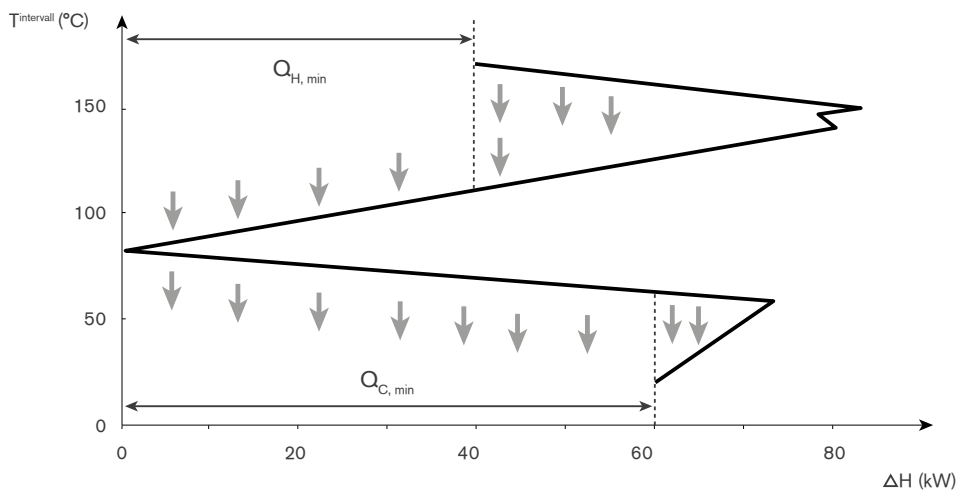


Figure 8.2 Example of a Grand Composite Curve (GCC).

Another way to represent the heat flows in a process in a temperature-enthalpy diagram is to construct a Grand Composite Curve (GCC) for a certain value of DT_{min} . Figure 8.2 shows an example of a GCC (for the same process as in Figure 8.1 with a DT_{min} value of 10°C). The point of contact between the curve and the y-axis is the pinch. Above the pinch, the process has a net deficit of heat and below the pinch the process has a net surplus of heat. The curve also shows areas where there is a net excess heat available at temperatures above levels where there is a net heat deficit. These areas indicate opportunities for process-to-process heat recovery, often referred to as heat recovery pockets.

In order for a process heat exchanger network to reach the energy target, it cannot contain any violations of the following three golden rules of pinch analysis:

- Do not transfer heat through the pinch.
- Do not cool process streams with cold utility above the pinch.
- Do not heat process streams with hot utility below the pinch.

To transfer heat through the pinch means that heat is transferred from a system with a deficit of heat to a system with a surplus of heat. The same amount of heat must therefore be added with external heaters and the same amount must therefore also be cooled with external coolers. To cool above the pinch means that heat is extracted from a system, which has a deficit of heat. The same amount of heat must therefore be added from hot utility. To heat below the pinch means that heat is added to a system that already has an excess of heat. The same amount of heat must therefore be cooled with cold utility.

Pinch analysis is commonly used when investigating retrofit options of existing heat exchanger networks. The energy targets are compared with the existing energy usage in order to estimate the possibilities for savings. In retrofit situations it is usually not profitable to modify the existing heat exchanger network in order to reach the energy target. In greenfield design situations, for example when building a new biorefinery process, it is likely more profitable to design the process energy system so as to be closer to the energy targets for the selected value of DT_{min} .

By studying the results from a pinch analysis, particularly the GCC of the process, the opportunities for heat integration of new technologies and processes can be identified. This type of analysis is usually called a background/foreground analysis. The GCC of the existing process is considered as the background and the foreground is constituted by the GCC of the new technology or process. Thus, by for example studying the GCC for a pulp mill process and the GCC for an ethanol plant, an estimation of the potential for heat integration between the processes can be identified.

ILLUSTRATING THE GAINS OF BIOREFINERY CO-LOCATION

This section shows an example that illustrates the consequences of co-locating different steps in a biomass conversion chain with each other and also in connection to an existing industrial process site.

Ethylene is used to a large extent in the petrochemical industry and is mainly produced using natural gas as feedstock (see Chapter 3 for information about how ethylene is used). One way to produce ethylene from a renewable feedstock is catalytic dehydration of bio-ethanol. The example presented here, taken from studies by Hackl et al. (2011)⁷ and Arvidsson and Lundin (2011)⁸, quantifies the energy consequences of co-locating the ethanol production plant and the ethanol dehydration plant producing ethylene. In addition, the consequences of co-locating

⁷ Hackl, R. et al. (2011) Process integration study of a biorefinery producing ethylene from lignocellulosic feedstock for a chemical cluster. 6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems.

⁸ Arvidsson, M., and Lundin, B. (2011) Process integration study of a biorefinery producing ethylene from lignocellulosic feedstock for a chemical cluster. MSc Thesis, Chalmers University of Technology.

these processes at a petrochemical cluster site are also investigated. The site considered is located in Stenungsund, on the west coast of Sweden. The ethanol process considered uses lignocellulosic feedstock. Figure 8.3 illustrates the studied cases with different degrees of integration between the new processes and the new processes and an existing chemical cluster.

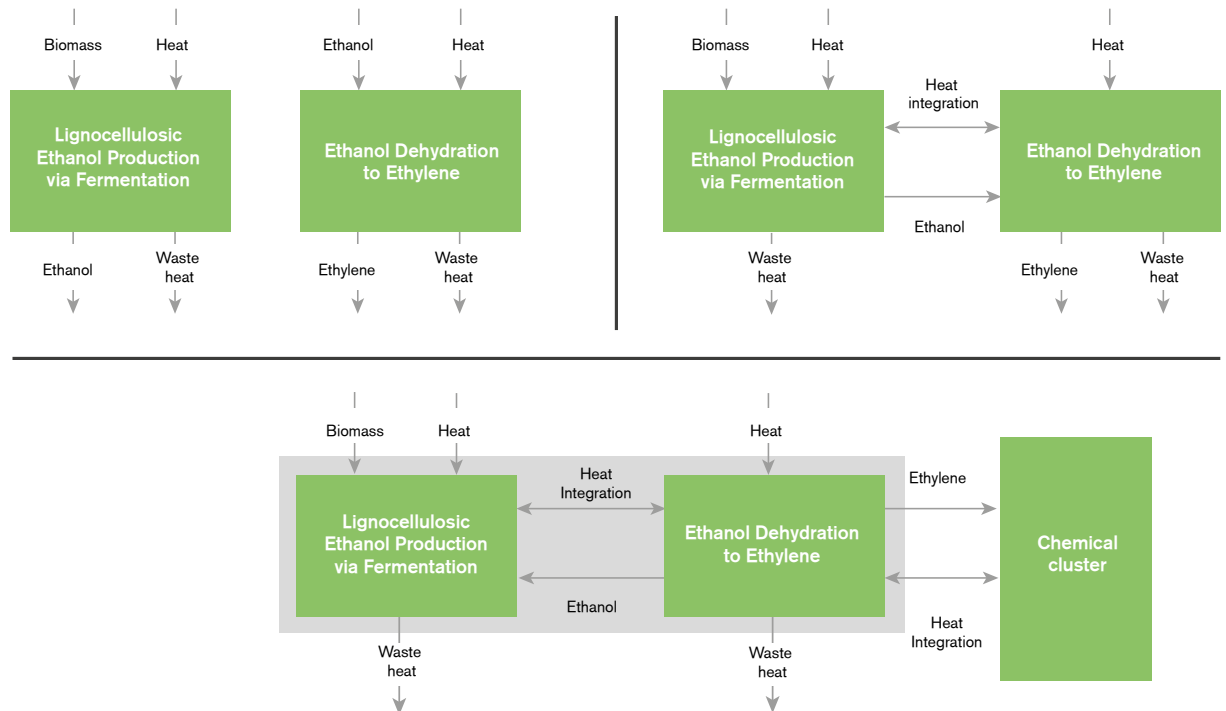


Figure 8.3 Illustration of the studied cases; upper left (base case, Case 1): no integration between ethanol and ethylene processes, upper right (Case 2): heat and material integration between the two processes, lower right (Case 3): heat and material integration between the two processes and the existing chemical cluster.

Figure 8.4 shows the GCC for the ethanol production process (producing 337 MW ethanol from 758 MW wood fuel) and the GCC for the ethanol dehydration process (producing 307 MW ethylene from the ethanol produced in the first process). If these processes are operated separately (Case 1), the combined minimum heating demand for producing renewable ethylene for the chemical cluster is 131 MW (112 + 19 MW).

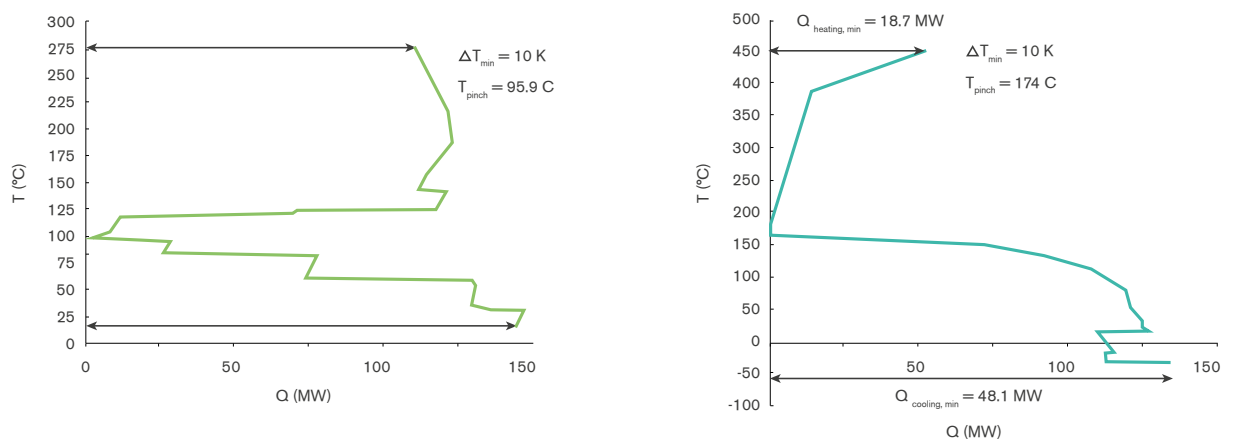


Figure 8.4 GCCs of the ethanol production process from lignocellulosic biomass (left) and ethanol dehydration process (right).

If the two processes are instead co-located (Case 2), the minimum heating demand is reduced to 82 MW. Excess heat from the ethanol dehydration process is used to cover a part of the heat demand in the ethanol process, as illustrated in Figure 8.5. Furthermore, co-locating these plants means that ethanol can be directly delivered to the dehydration plant in the vapour phase, thereby avoiding the energy costs of condensing the vapour in the ethanol process and then revaporizing it at the inlet of the dehydration process.

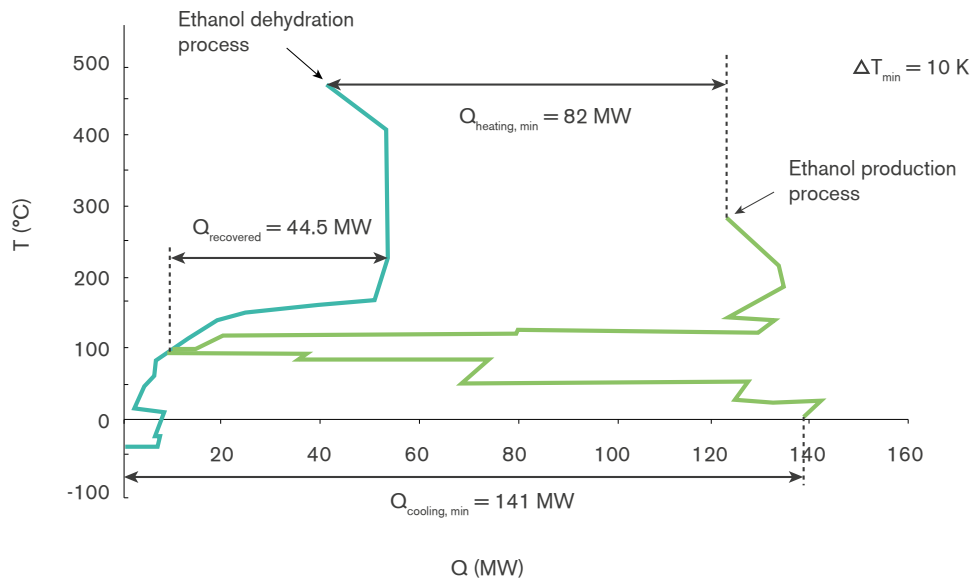


Figure 8.5 Background/Foreground analysis of the ethanol production and ethanol dehydration process; direct delivery of ethanol between the processes is accounted for in the stream data.

If the processes also are co-located with the chemical cluster (Case 3), an additional 18 MW heat can be saved by using excess heat from the chemical cluster. This is illustrated in Figure 8.6.

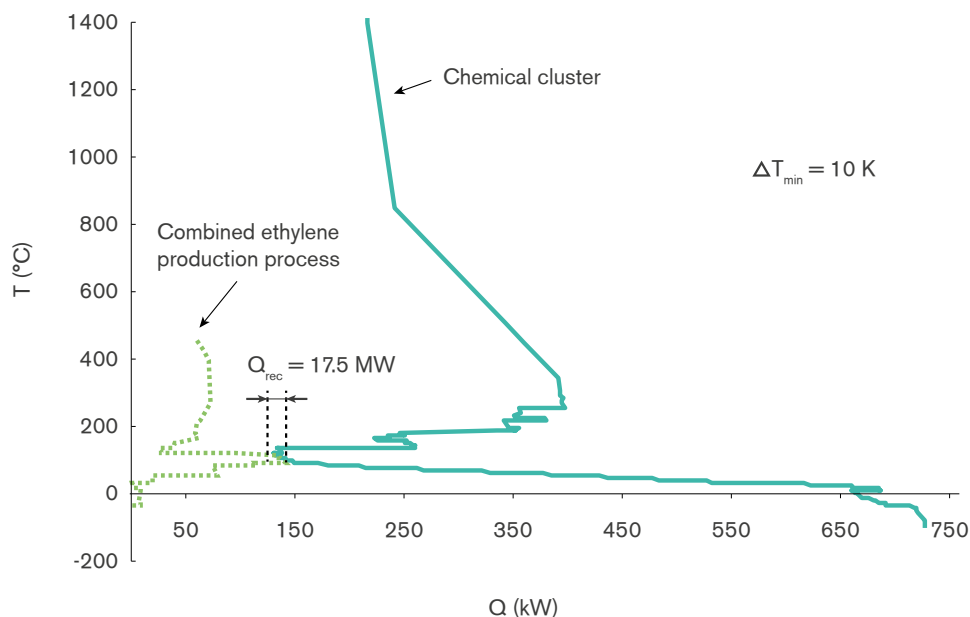


Figure 8.6 Heat integration analysis of the existing chemical cluster with the combined ethylene production process.

Altogether the maximum achievable savings by co-locating these processes amount to 66 MW corresponding to 51%. The cooling demand is also reduced by 55 MW corresponding to 28%. Table 8.1 summaries the minimum heating and cooling demands for the studied cases.

It is not only about co-location, but also doing the correct design. Maybe it is not worth designing a heat exchanger network going all the way to minimum heating demand in any of the cases. However, achievable savings by co-locating the processes will likely be approximately the same but with higher heating demands for each case.

Table 8.1 Summary of process integration results.

	Overall minimum heating demand (MW)	Overall minimum cooling demand (MW)
Separate processes (Case 1)	131	196
Heat and material integrated processes (Case 2)	82	141
Integration with chemical cluster (Case 3)	65	141**
Maximum achievable savings	66	55

**the 17.5 MW of cooling that can be saved in the chemical cluster are allocated to the cluster and not to the combined ethylene production process

The different heating demands will result in different net usage of biomass in the different cases (assuming that biomass fuel is used to satisfy the heating requirements of the different processes). 758 MW of biomass is used to produce 307 MW of ethylene. In addition, by-products in the form of different fuels are produced, altogether 489 MW. Part of these fuels are used internally in a CHP plant to cover the heating demand of the process/es and at the same time co-generate electricity. Thus, more fuel is used for this purpose in the base case (Case 1) where the two processes are located separately compared with the integrated cases (Cases 2 and 3). Table 8.2 presents the energy balances for the studied cases. As can be seen in the table, the net usage of biomass can be decreased by 107 MW, corresponding to more than 20% if the processes are colocated with each other and the chemical cluster. However, at the same time the electricity generation decreases from 57 MW to 27 MW.

Table 8.2 Energy balances for the studied cases. Ethylene is also presented as an energy flow. All energy flows in [MW].

	Case 1. Separate processes	Case 2. Heat and mate- rial integrated processes	Case 3. Integration with chemical cluster
<i>Biomass (LHV)</i>			
Input	758	758	758
By-products	489	489	489
By-products used for energy purposes	264	185	156
Net biomass**	-533	-454	-426
<i>Electricity</i>			
Production	57	35	27
Usage	32	32	32
Net electricity	25	3	-5
Ethylene (LHV)	307	307	307

**-(Input – (By-products – By-products used for energy purposes))

It is reasonable to assume that Case 1 will be located with relatively short transportation distance for the biomass feedstock, but longer transport distance for the ethanol (assuming that the dehydration plant is located within the chemical cluster but no heat integration possibilities with the chemical cluster is considered). In Case 2, ethylene is transported instead of ethanol. In case 3 it is reasonable to assume that the transport distances for the biomass feedstock is longer, but no transport of either ethanol or ethylene is necessary. Given this assumptions and a worst case scenario with only road transportation by truck, the consumption of diesel fuel for transportation could increase with approximately 3 MW⁹ if comparing Case 3 with Case 1 (5 MW in Case 3 compared to 2 MW in Case 1). This is because the weight of a certain amount of ethanol (and ethylene) in terms of energy is substantially lower.

What would then total efficiency be for these different cases considering both on-site and off-site energy use? The efficiency for the different cases is calculated by dividing ethylene produced by primary energy use (biomass, fuel for electricity (credit for export) and fuel for diesel production). The results show that the efficiency is clearly higher in Case 3 compared with Case 1, approximately 70% compared with 64%.¹⁰ Thus, the loss of electricity production and increase of diesel usage is significantly lower (also in terms of primary energy) compared with the decreased use of biomass in Case 3 compared to Case 1.

The profitability of producing ethylene from woody biomass instead of natural gas will primarily be dependent on the required investment cost, future prices of

9 Assuming that one truck consumes 4,1 MJ diesel/km, that one truck transports 293 GJ biomass, 883 GJ ethanol and 1513 GJ ethylene and that the transport distances (km) are 150, 450 and 0 in Case 1, 150, 0 and 450 in Case 2 and 450, 0 and 0 in Case 3 for biomass, ethanol and ethylene respectively.

10 Assuming a fuel-to-electricity efficiency of 45% and a fuel-to-diesel efficiency of 80%.

natural gas and wood fuel, and possible revenues from policy instruments promoting production of renewable chemicals and materials. The decreased wood fuel usage achieved in Case 3 compared with Case 1 could be crucial in order to reach profitability for renewable ethylene production.

Dehydration of ethanol to ethylene is a commercial process, while production of lignocellulosic ethanol is not. Therefore, renewable ethylene production could be introduced using bio-ethanol available today e.g. produced from sugar cane in Brazil. Thus, this situation will correspond to Case 1 (illustrated in Figure 8.4), where the ethanol process and the ethylene process are not co-located.

As has been shown, the main part of the heat integration is achieved by co-locating the ethanol and ethylene processes. These processes have large amounts of low temperature excess heat suitable for district heating production. Therefore, even larger heat integration opportunities could be achieved if these processes are co-located with a district heating network compared to if heat integrated with the chemical cluster. Naturally, the ideal situation is that both integration possibilities can be achieved at the same location. As has been mentioned, one can also investigate other alternatives for making use of low temperature excess heat such as an organic Rankine cycle.

CONCLUDING REMARKS

There are different criteria for selecting the location of biorefineries such as closeness to raw material, product markets and heat sinks and sources or existing experience and know-how concerning raw material, processes or products. Different locations could be suitable for different biorefinery technologies. There are general advantages when co-locating biorefineries with existing industries such as making use of existing infrastructure. In a Swedish perspective, the pulp and paper industry is a major industry that accounts for a large share of potential sites of interest for co-location of biorefineries. There are several reasons why the pulp and paper industry is interesting for co-location of biorefineries including long-term experience and well-developed infrastructure for handling large volumes of biomass. Possible disadvantages include lack of knowledge about the products and their markets. Industrial plants such as oil refineries and petrochemical complexes are based on fossil feedstocks and are currently exploring options to integrate renewable feedstock into their operations. There are a number of advantages when co-locating biorefineries at oil refinery and petrochemical cluster sites. These industries can often use biorefinery products directly as feedstocks in their production processes and they have experience and know-how concerning the (final) products and their market. Possible disadvantages could for example be long distances to and lack of experience of handling large biomass resources.

In this chapter pros and cons with different biorefinery locations have been described from different perspectives: technology and existing industry. From a societal perspective it is desirable that biomass is used in a way to achieve e.g. high overall efficiency and large GHG reductions in combination with businesses with sufficient profitability. It is easier to quantify the effect of certain parameters such as transportation distances for raw material or products or the degree of heat

integration, whereas the effect of other parameters are more difficult to quantify, e.g. experience and know-how concerning handling of the raw material, the processes or the products. However, experience and know-how could be crucial in order to reduce different risks of implementing new biorefinery technologies and thereby increase the probability of commercialisation and technology diffusion. Thus, since different industries would enjoy different advantages when selecting a location for a biorefinery, co-operation between different industries where they each use their experiences and know-how could be a key to success. In the development of biorefinery industries, one can observe that for example industries that previously have not been in contact, now have joint interests and therefore have started to cooperate.

One important driving force for location of biorefineries is the opportunities for heat integration, which was the focus of the latter part of this chapter. An example has been included that shows the consequences of different locations with different possibilities for heat integration. The example illustrates that choosing the appropriate location for different parts of the biomass conversion chain in relation to each other and to existing industry could be very important and that heat integration possibilities could be more important than for example transportation distances for raw material. In order to reach sufficient profitability for biorefinery processes, co-location with possibilities for heat integration could be important.

9

WHAT IS THE EFFICIENCY OF A BIOREFINERY?

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INTRODUCTION

The thermal efficiency is a key characteristic of thermal processes, defining how much of the fuel input that is converted to desired energy services and products. The thermal efficiency is closely related to the cost, in both economic and environmental terms, of generating a specific energy service. Development of energy efficient systems has been a prerequisite of industrialisation and economic growth. A modern state of the art 1000 MW coal fired power plant may have a thermal efficiency of some 47% whereas the first Newcomen steam engine that set in motion the industrial revolution 300 years ago had an efficiency of less than 1%. Given the limited availability of biomass (see Chapter 4), energy efficiency is now a key issue also for bioenergy-based systems.

However, care has to be taken when comparing thermal efficiencies between processes since different assessments may have used different definitions of thermal efficiency and applied different system boundaries. This chapter concerns biorefinery processes for which the efficiency concept is associated with the additional difficulty of comparing different energy services and products. Biorefineries typically produce a variety of products such as fuels, heat, electricity, chemicals and materials (see e.g. Chapters 3 and 6). Consequently, different markets and users may value the output according to different standards.

As an example, combined heat and power (CHP) may cause confusion since the thermal efficiency is often defined by adding the two energy services heat (for e.g. district heating) and electricity and dividing these with the fuel input to obtain the thermal efficiency of the CHP plant in spite of that such a ratio is not very

informative (some would say incorrect) from a thermodynamic point of view. Yet, for a local heat market such efficiency gives important information on the extent to which the fuel is efficiently converted to heat and electricity. Furthermore, in a municipal energy system with district heating CHP units one typically considers heat to be the main product while the electricity is produced as a co-product that increases the income of the local utility. There are also examples of heat produced as a by-product from a large power plant where the electricity is the main product. In the latter case, the relevant efficiency for the plant owner would instead be the electric efficiency.

In summary, it is difficult to define a standard expression for evaluating efficiencies for biomass conversion processes, especially for biorefineries producing several products and energy services. Thus, when evaluating and comparing different processes it should always be clear how the thermal efficiency is defined. If the definition is not clear, there is a risk that a process may be perceived as more favourable than it is, or the opposite. The aim of this chapter is to illustrate how the concept of thermal efficiency can be used to evaluate biorefinery processes and highlight risks of comparing efficiencies from different sources. Some commonly used definitions are illustrated and their advantages and drawbacks are discussed. Several examples are used to emphasise the importance of transparency and of clearly defining performance measures and system boundaries.

MEASURES OF ENERGY INPUT

A general expression for thermal efficiency is given in Eq. 1. As is clear from the introduction such a general expression can be given different meaning depending on context. In this chapter we will elaborate on different ways to quantify thermal efficiency.

$$\eta_{th} = \frac{\text{Useful energy services and products}}{\text{Fuel input}} \quad (1)$$

In this section we will start with the denominator in Eq. 1 and discuss what can be meant by “fuel input”. Biomass is a heterogeneous fuel (compared to natural gas, coal and oil) and may therefore vary substantially in composition and water content. Thus, it is important to consistently define its energy and water content.

The *moisture fraction* (f_M) of the fuel ($\text{kg}_{\text{water}}/\text{kg}_{\text{wet fuel}}$) is defined in Eq. 2, where m_{dry} is the mass of the dry part of the fuel (dry matter) and m_{wet} is the total mass of the wet fuel.

$$f_M = \frac{m_{\text{water}}}{m_{\text{wet}}} = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{wet}}} = 1 - \frac{m_{\text{dry}}}{m_{\text{wet}}} \quad (2)$$

The heating value defines the chemically bound energy within a certain fuel ($\text{J}/\text{kg}_{\text{fuel}}$). The heating value is calculated from the heat release of the fuel when the fuel is reacting completely with oxygen and the products are returned to the initial temperature before heating (e.g. 25 °C). The value is given as *Higher Heating Value* (HHV, also called higher calorific value) where the water is condensed or as *Lower Heating Value* (LHV) where the water is not condensed. The water that can

be condensed comes partly from the water in the fuel (moisture) and partly from the reaction between hydrogen in the fuel and oxygen.

The heating value of a fuel can be specified for the dry matter of the fuel and for the wet fuel including moisture. While the former is a constant for a given fuel (LHV_{DM} and HHV_{DM}), the latter depends on the moisture fraction ($LHV(f_M)$ and $HHV(f_M)$). The former is simply the latter with a zero moisture fraction. In addition, depending on the process to be described the heating value of a wet fuel can be given specific to the dry fuel mass (index “dry” below) or the wet fuel mass (index “wet”). For example, during a drying process the mass of dry fuel will remain unchanged while the total (= wet) mass will change. It may therefore be more convenient in that case to define the heating value on a dry basis. It is important when stating efficiencies to clearly indicate what heating value has been used as well as the moisture content of the fuel it has been calculated for.

The HHV on a dry basis (HHV_{dry}) does not change with increasing moisture content but is always equal to HHV_{DM} since the energy that is required to vaporise the moisture equalises the energy that is later gained from the condensation (see definition above). The HHV on a wet basis (HHV_{wet}) declines linearly with increasing moisture fraction since the mass fraction of the combustible part of the wet fuel decreases.

$$HHV_{wet}(f_M) = (1 - f_M) \cdot HHV_{DM} \quad (3)$$

The calculation of the lower heating values is somewhat more complicated. First, the energy that is not recovered from condensation of the water from the reaction between hydrogen and oxygen (Q_H) needs to be deduced from the HHV , second the energy required for vaporization of the moisture content (Q_M) needs to be deduced. The LHV of a given fuel as a function of moisture fraction can then be expressed either on dry fuel basis ($MJ/kg_{dry\ fuel}$)

$$\begin{aligned} LHV_{dry}(f_M) &= HHV_{DM} - Q_H - Q_M = \\ &= HHV_{DM} - H_{evap} \left(w_H \cdot \frac{M_{water}}{M_H} + \frac{f_M}{1 - f_M} \right) \end{aligned} \quad (4)$$

or on wet fuel basis

$$LHV_{wet}(f_M) = LHV_{dry} \cdot \frac{m_{dry}}{m_{wet}} = LHV_{dry} \cdot (1 - f_M) \quad (5)$$

where H_{evap} is the latent heat of vaporization of water at 25°C (2440 kJ/kg_{water}), w_H is the mass fraction of hydrogen in the dry fuel and M_{water} and M_H is the molar mass for water (0.018 kg/mol_{water}) and hydrogen (0.002 kg/mol_{hydrogen}), respectively.

The moisture fraction of fresh wood chips typically ranges from 40 to 60%. This means that only half of the fuel is combustible. Thus, part of the energy content should provide the energy needed to heat and evaporate the free and bound water in the fuel. Figure 9.1 plots the LHV of stem-wood with a typical HHV_{DM} of 21 MJ/

$\text{kg}_{\text{dry}}^{-1}$ as a function of moisture fraction. It can be seen that the *LHV* on dry basis can be increased by 22% if the fuel is dried from a f_M of around 0.7 to 0.5. But if the fuel is further dried from a f_M of 0.5 to 0.2, the increase in *LHV* is only around 9%. For biomass combustion processes it is usually advantageous to dry fuels to around 40-50% moisture content.

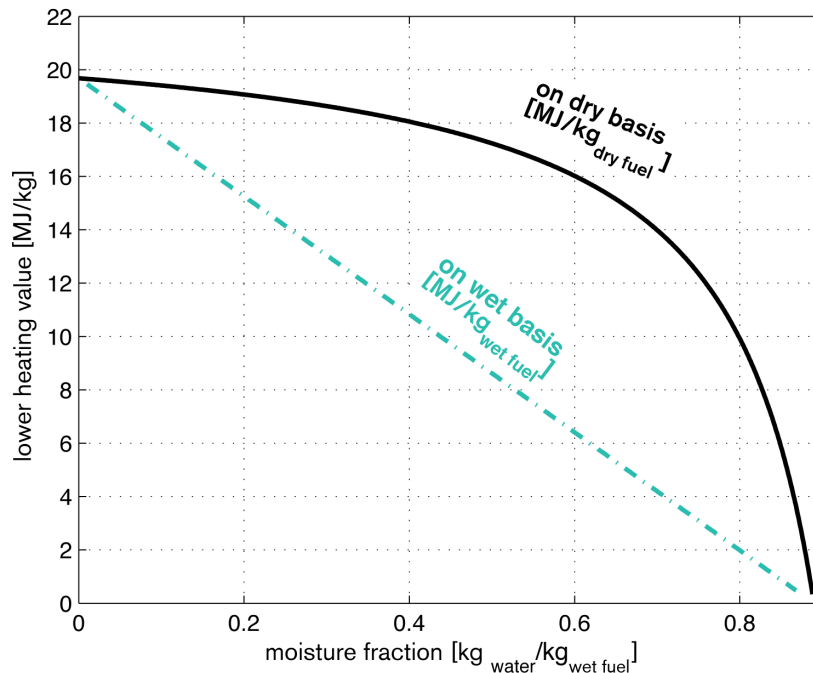


Figure 9.1 Lower heating value as a function of fuel moisture content.

In Sweden (and rest of Europe) it is common to use the *LHV* to rank fuels. An argument for this is that it is not always feasible to make use of the energy that potentially could be gained from condensing the water vapour. However, in other countries such as USA it is common to use the *HHV*. Since both *LHV* and *HHV* are used it is obviously important to clearly state which one that is used when the energy content in the fuel is specified (i.e. not only using the term “heating value”).

THE THERMAL EFFICIENCY OF A BIOMASS CHP

When interpreting a figure of the thermal efficiency of a biomass-fuelled process it must be clear if it is based on the *HHV* or the *LHV*. In the following example, a biomass fired CHP plant is used to illustrate how the thermal efficiency differs depending on which heating value is used to define the energy content in the fuel.

The thermal efficiency of a stand-alone biomass fired power plant, which produces only electricity (as opposed to a CHP plant), is in the order of 35-40%. This can be compared to a biomass boiler for heat production, e.g. hot water for industrial use or for district heating, where the thermal efficiency is in the order of 95%.² If

¹ Strömberg, B. (2005) *Bränslehandboken*. Stockholm, Sweden: Värmeforsk.

² Note that we here discuss efficiency in energy terms and do not take into account the quality of the energy. Exergy is a concept that captures the difference in quality between chemical energy in the biomass and electricity (high exergy content) and heat (low exergy content). Hence, the conversion of bioenergy to heat only would have an exergy efficiency at the same level as that for electricity production or lower, depending on the temperature of the heat.

we instead define the efficiency of a CHP plant which can be seen as a “biorefinery” in that two products are produced (see Chapter 2 for alternative definitions), namely heat and electricity, we can illustrate both the influence of the choice of heating value (LHV or HHV) and the effect of combining two different products.

Figure 9.2 gives a simplified process scheme for a biomass CHP plant in a district heating system. The process consists of a boiler with a convection part (including a flue gas condenser) for steam production, a back-pressure steam turbine, an electricity generator and a heat exchanger for distributing the produced heat to the district heating system. Here, the efficiencies in Figure 9.2 are calculated according to Eqs 6-8, where η_B is the efficiency of the boiler.

$$\eta_B = \frac{\text{Heat to process}}{\text{Fuel to boiler}} \quad (6)$$

The efficiency for electricity production is calculated according to Eq. 7, where η_M is losses due to mechanical friction e.g. in bearings, which is typically a few percent, implying that η_M is in the range of 0.98-0.99. The η_G is coupled to losses in the generator and is usually in the range of 0.96-0.98. The turbine efficiency (η_T) is here put to 0.25 which is a typical value for combined heat and power operation.

$$\eta_{EI} = \eta_M \cdot \eta_G \cdot \eta_T \cdot \eta_B \quad (7)$$

The total thermal efficiency (η_{Tot}) when both heat and power production is combined is then calculated according to

$$\eta_{Tot} = \eta_{EI} + \eta_Q \quad (8)$$

where η_Q is the efficiency of heat transfer to the district heating system.

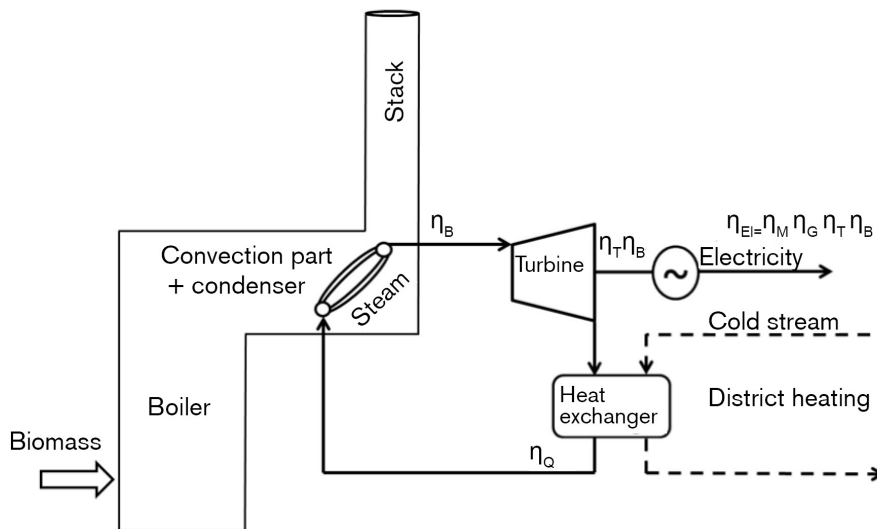


Figure 9.2 Biomass fired combined heat and power plant.

In this example, the boiler is fired with wood chips that contain 50% moisture (f_M). The mass fraction of hydrogen (w_H) is 6% and the HHV_{DM} of the fuel is 21 MJ/kg.

The total thermal efficiency when both electricity and heat is included is 87% ($\eta_{El} = 22\%$, $\eta_Q = 65\%$) based on the *HHV*. What would the total thermal efficiency of the plant be if the efficiency is based on the *LHV* instead of the *HHV*?

The *LHV* of the wet fuel is obtained by combining Eqs. 4 and 5

$$LHV_{wet} = \left(HHV_{DM} - H_{evap} \left(w_H \cdot \frac{M_{water}}{M_{hydrogen}} + \frac{Mf}{1-Mf} \right) \right) \cdot (1-f_M) =$$

$$= \left(21 \cdot 2.44 \left(0.06 \cdot \frac{0.018}{0.002} + \frac{0.5}{1-0.5} \right) \right) \cdot 0.5 = 8.62 \left[\text{MJ}/\text{kg}_{wet} \right]$$

Using Eq. 3 and the energy efficiency based on *HHV* to derive the energy output in the numerator, the total efficiency of the plant based on the *LHV* of the wet fuel can then be calculated

$$\eta_{total,LHV} = \frac{\eta_{total,HHV} \cdot HHV_{wet}}{LHV_{wet}} = \frac{0.87 \cdot 21 \cdot 0.5}{8.62} = 1.06$$

Thus, for the CHP unit the total thermal efficiency becomes 106% based on the *LHV* of the wet fuel. The question is how can we reach an efficiency above 100%? This can be explained from the definition of *LHV* and the fact that this plant is equipped with a flue gas condenser as indicated in Figure 9.2 (convective part + condenser). The heat of vaporization is not included in the definition of *LHV*, but in this plant the heat of vaporization from the condensing water in the flue gases is used. In fact, from a theoretically point of view for the *LHV*, the total efficiency of this plant will increase with increased moisture content in the fuel as shown in Figure 9.3. However, the ratio between produced heat and electricity is not shown in Figure 9.3.

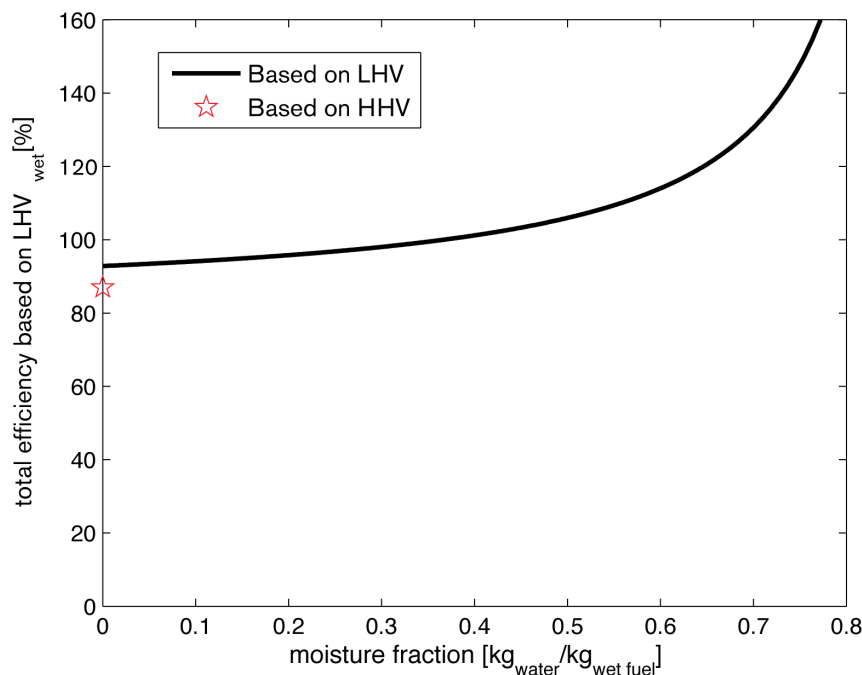


Figure 9.3 Total efficiency of CHP plant, based on the LHV on wet basis.

What actually occurs is that the combustion temperature decreases as the moisture content in the fuel increases. A consequence of this is that less high-grade steam is produced resulting in less electricity and more heat. This is shown in Figure 9.4. The decrease in electricity production is proportional to the increase in heat production as more water is fed into the boiler.

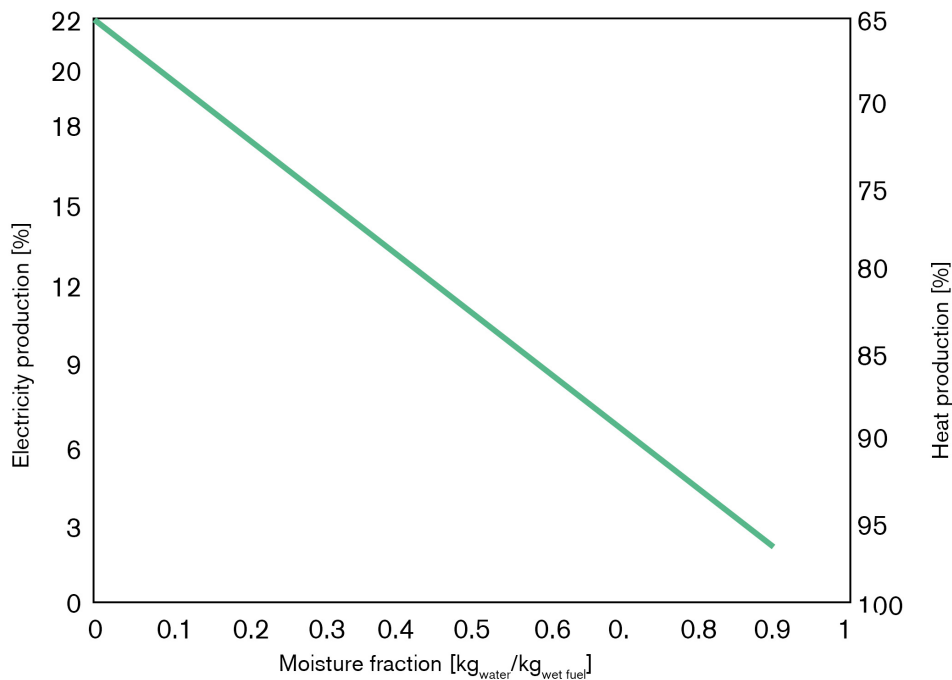


Figure 9.4 Electricity and heat production as a function of the moisture fraction in the fuel.

THERMAL EFFICIENCY OF A BIOREFINERY PROCESS

The above example shows that thermal efficiency of a CHP plant, that produces the two products heat and electricity, is crucially dependent on the exact measures used. Hence, it is of great importance to specify how the thermal efficiency is calculated. This also provides an illustration of the difficulty of defining a standard measure of conversion efficiency, especially for biorefineries that produce several products and energy services at the same time (see also discussions on multiple outputs in Chapters 3 and 6, and on system expansion and allocation of emissions between products in Chapter 10).

Figure 9.5 shows a general representation of input and output of a biorefinery process. There may be several biomass fuels used within the process and several products and services may be produced at the same time. For example, electricity and heat might be co-generated from a process having a biofuel as main product. In the thermal energy efficiency definitions proposed here, it is assumed that the biorefinery process is supplied with one or several fuels and that it produces one main product (product 1 in Figure 9.5) and possibly several by-products. Depending on the process, electricity and heat are inputs or outputs.

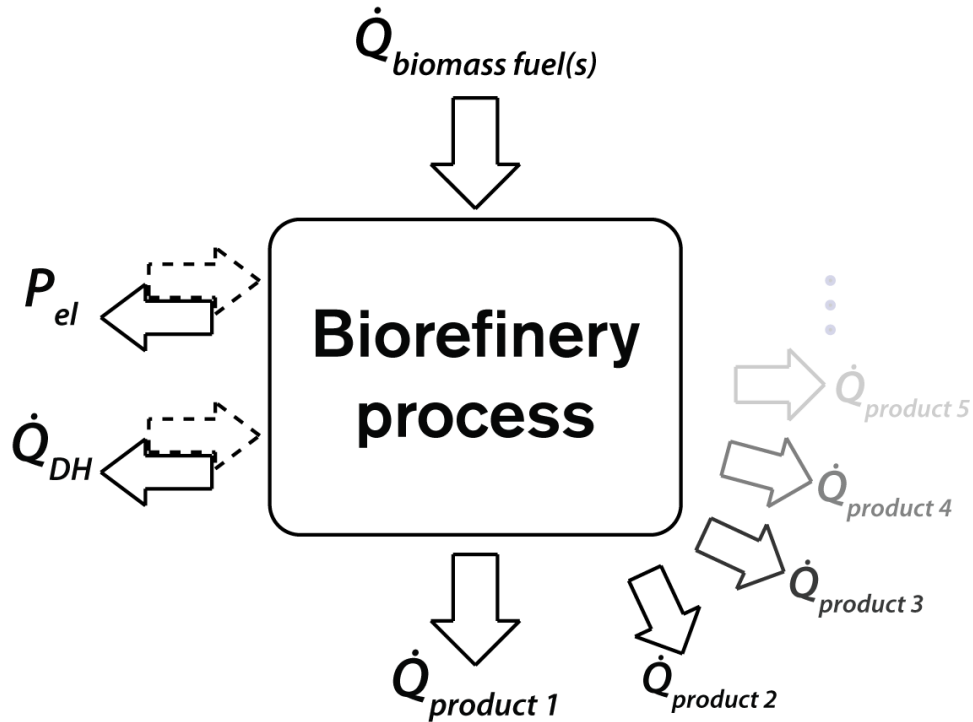


Figure 9.5 Energy input and output of a biorefinery process.

The evaluation of the thermal efficiency of a biorefinery process can be done in various ways. It is difficult to point out an efficiency definition that is superior and applicable to all kinds of biorefinery concepts and processes. The aim of this section is to illustrate several alternatives for the thermodynamic process evaluation and to, once more, stress the importance of clearly defining the way the evaluation is done. Different definitions for the thermal efficiency aim at illustrating different process aspects, but care has to be taken when different measures are compared. In order to be able to recalculate one efficiency number into another one must know the underlying assumptions and the definitions used. Unfortunately, published information on efficiency figures often lacks this clarity, making it very hard to compare results from different sources.

The most general form of the thermal efficiency is provided in Eq. 1. For a biorefinery process this equation can be expressed more explicitly as

$$\eta_{th} = \frac{\sum_i \dot{Q}_{prod,i} + (P_{el}^- \cdot P_{el}^+) + (\dot{Q}^- \cdot \dot{Q}^+)}{\sum_j \dot{Q}_{biomass,j} + (P_{el}^+ \cdot P_{el}^-) + (\dot{Q}^+ \cdot \dot{Q}^-)} \quad (9)$$

where \dot{Q}_{prod} and $\dot{Q}_{biomass}$ are the energy values of the resulting product(s) and biomass input(s), respectively. P_{el} represents the electricity and \dot{Q} the useful heat (often in the form of e.g. district heating) that either is exported (superscript “-”) or imported (superscript “+”). For electricity and heat only net flows are accounted for, meaning that the terms only can appear either in the numerator or the denominator. The thermal efficiency rates all energy services at the same level, not taking into account their quality (see Footnote 4). A certain amount of energy available as excess heat from the process (\dot{Q}^-) is valued equally to the corresponding amount

of electricity export (P_{el}) or product energy (Q_{prod}). This reveals the ambiguities with the thermal efficiency use that have been illustrated in the example of the CHP plant above (see also Chapter 11 on the value of excess heat).

For biorefinery concepts producing biofuels (e.g. ethanol, bio-diesel, dimethyl ether (DME) or synthetic natural gas (SNG)) another commonly used form of thermal energy efficiency definition is the biomass-to-fuel thermal efficiency (for gasification-based processes sometimes also referred to as cold gas efficiency) comparing the energy input in form of biomass only to the energetic value of the produced biofuel. This gives a good indication on how much of the biomass energy that is conserved in the final product, but may of course be misleading in case there is a significant input of electric energy to the process, since this is not accounted for. The biomass-to-fuel thermal efficiency (η_{btf}) can be defined as:

$$\eta_{btf} = \frac{\dot{Q}_{prod}}{\sum_j \dot{Q}_{biomass,j}} \quad (10)$$

SYSTEM THERMAL EFFICIENCY

The definitions in the previous section provide estimates of the thermal efficiency of a process as such, but they leave out crucial aspects linked to the evaluation from an overall system perspective. If a process, for example, is a net user of electricity it is important to have an idea about how the imported electricity is produced and how this influences the overall thermodynamic performance. In order to be able to account for such facts, it is necessary to expand the system and take the surrounding energy system into account as illustrated in Figure 9.6.

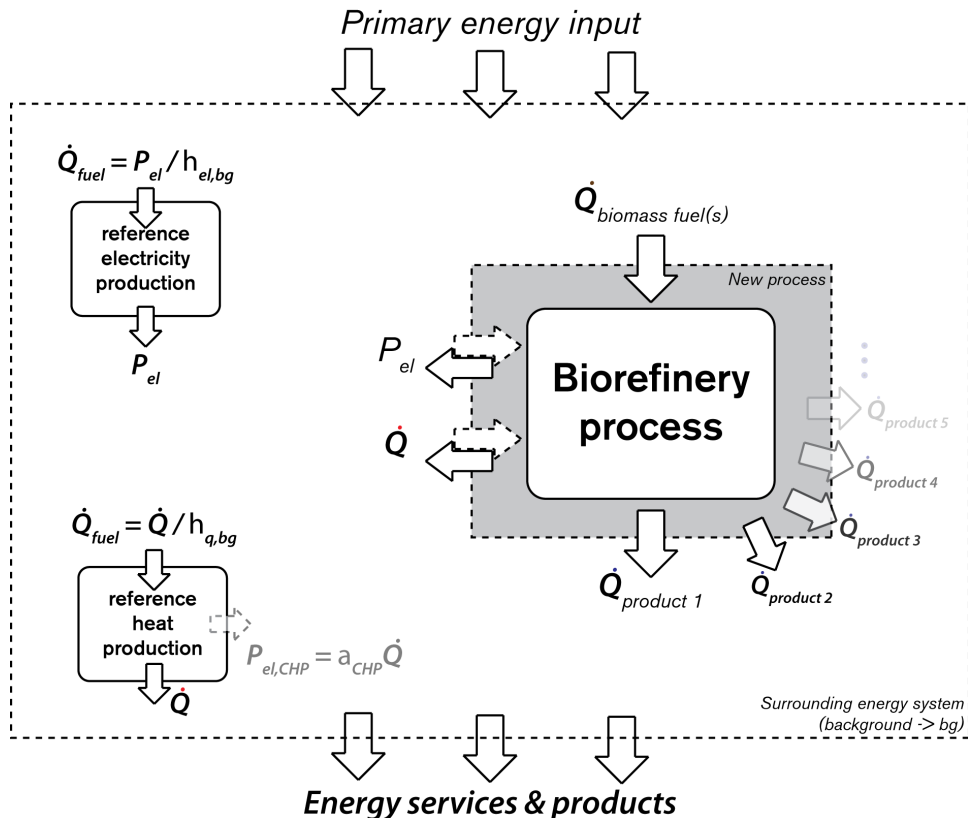


Figure 9.6 Schematic illustration of system boundary and energy flows involved in a biorefinery process.

Taking into account the surrounding energy system, it is possible to recalculate all energy services supplied and used by a process to primary energy using the corresponding reference conversion technology (see also the discussion on reference system in Chapter 10).

The overall system efficiency (η_{sys}) of a biorefinery process defined in Eq. 11 compares all primary energy inputs into the process to the energetic value of all outputs. This represents an adaptation of the thermal efficiency definition in Eq. 7.

$$\eta_{sys} = \frac{\sum_i \dot{Q}_{prod,i} + \frac{P_{el}^- - P_{el}^+}{\eta_{el,bg}} + \frac{\dot{Q}^- - \dot{Q}^+}{\eta_{q,bg}}}{\sum_j \dot{Q}_{biomass,j} + \frac{P_{el}^+ - P_{el}^-}{\eta_{el,bg}} + \frac{\dot{Q}^+ - \dot{Q}^-}{\eta_{q,bg}}} \quad (11)$$

Only net flows are considered, meaning that only heat and electricity import or export is accounted for. The efficiencies for electricity and heat production, $\eta_{el,bg}$ and $\eta_{q,bg}$ in the surrounding energy system need to be specified. If heat is a useful product that should be accounted for again depends on the surrounding energy system, i.e. on the availability of a district heating network or any other heat demanding process such as drying that actually can act as a sink for the available excess heat from the process (see Chapter 11 on the value of heat).

An adaption of Eq. 8 to the system level is possible by accounting for all fuel inputs that is necessary for the production of the main product of the biorefinery (product 1) – that is the biofuel in this case. The by-products (product 2,3...n) are in this case accounted for as a reduction of primary energy input, i.e. their energy values are deduced from the energy input. Electricity and heat input (P_{el}^+ and Q^+) are converted to primary energy input based on the reference technology for the system under consideration.

$$\eta_{btf} = \frac{\dot{Q}_{prod,1}}{\sum_j \dot{Q}_{biomass,j} - \sum_{i=2}^n \dot{Q}_{prod,i} + \frac{P_{el}^+}{\eta_{el,bg}} + \frac{\dot{Q}^+}{\eta_{q,bg}}} \quad (12)$$

This definition gives an idea about how much energy is needed for the biofuel production. However, co-generation of power and heat are not accounted for. However, this can (and should) be done. Taking into account the decrease in use of primary energy at the system level in case electricity is co-generated within the process, a fuel system thermal efficiency $\eta_{sys,fuel}$ can be defined according to:

$$\eta_{sys,fuel} = \frac{\dot{Q}_{prod,1}}{\sum_j \dot{Q}_{biomass,j} - \sum_{i=2}^n \dot{Q}_{prod,i} + \frac{P_{el}^+ - P_{el}^-}{\eta_{el,bg}} + \frac{\dot{Q}^+ - \dot{Q}^-}{\eta_{q,bg}}} \quad (13)$$

It needs to be stated that heat export (Q^-) should only be accounted for if there actually is some suitable heat sink available.

SOME ILLUSTRATIVE EXAMPLES

To illustrate the difference between the efficiency definitions and the importance of clearly stating the underlying assumptions when presenting efficiencies, a number of biofuel conversion processes are evaluated (compare the processes presented in Chapter 2). The examples are taken from a report available in Swedish.³

The different process alternatives evaluated are: wood pellet production; lignin pellet production; torrefied wood pellet production; pyrolysis oil production; ethanol production via hydrolysis followed by fermentation of the sugars; methane production via hydrolysis and fermentation; methane production via gasification; DME (dimethyl ether) production via gasification and methanol production via gasification.

The evaluation is based on the LHV on a dry-mass basis and a biomass moisture-fraction of 0.5 ($\text{LHV}_{\text{DM}} = 18.6 \text{ MJ/kg}_{\text{dry}}$) corresponding to average values for wood fuel. The reference technologies in the assumed reference (or background) energy system (according to Figure 9.5) have an efficiency of $\eta_{\text{el,bg}} = 0.4$ and $\eta_{\text{q,bg}} = 0.9$ for power and heat production, respectively. (See Chapter 10 for an illustration of what might happen when reference system parameters are changed.)

In Figures 9.7 to 9.9 the above listed processes are characterised by means of the different efficiency definitions presented in Eqs. 9-11 and 13.

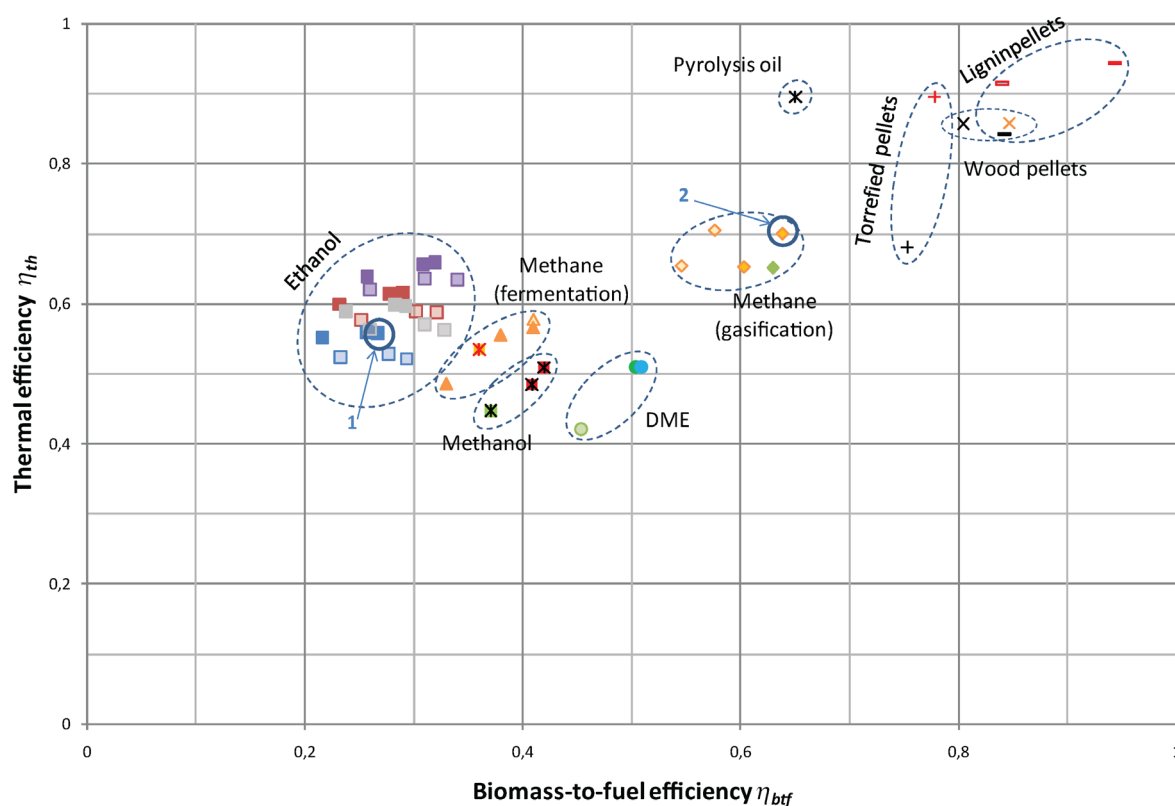


Figure 9.7 Overall thermal efficiency (Eq. 9) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Both heat and electricity are accounted for as useful by-products.

³ For details about the production pathways and technologies the reader is referred to: Thunman, H. et al. (2008) *Inventering av framtidens el- och värmeproduktionstekniker*. Stockholm, Sweden: Elforsk. (Report 08:82)

In the report, overall energy balances are set up for the different process alternatives and in some cases for varying plant sizes.

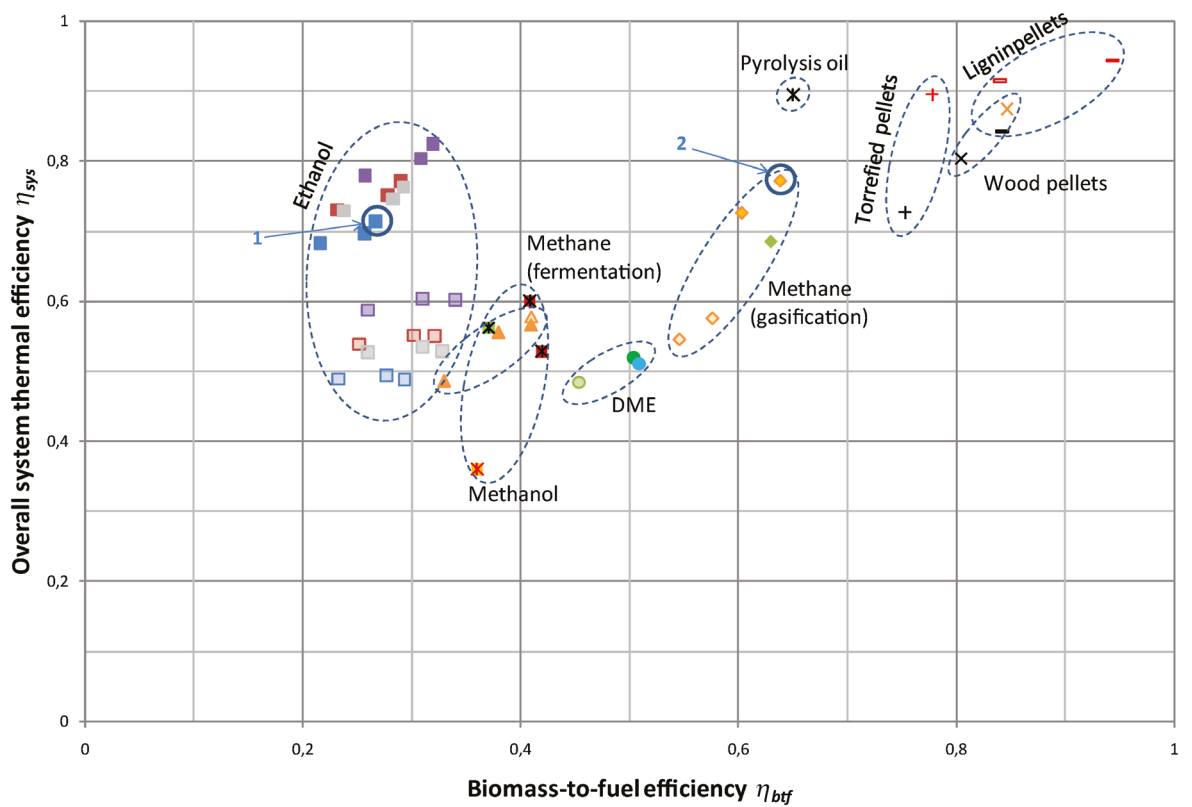


Figure 9.8 Overall system thermal efficiency (Eq. 11) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Only electricity is accounted for as useful by-product while excess heat is not accounted for as useful product.

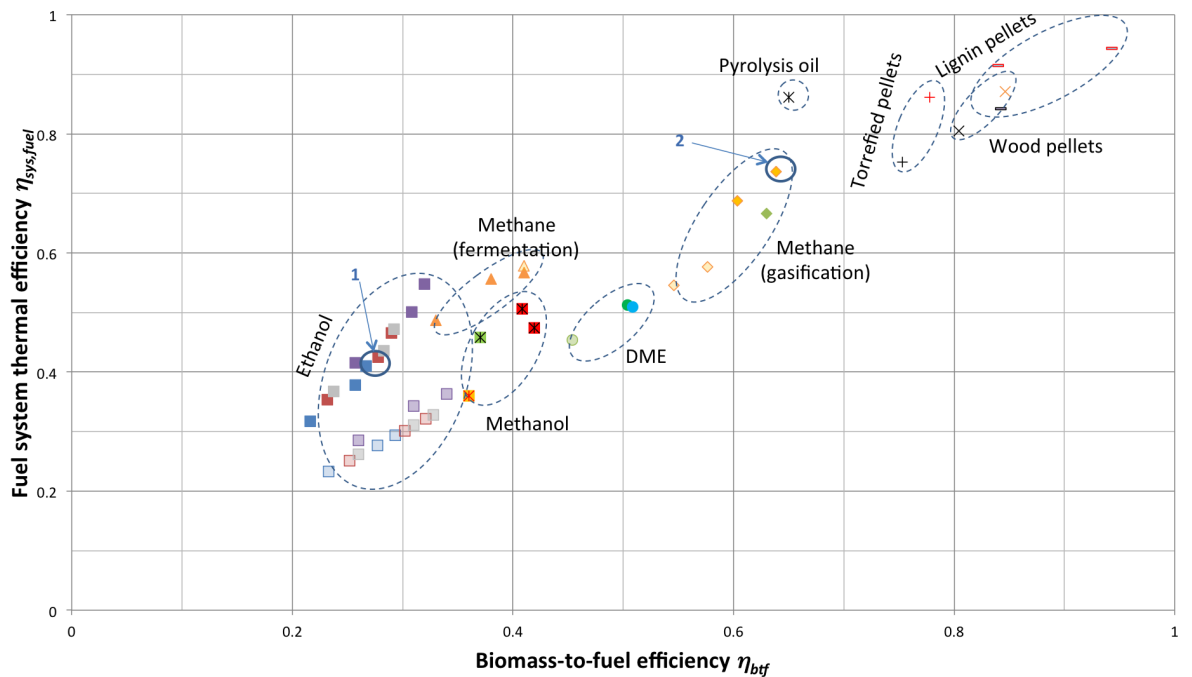


Figure 9.9 Fuel system thermal efficiency (Eq. 13) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Only electricity is accounted for as by-product.

A number of observations can be made from these figures. First, the pellet processes stand out as most efficient regardless of which efficiency definition that is used. In a sense, it is true that the energy conservation is most efficient for these processes but it has to be taken into account that the product resulting from the processes basically still is a solid biofuel not much different from the biomass input.

A second interesting aspect is to compare the thermal efficiency figures for the ethanol process alternatives. Both the overall system efficiency (η_{sys}) and fuel system efficiency ($\eta_{\text{sys,fuel}}$) rank the process alternatives with combined heat and power production (filled squares in Figures 9.8 to 9.9) higher than the stand-alone ethanol processes (semi-transparent squares). The simple definition of the thermal efficiency (η_{th}) cannot account for the differences as can be seen in Figure 9.7.

Finally, when comparing methane production via gasification and ethanol production one can observe that the overall system efficiency (η_{sys}) points out the ethanol process as performing equally well as or even better than the methane process, while the fuel system thermal efficiency ($\eta_{\text{sys,fuel}}$) gives results in favour of methane production. To explain the difference, two cases are depicted for a more detailed investigation of the influence of efficiency definition.

In Case 1, *methane is produced via gasification* with methane being the only fuel product. In order to make use of the large amounts of excess heat available from gas cooling and fuel synthesis a CHP steam cycle is used to co-generate both electricity and heat. The process is a net exporter of heat and electricity.

In Case 2, *ethanol via hydrolysis* is the main product, but considerable amounts of by-products (lignin and sugars) are generated as well. The process has a large heat demand (mainly for ethanol distillation). This heat demand is covered by a CHP steam cycle that needs extra fuel input. The size of the CHP plant is adjusted to cover the ethanol processes heat demand, resulting in a large production of electricity but no net heat export from the overall process.

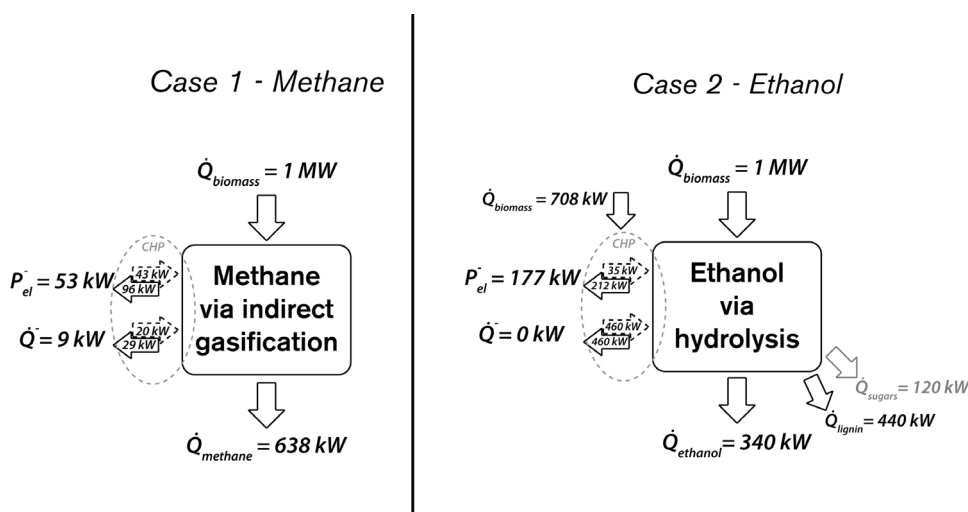


Figure 9.10 Overall energy balance for two biorefinery cases (heat losses during conversion not specifically shown).

The overall energy efficiencies are highlighted for the two cases in Figures 9.7-9.9 with the corresponding number. The energy flows of the two processes are illustrated in Figure 9.10. Table 9.1 provides the energy figures as well as calculated efficiencies. What process is considered being the more efficient one depends on whether the biofuel yield or overall energy efficiency is in focus. The methane production process (Case 1) has a substantially higher yield of biofuel compared to the ethanol process (Case 2) resulting in better figures for η_{btf} and $\eta_{\text{sys,fuel}}$. When looking at all energy services provided (η_{sys}) the picture changes drastically with both processes performing about equally well and the ethanol process even having the potential to outperform the methane process (when energy by-product 2 (sugars) are accounted for η_{sys} becomes 0.79). So again, simply stating efficiency numbers without clear definition may therefore result in misleading conclusions on the process performance.

Table 9.1 Energy performance analysis of the two process examples of methane and ethanol production.

Property	Variable	Units	Case 1 (methane)	Case 2 (ethanol)
Primary fuel supply	$\dot{Q}_{\text{fuel},1}$	kW	1000	1000
Secondary fuel supply	$\dot{Q}_{\text{fuel},2}$	kW	0	708
Process electricity demand	P_{el}^+	kW	43	35
Process electricity co-generation	P_{el}^-	kW	96	212
Process heat demand	Q^+	kW	20	460
Useful process excess heat	Q^-	kW	29	460
Energy value main product	$\dot{Q}_{\text{prod},1}$	kW	638	340
Energy value by-product 1	$\dot{Q}_{\text{prod},2}$	kW	0	440
Energy value by-product 2	$\dot{Q}_{\text{prod},3}$	kW	0	(120)*
Thermal efficiency (eq. (9))	η_{th}	-	0.700	0.560
Biomass-to-fuel efficiency (eq. (12))	η_{btf}	-	0.638	0.268
Fuel system thermal efficiency (eq. (13))	$\eta_{\text{sys,fuel}}$	-	0.735	0.412
Overall system thermal efficiency (eq. (11))	η_{sys}	-	0.771	0.716
Overall system thermal efficiency (heat export possible)	η_{sys}	-	0.781	0.716

* not accounted for in efficiency calculation

CONCLUDING REMARKS

Due to the nature of biorefinery processes having a large spectrum of possible products it is hard to define a common thermal energy definition that can be applied to all processes. The aim of this chapter is to illustrate the difficulties in judging published efficiency figures and point out important factors that affect efficiency calculations. There are certain aspects that apply to all thermal energy efficiency definitions. First, it is of utmost importance to be clear about the underlying assumptions in the definition. What heating value is the efficiency based on? What services and products are accounted for? Are all forms of energy equally valued or is there any recalculating done using conversion factors? If numbers from different studies are to be compared, the underlying assumptions need to be harmonised. Thermal efficiencies that are stated without a clear description of assumptions and definitions are not too seldom used in a way which favours a certain process and should be taken with care.

When trying to classify the introduced efficiency definitions it can be stated that the simple thermal efficiency (η_{th}) does not give sufficient information on the process performance within an energy system as all energy services and products are valued equally in this definition. The overall system efficiency η_{sys} gives a good idea on how efficient all primary energy input to the process is converted to products and services. This is generally a good indication of the process performance as it indicates how well primary energy input is converted into useful products. A drawback is the necessity to specify the surrounding energy system and conversion efficiencies of several processes. Varying the assumptions about the surrounding energy system may result in quite different numbers for the overall system efficiency (η_{sys}). When the production of a single product is in focus the fuel system efficiency ($\eta_{sys, fuel}$) is a good choice, indicating how much primary energy is required for producing a specific fuel.

Finally, there are of course more dimensions to biomass conversion efficiency than energy efficiency, which is the focus of this chapter. As the biorefinery concept is closely related to sustainability issues, one could name the economic, environmental and social dimensions of sustainability and, not at least, the climate benefit of different types of biomass production system associated with the biomass fuel used in the biorefinery. While conversion efficiency is linked to environmental and economic aspects, the environmental and economic dimension of sustainability involves a great deal more.

10

HOW MUCH CAN BIOFUELS REDUCE GREENHOUSE GAS EMISSIONS?

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INTRODUCTION

The transport sector is today totally dominated by fossil oil-based fuels, above all gasoline and diesel. In order to decrease the fossil greenhouse gas (GHG) emissions from the transport sector, and the dependency on crude oil which is a scarce resource, one option is to introduce biomass derived motor fuels, here called biofuels. However, biomass is also a limited resource which makes efficient resource utilization essential. Therefore, the usage of biomass for biofuel production will have to be compared to other possible ways to use the limited biomass resource.

The biomass derived transportation fuels that are available today includes, for example, ethanol from sugar or starch crops and biodiesel from esterified vegetable oil. Biofuels based on lignocellulosic feedstock are under development. The two main production routes are gasification of solid biomass or black liquor followed by synthesis into, for example, methanol, dimethyl ether (DME), synthetic natural gas (SNG) or Fischer-Tropsch diesel (FTD), and ethanol produced from lignocellulosic biomass (see also e.g. Chapters [2](#), [6](#) and [8](#)). Potential lignocellulosic feedstocks include forest residues, waste wood, black liquor and farmed wood. What feedstock will come to predominate in a country or region will very much depend on local conditions (see Chapters [4](#) and [5](#)).

When evaluating the greenhouse gas emission balances or overall energy efficiency of introduction of new biomass-based technologies, it is important to adopt

a life cycle perspective and consider the impact of all steps from feedstock to final product(s) (see Chapter 9 for definitions of overall energy efficiencies). There are a number of different approaches that can be used for this purpose, and different choices can be made for each step from feedstock to product. Thus, different studies can come to very different conclusions about, for example, the climate effect for a given product and feedstock. These issues have been heavily debated, particularly regarding evaluation of different biofuel routes. Parameters identified as responsible for introducing the largest variations and uncertainties are to a large part connected to system related assumptions, for example system boundaries, reference system, allocation methods, time frame and functional unit. The purpose of this chapter is to discuss a selection of these issues, in order to give the reader an improved understanding of the complexity of evaluating GHG emission balances for different biorefinery products, with biofuels used as an example.

ASSESSING GHG EMISSIONS FROM BIOFUEL SYSTEMS

The evaluation of energy efficiency and climate impact of biofuels and other transportation options is usually done from a well-to-wheel (WTW) perspective. A WTW study is a form of life cycle analysis (LCA) that is normally limited to the fuel cycle, from feedstock to tank, together with the vehicle operation, and that typically focuses on air emissions and energy efficiency¹ (see also discussion in Chapter 1 and Figure 1.2). A WTW analysis generally does not consider the energy or the emissions involved in building facilities and vehicles, or end of life aspects. The main reason for this simplified life cycle analysis is that the fuel cycle and vehicle operation stages are the life cycle stages with the greatest differences in energy use and GHG emissions compared to conventional fuels. In this chapter, WTW analysis will be used to illustrate different methodological approaches and issues regarding the different steps from feedstock to product. However, the discussion can easily be generalised to apply to other products as well.

Figure 10.1 illustrates possible main energy and material flows between the main steps in a WTW analysis of biofuels. If a biofuel is produced integrated with an industrial process, such as a pulp mill, the flows represented are net differences compared to a reference case representing the industrial process as it would have been non-integrated with the biofuel plant.

The first step in a WTW chain includes operations required to extract, capture or cultivate the primary energy source, in this case biomass feedstock. Thereafter, the biomass needs to be transported to the biofuel production plant. At the biofuel production plant, the biomass is processed into a biofuel and possibly also other products such as electricity, heat or other co-products. The biofuel production plant may have a deficit of electricity. The biofuel production process may also have a net deficit of steam. However, this is usually handled within the plant by firing additional fuel, or by using internal co-products. Thus, the biofuel plant will not have a heat deficit. It could also be possible to capture CO₂ in the process (see further below). The produced biofuel is then distributed to refueling stations. The final step includes the vehicle operation where the biofuel is used to fuel

¹ MacLean, H.L. and Lave, L.B. (2003) Evaluating automobile fuel/propulsion system technologies. *Progress in Energy and Combustion Science* 29(1):1-69.; Edwards, R. et al. (2007) *Well-to-wheels analysis of future automotive fuels and powertrains in the European context, version 2c*. JRC, EUCAR and CONCAWE.

the vehicle's powertrain. A well-to-tank (WTT) analysis includes the steps from feedstock to tank, and thus does not include the vehicle operation stage. This type of analysis could be used for example when comparing different ways to produce a specific biofuel. Most studies are focused on direct effects from physical flows in the WTW chain, but some studies also include an estimation of contributions to system change² (see also discussion in Chapter 1).

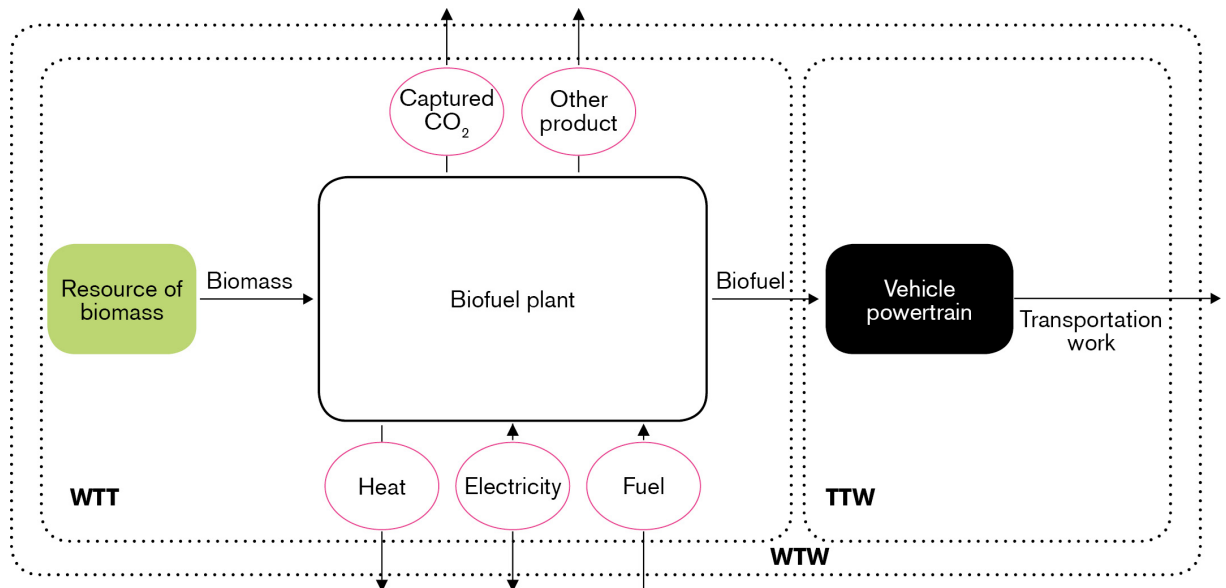


Figure 10.1 Simplified illustration of possible main energy and material flows between the main steps in a well-to-wheel (WTW) analysis of biofuels, where also the well-to-tank (WTT) and tank-to-wheel (TTW) parts are illustrated.

CO-PRODUCTS AND ALLOCATION PROBLEMS

How to allocate the distribution of environmental burdens between the different outputs of a process producing more than one product has been one of the most controversial and heavily debated issues of LCA methodology, as it can have significant impact on the results.³ Several reviews of WTW studies of various biofuels show that co-product allocation is one of the key issues that influence the GHG and energy efficiency results.⁴ (See also examples in Chapters 9 and 11 and the general discussion in Chapter 1.)

Allocation can be done on the basis of physical properties (mass, energy content, volume, etc.) or on the basis of economic value. Allocation can also be avoided through system expansion or substitution, that is, expansion of the system's

2 See for example Sandén, B. A. and M. Karlström (2007) Positive and negative feedback in consequential life-cycle assessment. *Journal of Cleaner Production* 15(15):1469-1481; Hillman, K. (2008) *Environmental Assessment and Strategic Technology Choice – The Case of Renewable Transport Fuels*. PhD Thesis. Department of Energy and Environment, Division of Environmental Systems Analysis, Chalmers University of Technology.

3 See for example Finnveden, G. et al. (2009) Recent developments in Life Cycle Assessment. *Journal of Environmental Management* 91(1):1-21.

4 Börjesson, P. (2009) Good or bad bioethanol from a greenhouse gas perspective – What determines this? *Applied Energy* 86(5):589-594.

Delucchi, M. (2006) *Lifecycle analyses of biofuels*. Draft report. Institute of Transportation Studies, University of California, Davis.; Larson, E. (2006) A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. *Energy for Sustainable Development* 10(2):109-126.

Fleming, J.S., et al. (2006) Investigating the sustainability of lignocellulose-derived fuels for light-duty vehicles. *Transportation Research Part D-Transport and Environment* 11(2):146-159.

boundaries to include the additional functions of all co-products. Co-product credits can sometimes also be handled by recalculating co-product streams into the same raw material as used for the main product and then subtracting the calculated amount from the raw material usage (see Eq. 12 in Chapter 9).

Using physical or economic allocation, or recalculation of co-product streams, to handle coproduced electricity, heat or other co-products, may hide wider system implications. Furthermore, the size of certain co-product markets are limited and this also needs to be taken into consideration, especially for large scale technology implementation.⁵ Therefore, to fully see the impact of a biofuel technology one has to estimate the impact of the co-products by using system expansion, as recommended by for example the ISO standard.⁶

REFERENCE SYSTEM

In systems analyses with the purpose of assessing global fossil GHG emissions, a baseline or reference system must be defined, based on an estimation of what would have occurred in the technology's absence. The reference system should include alternative pathways for the production of transportation fuel as well as for electricity, heat, and other coproducts. If the feedstock production results in land-use change, an alternative land use must also be included in the reference system. Similarly, when the same feedstock is in demand for other purposes an alternative biomass use should be included, as the increased use of a resource with constrained production volume results in less of that resource being available for other parts of the system, which can cause important effects that may significantly affect the results.⁷

The choice of reference system depends largely on the aim and time frame of the study. The reference system should constitute a close alternative to the studied system, adopting the same technology level. Thus, if the study includes technology for which commercialization is not imminent, the reference system should incorporate projected best available technology for the same time frame rather than presenting average technology.

Several studies show that the reference system selected results in a large degree of variation in the WTW GHG emissions, and that it may have consequences for the ranking order of the studied biofuels.⁸ This makes it reasonable to include several different reference systems (scenarios) in biofuel WTW studies, or studies of other biomass conversion systems, in particular when studies are made for a future situation.

FUNCTIONAL UNIT

⁵ Hillman, K. M. and B. A. Sandén (2008) Time and scale in life cycle assessment: The case of fuel choice in the transport sector. *International Journal of Alternative Propulsion* 2(1):1-12.

⁶ ISO (2006) *Environmental Management - Life cycle assessment - Requirements and guidelines*. European Committee for Standardization. (ISO 14044:2006)

⁷ Merrill, H. et al. (2008) Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. *Resources Conservation and Recycling* 52(12):1391-1398.

⁸ See for example Hillman, K.M. and Sanden, B.A. et al. (2008).; Wetterlund E, Pettersson K. et al. (2010) Implications of system expansion for the assessment of well-to-wheel CO₂ emissions from biomass-based transportation. *International Journal of Energy Research* 34(13):1136-1154.

In studies where different systems are compared, the functional unit must be carefully selected and defined. When biofuels are compared to each other and/or to fossil-based motor fuels, the service provided – such as the distance travelled – can be chosen as the functional unit.⁹

If biofuels are to be compared with other bioenergy applications, another functional unit must be chosen. Several studies emphasise the importance of considering the resource that will be limiting, for example in order to reach reduction of fossil GHG¹⁰. For bioenergy systems, this will typically be the available amount of biomass or the available land for biomass production. If the feedstock is the same in all considered cases, for example forest residues, the relative order of the results will of course be the same when reporting per ha and year as when reporting per unit biomass. When different feedstocks are compared, however, land use efficiency becomes increasingly important, since the land area available for biomass production is limited (see discussion in Chapter 1 on vertical system expansion and the different dimensions in Figure 1.2).

The choice of functional unit is associated with several methodological considerations. If, for example, the results are presented as driving distance per ha, adjustments of included processes need to be made by recalculation to the considered type of biomass. Thus, all flows leaving or entering the biofuel system are assumed to replace or originate from biomass-based technologies. This may lead to the inclusion of unlikely components in the system studied. For example, surplus heat from a biofuel system in current central Europe are more likely to replace fossil-based than biomass-based district heat.

If system expansion is used for a system with a relatively low biofuel output and a large output of a co-product, such as electricity, a high GHG emissions reduction potential may be erroneously attributed to the properties of the biofuel when it is really an effect of a large electricity output. To counter this problem, the functional unit can be expanded to include all energy carriers or products produced.¹¹ Using the method of an expanded functional unit, however, may lead to the inclusion of unlikely components in the system studied, since for example inclusion of stand-alone plants for production of products that are not produced in this way could be required in order for the systems to produce the same output or function. Furthermore, this approach is suitable when comparing only a few systems. With increasing number of systems, the difficulty to define relevant systems producing the same output or function increases (extensive horizontal system expansion, see Chapter 1).

CRITICAL ISSUES FOR SPECIFIC ENERGY AND MATERIAL FLOWS

Unless fallow land or waste biomass is used, both direct and indirect land-use changes associated with biomass usage can cause large increases of GHG

9 See for example Edwards, R. et al. (2007) *Well-to-wheels analysis of future automotive fuels and powertrains in the European context, version 2c*. JRC, EUCAR and CONCAWE.

10 See for example Schlamadinger, B. et al. (1997) Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. *Biomass & Bioenergy* 13(6):359-375.; Gustavsson, L. et al. (2007) Using biomass for climate change mitigation and oil use reduction. *Energy Policy* 35(11):5671-5691.

11 See for example Schlamadinger, B. et al. (1997); Gustavsson, L. And Karlsson, Å. (2006) CO₂ mitigation: On methods and parameters for comparison of fossil-fuel and biofuel systems. *Mitigation and Adaptation Strategies for Global Change* 11(5-6):935-959.

emissions (see also Chapter 4). However, also for waste biomass, such as forest residues, soil carbon dynamics can have a substantial impact. When logging residues are removed from the forest, the soil carbon stock will in general be lower than if the residues were left in the forest to decompose, particularly if looked at over a short time period. The magnitude of the impact of the soil carbon decrease is, however, uncertain.¹²

How large emissions are and how much energy is needed for the transportation, handling and distribution of the feedstock, will depend on the type of biomass, the size of the production plant, and whether it is possible to supply the plant with biomass from the local region, or whether biomass must be transported from a larger area or even imported from another country.

A net deficit or surplus of electricity can be handled in different ways, as discussed. When the system is expanded to include the electricity grids, one can use the average GHG or energy intensity of the entire system, the build margin or the operating margin.¹³ What is a relevant grid electricity mix or marginal technology to use is dependent on, for example, the time frame of the study, if one compare technical systems or impact of system intervention, and which cause-effect chains that are considered to be relevant in the given decision context (see discussion in Chapter 1). An electricity deficit or surplus can also be handled by assuming that the electricity is produced in a biomass-fired power plant. For production processes with a deficit of electricity, the calculated amount of biomass for electricity production is added to the amount of biomass feedstock, and vice versa for processes with a surplus of electricity. When doing this, the assumed biomass-to-electricity efficiency becomes important.¹⁴

Biorefinery excess heat could be used in district heating systems. However, in order for this to be possible the production plant has to be located within reasonable distance from a district heating system. The alternative district heating production is very much dependent on local conditions, such as the heat demand and availability of different fuels. For example, in a Swedish perspective a biomass CHP plant is often considered as a technique competing against industrial excess heat.¹⁵ When excess heat replaces CHP heat, biomass is released for other uses. Thus, it is important to be able to attribute a GHG emission credit for the indirect contribution to a decreased use of biomass. In a European perspective, coal-based CHP could be considered as a technique competing against industrial excess heat¹⁶. (See Chapter 11 for a thorough discussion on the use of excess heat in district heating systems.)

12 Holmgren, K. et al. (2007) *Biofuels and climate neutrality - system analysis of production and utilisation*. Stockholm, Sweden: Elforsk.

13 See for example Kartha, S. et al. (2004) Baseline recommendations for greenhouse gas mitigation projects in the electric power sector. *Energy Policy* 32(4):545-566.; Schlamadinger, B. et al. (2005) Optimizing the greenhouse gas benefits of bioenergy systems. *14th European Biomass Conference 2029-2032*. Paris, France, Oct. 17 - 21.; Ådahl, A. And Harvey, S. (2007) Energy efficiency investments in Kraft pulp mills given uncertain climate policy. *International Journal of Energy Research* 31(5):486-505.

14 See for example Joelsson, J.M. et al. (2009) CO₂ balance and oil use reduction of syngas-derived motor fuels co-produced in pulp and paper mills. *17th European Biomass Conference & Exhibition*. Hamburg, Germany, Jun. 29 – Jul. 3.

15 See for example Jönsson J et al. (2008) Excess heat from kraft pulp mills: Trade-offs between internal and external use in the case of Sweden – Part 2: Results for future energy market scenarios. *Energy Policy* 36(11):4186-4197.

16 Axelsson, E. and Harvey, S. (2010) *Scenarios for assessing profitability and carbon balances of energy investments in industry*. Göteborg, Sweden: The alliance for global sustainability (AGS).(AGS Pathways report 2010:EU1).

Even if the markets for other possible co-products such as different chemicals, are not local – as is the case for heat – it is important to consider the size of the market (see Chapter 3). Different co-product credits could for example be given depending on the degree of market penetration of the studied biofuel and its co-products.¹⁷

The possibility of CCS could affect the CO₂ emissions of a biofuel system, or other biomass conversion systems, both directly – if CO₂ capture is possible in the production process and the plant is located near an infrastructure for CCS – and indirectly if, for example, CCS is implemented in coal power plants (lowering CO₂ emissions from grid electricity) (see Chapters 2 and 7).

The final steps in the WTW chain include distribution, dispensing and usage of the biofuels. Today oil-based fuels, above all gasoline and diesel, totally dominate the transport sector and different biofuels are likely to replace these fuels. However, since crude oil is a considerably limited resource, the dominant transportation fuels of the future could be e.g. coal-based. For example, FTD produced via gasification of coal, with as well as without CCS, could be considered for the future reference transportation system. Most studies assume that produced biofuels replace gasoline and diesel, whereas other studies also consider replacement of other fuels.¹⁸ These comparisons are still relevant also if electricity is used to a larger extent in the transportation sector. Pure electrical vehicles are primary an option for personal transportation, not for heavy vehicle, and can thus only be expected to cover a part of the transportation need. For heavy vehicles, plug-in hybrids using an internal combustion engine running on biofuels or fossil-based fuels to complement the electric drive train could be an option.

AN ILLUSTRATIVE EXAMPLE

As is apparent from the descriptions in this chapter, to be able to calculate the GHG emissions for biofuels a number of choices have to be made. In this section, an example of GHG emission balance for the use of DME will be presented that illustrate how different choices regarding perhaps the most critical issue, the reference system, affect the avoided GHG emissions from biofuels.

Figure 10.2 shows how the reduction of CO₂ emissions for two biofuel production processes producing DME via gasification varies depending on assumptions about the future reference system.¹⁹ The difference between the processes are that in Process 1 (green bars) the production of DME is not maximised and the plant co-produces considerable amounts of electricity, resulting in a significant electricity surplus, while in Process 2 (grey bars) the DME production is maximised, resulting in less produced electricity and in total an electricity deficit.²⁰ There

17 See for example Hillman, K. M. and B. A. Sandén (2008) Time and scale in life cycle assessment: The case of fuel choice in the transport sector. *International Journal of Alternative Propulsion* 2(1):1-12..

18 See for example Andersson E. (2007) *Benefits of Integrated Upgrading of Biofuels in Biorefineries – System Analysis*. PhD Thesis. Department of Energy and Environment, Division of Heat and Power Technology, Chalmers University of Technology, Edwards, R. et al. (2007) *Well-to-wheels analysis of future automotive fuels and powertrains in the European context, version 2c*. JRC, EUCAR and CONCAWE.

19 For a discussion on what it would take to commercialise such a technology see Chapter 12.

20 Process 1: 100 MW biomass input resulting in 34 MW DME and 13 MW electricity. Process 2: 100 MW biomass and 6 MW electricity input resulting in 65 MW DME. Possible to capture 46 kg CO₂/GJ biomass in each process at a cost of 70 MJ electricity.

is a possibility to capture and store CO₂ from both processes. Three reference transportation options are considered: oil-based transportation fuel (in this case diesel) and production of FTD via gasification of coal with and without CCS.²¹ Four different electricity production technologies are considered: coal, NGCC (natural gas combined cycle), coal with CCS and a CO₂-neutral option (for example wind power).²² As Figure 10.2 shows, the reduction of CO₂ emissions varies significantly depending on the assumptions about future reference transportation and electricity production systems.

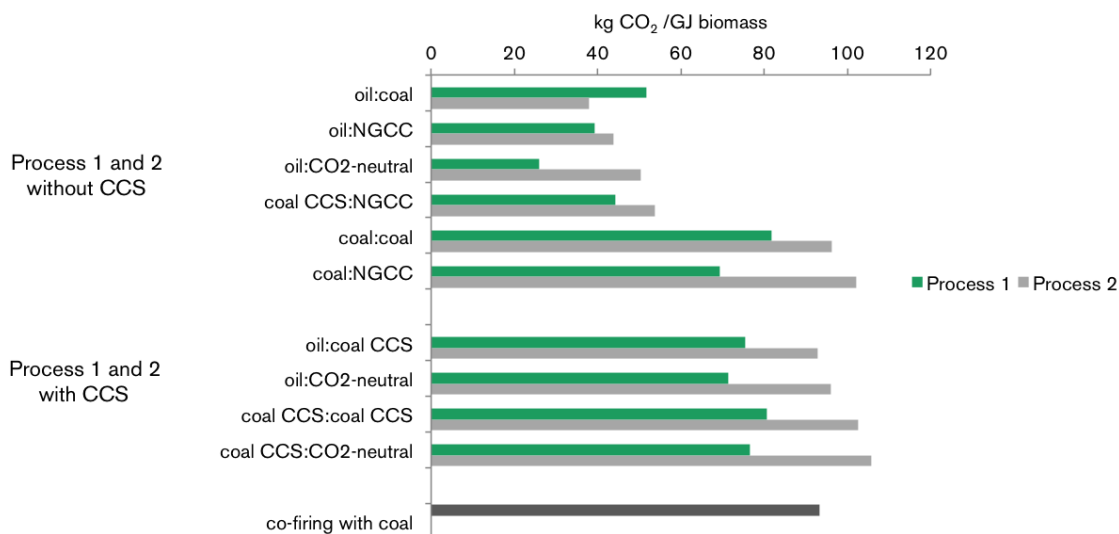


Figure 10.2. Reduction of CO₂ emissions for two biofuel production processes producing DME via gasification (see text for process descriptions). The impact of different assumptions regarding reference transportation and electricity production systems is illustrated (e.g. “oil:coal” refers to transportation based on oil and electricity based on coal). The potential CO₂ emission reduction if biomass is co-fired with coal is also shown.

Combinations that are considered to be less probable have been omitted from Figure 10.2. This significantly reduces the number of possible outcomes. If CCS is not implemented in the power sector with its very large emission point sources, it is assumed unlikely that an infrastructure for CCS is established. Thus, both CCS in the biofuel processes and in connection with motor fuels produced from coal are assumed less probable if the electricity production are coal or NGCC without CCS. On the other hand, if the electricity production in the reference system is coal with CCS, it is assumed unlikely that CO₂ is not captured in the biofuel processes and in connection with motor fuels produced from coal since CO₂ in this cases are separated as part of the processes. An electricity system dominated by CO₂-neutral technologies will probably be an indication of strong policy instruments promoting reduction of GHG in the atmosphere. Hence, if the electricity production in the reference system is CO₂-neutral, a reference transportation technology based on coal (without CCS) is considered less probable.²³

²¹ Oil (diesel): 77 kg CO₂/GJ_{fuel}, Coal with CCS (FTD): 92 kg CO₂/GJ_{fuel}, Coal (FTD): 166 kg CO₂/GJ_{fuel}.

²² Coal: 201 kg CO₂/GJ_{el}, NGCC: 104 kg CO₂/GJ_{el}, Coal with CCS: 38 kg CO₂/GJ_{el}, CO₂-neutral: 0 kg CO₂/GJ_{el}.

²³ Any larger real world system is likely to display a mix of technologies. This applies to the installed capacity as well as to annual additions to capacity. For example, in 2011 the additions to the European electricity supply comprised of a mix of solar PV, natural gas power, wind power, coal power and a range of minor sources including biomass power as well as a decrease of fuel oil and nuclear power (European Wind Energy Association (2012) *Wind in power: 2011 European statistics*: EWEA).

Process 1, with a surplus of electricity, benefits from a high CO₂ emitting electricity production technology, while Process 2, with a deficit of electricity, benefits from a low CO₂ emitting electricity production technology. Both processes benefit from a high CO₂ emitting transportation technology, however Process 2 are benefited to a larger extent. As can be seen in Figure 10.2, it is only for one of the probable reference systems, the one with oil in the transport sector and coal in the electricity sector that Process 1 leads to the largest reduction of CO₂ emissions. This reference system is representative for the current situation and therefore frequently used in these types of assessments. However, as for the example here, if it is future implementation of technologies that are currently under development, it is important to make some kind of sensitivity analysis or include a discussion regarding the influence of different assumptions regarding the future reference system. This is however not always done. Furthermore, the assumptions regarding the reference system, or other parameters that influence the results, can naturally be chosen in order to obtain specific results, for example in order to promote a certain technology or product. Thus, when interpreting results from WTW studies, or studies estimating the possibilities for GHG emission reduction from other biorefinery products, it is very important to be aware of the assumptions made in the study about the surrounding system and how they affect the potential to reduce GHG for different technologies.

The examples of results presented here show that substantial reductions of GHG emissions can be achieved by substituting fossil-based motor fuels with certain biofuels. However, biomass is a limited resource and it is not possible to solve the whole climate problem by substituting biomass for fossil fuels. Therefore, it is important to compare the usage of biomass for biofuels with other ways to use the limited biomass resource. In Figure 10.2, the CO₂ reduction potential of the biofuel processes is compared with using biomass in a coal power plant (co-firing biomass and coal). As can be seen in Figure 10.2, the reduction of CO₂ emissions are in most, but not all, more probable cases larger if biomass is used in the coal power plant than in the biofuel processes. However, there are more renewable options for electricity production than using biomass, while for transportation fuels, and other chemicals, using biomass might be the only way to go renewable.

CONCLUDING REMARKS

When evaluating the GHG emission balances or overall energy efficiency of introduction of new biomass-based technologies, it is important to adopt a life cycle perspective and consider the impact of all steps from feedstock to final product(s). There are a number of different approaches that can be used for this purpose, and different choices can be made for each step from feedstock to product. Thus, different studies can come to very different conclusions about, for example, the climate effect for a given product and feedstock. This chapter has presented and discussed different methodological approaches and choices for the different steps in the life cycle in order to give the reader an improved understanding of the complexity of evaluating GHG emission balances for biorefinery products, with biofuels used as an example.

The choice of for example allocation method, reference system and functional unit influence the potential to reduce GHG emissions. Therefore, it is very important that the calculations are transparent and the reader is able to understand the underlying assumptions. It is also important to make a sensitivity analysis and show how different assumptions regarding for example the reference system influence the results. This is especially important when evaluating technologies as part of future systems, since the actual conditions for such systems are highly uncertain (see also discussion in Chapter 1). However, it is important to be consistent and clearly distinguish between likely and unlikely combinations of different reference technologies. Using different assumptions will naturally influence the absolute potential for GHG emissions reductions from biofuels, and other biomass-based products, but it could also influence the ranking of different biofuels, and of biofuels in relation to other biomass-based products. However, some technology pathways can hopefully be identified as more robust than others, giving a guideline as how to use the limited biomass resource in order to maximise the climate benefit.

11

THE VALUE OF EXCESS HEAT - PROFITABILITY AND CO₂ BALANCES

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INTRODUCTION

Biorefineries produce many different types of products for a wide range of markets with specific characteristics (see e.g. Chapter 3). In this chapter we will discuss the implication of the availability of markets for one particular product, heat. Heat may be regarded either as waste or as a co-product of the process and the usability of heat depends largely on two issues: the temperature of the heat, and the opportunities for integrating the biorefinery with activities demanding heat, e.g. district heating systems or heat-demanding industrial processes (see also Chapters 2, 6 and 8). The aim of the present chapter is to present and discuss the importance and limitations of integration with district heating systems (DH-systems) for the profitability and CO₂ mitigation potential of biorefineries.

All processes that refine biomass generate heat which either may be useful for keeping the process at a certain temperature, may be used in connected processes (process integration), can be used to supply an external heat demand (e.g. through a district heating grid), or has to be wasted. In the last case, when there is no use of the heat, generation of excess heat should be avoided. In the other cases, from an economic perspective, it is not certain that the amount of excess heat should be minimised. The revenues from heat sales determine the optimal amount of excess heat of different temperatures. Since the optimal heat production in a process depends on local heat demand conditions, also the optimal design of the biorefinery depends on local conditions and may thus be site specific.

It is not only the local conditions that determine the optimal use of heat. A systems perspective needs to be applied to take into account changes at higher system levels (see discussions in Chapters 1, 9 and 10). Issues related to the future development of the entire energy system will affect the desirability of different options. How much heat that will be needed in district heating systems; if available biomass resources will be used for bio-materials, biofuels, heat or power generation; how the cost of electricity will change, are all questions that affect how heat can, or should, be produced and used.

The main question to be answered in this chapter may be broken up in two sub-questions: *What is affecting the possibilities for profitable utilization of process excess heat? And, how might a profitable utilization of excess heat affect different biorefinery concepts and designs as well as CO₂ emissions?* These questions cannot be treated separately but are strongly interrelated.

Most of the current literature on this subject concerns Swedish conditions. Hence, we mainly use Swedish examples to illustrate general issues. However, at some points we also include a European perspective.

THE VALUE OF EXCESS HEAT: AN ISSUE OF DELIVERY RESPONSIBILITY

The profitability of selling excess heat depends mainly on two factors: price and amount of heat that can be delivered. The amount and, especially, the price are in a real situation matters of negotiation. Hence, to be able to investigate the profitability of heat deliveries, one has to make assumptions about the price of heat, e.g. by relating to the heat production cost in the local heat production system. For instance, the price of the heat delivered can be set to the reduction in production cost of heat from other sources. Then, one can either base the production cost on running costs only, or include the capital cost. If the total cost, including capital cost, is used, the heat deliveries from the biorefinery should be as secure as if the local energy company would have invested in new capacity, i.e. the biorefinery has to take on *delivery responsibility*.

Delivery responsibility means, in this case, that the biorefinery always is ready to deliver a certain amount of heat if needed. In many cases deliveries of industrial excess heat does not come with a delivery responsibility. Instead, the industrial site delivers heat when there is excess heat available at the industry and there is a need of that heat in the district heating system. The reason that suppliers of excess heat are not willing to take on a delivery responsibility is that they prioritise the industrial process and want to have the possibility to stop heat deliveries if needed for their industrial process – to let the industrial process be dictated by heat deliveries can simply be a costly option.

If the supplier of excess heat does not have delivery responsibility, the distributor of district heating (the local energy company) has to have back-up plants to cover the energy demand when the excess heat is not delivered. This implies that the distributor of district heating needs to invest in spare capacity corresponding to the supply of excess heat. Thus, in this case excess heat will be compared to the running cost of these heat plants.

The running costs of base load production units can be very low. In Sweden for instance, waste incineration is common as base load in larger district heating system, which has negative running costs (there is a cost associated with not incinerating the waste). Another common base (or medium) load in Sweden is biomass fuelled combined heat and power plants (bio CHP) which can have running costs close to zero with the existing support schemes for renewable electricity (the revenues of electricity production cover the running costs). In a European perspective, waste incineration and bio CHP is not as common for base load production, but exists and are expected to grow considering the EU sustainability goals.¹

If the running costs of base load generation are negative or close to zero, the value of excess heat from a biorefinery is low. Certainly, the value per unit of utilised excess heat is higher if the biorefinery instead can deliver heat higher up in the merit order, and compete with middle and top load production units, which gives a considerably higher price of the excess heat. On the other hand, the utilization time is then reduced since there is no need for middle and top load all year round, which reduces the total amount of heat that can be delivered, see Figure 11.1. As also shown in the figure, the amount of heat that can be delivered depends on the size of the district heating system compared to the heat available in the biorefinery; with a comparably large amount of excess heat, the amount delivered compared to the delivery capacity decreases.

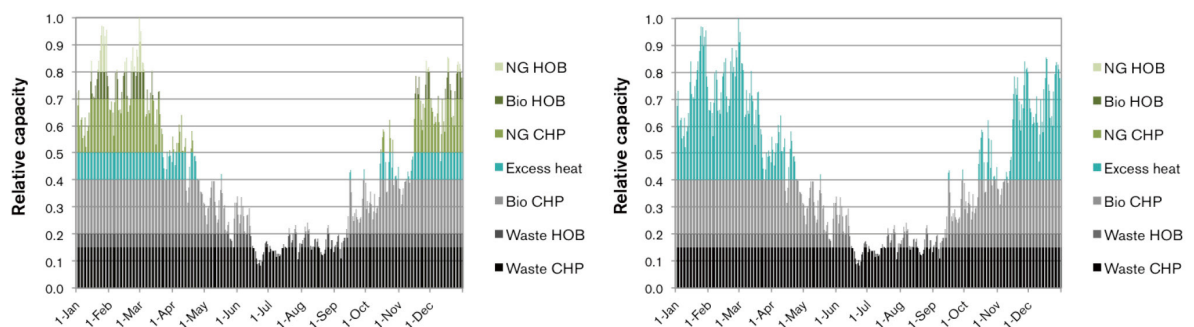


Figure 11.1 In a district heating system with low running cost of base load units it is more favourable to deliver excess heat higher up in the merit order, implying reduced utilization time due to deliveries only a limited part of the year. If the excess heat delivery capacity is large compared to the heat demand of the district heating system, the actual deliveries compared to delivery capacity decrease (compare right with left in figure). CHP = combined heat and power, HOB = heat only boiler.

If the biorefinery is ready to take on a delivery responsibility, the biorefinery can be compared to any other boiler alternative from the district heating suppliers' point of view. This means that in a case where the district heating system is in need of new capacity (preferably base load capacity), the value of excess heat can be derived from the total heat production cost, including not only running costs but also investment costs. In this case, excess heat can be a very competitive option at relatively high prices for excess heat, thus facilitating good profitability for the biorefinery heat deliveries. On the other hand, delivery responsibility might imply that the biorefinery has to make additional investments in order to be able to deliver top load heat when the main process for some reason is not operating.

¹ Johnsson F. (editor) (2010) *European Energy Pathway*. Mölndal, Sweden: Alliance for Global Sustainability (AGS).

THE ECONOMIC CONTRIBUTION OF SELLING EXCESS HEAT

One central question regarding the use of excess heat is the importance of the economic contribution from excess heat revenues. To illustrate the value of excess heat revenues, an example is constructed, see Figure 11.2. In this simplified example we consider a gasification process where 50% of the input energy is converted to a biofuel and 10% to usable excess heat (the remaining 40% are losses).² Representative energy prices for the energy flows are also assumed in order to illustrate cash flows. Two heat price levels are used to analyse the impact of excess heat revenues. To get a more complete picture also the investment cost as well as the operating and maintenance cost can be included, here taken from Boding H. et al. 2003³ where a DME (Dimethyl ether) plant is described.

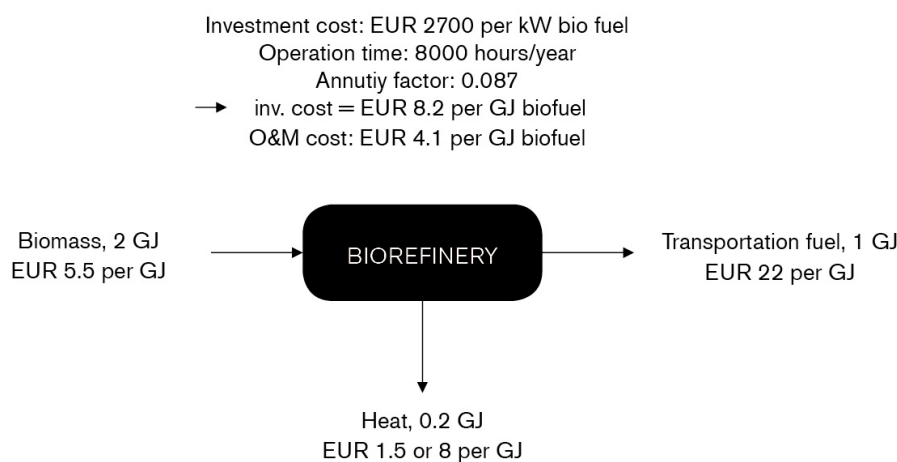


Figure 11.2 Simplification of a biorefinery, with energy flows, related energy prices as well as capital and operation costs.

With these assumptions for energy flows and energy prices, the excess heat revenues are relatively small compared to the cost of input resources in the form of wood and the revenues from sales of biofuel, see Figure 11.3. Hence, in this example, with a rather small amount of heat being utilised, the excess heat revenues are of minor importance in the overall economic picture. However, if investment cost as well as operation and maintenance cost are included, the profit margin decreases and the importance of excess heat revenues grow. In fact, with the figures used in this example, a high price on excess heat is needed to get the in-payments higher than the out-payments in this cash flow analysis.

Another way of turning the issue of heat utilisation and its profitability is to start from a long-term sustainability perspective since it might be argued that in the long term no useful heat should be wasted and, thus, when constructing new plants, all useful excess heat should be absorbed by a heat sink, e.g. a district heating system. This would introduce rather strict constraints on the design of a biorefinery

² According to the approach used in Egeskog A. et al (2009) Co-generation of biofuels for transportation and heat for district heating systems—an assessment of the national possibilities in the EU. *Energy Policy* 37: 5260–5272.

³ Boding H. et al (2003) *BioMeeT II – Stakeholders for biomass based Methanol/DME/Power/Heat energy combine*. Trollhättan, Sweden: Eco-traffic and Nykomb Synergetics.

and its system settings, and the operation of a biorefinery could be optimised as an integrated part of a district heating system.⁴

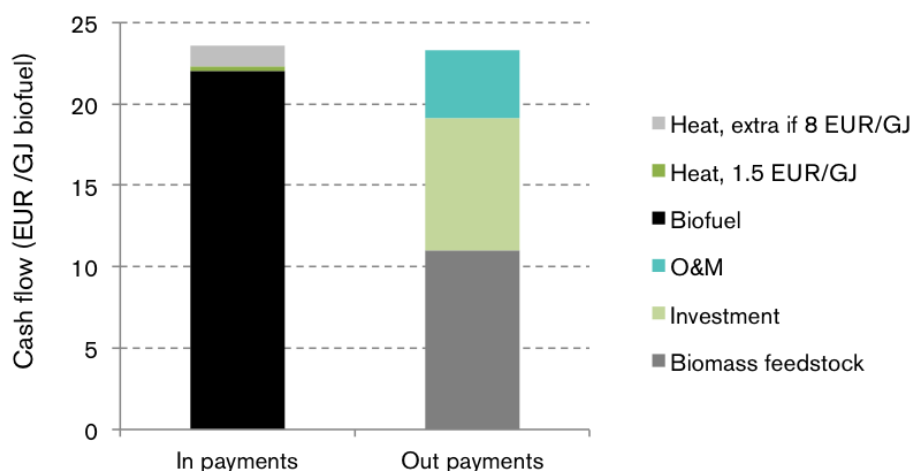


Figure 11.3 Cash flow analysis based on data in Figure 11.2.

To sum up, the profitability of selling excess heat from a biorefinery depends on the price of heat and the amounts that can be sold. As described above, these two factors in turn depend on the size of the nearby district heating system, its heat production technologies and its need for new capacity. It also depends on if the biorefinery has delivery responsibility or not and how various policy instruments affect relative prices.

Clearly, the prerequisites at the nearby district heating system are very important for the value of excess heat. Hence, localization of the biorefinery can be decisive for the profitability of heat sales. As also shown in the examples above, the income from selling heat can be an important contribution to the profitability of the whole biorefinery.

CO₂ MITIGATION POTENTIAL OF EXCESS HEAT UTILIZATION

Besides profitability of selling excess heat, the CO₂ emission consequences of using the excess heat for district heating are of interest. The use of excess heat affects emissions not only at the biorefinery but also in the district heating system and in the power generation system.⁵

At the biorefinery, the consequences on CO₂ emission of utilizing excess heat can be close to zero if the heat is true excess with no other use. If, on the other hand, the economic optimization of the biorefinery implies that some heat delivery is favoured before other use, heat deliveries imply increased resource use in other parts of the plant. One example of this could be that low pressure steam is used for district heating with very high efficiency instead of electricity production with relatively low efficiency. In this case, the CO₂ emission consequence of using steam for heat can be quantified by comparison to emissions from electricity

⁴ See e.g. Fahlén E och Ahlgren EO (2009) Assessment of integration of different biomass gasification alternatives in a district-heating system. *Energy* 34: 2184-2195.

⁵ See e.g. Fahlén E och Ahlgren EO (2009).

production in the surrounding energy system (e.g. in a reference or background system), considering the amount of electricity that could have been produced from the steam (see also discussion on system efficiency in Chapter 9 and reference systems in Chapter 10).

The CO₂ emission consequences at the district heating system of utilizing the excess heat depends on the district heating system and how the heat is used. In principal, external heat deliveries replace some kind of alternative heat production in the district heating system. Hence, the CO₂ emission consequence of heat delivery can be quantified by analyzing the heat production before and after heat deliveries from the biorefinery. This approach is exemplified in Figures 11.4 and 11.5 below. Since the CO₂ emission consequences can be very different with different configurations of the district heating system, two examples are given.

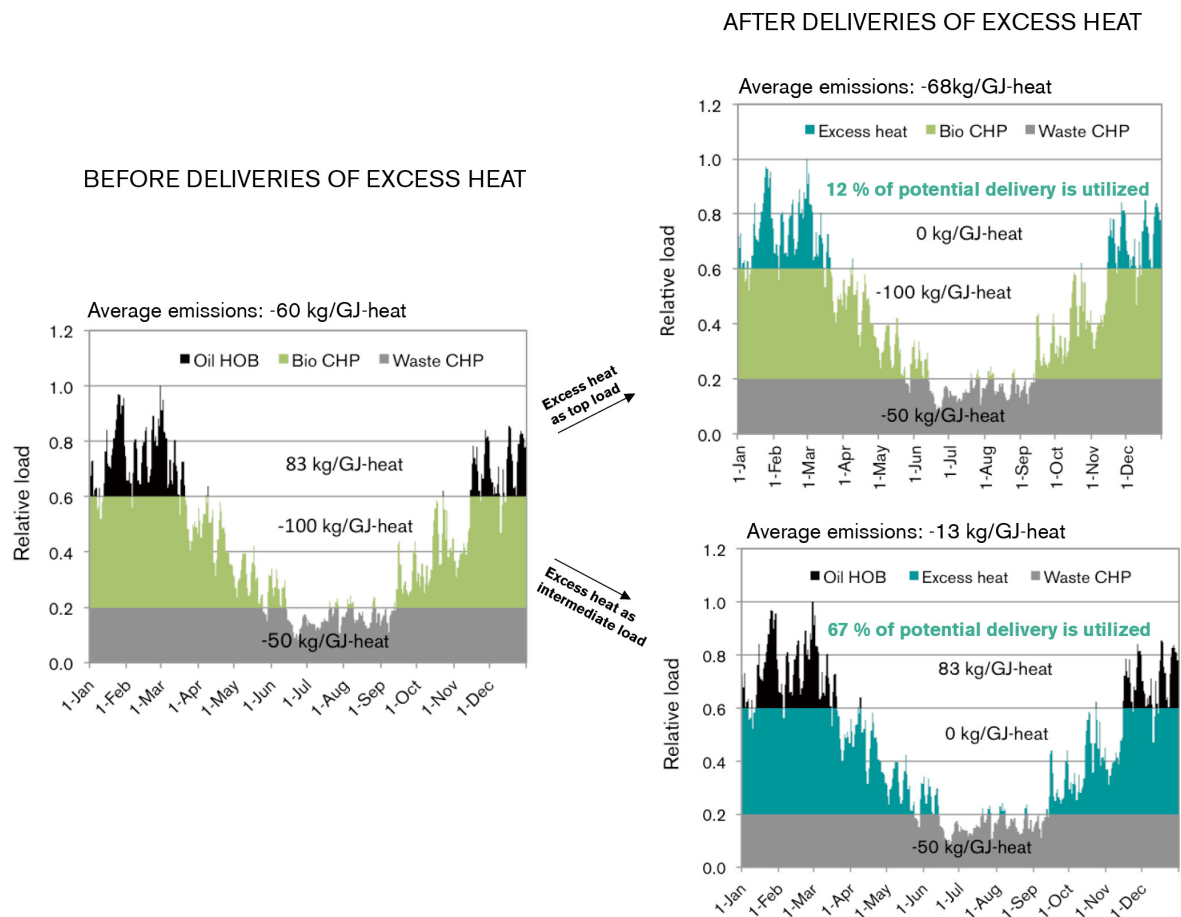


Figure 11.4 CO₂ consequences of excess heat deliveries to a typical Swedish district heating system. Emissions if excess heat is used as top load (right, above) and as intermediate load (right, below) can be compared to the case without excess heat (left).

In the first example we consider a typical Swedish district heating system with waste incineration as base load, heat from bio fuelled combined heat and power plants (bio CHP) as intermediate load, and fuel oil as top load, see Figure 11.4. As can be seen in the figure, base and intermediate load production are assumed to have negative CO₂ emissions from a system perspective. In the case of waste incineration, the negative emissions can be explained by the assumption that the

alternative treatment of waste is landfill dumping causing methane emissions. For a waste CHP there is also the effect of decreased marginal electricity generation (assuming 400 kg/MWh emissions from marginal electricity). Decrease of marginal electricity generation is also the reason for negative emissions from a bio CHP. (See Chapters 1 and 10 for more discussions about when and how different kinds of marginal effects can and should be taken into account.)

If excess heat is used to replace top load production, the CO₂ emissions decrease. As discussed in the section above, using excess heat as top load can be a relevant consideration in a case where the biorefinery cannot take delivery responsibility. As also discussed in the same section, using excess heat as top load imply that only a part of the total possible heat deliveries can be utilised, in this case 12 %.

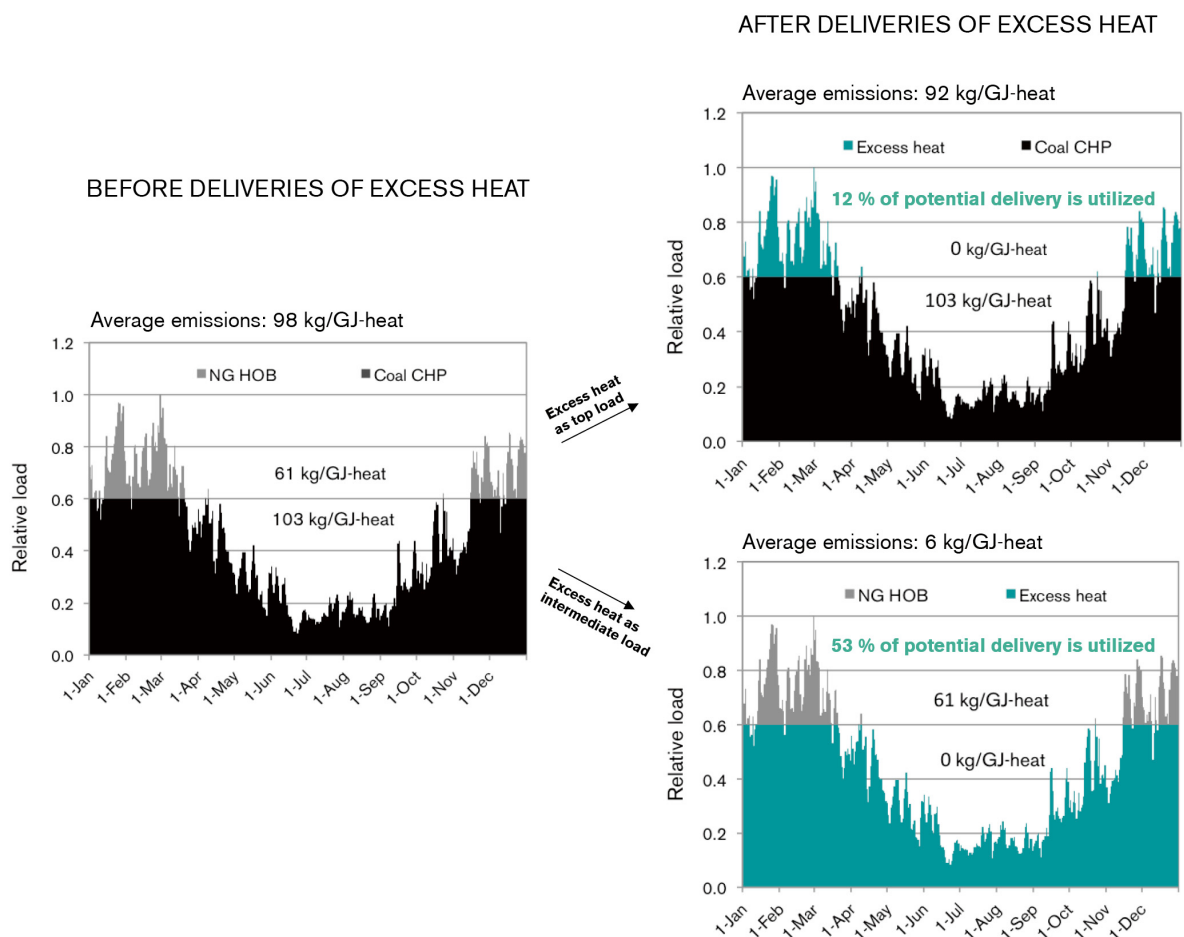


Figure 11.5 CO₂ consequences of excess heat deliveries to a fossil fuel based district heating system. Emissions if excess heat is used as top load (right, above) and as intermediate load (right, below) can be compared to the case without excess heat (left).

If a longer utilization time is desired, the biorefinery can take on delivery responsibility and, as discussed above, compete with intermediate production units in a situation where a new production unit is needed. In the example in Figure 11.4, this would lead to that 53 % of the potential heat deliveries are utilised. On the other hand, the CO₂ emissions increase when a unit with negative emission is replaced

with excess heat having zero emissions. This arguing is correct if biomass is considered to be CO₂-neutral. The CO₂-neutrality of biomass can be discussed from a wider system perspective. If wood fuel is considered as a limited resource, there is always an alternative use of biomass that sets the CO₂ emissions related to the marginal use of biomass (see the concluding section below for some further considerations that put the numbers in figure 11.4 into perspective).

In the second example we instead consider a fossil-fuel based district heating system with a coal fired combined heat and power plant as base load and a natural gas heat only boiler as top load. This kind of district heating production is more common in a European perspective. Again, the principle with top load utilization for no delivery responsibility and base load utilization with delivery responsibility can be applied, since heat production cost in existing coal plants can be very low. In contrast to the first example, excess heat deliveries imply CO₂ emission reduction in both cases, and even larger reductions in the case when excess heat replaces base load.

From the above examples it is clear that the CO₂ emission consequences of heat deliveries depend on the configuration of the district heating system and how the heat is utilised. As discussed in the previous section, the profitability of excess heat deliveries can potentially be higher if the biorefinery can take on delivery responsibility. Generally, delivery responsibility means that excess heat can compete with production units lower in the merit order, generally having lower or even negative, CO₂ emissions.

With this reasoning, there would be a trade-off between profitability and CO₂ emission reductions of excess heat deliveries from a biorefinery. The above discussion also clearly shows that the design and operation in terms of how much effort that should be devoted to the optimisation of output of primary products (electricity and fuels) strongly depend on local heat system characteristics. Further, there is also a time aspect to this since also in a European context a development towards lower emission base load is necessary in order to meet the sustainability goals of the EU, which in turn would decrease the value of excess heat deliveries from a CO₂ reduction perspective.⁶

HEAT UTILIZATION AND THE OPTIMAL SCALE OF BIOREFINERIES

There are a number of factors governing the optimal size and distribution of biorefineries and bio CHP plants. In a plant perspective, most factors improve with increased plant scale, while in a wider system perspective there are a number of factors showing opposite behaviour.

At the level of the individual plant, conversion efficiencies normally increase and costs per output decrease with size while in the surrounding energy and materials systems costs typically increase with scale. This applies to both distribution of the biomass feedstock to the plant and distribution of the plant outputs, i.e. heat and electricity, to the consumers (compare system levels in Figure 1.2). While power can be distributed over long distances many biomass fractions are local in their

⁶ See e.g. Johnsson F. (editor) (2010) *European Energy Pathway*. Mölndal, Sweden: Alliance for Global Sustainability (AGS).

character either due to transportation difficulties or due to non-mature biomass markets. These system scale factors influence the optimal plant size. Heat is an even more local product, and the market for heat is limited to the local heat demand (e.g. a city nearby the biorefinery). The heat output from a biorefinery can be enough to cover the entire heat demand of a smaller city. Hence, the local heat market can be an important factor when optimizing the size of the biorefinery.

Other energy infrastructures are also influencing the optimal scale of plants. Regarding the power grid, decentralised options might require costly grid extensions while on the other hand this more dispersed power generation might reduce the risk of power failures in areas with weaker grids. Natural gas infrastructures may also play a role for plant scaling and localisation, not only through heat market competition between natural gas and biomass but also for market access for products from gasification-based biorefineries. If synthetic natural gas (SNG), i.e. bio methane, is an output, the market access through natural gas grids may improve the possibility to maximise revenues.

PROFITABILITY AND CO₂ MITIGATION POTENTIAL IN THE RECENT LITERATURE

The issue of biorefinery and waste heat utilization has been covered in a small number of recent publications. The point of departure is often the investigation of an optimal utilization of available biomass resources; how are available biomass resources being best utilised from a carbon mitigation point of view (tonnes of CO₂ mitigated), or how the resources best are utilised from a carbon cost perspective (EUR/tonnes of CO₂ mitigated).

The profitability of biorefineries has been in focus in a few recent investigations assessing various designs connected to district heating. Major issues in the analysis have been whether the biorefinery from a system economic point of view preferably should produce transport biofuels or combined heat and power, how sensitive the technologies are to variations in electricity price and policy support such as certificates for green electricity and transport biofuels and the importance of the heat sales for the overall economics of the plants (see also Chapter 12 for a discussion of the effectiveness of different policy instruments). Generally, the time perspective has been a mid-term future, typically 2020-2025, and it has been assumed that at that time the technology is already mature and commercially available. These studies have all been assuming a Swedish setting but some conclusions could be applicable also to a more general European setting.

In a study comparing the profitability and CO₂ emissions of different biorefinery concepts including integration of a biorefinery with an existing NGCC CHP, it was found that the results are highly sensitive to assumptions regarding the production mix in the DH system and energy market developments but generally the most cost-optimal solution is a stand-alone SNG plant with DH delivery.⁷

In a techno-economic optimization of biomass utilization in the Västra Götaland region of Sweden, different bio CHP and biorefinery options connected to district

⁷ Fahlén E och Ahlgren EO (2009) Assessment of integration of different biomass gasification alternatives in a district-heating system. *Energy* 34: 2184-2195.

heating were contrasted.⁸ Policies for CO₂ reduction and renewable power promotion were assumed, and the required subsidy levels for large-scale production of transport biofuels were estimated. Results indicate a trade-off between biomass CHP generation with high electrical output and transport biofuel production. The trade-off is a consequence of constraints on local, lower cost, biomass supply. Thus, large transport biofuel production might be linked to a lower bio power generation which in a short-term perspective, assuming CO₂ intensive marginal power generation, implies minor climate benefits of transport biofuels (see also discussion on different reference systems in Chapter 10 and the example in Figure 10.2).

In two studies using the DH system in Linköping as a case, it was found that it is profitable to apply a small amount of cooling of the DH supply when a biomass gasification plant is integrated into the DH system.^{9,10} Both studies further conclude that the introduction of a biomass gasification plant into a DH system is profitable but whether transport biofuel production or combined heat and power generation is most profitable depends on energy market conditions and economic policy support levels. It is also concluded that with the applied assumptions the obtained results are relatively robust with regards to biorefinery capital cost variations.

CONCLUDING REMARKS

To sum up, the profitability and, especially, the CO₂ consequences of excess heat deliveries are complex and highly site specific. Hence, the economic and environmental impacts of heat deliveries should be evaluated for every specific case. If the targeted district heating system has low production costs and low CO₂ emissions, it can be difficult to justify utilization of excess heat.

A general conclusion could be that the profitability of heat deliveries from a biorefinery can potentially be substantially higher in a situation where the biorefinery can compete with a new base or intermediate load production unit. However, as shown above, replacement of a biomass-based production unit can have adverse CO₂ emission consequences when biomass is considered as CO₂-neutral and in abundant supply.

The conclusion that utilizing excess heat can lead to increased CO₂ emissions might seem contra intuitive and, in fact, this conclusion might be a product of too narrow system boundaries. In a wider perspective it is probably correct to utilise heat with no cost and no emissions as long as there are costs related to heat production and emissions in our energy system. If excess heat from biorefineries and other industrial processes can cover the heat demand, saved biomass in alternative heat production can be utilised in other parts of the energy system, for instance for electricity or biofuel production (e.g. in a biorefinery).

8 Börjesson M. and Ahlgren, E.O. (2010) Biomass gasification in cost-optimized district heating systems – a regional modelling analysis. *Energy Policy* 38:168-180.

9 Difs, K. et al (2010) Biomass gasification opportunities in a district heating system. *Biomass and Bioenergy* 34: 637-651.

10 Wetterlund E. and Söderström M. (2010) Biomass gasification in district heating systems – The effect of economic energy policies. *Applied Energy* 87:2914-2922.

Looking at a mature district heating market as Sweden, the situation is not always favourable for added excess heat deliveries since there will be a competition with existing base load production units as waste incineration and bio CHP. Waste incineration has a negative cost since alternative waste handling is expensive (land fill is not allowed and has to be phased out) and bio CHP has a low or negative production cost since there are policy instruments promoting this technology. This leads to the conclusion that policy instruments are decisive for how excess heat will be used. Hence, it is important that policy makers consider the system consequences when designing policy instruments to avoid any secondary, maybe unwanted, side effects.

12

POLICY CHALLENGES IN REALISING BIOMASS GASIFICATION IN THE EUROPEAN UNION

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Chapter reviewers: Maria Grahn, Daniel Johansson, Physical Resource Theory, Energy and Environment, Chalmers

INTRODUCTION

A core technology in biorefineries is that of biomass gasification (see Chapter 2). Over the last three decades, experiments have been undertaken where different applications have been explored. In the 1980s, gasified biomass replaced oil in some lime kilns in the kraft pulp industry and experiments were later made with electricity production. The current focus (and the focus of this chapter) is on synthetic fuels from biomass gasification. Within the EU nine prominent demonstration facilities have emerged since the late 1990s. These are located in Austria, Finland, Germany and Sweden, and where each plant is focusing on one of the three dominating technological trajectories outlined in Figure 12.1.

Each of these demonstration plants is at the heart of an alliance consisting of a wide range of firms, institutes and universities. Whereas some of these plants are well under way, none of them have yet completed the initial demonstration phase for production of synthetic fuels. Moreover, this phase is followed by a dramatic, and very costly, up-scaling of the plants to full scale semi-commercial demonstrations and, eventually, commercial plants. The various biomass gasification technologies are, hence, largely untried.

In such early phases of development, there are generic uncertainties facing investors in terms of technology, markets and institutions.¹ These uncertainties also abound in this case and risk delaying or even jeopardizing progress towards commercial plants. This calls into question how policy may continue to support the development of a technological field which is seen as one, of many, that may help us reduce the threat of climate change.² They also raise questions about the realism of EU's expectations of the time scale involved in creating a substantial supply of biofuels from lignocellulosic feedstock (see Chapter 4 on biomass resources and Chapter 9, Figures 9.7-9.9, on conversion efficiencies). The purpose of this chapter is, therefore, to identify policy challenges and discuss options for moving from the current small scale pilot and demonstration plants to a larger scale diffusion of gasified biomass in the EU in the course of the next decades.

Knowledge of the three technological trajectories and of the actors engaged in these is essential for our policy analysis. In the next section, we describe, therefore, the technologies associated with the current demonstration projects, identify the main technical uncertainties associated with these and the coalitions of actors that are formed around the plants. We then address the size of the financial risks for investors stemming from technical and market related uncertainties and discuss different policy instruments which can reduce the effects of these uncertainties for investors.³

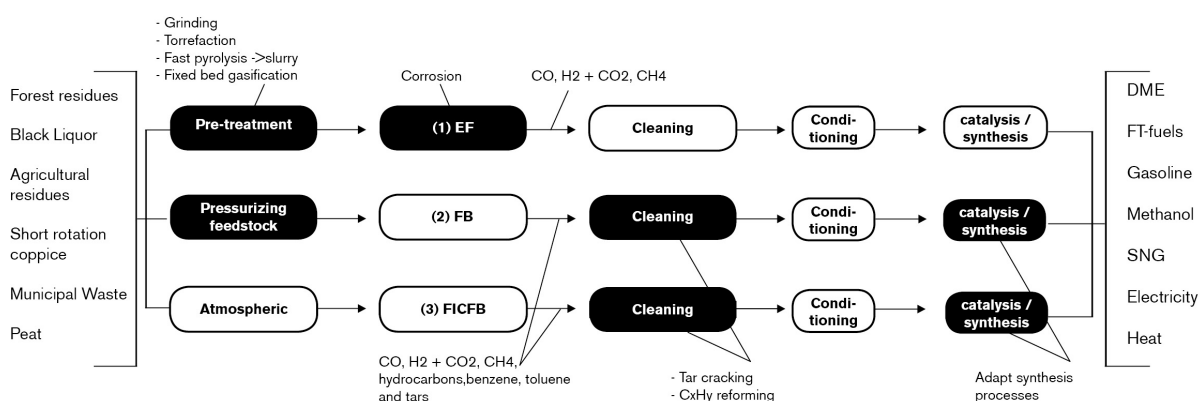


Figure 12.1 The three main trajectories for biomass gasification and main technical challenges (marked in black). The three main trajectories are: (1) Entrained Flow (EF) gasification, (2) Fluidised Bed (FB) gasification, and (3) Fast Internal Circulating Fluidised Bed (FICFB). Source: Hellsmark (2010)⁴.

TECHNOLOGY, DEMONSTRATION PROJECTS AND SUPPORTING ALLIANCES

Gasification technology rests on a set of technological capabilities associated with the thermal conversion of carbon-based fuels to a gaseous product with a usable

1 Rosenberg, N. (1996) Uncertainty and Technological Change. In: *The Mosaic of Economic Growth* 334-355 (eds. Landau, R., Taylor, T., Wright, G.). Stanford, California: Stanford University Press.

2 Our starting point is that synthetic fuels produced through gasifying biomass is an important technology for reducing emissions of GHG in the transport sector and it is, therefore, of great social interest to develop the technology (see also Chapter 10).

3 This chapter is based on Hellsmark, H., Jacobsson, S. (2012) Realising the potential of gasified biomass in the European Union—Policy challenges in moving from demonstration plants to a larger scale diffusion. *Energy Policy* 41:507-518.

4 Hellsmark, H.R.A (2010) *Unfolding the formative phase of gasified biomass in the European Union*. Doctoral thesis, Environmental System Analysis, Department of Energy and Environment Chalmers university of technology.

heating value.⁵ Many types of feedstocks can, in principle, be used, e.g. municipal waste, oil, coal and biomass, and a wide range of synthetic fuels may be produced from the gas, e.g. FT fuels, hydrogen, dimethylether (DME), methane (i.e. synthetic natural gas, SNG) and methanol, see Figure 12.1.

To some extent, biomass gasification can draw upon the knowledge base of fossil fuel gasification. However, both the physical and chemical properties of biomass are different from coal, oil and natural gas. The demands on the feeding system, reactor design as well as the downstream processes are, therefore, different. Producing a synthetic fuel based on biomass gasification consequently means that a set of additional competences related to feeding, reactor design, cleaning, conditioning and catalysis of the gas are required. Attempts to solve the technical challenges of biomass gasification, and associated uncertainties, are currently pursued along three trajectories - see Figure 12.1 where the technical challenges are marked in black.⁶

The Entrained Flow (EF) trajectory draws primarily on technologies that have been developed for oil and coal gasification. It involves gasifying biomass with oxygen under high temperature and pressure. The process results in a relatively clean gas that can be synthesised into advanced chemicals and transportation fuels with, more or less, existing downstream coal technologies. The drawback with this route, however, is that a system for pre-treating the biomass is necessary and such systems are currently not commercially available.

The two other trajectories have evolved from combustion technology into pressurised Fluidised Bed (FB) and atmospheric Fast Internal Circulating Fluidised Bed (FICFB) gasification. In the FB system, biomass reacts with a mixture of oxygen and steam. Since it is pressurised, it can be operated on a large scale, while the atmospheric process (FICFB) can be operated on a smaller scale without an external oxygen supply (indirectly heated gasification). Fluidised bed technologies are well suited to the physical and chemical properties of biomass and feeding biomass to the gasification reactor poses, therefore, few problems, although there are limited experiences with pressurised feeding systems. More importantly, the gas from both processes is more contaminated by tars, alkaloids, hydrocarbons, benzene, nitrogen and toluene, etc. than the gas from EF gasification. For transport fuels, ultra clean gas is required and there are limited experiences with producing such a gas with conventional cleaning methods. Producing transport fuel means, therefore, that competences related to cleaning, conditioning and catalysis of the gas are required.⁷

⁵ Higman, C., van der Burgt, M. (2008) *Gasification*. 2nd ed. Burlington, VT, USA: Gulf Professional Publishing.

⁶ These nine projects were identified in 2008 through an extensive literature review and interviews with industry experts. This implies that some important but more recent projects are excluded. See Hellsmark, H.R.A (2010) *Unfolding the formative phase of gasified biomass in the European Union*. Doctoral thesis, Environmental System Analysis, Department of Energy and Environment Chalmers university of technology.

⁷ For a longer discussion of these matters, including sources, see Hellsmark, H. (2010).

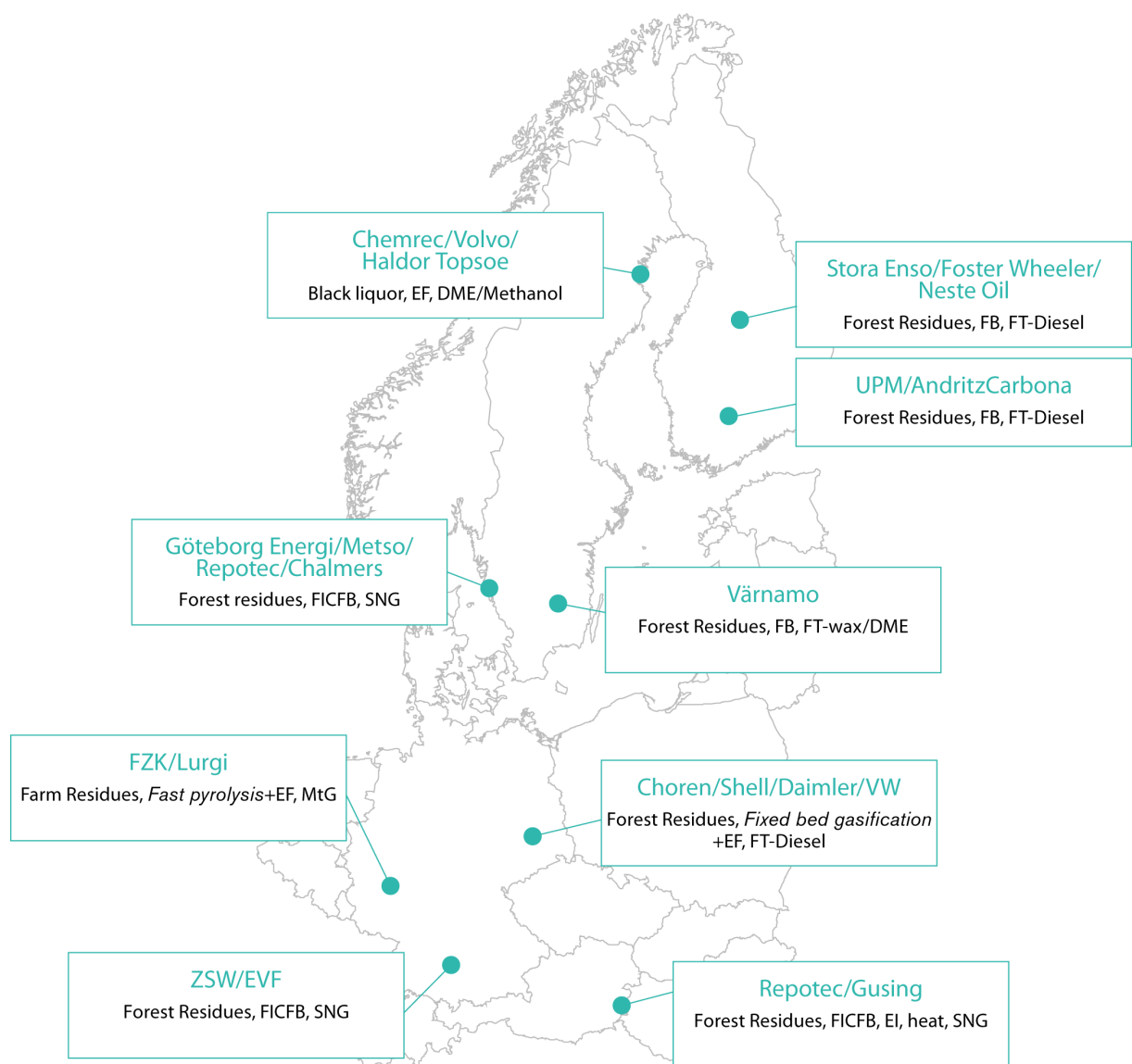


Figure 12.2 Overview of major gasification projects in Europe pursued for the production of synthetic fuels from biomass. When relevant, methods for pre-treatment are mentioned in italics. Acronyms used in the figure are: EF: Entrained Flow, FB=Fluidised Bed, FICFB=Fast Internal Circulating Fluidised Bed, SNG=Synthetic Natural Gas, DME= dimethyl ether, MtG=Methanol to Gasoline. Source: Hellsmark (2010) ⁸.

These competences reside not within the boiler industry (mastering combustion technology) but within the chemical industry, associated institutes and university departments. This means that firms have to acquire the required competences or operate in alliances. A feature of the technological field of biomass gasification for the production of synthetic fuels is, indeed, that such alliances are formed.⁹ These alliances include actors along the whole value chain, e.g. actors in the agricultural and forestry sectors supplying the feedstock, the capital goods industry, suppliers of gas (including the petrochemical industry) and manufacturers of transport

⁸ Hellsmark, H.R.A. (2010) *Unfolding the formative phase of gasified biomass in the European Union*. Doctoral thesis, Environmental System Analysis, Department of Energy and Environment Chalmers university of technology.

⁹ There are also other reasons for forming alliances, such as political leverage and securing complementary products as well as funding.

equipment. Nine such alliances are found in Figure 12.2.¹⁰ Each of these focuses on a specific pilot or demonstration plant. These projects target different types of biomass as feedstock, employ different gasification technologies (all of the three trajectories discussed above are represented) and aim for different types of synthetic fuels such as FT fuels, DME, methanol and methane. Some of the projects are in a pilot phase whereas others are in an early demonstration phase, see Table 12.1.

As the development of the technological field progresses towards commercially sized demonstration plants, we expect to see challenges for private actors to coordinate simultaneous investments along the entire value chain. These coordination and development activities range from increased biomass production to technology integration in the pulp and paper industry, in refineries or in other existing industries where potential synergies can be found (see Chapters 2, 6 and 8), to the development of new infrastructure and vehicles. However, judging from the ability to form alliances hitherto, this coordination may not be a primary obstacle. A more significant obstacle arguably lies in managing the substantial technical uncertainties indicated above and the even more substantial market uncertainties.

TECHNICAL UNCERTAINTIES FACING INVESTORS

The nine projects described above are or have all been in the process of moving from the pilot stage to constructing the first demonstration units. The cost of these demonstration plants ranges from 1 to 100 MEUR. However, not all of them include demonstration of the synthesis process, see Table 12.1.

Table 12.1 Industry estimates of costs and time line for the major development projects in the EU. Source: Hellsmark and Jacobsson (2012)¹¹. The table indicates when the various alliances predict that their projects will pass through the different phases. The year refers to completed construction, not to plant in operation. The pilot, demonstration and some of the pre-commercial plants will not operate in a continuous mode. It is, therefore, not meaningful to convert a physical size (MW) into a production volume (PJ/year) for these plants. In the case of Värnamo, a demonstration plant was taken into operation for the production of heat and electricity in 1993. Attempts to reconstruct the plant for demonstrating the production of synthesis gas have been made since early 2000, but these have not been successful. TBD=To be decided. The data in the Pre-commercial Demo and Commercial size columns are uncertain and may be changed on short notice.

	Pilot			Demo			Pre-Commercial Demo			Commercial size		
	Year	Size (MW)	Cost (MEUR)	Year	Size (MW)	Cost (MEUR)	Year	Size	Cost (MEUR)	Year	Size (PJ)	Cost (MEUR)
TU-Vienna/Repotec	1995	0.1	NA	2002	8	10						
Chalmers/Metso	2008	6	1.1	2008	6	1.1	2013	0.1PJ	75	2016-	3	150
ZSW/EVF	2002	8	2.4	2010	10	18	2013-	10 MW	NA	2016-	3	150
Chemrec	2005	5	7	2010	5	28	TBD	4 PJ	300	2016-	8	400
Värnamo				1993	18	45				2016-	8	400
Carbona/UPM	2005	6	10				TBD	8 PJ	400	2016-	8	500
FW/SE/Nestlé				2009	12	40	TBD	4 PJ	400	2016-	8	500
Choren	1998	1	NA	2008	45	100				2016-	8	800
FZK/Lurgi	2005	0.1	NA	2008	5	4	2012	5 MW	70	2016-	8	900

The subsequent shift to pre-commercial demonstration plants and fully commercial plants involves dramatic up-scaling of the size and cost of the plants. For instance,

¹⁰ However, since 2008 some of these alliances have experienced major set-backs. For example, Choren filed for bankruptcy in 2011, the Värnamo project has been officially terminated, the pilot facility and all the personal of Chemrec has been sold to Luleå Technical University, with the consequence of significantly weakening or terminating the alliances around those plants.

¹¹ Hellsmark, H., Jacobsson, S. (2012) Realising the potential of gasified biomass in the European Union—Policy challenges in moving from demonstration plants to a larger scale diffusion. *Energy Policy* 41:507-518.

for the Chemrec plant (EF gasification of black liquor in Sweden) this will involve an increase in output from less than 0.1 PJ per year¹² (28 MEUR) in a demonstration plant that was taken into operation in 2011 to 4 PJ per year (300 MEUR) in a pre-commercial plant and to 8 PJ per year (400 MEUR).¹³ The investment costs would typically be between 400-800 MEUR for commercial plants with a production capacity in the range of 8 PJ per year (0.2 Mtoe per year).

Throughout the up-scaling process, uncertainties of a technical nature are likely to remain although they are expected to get smaller as the scaling process proceeds. On the other hand, the sums involved are much larger, so technical uncertainties will remain a serious obstacle to investment. Conventionally, demonstration plants receive investment subsidies from governments but government sponsored risk absorption schemes may also be applied, reducing the risks of the lending bank.

Given the costs involved, any government programme has to be very large. In the Swedish case, for instance, a funding scheme for demonstration of synthetic fuels from gasified biomass and other energy technologies instituted in 2008 involves about 875 MSEK (87 MEUR) over a period of 3-4 years.¹⁴ This scheme represents a major increase in the availability of such funding. Through this scheme, the company Chemrec has been granted 500 MSEK (about 50 MEUR) and Gothenburg Energy 222 MSEK (about 20 MEUR) to complete the pre-commercial demonstration phase, see Table 12.1.¹⁵

Continuing with the case of Sweden, assuming that one plant from each of the three trajectories will be constructed in the next phase, an additional 1,000 MEUR will have to be raised. To cover, say, 20% of the total investment, a funding scheme of an additional 200 MEUR would, therefore, be required. An obvious policy challenge is, thus, to devise large enough programmes that can induce investors to face the technical uncertainties in moving to the first commercial plants. Such programmes must have a long-term commitment from policy makers in order to be effective.

It is a complex process to produce synthetic fuels from biomass gasification and significant delays are common. Given all uncertainties it is reasonable to assume that it will take at least three years¹⁶, probably more, from when a first (and smaller) demonstration plant has been constructed until an investor is willing to commit to a (larger) pre-commercial demonstration plant.

Investors would, thus, be able to decide whether to start constructing the first pre-commercial demonstration plants no earlier than 2014. It may then take three

12 Approximately 1.5 ktoe (tonnes of oil equivalent), 1 Mtoe equals 41.9 PJ.

13 In 2009, Domsjö Fabriker was granted a 55MEUR investment subsidy to build the first pre-commercial demonstration plant at their pulp and paper mill in Domsjö based on the technology provided by Chemrec. However, in 2011 the new owner of the plant announced that they had no intention of moving forward with the project. The future of this trajectory is now very uncertain.

14 Swedish Energy Agency (2008) *Utllysning: Intresseanmälan för demonstration och kommersialisering av andra generationens drivmedel och annan energiteknik*. Dnr: 410-2008-003385. Eskilstuna.

15 The Gothenburg Energy plant is a variant of the TU-Vienna/Repotec technology and represents the pre-commercial plant on the first row in Table 12.1.

16 The figure is a very rough estimate based on previous and similar gasification projects. For a longer discussion, see Hellsmark, H.R.A (2010) *Unfolding the formative phase of gasified biomass in the European Union*. Doctoral thesis, Environmental System Analysis, Department of Energy and Environment Chalmers university of technology.

to four years to construct and demonstrate these larger plants which mean that an investment decision for the first commercial-sized plant cannot be taken until 2017-18. The first commercial fuels from biomass gasification cannot, therefore, be expected to be available earlier than about 2020.

In sum, the high risks, large capital expenditures and long time scale involved in developing the complex and large-scale technology for producing fuels from biomass gasification dictates that, from an investor's perspective, it is vital that policy intervention has a long term perspective and involve substantial sums.¹⁷ The expected time scale involved in shifting from the current demonstration phase to a situation where synthetic fuels from biomass may begin to have an impact on the market may also have to be adjusted.

MARKET UNCERTAINTIES

The EU Directive 2009/28/EC¹⁸ mandates 10% share of renewable transportation fuels (by energy content) by 2020, which translates into approximately 1,300 PJ per year (30 Mtoe per year) based on the road transport fuel consumption in 2005-2010.¹⁹ On the basis on the analysis in the previous section we expect only a small share in the form of fuels from gasified biomass.²⁰

Assuming, however, that the supply of synthetic fuels from biomass gasification takes off after 2020 and captures a market of, say, 1,300 PJ per year by 2030 it would involve building some 150 plants, each supplying 8 PJ per year (0.2 Mtoe per year) of fuel. The total value of the fuel supplied would be about 15-30 billion EUR per year, and the total investment 60-120 billion EUR. Hence, a subsequent large scale transformation of the fuel market would entail huge market opportunities for both fuel and capital goods suppliers.

Yet, there are very substantial uncertainties facing investors with respect to market formation that must be addressed if the potential of gasified biomass is to be realised. The main market uncertainty is threats from substitutes in that investments that may eventually deliver synthetic fuels from biomass gasification have to compete not only with the lower cost sugar- and starch-based biofuels but also with fossil-based alternatives, conventional fuels and maybe also with hydrogen and electricity.

With respect to conventional fossil-based fuels, potential investors would, in the absence of a deployment policy, face very substantial market uncertainties for both

17 The Committee on Climate Change in the UK explains why public intervention must go beyond addressing negative externalities: "Investments in innovation is characterised by uncertainty – i.e. it is known that investments may fail, but a precise probability cannot be placed on failure. Unable to calculate precise risks, investors will act upon imperfect information and will often be risk averse. Long time scales for investment and deployment of technologies increase the length of time investments are at risk and increase risk aversion. For high capital cost investments, frequent in the energy sector, this may be a particular barrier." See page 9 in CCC (2010) *Building a low-carbon economy – the UK's innovation challenge*. London, UK: Committee on Climate Change.

18 EC (2009) *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance)*. Brussels, Belgium: European Commission.

19 Eurostat (2012) *Energy statistics*. European Commission.

20 Even though perhaps unrealistically, we assume that all of the projects in Table 1 are realised and at least one commercial scale plant will be built for each project, the combined production capacity of these commercial scale plants would be approximately 60 PJ per year. This amounts to less than 0.5% of the EU transport fuel market. Hence, synthetic fuels from gasified biomass may be available by 2020, but the volumes cannot be expected to be significant by then.

the initial nine plants and for the subsequent 100 or more plants. These uncertainties are illustrated in Figure 12.3. In the figure, we distinguish between low and high cost levels (10-20 EUR/GJ) for producing synthetic fuels from biomass gasification.²¹

These cost levels can be set against past and predicted prices of oil. The average world oil price from 1970 to 2009 was 36 USD (in 2008 dollars). In the World Energy Outlook²², IEA predicts the real oil price by 2030 in two main scenarios. In the reference scenario, it is set at 115 USD/barrel and in the high price scenario it is increased to 150 USD/barrel.

Figure 12.3 provides a base for assessing the financial magnitude of the market uncertainties caused by uncertain future oil price. It points to the hypothetical annual losses (or gains) for investors if a 10% market for synthetic fuels from biomass gasification (1,300 PJ per year) is realised in the future. Investors would lose more than 20 billion EUR if that market were to be realised at a production cost of 20 EUR/GJ (corresponding to 163 USD/barrel) and with an oil price at an historic average of 35 USD/barrel (Arrow 1 in Figure 12.3).²³ On the other hand, with production costs of 10 EUR/GJ and with the oil price at 150 USD/barrel, investors would gain more than 10 billion EUR (Arrow 2).

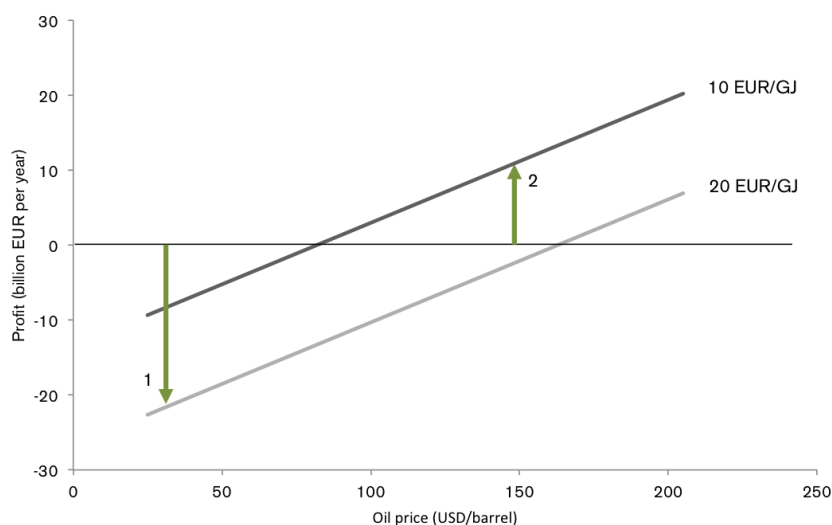


Figure 12.3 A tentative assessment of financial risk for commercially sized plants – annual losses or gains in realizing a 10% market for synthetic fuels from biomass gasification by 2030 (billion EUR). Arrows 1 and 2 are discussed in the text.

In sum, there are not only substantial technical but also market related uncertainties for all the actors that need to participate to realise the potential. Moreover, these uncertainties are not of a short term character but are expected to stay

²¹ These cost levels were provided by advocates of the different projects in Table 12.1 and Figure 12.2; they are further discussed in Hellsmark, H.R.A (2010) *Unfolding the formative phase of gasified biomass in the European Union*. Doctoral thesis, Environmental System Analysis, Department of Energy and Environment Chalmers university of technology..

²² IEA (2009) *World Energy Outlook*. Paris, France: International Energy Agency

²³ We here assume an exchange rate of 0.75 EUR/USD.

for many years. Only very powerful and durable²⁴ incentives may, therefore, be expected to induce the necessary investments to take the industry into a pre-commercial demonstration phase and, eventually, form a significant supply capacity for synthetic fuels based on biomass.

CRITERIA FOR ASSESSING POLICY OPTIONS

Reducing these technical and market uncertainties is the main challenge ahead for policy makers and we will discuss various means of doing so. We will focus on market uncertainties since investment subsidies or risk absorption schemes (managing technical uncertainties) may not be enough to stimulate investments even for the first set of plants (about 4 billion EUR, see Table 1) due to the very large market uncertainties. Before we discuss the usefulness of various policy instruments, we need, however, to specify the assessment criteria, in particular what effectiveness entails.

Effectiveness, efficiency and equity are three commonly used criteria for assessing policy options.²⁵ The effectiveness of an instrument is assessed by its ability to meet a certain target, e.g. 10% renewable transportation fuels by 2020 or 100% by 2050.

Efficiency²⁶, or cost-effectiveness, is assessed by the social costs involved in meeting a given target. There are two challenges in applying this criterion. First, by definition, it makes sense to assess the cost-effectiveness of instruments only if they are expected to lead to the achievement of a certain target, i.e. if the effectiveness criterion is fulfilled (see below). Second, minimising costs, not in the short term, but over several decades means that we need to focus on what policy instruments can be expected to generate the lowest cost solution over the whole period, taking technical change into account. This rests, to a large extent, on the innovative capabilities in the capital goods industry. Hence, applying this criterion requires that we understand the impact of various instruments on the behaviour of the capital goods sector and its ability, in turn, to drive technical change.

The third criterion is equity which is a factor in creating social legitimacy for policies supporting new technology. Excess profits threaten legitimacy and must be avoided.²⁷

In order to assess the effectiveness of a policy instrument, we need to specify the goal of intervention. As far as we are aware, a goal has not been set for the diffusion of synthetic fuels, neither in individual countries, nor at the EU level. However, as we move beyond 2020, an aggressive strategy to cut emissions is argued to require a major increase in the supply of biofuels from lignocellulosic feedstock (compare discussion in Chapter 4), including synthetic fuels from biomass gasification.²⁸

24 The time scale involved here is not unique. Mobile telephony dates back to the 1950s and a large scale diffusion took place in the second half of the 1990s. The first offshore wind farm was built in 1991 and in 2011, 14 TWh was supplied in Europe and the European Wind Energy Association expects a large scale diffusion to begin after 2020.

25 Jacobsson, S. et al. (2009) EU renewable energy support policy: Faith or facts? *Energy Policy* 37:2143-2146.

26 We here refer to economic efficiency. See e.g. Chapter 9 for a discussion of different measures of energy efficiency.

27 Verbruggen, A. (2008) Windfalls and other profits. *Energy Policy* 36:3249-3251.

28 Page 473 in: IEA (2008) *World Energy Outlook*. Paris, France: International Energy Agency.

What goal should then the effectiveness criterion be related to? The effectiveness of any policy instrument must be assessed, as is evident from the sections above, by its ability to influence the strategic decisions of actors to explore and develop alternative technical solutions, fill the whole value chain and coordinate actions. Arguably, for the period from now until 2020, a first goal would be to move from smaller demonstration plants to having fully commercially sized plants from the different trajectories up and running. Hence, a first goal is to “put the various technologies on the shelf”. This is likely to be achieved no earlier than 2020. In the next stage, a second goal for 2030 could be set at 20% renewable transportation fuels, of which half could be synthetic fuels from biomass gasification. This would amount to about 1,300 PJ (30 Mtoe) or about 150 plants.²⁹

This means that policies must be assessed with respect to their ability to meet these two goals within the specified time frame. To be effective, we will argue that several alternative technologies need to be developed. This is, of course, inherent in the first goal but also, arguably, a necessity if the second goal is to be reached.

The different technological trajectories do not represent conventional “competing designs”, i.e. design configurations that can fully substitute for each other.³⁰ The applications of the technologies in the three trajectories to specific contexts are more or less constrained in their potential. For instance, feedstocks vary in their availability, e.g. the use of EF with black liquor as feedstock is constrained by the number of chemical pulp mills (in contrast to mechanical pulp mills). Moreover, there are joint production opportunities in the pulp and paper (Chapters 2, 6 and 8), petrochemical and oil refinery (Chapters 2 and 8) and district heating industries (Chapter 11) but, of course, these are limited by the size of these industries and by existing technical infrastructure.

The lowest cost level for producing synthetic fuels from biomass gasification in Europe, based on domestic biomass resources, can be expected to be found in Sweden and Finland due to large heat sinks and a pulp and paper industry in which the technologies (all three trajectories) can be integrated. The potential in a European market perspective is, however, quite limited. Ekbom et al.³¹ show that the potential for FT diesel production using black liquor is about 80 PJ for Sweden and Finland together. This would substitute for about 20% of the petrol and diesel consumption in these two countries. Even if production were to be doubled by the inclusion of fuel production in mechanical pulp and paper mills and district heating systems (using other biomass feedstock than black liquor), meeting a goal of 1300 PJ by 2030, and going beyond it, would certainly require that the higher cost applications of the technologies would also need to be developed and exploited.

With the long time taken to go from small demonstrations to fully commercial plants, i.e. “putting the technologies on the shelf” and the extension of that time axis in their subsequent diffusion, effectiveness involves creating markets for all

29 This is broadly in line with the 450 Policy Scenario in IEA (2008) *Scenarios and Projections*, if EU maintains its share of the global biofuel market.

30 Utterback, J.M. (1994) *Mastering the dynamics of innovation: how companies can seize opportunities in the face of technological change*. Boston, MA, USA: Harvard Business School Press.

31 Table 10.1 in Ekbom, T. et al. (2003) *Technical and Commercial Feasibility Study of Black Liquor Gasification with Methanol/DME Production as Motor Fuels for Automotive Uses - BLGMF*. Stockholm, Sweden: Nykomb Synergetics AB.

the three trajectories applied to different contexts, which then will develop in parallel rather than sequentially, jointly gaining market shares from fossil alternatives and not from each other.

POLICY OPTIONS FOR REDUCING MARKET UNCERTAINTIES

Having established a key criterion for assessing the effectiveness of various policy instruments, we will now proceed to discuss a number of options where we assume that the policy instruments operate at the EU level. The main instruments of interest are a general quota for all types of biofuels, separate quotas for conventional biofuels from crops, and for biofuels from lignocellulosic material and waste (sometimes referred to as “first” and “second generation” of biofuels, respectively), and finally separate feed-in tariffs for many different conversion pathways. Before we turn to these, we will comment on another option, namely the inclusion of the transport sector in the EU ETS. This is sometimes advocated as a solution but it is plain that the volatility of the price for emission permits and the highly uncertain future of the size of the cap create very large uncertainties for investors who have to estimate income streams over two or more decades. Hence, in terms of Figure 12.3, the market uncertainty is very high indeed, which strongly discourages investments.

A quota for biofuels is currently operating in e.g. Germany. A general quota induces, however, an expansion of the least cost options first, i.e. first generation biofuels.³² Whereas the desirability of conventional biofuels from crops is questioned (in terms of both its ability to reduce emissions and its use of arable land), the potential is large, especially if we consider import opportunities from Latin America and Africa (see also discussions in Chapters 4 and 5). A general quota would, therefore, not be a strong inducement mechanism for firms to invest in up-scaling and further developing biomass gasification for the production of synthetic transportation fuels.

To stimulate such development, the European Commission has decided that the “... contribution made by biofuels produced from municipal waste, residues, non food cellulosic material, and ligno-cellulosic material shall be considered twice that made by other biofuels”.³³ Such a double counting would, of course, mean that a 10% goal for synthetic fuels (see above) can be reached by supplying 650 PJ per year only. Yet, our conclusion of the need for a parallel development of the three trajectories in many countries holds; as shown above the supply capacity from lower cost options in the Nordic countries is still quite limited in comparison.³⁴

32 Tradable green certificates (TGC) is a more advanced form of quota system that has been favoured by the EU Commission as a deployment policy in the field of renewable electricity, see e.g. Jacobsson et al. (2009) EU renewable energy support policy: Faith or facts? *Energy Policy* 27(6):2143-2146. The core of this policy is, as for quota systems in general, to select the *currently* most cost-effective technology and only in a step-wise manner introduce more costly technologies. Hence, the aim is to avoid a parallel development of technical alternatives with different cost levels. It cannot be expected to fulfil the effectiveness criterion as this requires creating markets for all the three trajectories in parallel.

33 In addition, the EC proposes that when Member States design their support systems they may give “... additional benefits to ... biofuels made from waste, residues, non-food cellulosic material, ligno-cellulosic material and algae, as well as non-irrigated plants grown in arid areas to fight desertification ...”, see page 26 in EC (2009) *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance)*. Brussels, Belgium: European Commission..

34 Double counting would, of course, easily lead us to set a higher goal in terms of percentage of fuel consumption, maintaining the goal of 1300 PJ per year.

A double counting of fuels from lignocellulosic materials and waste would provide an added incentive to investors in fuels from gasified biomass that better reflect their performance in terms of CO₂ emissions. Market uncertainty remains high, however, and is magnified by the interdependency with the price of conventional fuel. Assuming that both first and second generation biofuels are blended into conventional fuels, the competitiveness of the latter vis-à-vis the former will depend on the price of conventional fuels. If that price increases, first generation biofuels gains a competitive edge simply since it, in terms of volume, replaces about twice as much conventional fuels as the synthetic alternatives.³⁵ Potential investors, thus, have to consider the future prices (over decades) of not only different kinds of biofuels but also of conventional fuels. This adds uncertainty to any investment analysis.

A separate blending quota for synthetic fuels from lignocellulosic materials and waste would alleviate the problem of interdependency with the price of conventional fuel and take away the market uncertainty with respect to competition with more mature biofuels. As and when the first larger plants have been taken into operation, a predetermined quota could be applied. In order to stimulate a supply capacity in the Nordic countries, a unified EU blending quota for second generation biofuels may have to be coupled to trading opportunities, i.e. an export from Sweden and Finland to other countries (as is specified in Directive 2009/28/EC³⁶). Integrating the Nordic and German markets may, however, lead to equity problems. As discussed above, the estimated cost levels of synthetic fuels from biomass gasification differ a great deal, to the advantage of Swedish and Finnish suppliers. With an integration of the markets, price levels would be expected to be equalised, with potential huge excess profits gained by the Nordic suppliers.

An additional problem with a quota is the very substantial information requirements for a central planner in setting the quota, both its initial level and its escalation. Basically, today nobody can with certainty say when the first commercial plant will be operational. It is even more difficult to judge how quickly the supply capacity in the capital goods industry can grow – it depends not only on the strategic choice of a number of capital goods firms but also on the access to specialised skills in a range of areas, including gasification and catalysis.³⁷

Feed-in with cost covering payment that differs between technologies (and contexts of application) is a well proven regulatory framework to stimulate the diffusion and further development of a range of technologies in parallel, i.e. a feed-in tariff is expected to score high on the effectiveness criterion. Just as double counting in a quota system, a feed-in tariff may stimulate more expensive, but higher performing, alternatives through setting higher prices. In principle, excess profits may be avoided by a careful price setting routine. Such prices, which are normally set for a period of 15-20 years, would need to be adjusted for fluctuating feedstock prices.

³⁵ Choren. (2007) Suggestion presented on slideshow: CHOREN Stellungnahme Förderpolitik Biokraftstoffe_2007 12 engl 01, provided by Mattias Rudloff at Choren, Freiberg.

³⁶ EC (2009) *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance)*. Brussels, Belgium: European Commission.

³⁷ A recurrent theme in interviews with capital goods suppliers and other firms was the lack of specialised competences in the field.

However, there are two major problems with this instrument, at least at this stage. First, effectiveness necessitates that one tariff is set for each technological trajectory (and specific context). It is not, however, possible to calculate costs with the required precision without experience with full size commercial plants. Second, there is not, as yet, competition in the capital goods sector within each trajectory which means that setting a feed-in price would involve negotiations between government and monopolistic suppliers with access to superior information. This opens up for problems with respect to the equity criterion.

A dedicated quota for synthetic fuels from lignocellulosic materials and waste appears to be a more attractive option as prices do not need to be set for 15-20 years but may evolve as experience is gained. Yet, as explained above, there are very considerable information problems for a central authority to set a quota over a longer period of time. Moreover, it remains doubtful if a promise by current politicians of a future quota would be enough to convince firms that a market will materialise with prices that will cover costs.

In sum, none of the currently discussed policy options come out as a strong candidate, at least not at this stage of development of the industry. An option would be to implement a “bridging policy” that reduces the information needs among policy makers while taking away the market uncertainties for the first set of plants. One alternative would be to implement plant-specific tax exemptions (increasing the price competitiveness of synthetic fuels from biomass gasification) coupled to guaranteed market and off-take price from public sector customer or, possibly, traders or petrochemical firms. Such a price would, in effect, be a miniaturised plant specific feed-in tariff. The possible drawback in terms of information asymmetries would remain but be limited to a few specific investments.

With a bridging policy, the market uncertainty (in terms of relative price level vis-à-vis conventional fuels) is absorbed by the customer but the tax exemption would reduce the size of the potential losses. At the same time, as argued above, some of the technical risks would need to be absorbed by society at large. This limited and temporary construction would take the capital goods industry through to the stage where the first commercially sized plants are built, reducing technical uncertainties and completing the respective value chains. It would also give the added benefit of generating a pool of experience and competences on which a longer term policy can be based, be it a dedicated quota for lignocellulosic fuels or a targeted feed-in tariff. Of course, a possible outcome of this policy would be that a learning process reveals that gasification of biomass, or a particular trajectory, is not viable.

CONCLUDING REMARKS

The purpose of this chapter was to identify policy challenges and discuss options for moving from the current small scale pilot and demonstration plants in the European Union to a larger scale diffusion of gasified biomass.

In the EU, three main technological trajectories are being explored to gasify biomass. Nine alliances of firms, institutes and universities centre own their own

demonstration plant in which one of these trajectories is applied to a specific context. These plants use different production processes and different feedstocks for producing different types of synthetic fuels. For these alliances, the challenge is to complete the demonstrations and then scale them to supply synthetic fuels from the first commercial-sized plants by about 2020.

From an investor's perspective, a commitment to synthetic fuels from biomass gasification involves facing a number of technical uncertainties that can only be reduced through building demonstration plants. Demonstration programmes that absorb technical uncertainties need to be supplemented by policies that ensure that markets are formed. There is an abundance of different public policy instruments to form markets and assessing the usefulness of each of them requires that clear criteria are developed. The effectiveness of an instrument is assessed by its ability to meet a certain target whereas efficiency, or cost-effectiveness, refers to meeting this target at lowest cost. Equity is a third credible criterion.

Discussing the effectiveness of an instrument requires that a goal is specified. We suggested, as an example, that an EU goal for 2030 could be set at 20% renewable transportation fuels, out of which half could be synthetic fuels from biomass gasification. This would amount to about 1,300 PJ per year (30 Mtoe per year), involving some 150 plants. Reaching this goal necessitates the coexistence of a range of technologies applied to different contexts and with quite different cost levels. With the inherently long time axis in moving towards the first commercial scale plants, and the subsequent multiplication of these, effectiveness therefore involves creating markets for all three trajectories applied to a range of contexts which then will develop in parallel, rather than in sequence.

Most of the currently discussed policy instruments fail on this criterion of effectiveness. Equity issues would also arise. A way forward is a "bridging policy" that takes away market uncertainties for the first plants whilst reducing the information needs among policy makers. Such a bridge could be built by implementing a small number of plant-specific tax exemptions coupled to guaranteed market and off-take price. The market uncertainty is absorbed by the customer but the tax exemption would reduce the size of the potential losses. This bridge would a) ensure a market; b) demonstrate a strong commitment to the technology; c) take the capital goods industry through to the stage where the first commercially sized plants are built, reducing the technical uncertainties and populating the respective value chains; d) generate a pool of experience and competences on which a longer term policy can be based. A final advantage with this temporary and limited policy is to learn more about the viability of gasified biomass.

A SERIES OF EVOLVING E-BOOKS

The energy and climate challenge is enormous and the world is running full speed ahead into a very uncertain future. The role of technology is ambiguous: definitely part of the problem, but as surely, a necessary element of any transition to a more sustainable development. Hence, there is an urgent need to learn more about how to govern technical change.

“Systems perspectives on...” was initiated within Chalmers Energy Initiative. We set out to make a cross-disciplinary effort to evaluate technologies, in terms of benefits and drawbacks, and assess the technical, economic and political requirements for successful deployment and diffusion. We realised that this aim required something that was not only a product but also a process. The result is a series of evolving e-books. The ambition is to provide a platform for learning about systems issues related to critical technology areas. The series now comprises three books.

Systems Perspectives on Renewable Power investigates the potential to harness renewable energy flows to replace non-renewables and satisfy the varying demands for electrical power.

Systems Perspectives on Electromobility elaborates on the consequences and requirements of a transition to a transport system powered by electricity.

Systems Perspectives on Biorefineries explores the potential and desirability of biomass as carbon and energy feedstock in the numerous applications currently relying on fossil fuels.

At this point we can conclude that, while there are still plenty of hurdles to pass and pitfalls to avoid, the future is not without hope.

