SYSTEMS PERSPECTIVES ON BIOREFINERIES

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PREFACE

Replacing fossil fuels with biomass for the production of energy carriers, materials and specialty chemicals is a challenge that now confronts humanity. In which applications shall we use limited resources of biomass? How can biomass be refined into the products we want? What is an optimal design of a biorefinery? How is the most advantageous portfolio of policy instruments designed to realise the biorefineries of the future?

There is not one final answer to these questions. 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 2012 contains nine 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. The book is far from complete, but it is a contribution and a start...

Björn Sandén
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CONTENT

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

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 at 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 will emerge and what will be the most appropriate system boundaries. 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.

Biorefineries will not be developed and optimised in empty space. They will be developed in complex industrial and cultural settings. Chapter 2 and 5 provide examples of how new biorefinery concepts can be integrated in the processing industry and Chapters 6-8 discuss how economic and environmental performance of different technical designs depends on the character of larger surrounding technical systems.

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? How can a biorefinery be made as efficient as possible to save resources? Which configurations can maximize 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?

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 will apply various types of systems analysis to address some of these questions and also point out common pitfalls and how such analyses also can be used to mislead the less experienced. In the next sections of this chapter we will outline a typology of assessment methods and some critical methodological choices to guide the reader and also indicate what type of questions that may be addressed in coming editions of this Evolving E-book. Chapters 6-8 in this year's edition provide some examples of assessments of energy efficiency, profitability and reduction of green house gas (GHG) emissions.

The question of which technology to select is related to the question of how new technologies are selected and allowed to develop from idea to full blown industrial systems. How can such 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? Also this type of questions can be addressed by system studies. As an example, Chapter 9 discusses which policy instruments that could be effective in taking biomass gasification and synthetic biofuels from the demonstration stage to commercial production. In this introductory chapter we briefly outline a group of methodologies that can be used to further explore this territory.

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,

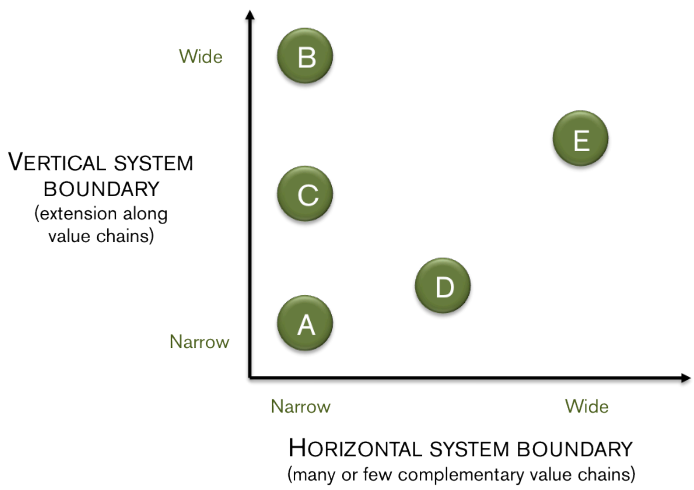

Figure 1.1 Different studies, as well as different standard methodologies, apply different system boundaries. A modelled system can encompass many or few value chains (horizontal system boundary) and smaller or larger parts of these value chains (vertical system boundary). The methodological positions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

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 6, we apply physical measures of performance, i.e. energy efficiency, and in Chapters 7 and 8 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) if 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.

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.

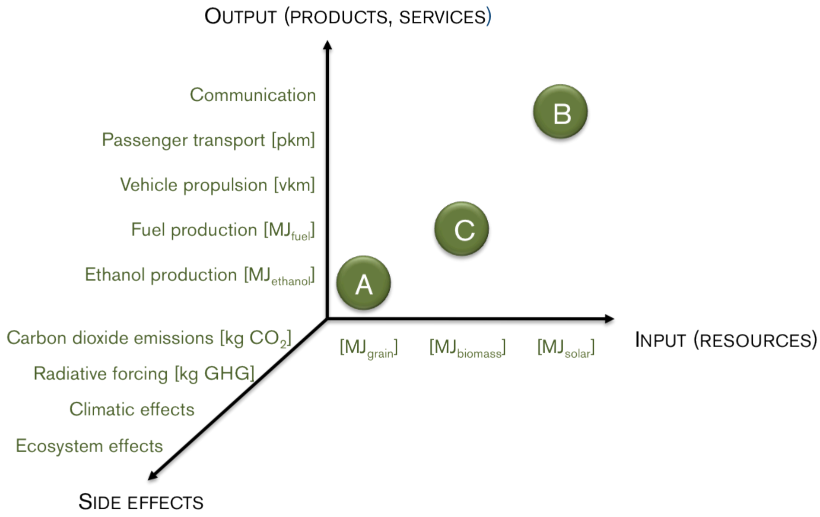

Figure 1.2 A system boundary can be more or less vertically extended towards final end use in the output dimension, towards primary resources and towards final side effects, depending on which performance measure that is relevant for the decision context at hand. The figure illustrates the example of 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.

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,[1] 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 propulsion. 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.

1 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

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 ($MJ_{ethanol}$) (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.

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 6 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 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 CO_2. But CO_2 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 7 and 8 discuss CO_2 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 8). While climate change, is the most popular impact category at present, there are also numerous other environmental and social categories that could be considered.

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.[2]

2 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, Universe Books. For the reader skilled in Swedish, Ingelstam (2012): System – att tänka över samhälle och teknik, andra upplagan, 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 (e.g. Jackson, T. (2009). Prosperity without growth : economics for a finite planet. London, Earthscan). Other contributions may be found in various qualitative scenarios and fiction novels.

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 7 (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 6 and 7 discuss the simultaneous production of fuel and electricity, and Chapters 6 and 8 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 becomes exceedingly difficult to construct relevant comparisons (see for example the multitude of possible biorefinery products listed in Chapters 3 and 5.

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 6), 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 categories (see for example the global energy system model GETOnline).

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 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 7.

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. [3] 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. 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.

3 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, Volume 1041, Pages 183-189 and Sandén and Karlström (2007). "Positive and negative feedback in consequential life-cycle assessment." Journal of Cleaner Production 15(15): 1469-1481.

However, the consequence of driving an electric car today may be that electricity production from coal increases. 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 8 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.

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 9 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 and 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. In this book we have strived to stimulate cross-comparison. As one example we have tried to present all energy figures in Joules (from gigajoules, GJ, to exajoules, EJ) and economic figures in euro (EUR) as a complement to other units that is traditionally used in different sub-disciplines and industrial contexts. We have also inserted a substantial number of cross references. Finally, we have used a process or 'cross-reading' where all chapters have been read and reviewed by authors of other chapters and some additional experts.

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...

Chapter 4 concludes that there is still great uncertainty about how much biomass resources that can become available at acceptable environmental and social costs for traditional as well as novel uses, but also that research has increased our knowledge of which factors that are most critical for the outcome. Chapters 2, 3 and 5 describe a plethora of opportunities to convert biomass into products, from small volumes of high value products to very large volumes of commodities. 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 6, 7 and 8 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.

On the one hand, the great prospects together with the varying and site specific conditions should lay the ground for an era of diversity and experimentation; on the other hand, the risks and the uncertainties may impede such a development. Chapter 9 concludes that the materialisation of novel concepts will require brave and cleverly designed technology specific governmental policies to reduce technical and market risks for investors.

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.[4]

The myriad of decisions that collectively decide how the global biomass resource is used to feed, enrich or impoverish people and if and how biomass can replace coal and oil in fuels, materials and specialty chemicals is of uttermost importance to humanity. We all need to learn about the system consequences of our actions. As we move across the dark sea into the future, we need a battery of assessments as guiding system. We are in the dark but we are not totally ignorant and we have the ability and responsibility to seek knowledge. This ebook is designed to evolve and continuously improve. It will always be incomplete but we hope that occasionally it will be useful as a platform for learning.

4 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]

1 IEA (International Energy Agency) Bioenergy Task 42 on Biorefineries. Minutes of the third Task meeting, Copenhagen, Denmark, 25 and 26 March (2008).
2 NREL Biomass Research, accessed 2011-11-07

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.

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. On 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.

3 Swedish Pulp Mill Biorefineries, Swedish Energy Agency, ER 2008:26

4 Paul Stuart, Biorefinery 101: Maximizing Benefits and Minimizing Risks Associated with Implementing the Forest Biorefinery", PIRA webinar, 2011-04-13.

5 http://circa.europa.eu/Public/irc/rtd/susbioref/library?l=/biorefinery_info/commissionerpdf/_EN_1.0_&a=d , accessed 2011-11-07.

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 5).

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.

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.

VGASIFICATION 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.

The biomass often needs some pre-treatment

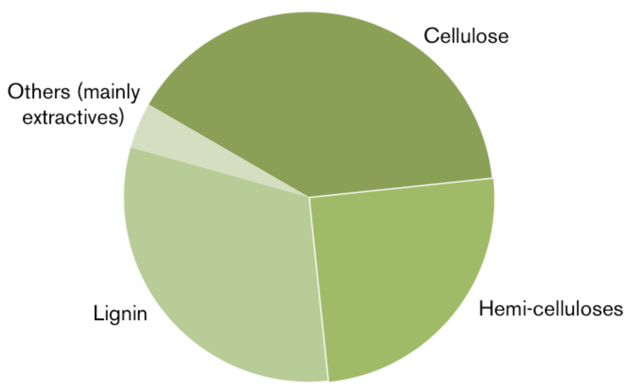

Figure 2.1 Example of wood component distribution (softwood)

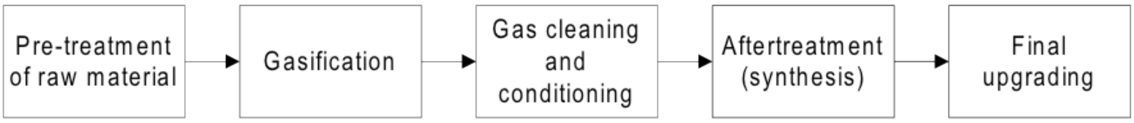

Figure 2.2 Schematic description of the gasification chain

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 9.1 in Chapter 9). 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 fluidized bed (FB) gasifiers the gasifying agent has a velocity high enough to fluidize a bed containing a small fraction of biomass. Biomass is continuously added to the bed. Two types of FB-gasifiers exist: bubbling and circulation fluidized 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 6), 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 pelletized 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 fludized 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 grinding[6] 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 pressurized (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 were 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'

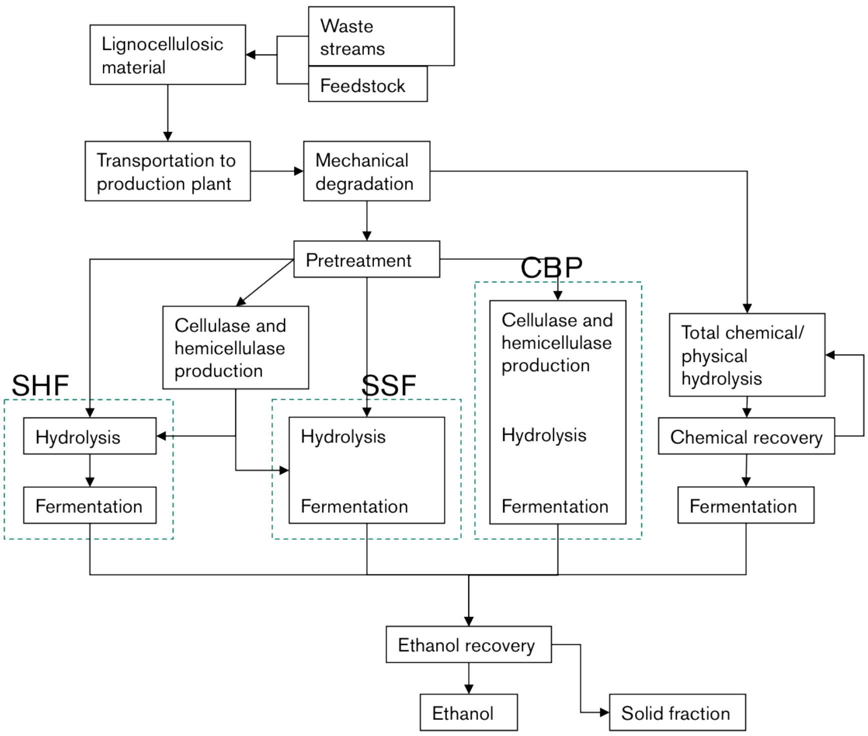

Figure 2.3 Examples of fermentation routes for producing bioethanol from lignocellulosic materials. SHF =Separate hydrolysis and fermentation, SSF=Simultaneous saccharification and fermentation and CPB=Consolidated bioprocessing. Figure based on Olsson L., H. Jørgensen, K. Krogh and C. Roca (2005). Chapter 42 Bioethanol production from lignocellulosic material. In: Polysaccharides: structural diversity and functional versatility, S. Dumitriu, Ed. Second Edition, revised & expanded. Marcel Dekker, Inc, New York. p: 957-993.

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.

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 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 6 for a discussion on how the valuation of byproducts affect the energy conversion efficiency of the process and Chapter 8 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 5), 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 5.

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

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

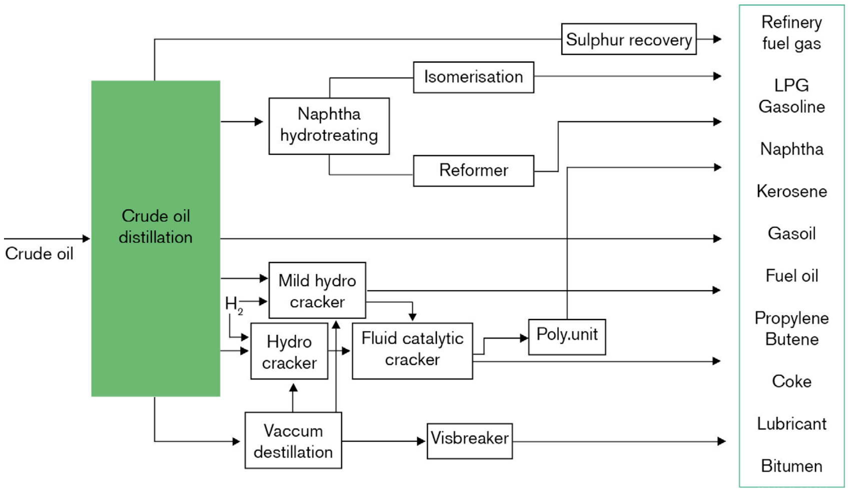

Figure 2.4 Schematic process flow chart for an oil refinery

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.[8]

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 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.

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.

8 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.

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 is 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 8) 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 m^3 diesel per year (11 PJ per year). The renewable feedstock is raw tall oil, which is a by-product from kraft pulp mills (Chapter 5). 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 CO_2 in e.g. flue gases from an industry is captured in an absorption medium and then desorbed in a separate vessel, pressurized and transported to an onshore or offshore storage. To reach very low CO_2 emission levels, or even negative emissions, such processes can become important components in future biorefineries and complement or compete with other biorefinery processes.

Currently four CO_2 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 CO_2 after combustion implies that the CO_2 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 CO_2. 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 CO_2 stream is produced. The CO_2 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 CO_2.

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 5 and 8).

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. 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.

Moreover, bio-based industries like the pulp and paper industry are looking for opportunities to revive their commodity-based business by considering the expansion of their product portfolios with added-value products. 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

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

Source: FPAC & FPInnovations. The New Face of the Canadian Forest Industry. Online. (2011).

Table 3.1 Estimated annual growth rate and value of a set of promising products based on wood fibre

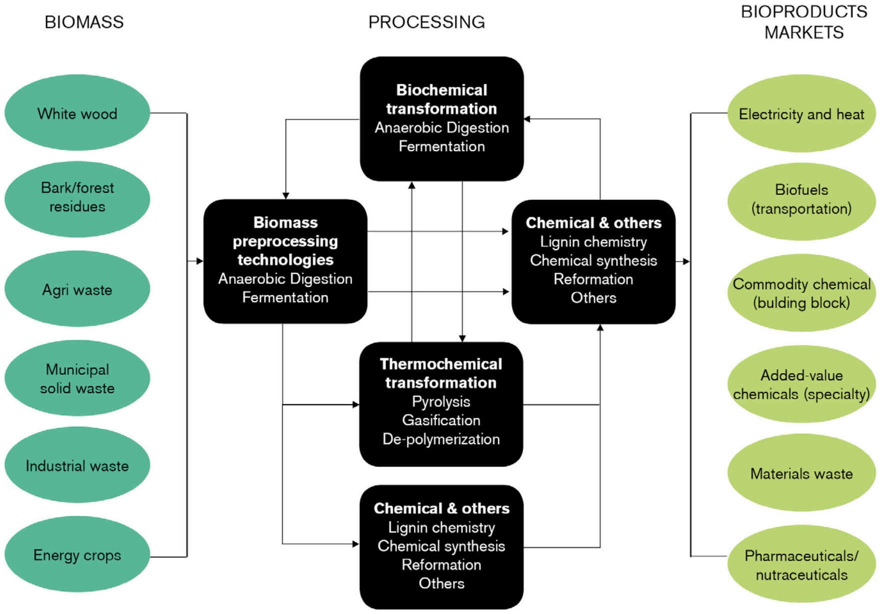

Figure 3.1 Biorefinery feedstocks, technologies and product markets (see also Chapter 2).

transformations (Figure 3.1).[1] (See Chapter 2 for alternative definitions and Chapters 2 and 5 for process descriptions.)

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.

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".[2] The biorefinery platform-based approach involves the production of a chemical building block or intermediate and this intermediate 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 5), 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 terephtalate) in the production of e.g. plastic bottles.[3]

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)

1 M. Janssen, V. Chambost and P.R. Stuart (2008). 'Successful partnerships for the forest biorefinery'. In: Industrial Biotechnology 4.4 (2008), pp. 352–362.

2 T. Simpson, J. Maier and F. Mistree. 'Product platform design: method and application'. In: Research in Engineering Design 13 (1 2001), pp. 2–22.

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

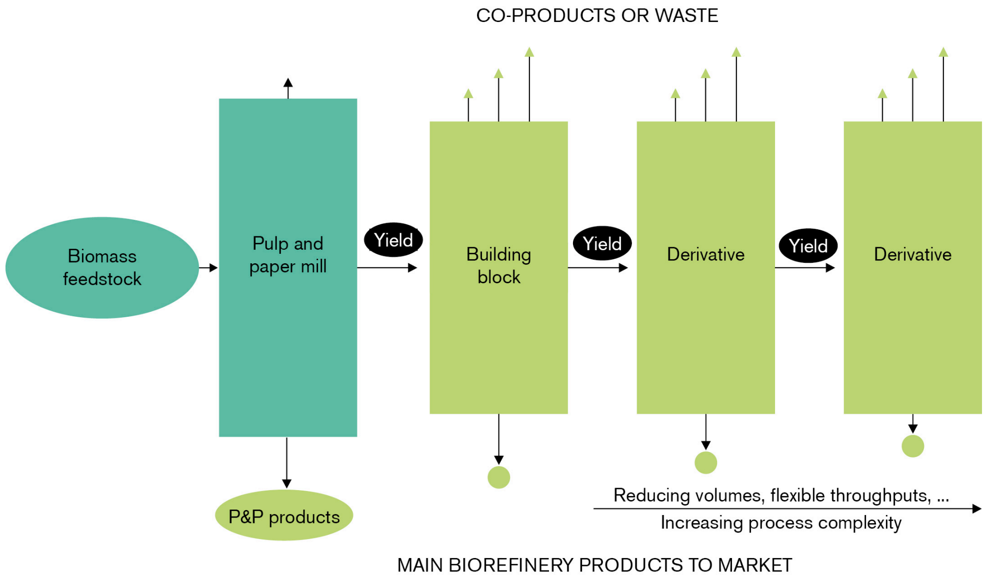

Figure 3.2 Forestry company product portfolio including a biorefinery product platform

and pharmaceuticals (e.g. chiral drugs) will typically have a significantly higher price.[4] 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.

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 product volumes) and supply chain network design.[5] 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 5 for a discussion on factors that influence process choice in pulp mills, Chapter 8 on the value of heat as a byproduct and Chapter 9 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.[6] 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).[7] Well-known examples in this list are ethanol, lactic acid and succinic acid.

Global fuel ethanol production was about 70

4 C. Cobden. Integrating Bioenergy with Forest Sector Facilities. Presentation at BC Bioenergy Network Conference. 2011.

5 B. Mansoornejad, V. Chambost and P. Stuart (2010). ‘Integrating product portfolio design and supply chain design for the forest biorefinery’. In: Computers & Chemical Engineering 34.9, pp. 1497–1506.

6 T. Werpy and G. Petersen. Top value-added chemicals from biomass, Volume I: Results of screening for poten- tial candidates from sugars and synthetic gas. Tech. rep. PNNL-14808. Pacific Northwest National Laboratory, 2004.

7 J. J. Bozell and G. R. Petersen. ‘Technology development for the production of biobased products from biore- finery carbohydrates – the US Department of Energy’s “Top 10” revisited’. In: Green Chemistry 12.4 (2010), pp. 539–554

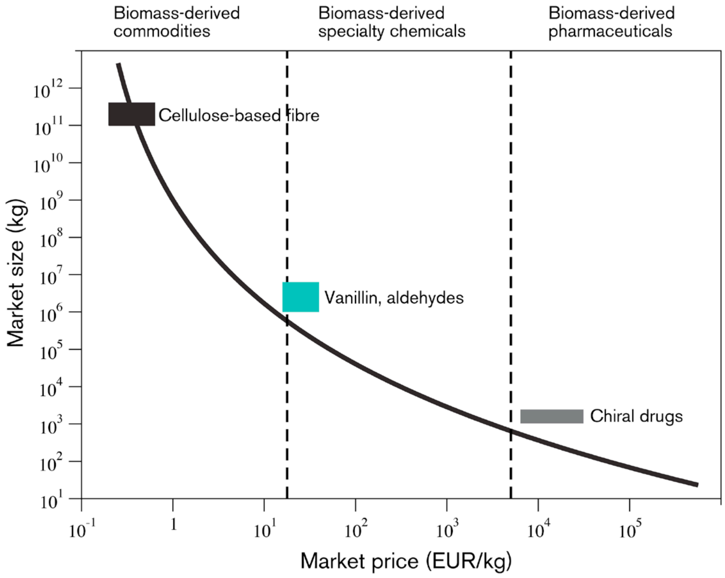

Figure 3.3 : Illustration of price-market size relationship for biobased products The squares indicate ranges regarding market volume and price

million tonnes (Mt), or 2 EJ, in 2010 and almost entirely produced by means of fermentation.[8] Not only is bioethanol used as a fuel (see section on bioenergy), it can also be used as a precursor for the production of ethylene which is a petrochemical with one of the highest production volumes. Ethylene can be produced at an extremely high conversion rate (99.5%) from ethanol by means of vapour phase dehydration.[9] It is an intermediate 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 ethylbenzene, alcohols, olefins, acetaldehyde and vinylacetate. The global production capacity for ethylene was 140 Mt per year in 2011 and continues to grow.[10] 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 bio-based lactic acid is about 350 thousand tonnes (kt) 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.[11]

Lactic acid can be used as a platform chemical for the production of a wide range of chemicals (Figure 4.4). 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

8 Renewable fuels association (2012).
9 J. J. Bozell and G. R. Petersen. 'Technology development for the production of biobased products from biore- finery carbohydrates – the US Department of Energy's "Top 10" revisited'. In: Green Chemistry 12.4 (2010), pp. 539–554
10 True, W. (2011). 'Global ethylene producers add record capacity in 2010'. In: Oil & Gas Journal 109.14 (2011), pp. 100–104.

11 Corma, A. et al. (2007). 'Chemical Routes for the Transformation of Biomass into Chemicals'. In: Chemical & Engineering News 107.6 , pp. 2411–2502.

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).

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	

replacement product for polyethylene terephtalate (PET) and thus can be used for the pro- duction 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.

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.11 Production has recently started at a scale of a few thousand tonnes per year but new larger production plants are planned.[12]

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 polymerized 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.

12 McCoy, M. (2009). 'Big Plans For Succinic Acid'. In: Chem. Eng. News 87.50 (2009), pp. 23–25.

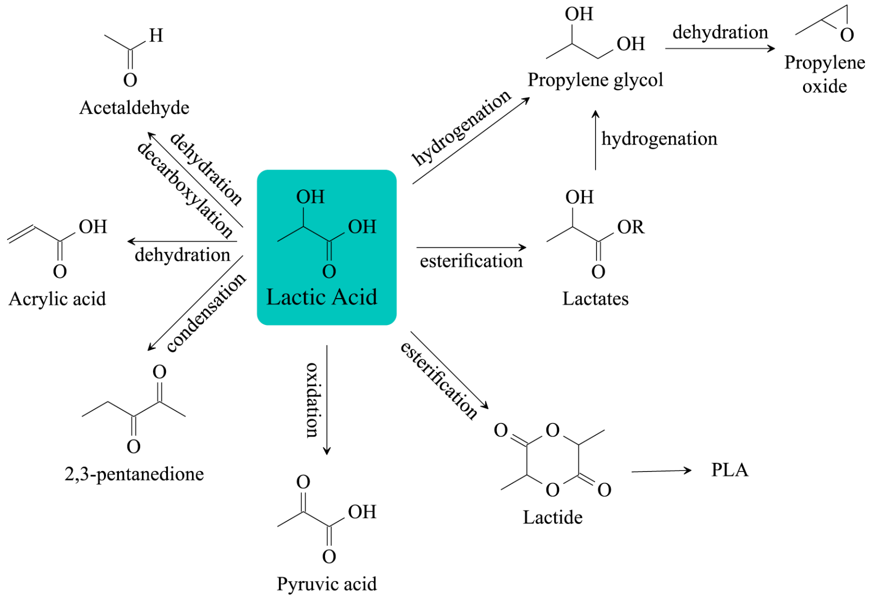

Figure 3.4 Lactic acid as a platform chemical

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.

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.[13]

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.[14] 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).[15] 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 5).

13 Mullauer, F. B. et al. (2009). 'Betulin Is a Potent Anti-Tumor Agent that Is Enhanced by Cholesterol'. In: PLoS ONE 4.4, e1.

14 Puri, M. et al. (2012). 'Enzyme-assisted extraction of bioactives from plants'. Trends in Biotechnology 30.1 (2012), pp. 37–44.

15 Kadam, K. et al. (2008). 'Flexible biorefinery for producing fermentation sugars, lignin and pulp from corn stover'. Journal of Industrial Microbiology & Biotechnology 35.5 (May 2008), pp. 331–341.

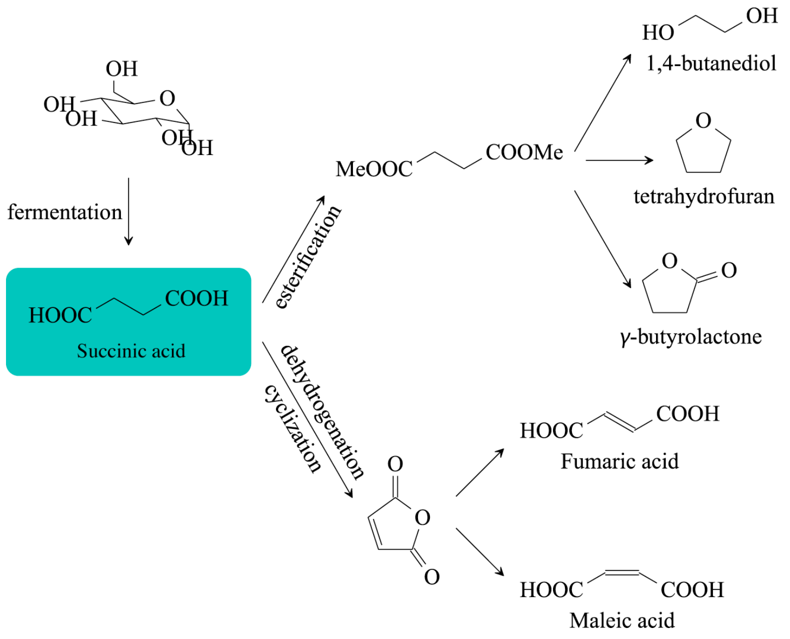

Figure 3.5 Succinic acid as a platform chemical. Source: Corma A. et al (2007).

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.[16] 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 terephtalate (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 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).[17] 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:

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

17 FAO Statistics (2012).

thermo-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) 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. This type of fibre is called man- made or regenerated cellulose fibres, and in 2005 the annual production was approximately 3.5 Mt.[18] 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.[19]

Biocomposites can be made by mixing plastics and fibres. Examples are a composite from L-polylactide 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 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.[20]

18 Shen, L. and M. K. Patel (2010). 'Life cycle assessment of man-made cellulose fibres'. In: Lenzinger Berichte 88 (2010), pp. 1–59.
19 See the soybean car, thehenryford.org.

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.[21,22] 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.[23] Biodiesel can be used as a car fuel, as a heating oil, and has been tested for railway and aircraft usage.

20 M.J. John & S. Thomas (2008). Biofibres and biocomposites. In: Carbohydrate Polymers, 71, pp. 343-364.
21 Energy Independence and Security Act of 2007.
22 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 9.
23 Carriquiry, M. A. et al. (2011). 'Second generation biofuels: Economics and policies'. In: Energy Policy 39.7 (2011), pp. 4222–4234.

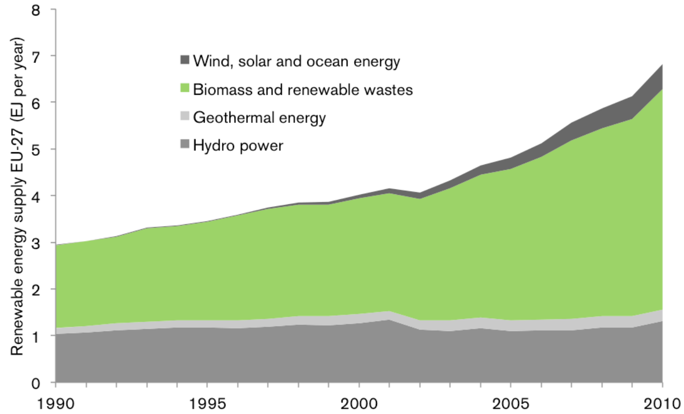

Figure 3.6 Supply of renewable energy in Europe. Source: Eurostat 2012.

Other examples of proposed transportation fuels based on renewable resources are hydrocarbons, 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.[24] 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, 5 and 9). 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 Chapter 2 and 6).

Other bioenergy products are mostly used for the 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 CO_2 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 the transportation of wood pellets from the west coast of Canada to Europe is taken into account, environmental benefits are expected.[25]

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.[26] Lastly, lignin can be separated in pulp plants and used as a biofuel (Chapter 5). 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).

24 Pfromm, P. H. et al (2010). 'Bio-butanol vs. bio-ethanol: A technical and economic assessment for corn and switchgrass fermented by yeast or Clostridium acetobutylicum'. In: Biomass & Bioenergy 34.4, pp. 515–524.

25 F. Magelli et al. (2009). 'An environmental impact assessment of exported wood pellets from Canada to Europe'. In: Biomass & Bioenergy 33.3 (2009), pp. 434–441.

26 Mohan, D. et al. (2006). 'Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review'. In: Energy & Fuels 20.3 (2006), pp. 848–889.

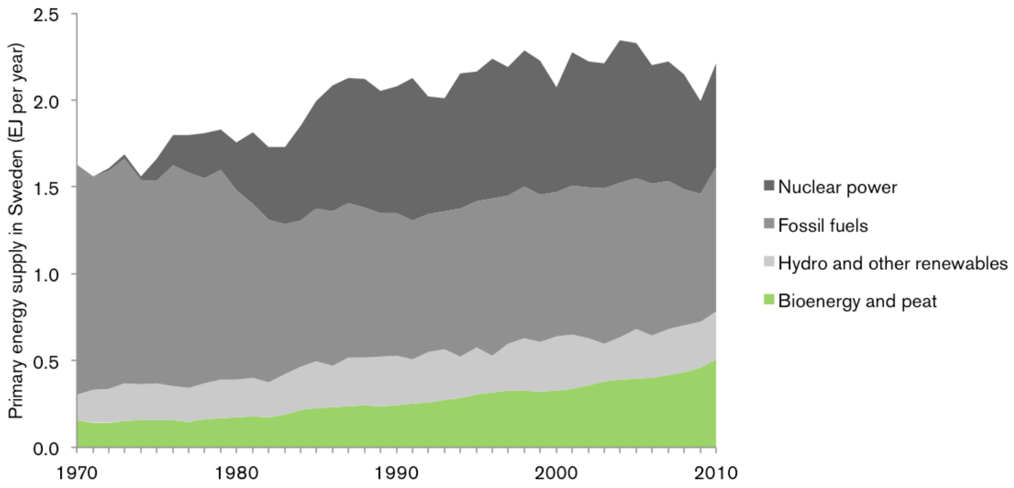

Figure 3.7 Resource mix of energy supply in Sweden. Source: The Swedish Energy Agency (2012)

Sweden has a significantly different energy mix (Figure 4.7). 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.

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 a 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 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.

HOW MUCH BIOMASS IS AVAILABLE?

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4

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 that largest prospective use.

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 EJ[2], 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

1 Some 10% of the coal is used in steel production.
2 Assuming an average carbon content in biomass of 50% and 18 GJ/ton (dry biomass and average lower heating value, see Chapter 6 for a discussion on heating values and water content of biomass feedstock).

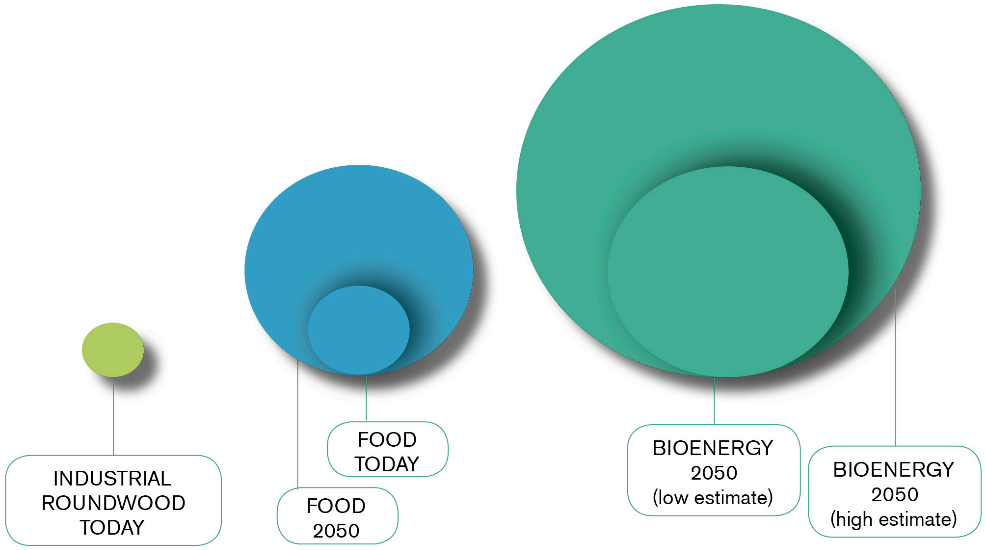

Figure 4.1 Comparison of the food and agriculture sector with a prospective bioenergy sector. The energy content in today's global industrial roundwood production is about 15-20 EJ per year, and the global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) corresponds to about 60 EJ per year (FAO 2011). 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 CO2eq concentration targets (118 to 190 EJ per year of primary biomass). Source: IPCC (2011).

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.

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, the character and development of agriculture and forestry, and factors connected to nature conservation and preservation of soil, water and biodiversity.[3] 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 refer 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.[4] 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.

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 mobilize, 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

3 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), pp. 1-28.

4 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), pp. 26- 43.

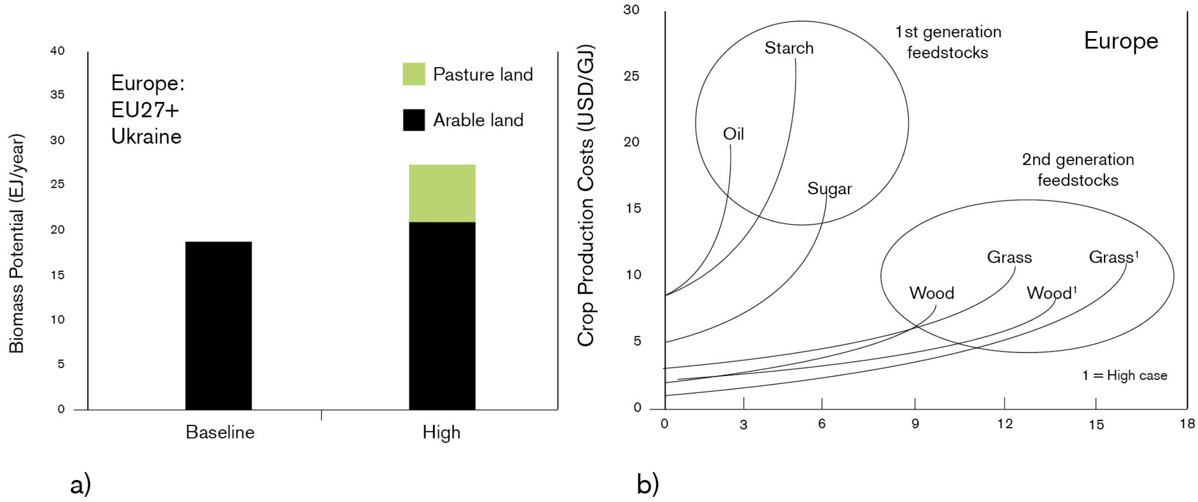

Figure 4.2 Examples of modelled market potentials 2030 (a) based on feedstock cost supply curves shown in (b) for European countries. Sources: (a): Fischer et al., (2010); (b): de Wit and Faaij, 2010

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.

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 characterize 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 to 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

Table 4.1 Overview of global technical potential of land-based bioenergy supply for a number of categories (primary energy, rounded numbers).

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).

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 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.[5]

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.[6] 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.[7] 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.[8] 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.

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

5 See also Chapter 6 for a discussion on the problems and risks of mixing results from studies that use different definitions and incompatible assumptions.

6 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), pp. 471-487.

7 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), pp. 418-426.

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

to improve stand growth will lead to increased availability of small roundwood suitable for energy uses.[9]

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.[10] 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. [11]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. [12] Yet, again, it can also lead to negative effects including reduced forest soil carbon and nutrient stocks, increased soil erosion and soil compaction.[13] 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 consumption 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.[14] Countries close to the dotted diagonal have a non-used NAI that is roughly 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.[15]

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. [16] However, concerns about biodiversity and other undesirable effects might restrict productivity-enhancing measures.

9 See Chapter 5 for an outline of current and potential utilization of residue flows in pulp mills.

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

11 Börjesson, P. (2000). Economic valuation of the environmental impact of logging residue recovery and nutrient compensation. Biomass and Bioenergy, 19(3), pp. 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), pp. 90-98.

12 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), pp. 349-356.

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

14 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).

15 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.

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

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.[17] 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 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 CO_2 concentrations[18] 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.[19]

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.[20]

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 4.4for 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

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

18 Elevated CO_2 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 CO_2.

19 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 (2010), doi: 10.1016/j.agsy.2010.07.005

20 See, e.g., Beringer et al. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. Global Change Biology Bioenergy, doi:10.1111/j.1757-1707.2010.01088.x; Fischer et al., (2009) Fischer, G., E. Hizsnyik, S. Prieler, M. Shah, and H. van Velthuizen (2009). Biofuels and Food Security. The OPEC Fund for International Development (OFID) and International Institute of Applied Systems Analysis (IIASA), Vienna, Austria, 228 pp

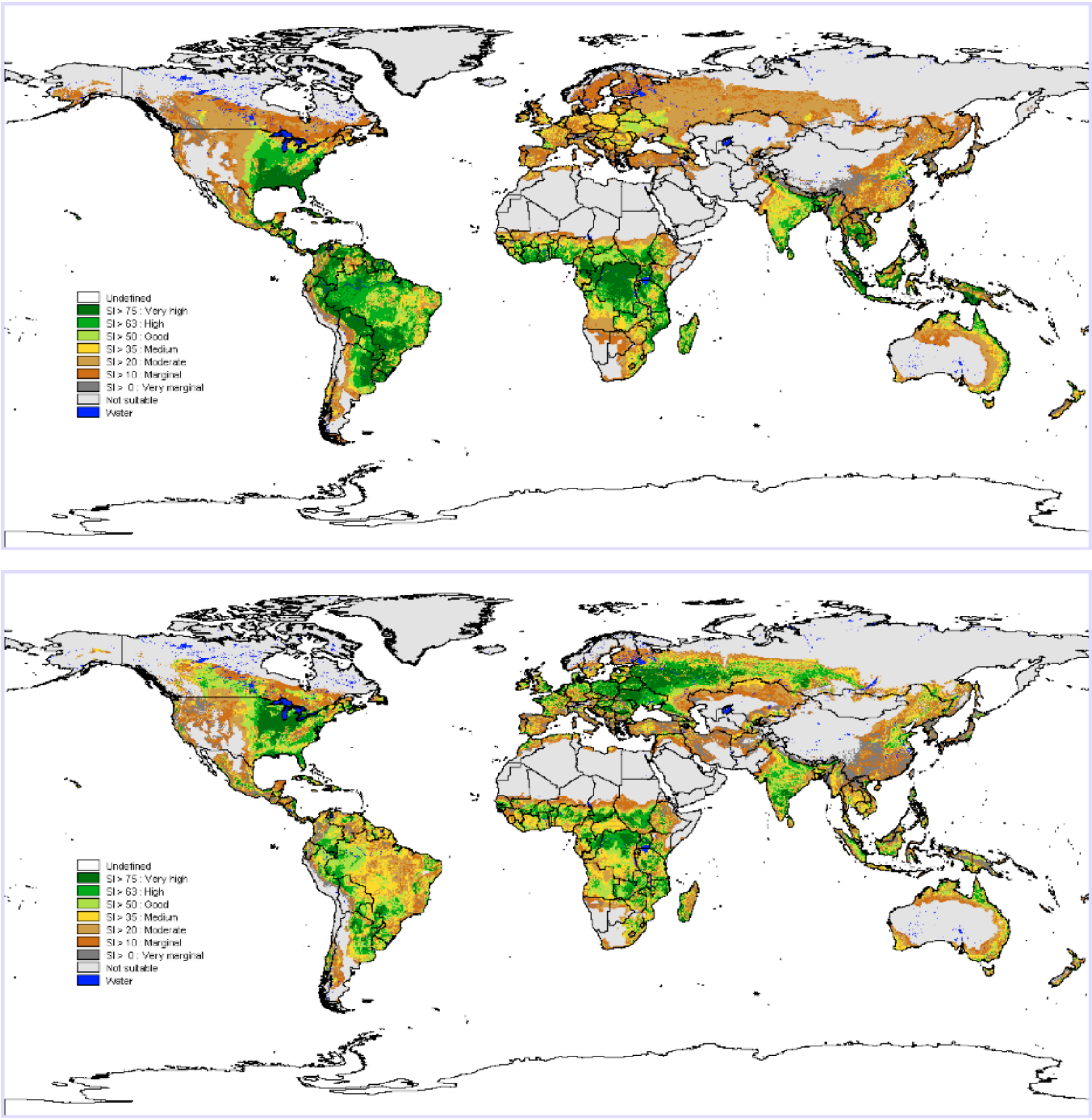

Figure 4.4 Global land suitability for bioenergy plantations. The upper map shows suitability for herbaceous and woody lignocellulosic plants (Miscanthus, switchgrass, reed canary grass, poplar, willow, eucalypt) and the lower map shows suitability for first generation biofuel feedstocks (sugarcane, 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).

potentials[21] and suitability (see caption to Figure 4.4).

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 protection – not least grassland ecosystems – and the present

21 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.

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 development [22] show lower expected yield growth than studies of the biomass resource potential that report very high potentials for biomass plantations.[23] 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 (IAASTD 2009). Water scarcity can limit both intensification possibilities and the prospects for expansion of bioenergy plantations.[24] 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.[25] However, agricultural productivity can be increased in many regions and systems with conventional or organic farming methods.[26]

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.[27] 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.[28] 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, such 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

22 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, 24-26 June 2009. Economic and Social Development Department, Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 78.
23 Johnston, M. et al. (2009). Resetting global expectations from agricultural biofuels. Environmental Research Letters, 4(1), 014004
24 Berndes, G. (2008). Water Demand for Global Bioenergy Production: Trends, Risks and Opportunities. Report commissioned by the German Advisory Council on Global Change. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, Berlin, Germany, 46 pp.

25 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), pp. 4513-4518.
26 Badgley, C., J. et al. (2007). Organic agriculture and the global food supply. Renewable Agriculture and Food Systems, 22(02), pp. 86-86.
27 Wirsenius, 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 (2010), doi: 10.1016/j.agsy.2010.07.005
28 Lal, R. (2003). Offsetting global CO_2 emissions by restoration of degraded soils and intensification of world agriculture and forestry. Land Degradation & Development, 14(3), pp. 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 (9 pp.).

plants.[29] 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.[30] 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.[31] 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.[32]

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

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

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

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

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.

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 models[33] 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.

33 See, e.g., Melillo et al. (2009). Indirect emissions from biofuels: How important? Science, 326(5958), pp. 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), pp. 381-393.Wise et al. (2009) Implications of limiting CO_2 concentrations for land use and energy. Science, 324(5931), pp. 1183-1186.

OPPORTUNITIES FOR BIOREFINERIES IN THE PULPING INDUSTRY

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5

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, 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 (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 (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.

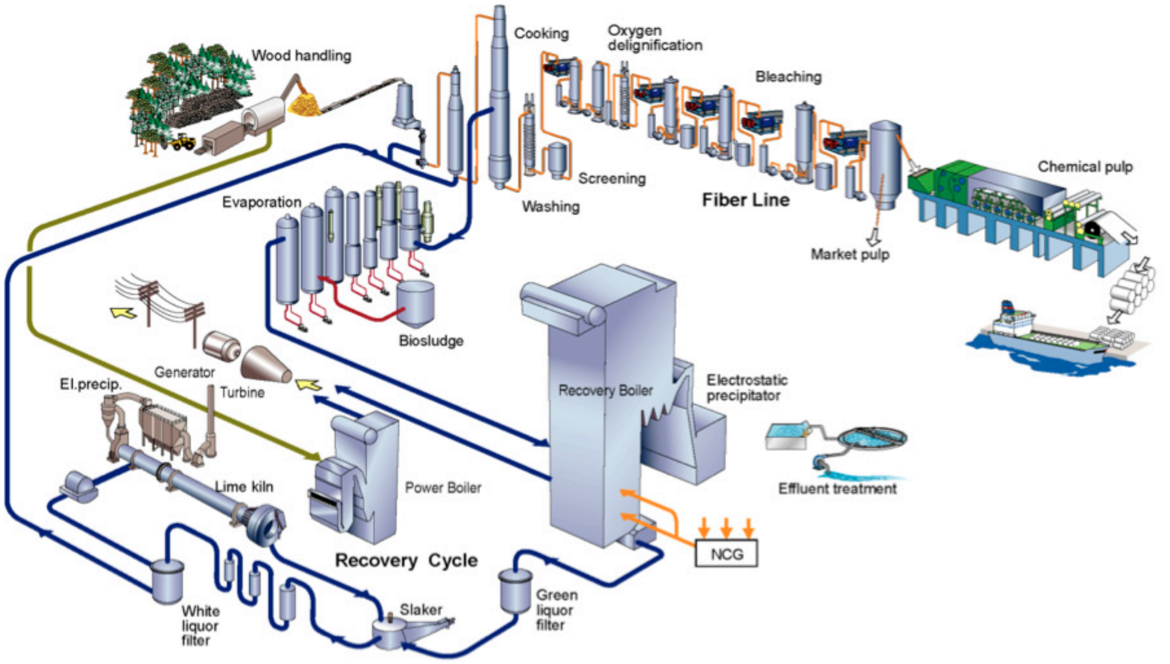

Figure 5.1 Overview of a conventional kraft pulp mill © 2008 Kvaerner Pulping

PULP PRODUCTION

There are two principle ways to produce pulp, by chemical or mechanical separation of the cellulose fibres. 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 5.1 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 Na_2S) 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 Na_2CO_3 and Na_2SO_4. 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.

1 Swedish Forest Industries, 2009. Skogsindustriernas miljödatabas: Bruk 2009.

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 8). 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]

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 5.2 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. 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 5.2, 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 CO_2 capture and storage. It could potentially contribute to large reductions of CO_2 emissions as well as high profits for large mills at future high costs for CO_2 emissions.[3]

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

3 Hektor E. (2008). Post-combustion CO_2 capture in kraft pulp and paper mills – Technical, economic and systems aspects. Chalmers University of Technology, Göteborg, Sweden. Jönsson J and Berntsson T. (2010). Analysing the Potential for CCS within the European Pulp and Paper Industry. In Proceedings of 23rd International ECOS Conference, Lausanne, Switzerland, June 14-17, 2010;676-683. Pettersson, K. (2011). Black Liquor Gasification-Based Biorefineries – Determining Factors for Economic Performance and CO_2 Emission Balances. PhD Thesis. Göteborg: Chalmers University of Technology.

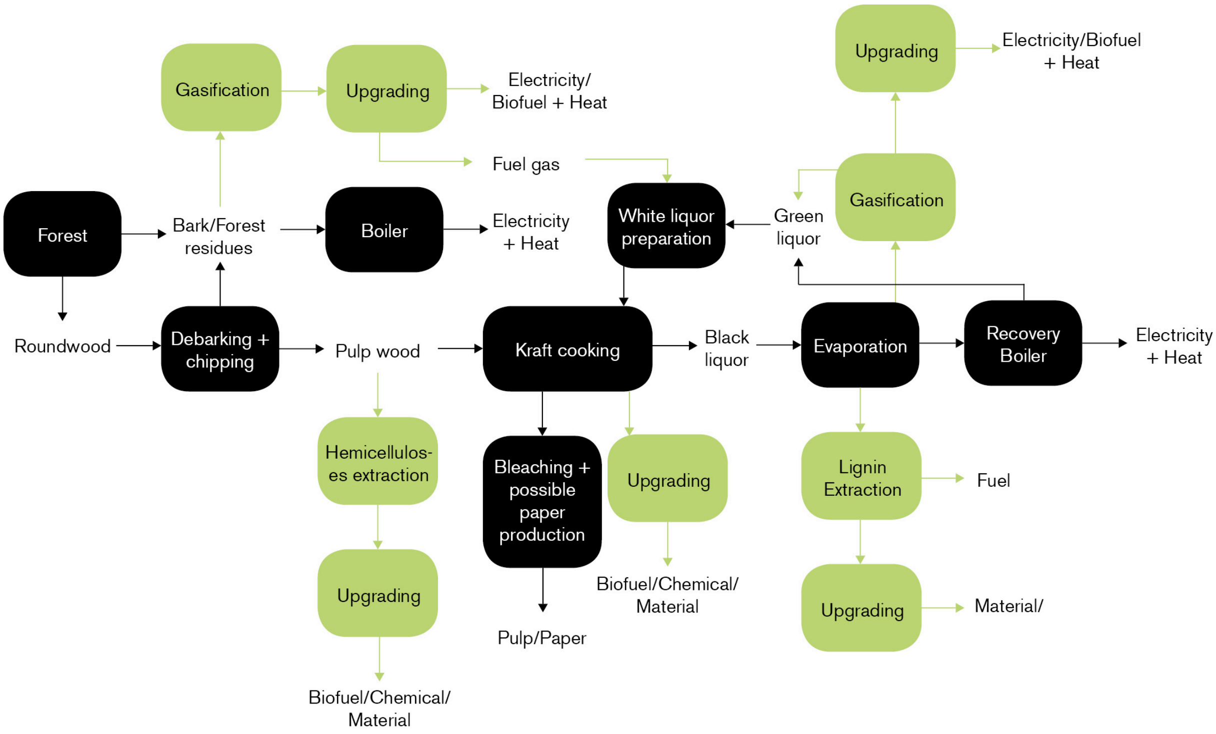

Figure 5.2 Example of biorefinery concepts and products (green process units) that could be implemented at a kraft pulp mill (conventional process units are black)

HEMICELLULOSES EXTRACTION

Hemicelluloses consist mainly of macro-molecular sugars with different characteristics, such as glucuronxylans 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.

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 5.2). 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

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 Proceeding, NWBC, Helsinki.
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). P., "Evaluation of a value prior to pulping - thermomechanical pulp business concept, part 2", TAPPI Journal, May 2011: 31- 38.

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.

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 boilers are 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 CO_2 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. Several BLG technologies have been under development during the past 30 years. Today, the major developer of BLG technology is the Swedish company Chemrec. Their technology is based on pressurized, high-temperature (950-1000°C), oxygen-blown, entrained-flow gasification.[9] (See Chapter 9 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

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.

Converting an existing pulp mill or one of the fibre lines, to an ethanol production plant is another alternative for utilizing cellulose. The ethanol

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

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

10 Pettersson, K. (2011). PhD Thesis, Chalmers University of Technology, Göteborg.

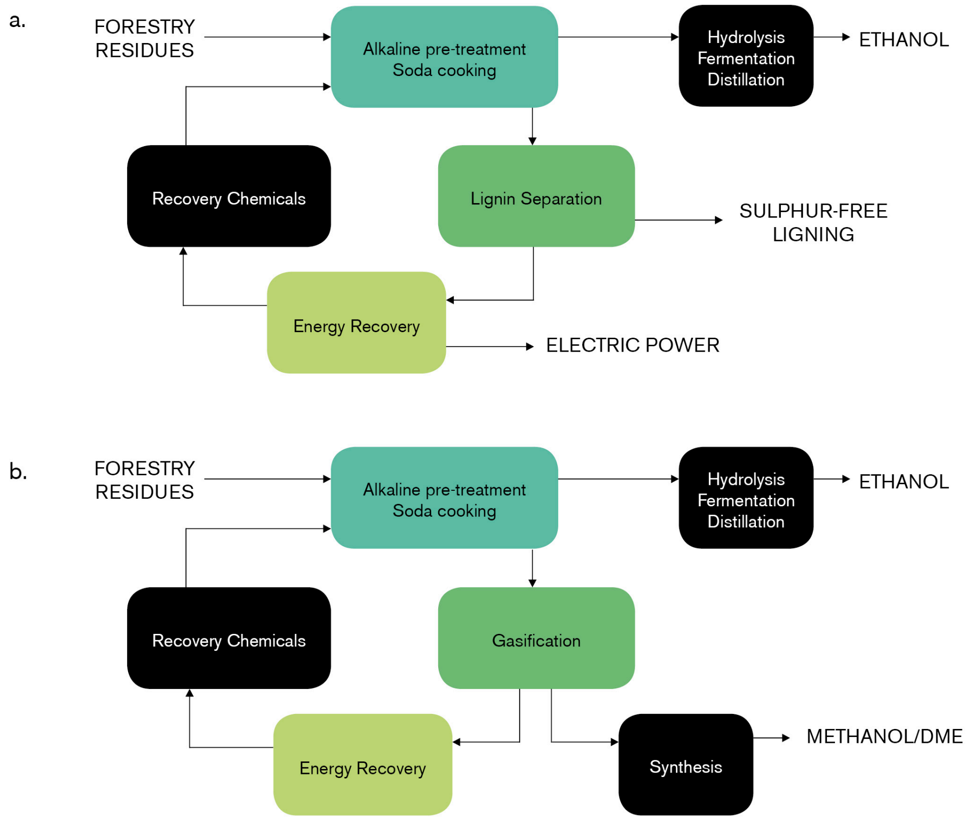

Figure 5.3 Conceptual designs of a pulp mill converted to an ethanol production plant. (a) – Option with lignin separation and (b) – Option with methanol/DME production. The black liquor could of course also go directly to the recovery boiler. Source: Olm L. et al (2007). Ethanol from Swedish wood raw material by simplified alkline cooking process. STFI-Packforsk report no. 291, August 2007.

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 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 5.3 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 has been called an "energy combine". In this concept, mills with a heat surplus can be integrated with processes such as lignocellulosic ethanol production[13] or different types of biomass upgrading, for example drying, torrefaction or pyroloysis 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

11 Jansson, M. et al. (2010), Cellulose Chem. Technol., 44(1-3): 47-52.

12 von Schenck A. et al (2011). Ethanol from Nordic wood raw material by alkaline simplified sodacooking pretreatment, Proceedings of the ISAF conference in Verona, Italy.

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.

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 CO_2 emission balances of the process (see Chapter 8). 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 9 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 summarized, structured and commented further in Table 5.1. Table 5.1 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 5.1.

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 utilize 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 7). 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 CO_2 emissions, is generally better for biorefinery processes such as lignin extraction and black liquor gasification at mills with a significant steam, or heat, surplus.[15] This emphasizes 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 that can be used for production

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), PhD Thesis, Chalmers University of Technology, Göteborg.

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 CO_2 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 5.1. 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 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 liquor, gasify the black liquor and at the same time also gasify solid biomass in

16 See e.g. Jönsson J and Algehed J (2010). Pathways to a sustainable European kraft pulp industry: Trade-offs between economy and CO_2 emissions for different technologies and system solutions. Applied Thermal Engineering 2010;30(16):2315-2325.

17 McKeough P and Kurkela E (2008). Process evaluations and designs in the UCG project 2004-2007. VTT, Espoo, Finland.

18 Frederick et al. (2008). Biomass and Bioenergy, 32: 1293-1302.

19 See e.g. Pettersson, K. (2011), PhD Thesis, Chalmers University of Technology, Göteborg.

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 prioritize. The level of the investment costs for the different biorefinery concepts are indicated in Table 5.1. The level varies from relatively low to very high. (See also Chapter 9 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.

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 CO_2 emissions, will to a large extent determine the future economic performance, and indirectly, the CO_2 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 5.1. 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 5.1 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 specialize 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 9 and Figure 9.3). 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).

Table 5.1 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, buthanol, 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 down-stream 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 down-stream 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 continuously 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 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.

Finally it should be emphasized 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 realized on a commercial scale.

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 to utilize 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 forest residues or 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 specialize on different products, and hence display a greater variety as compared to the more homogenous industry of today.

WHAT IS THE EFFICIENCY OF A BIOREFINERY?

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6

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 (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 5). 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 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 thermodynamics 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 byproduct 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 emphasize 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 the following we will elaborate on different ways to quantify thermal efficiency.

(1)

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

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 (kg_{water}/ $kg_{wet\ fuel}$) is defined in Eq. 2, where mdry is the mass of the dry part of the fuel (dry matter) and m_{wet} is the total mass of the wet fuel.

(2)

$$f_M = \frac{m_{water}}{m_{wet}} = \frac{m_{wet} - m_{dry}}{m_{wet}} = 1 - \frac{m_{dry}}{m_{wet}}$$

The heating value defines the chemically bound energy within a certain fuel (J/kg_{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 vaporize the moisture equalizes 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.

(3)

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

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.

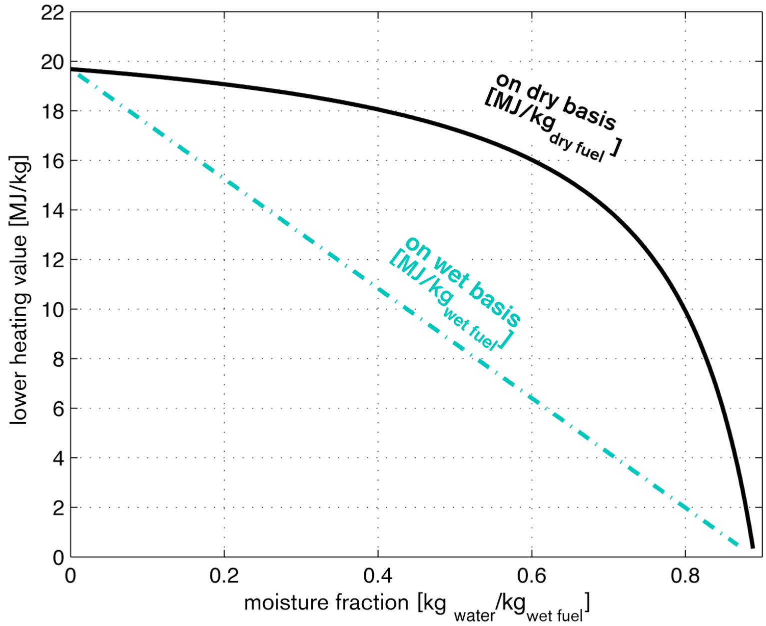

Figure 6.1 Lower heating value as a function of fuel moisture content

The *LHV* of a given fuel as a function of moisture fraction can then be expressed either on dry fuel basis ($MJ/kg_{dry\ fuel}$).

(4)

$$LHV_{dry}(f_M)=HHV_{DM}\text{-}Q_H\text{-}Q_M=$$
$$=HHV_{DM}\text{-}H_{evap}\left(w_H\cdot\frac{M_{water}}{M_H}+\frac{f_M}{1\text{-}f_M}\right)$$

or on wet fuel basis

(5)

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

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 Mwater and MH 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 6.1 plots the *LHV* of stem-wood with a typical HHV_{DM} of 21 MJ/kg_{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 f_M of around 0.7 to 0.5. But if the fuel is further dried from 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.

In Sweden 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 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").

1 Strömberg, B. (2005). Bränslehandboken, Värmeforsk, Stockholm.

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 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 6.2 gives a simplified process scheme for a biomass CHP-plant. 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 Fig. 6.2 are calculated according to Eqs 6-8, were ηB is the efficiency of the boiler.

(6)

$$\eta_B = \frac{\text{Heat to process}}{\text{Fuel to boiler}}$$

The efficiency for electricity production is calculated according to Eq. 6, 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.

(7)

$$\eta_{El} = \eta_M \cdot \eta_G \cdot \eta_T \cdot \eta_B$$

The total thermal efficiency η_{Tot} when both heat and power production is combined is then calculated according to Eq. (7)

(8)

$$\eta_{Tot} = \eta_{El} + \eta_Q$$

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

In this example, the boiler is fired with wood chips that contain 50% moisture (f_M). The mass fraction of hydrogen wH 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% (η_{El} = 22%, η_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:

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

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

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:

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

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. w_H

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 6.2 (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 efficiency of this plant will increase with increased moisture content in the fuel as shown in Figure 6.3. However, the ratio between produced heat and electricity it is not shown in Figure 6.3.

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 Fig. 6.4. The decrease in electricity production corresponds to the increase in heat production as more water is fed into the boiler.

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 5, and on system expansion and allocation of emissions between products in Chapter 7).

Figure 6.5 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 in the following, it is assumed that the biorefinery

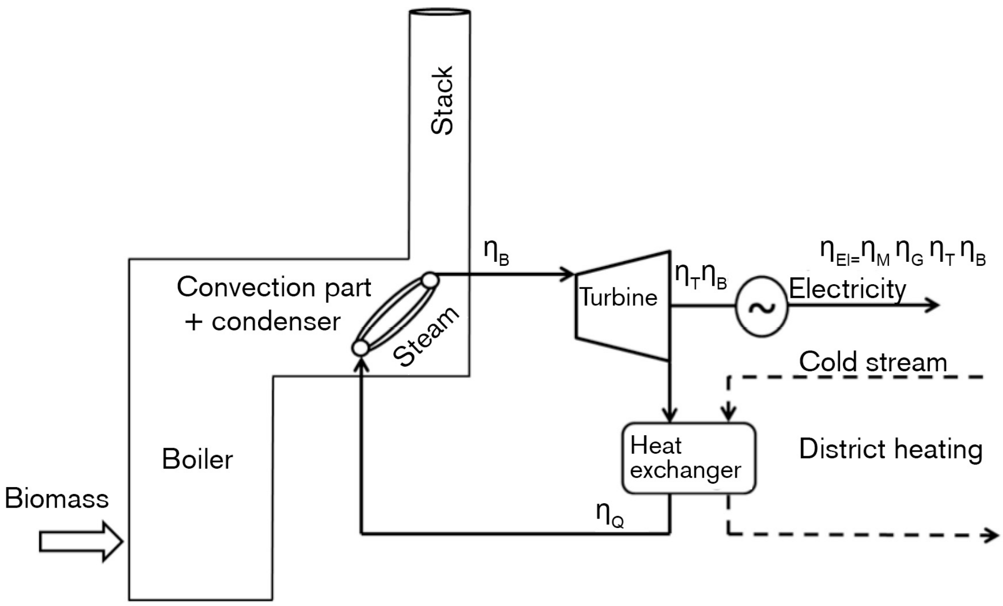

Figure 6.2 Biomass fired combined heat and power plant

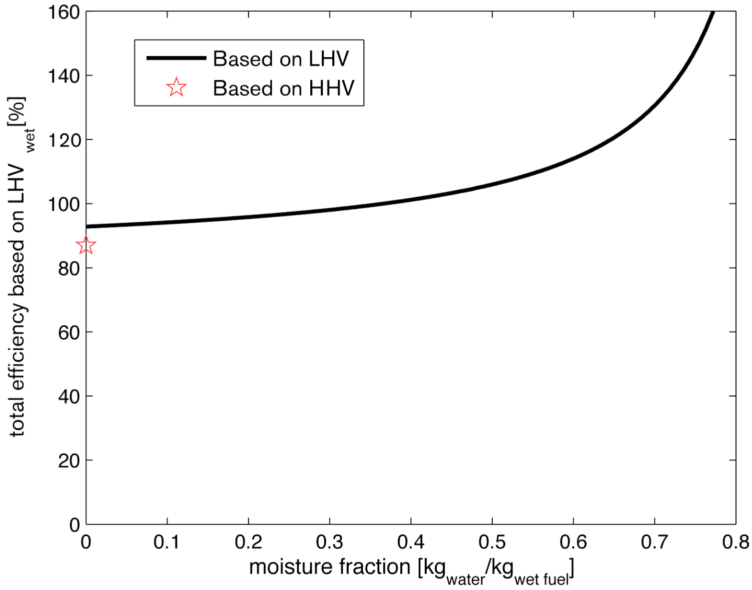

Figure 6.3 Total efficiency of CHP-plant, based on the LHV on wet basis

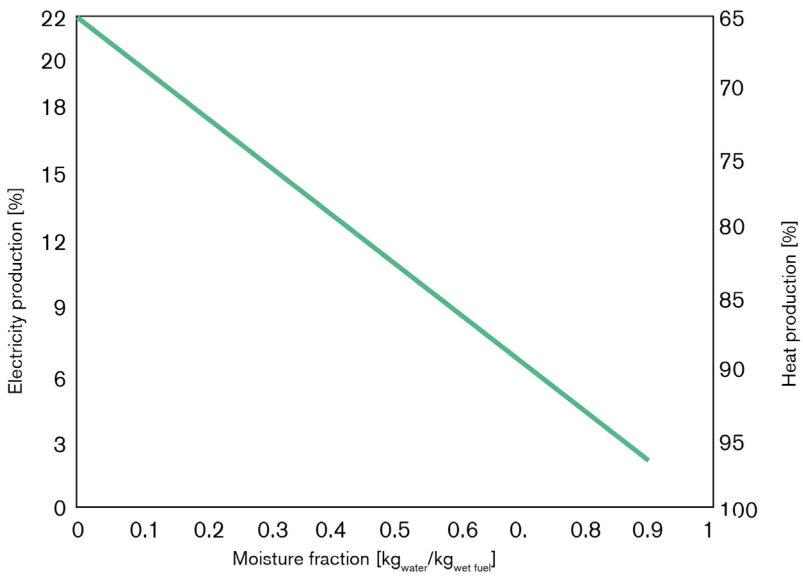

Figure 6.4 Electricity and heat production as a function of the moisture fraction in the fuel

process is supplied with one or several fuels and that it produces one main product (product 1 in Figure 6.5) and possibly several by-products. Depending on the process, electricity and heat are inputs or outputs.

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:

(9)

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

where and are the energy values of the resulting product(s) and biomass input(s), respectively. Pel represents the electricity and 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 () is valued equally to the corresponding amount of electricity export () or product energy (). This reveals the ambiguities with the thermal efficiency use that have been illustrated in the example of the CHP plant above (see also Chapter 8 on the value of excess heat).

For biorefinery concepts producing biofuels (e.g. ethanol, bio-diesel, dimethyl ester (DME) or synthetic natural gas (SNG)) another commonly used form of thermal energy efficiency definition is the biomass-to-fuel thermal efficiency (for

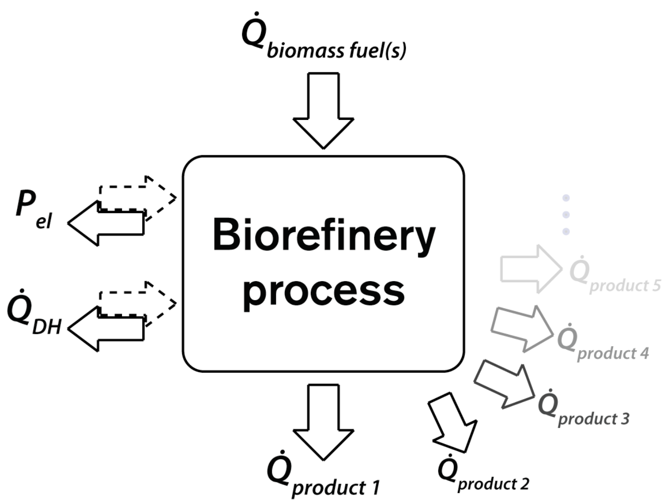

Figure 6.5 Energy input and output of a biorefinery process

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 hbtf can be defined as:

(10)

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

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 Fig. 6.6.

Taking into account the surrounding energy system, it is possible to recalculate all energy services supplied and consumed by a process to primary energy using the corresponding reference conversion technology (see also the discussion on reference system in Chapter 7).

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

(11)

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

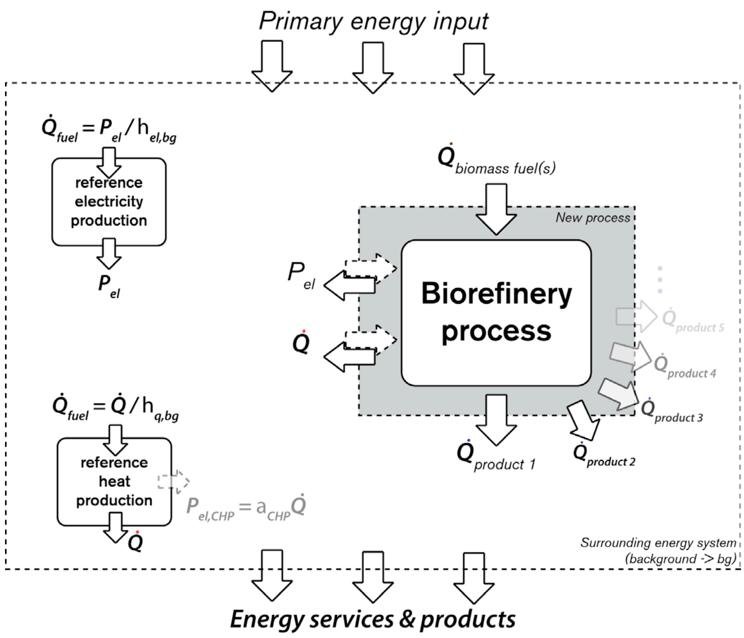

Figure 6.6 Schematic illustration of system boundary and energy flows involved in a biorefinery process.

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 8 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 (and) are converted to primary energy input based on the reference technology for the system under consideration.

(12)

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

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:

(13)

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

It needs to be stated that heat export () 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 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 (LHVDM = 18.6 MJ/kgdry) corresponding to average values for wood fuel. The reference technologies in the assumed reference (or background) energy system (according to Figure 6.5) have an efficiency of el,bg = 0.4 and $\eta_{q,bg} = 0.9$ for power and heat production, respectively. (See Chapter 7 for an illustration of what might happen when reference system parameters are changed.)

In Figures 6.7 to 6.9 the above listed processes are characterized by means of the different efficiency definitions presented in Eqs. 9-11 and 13.

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.

3 Thunman, H. et al. (2008). Inventering av framtidens el- och värmeproduktionstekniker, Elforsk, Stockholm. For details about the production pathways and technologies the reader is referred to this report. In the report, overall energy balances are set up for the different process alternatives and in some cases for varying plant sizes.

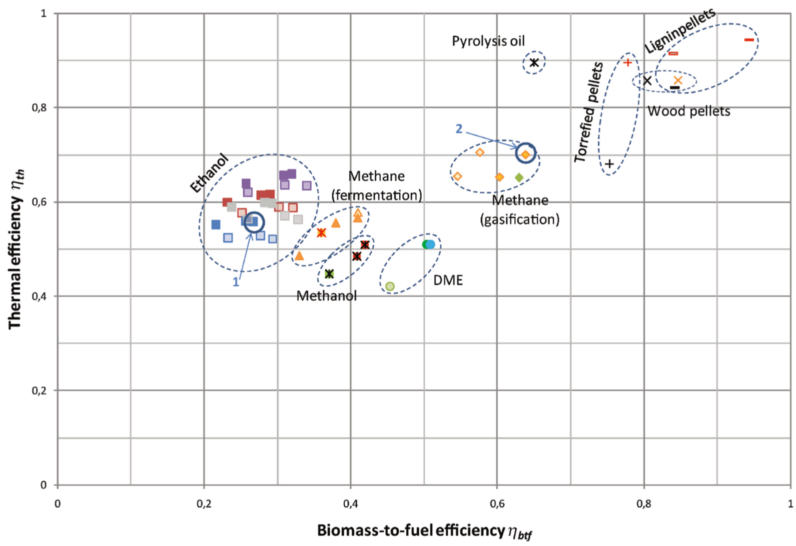

Figure 6.7 Overall thermal efficiency (Eq. 9) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Both heat and electricity are accounted for as useful by-products.

A second interesting aspect is to compare the thermal efficiency figures for the ethanol process alternatives. Both the overall system efficiency hsys and fuel system efficiency $\eta_{sys,fuel}$ rank the process alternatives with combined heat and power production (filled squares in Figures 6.8 to 6.9) 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 Fig. 6.7.

Finally, when comparing methane production via gasification and ethanol production one can observe that the overall system efficiency hsys points out the ethanol process as performing equally well as or even better than the methane process, while the fuel system thermal efficiency $\eta_{sys,fuel}$ 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.

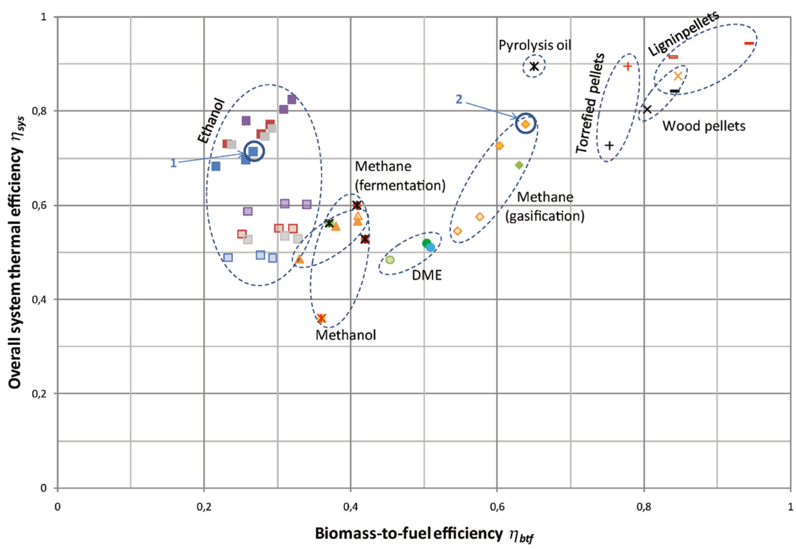

Figure 6.8 Overall system thermal efficiency (Eq. 11) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Only electricity is accounted for as useful by-product while excess heat is not accounted for as useful product.

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.

The overall energy efficiencies are highlighted for the two cases in Figures 6.7-6.9 with the corresponding number. The energy flows of the two processes are illustrated in Figure 7.10. Table 6.1 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 ηbtf and ηsys,fuel. When looking at all energy services provided (hsys) 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 hsys becomes 0.79). So again, simply stating efficiency numbers without clear definition may therefore result in misleading conclusions on the process performance.

Table 6.1 Energy performance analysis of the two process examples of methane and ethanol production.

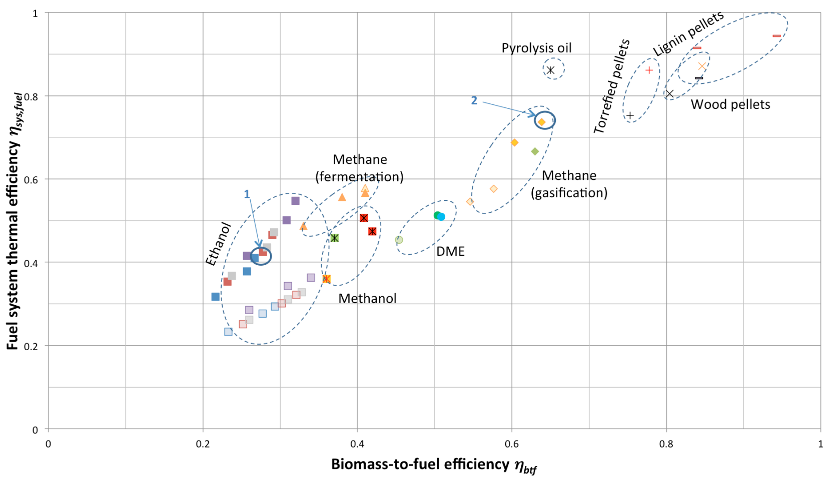

Figure 6.9 Fuel system thermal efficiency (Eq. 13) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Only electricity is accounted for as by-product.

Table 6.1 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	$\dot{Q}_{fuel,1}$	kW	1000	1000
Secondary fuel supply	$\dot{Q}_{fuel,2}$	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	$\dot{Q}_{prod,1}$	kW	638	340
Energy value by-product 1	$\dot{Q}_{prod,2}$	kW	0	440
Energy value by-product 2	$\dot{Q}_{prod,3}$	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))	$\eta_{sys,fuel}$	-	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

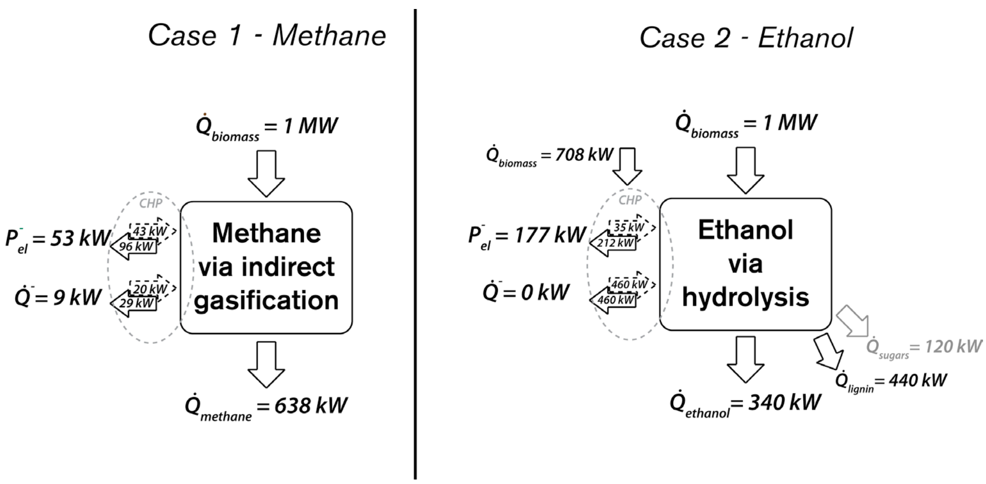

Figure 6.10 Overall energy balance for two biorefinery cases (heat losses during conversion not specifically shown)

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 harmonized. 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 hsys 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 hsys. 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.

HOW MUCH CAN BIOFUELS REDUCE GREENHOUSE GAS EMISSIONS?

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7

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. 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.

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). 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 efficiency[1] (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 generalized to apply to other products as well.

Figure 7.1 illustrates possible main energy and material flows between the main steps in a WTW analysis of biofuels. If 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 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 CO_2 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 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 change[2] (see also discussion in Chapter 1).

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 6 and 8 and the general discussion Chapter 1.)

Allocation can be done on the basis of physical properties (mass, energy content, volume, etc.)

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. And 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.

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 and 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, Göteborg, Sweden.

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.

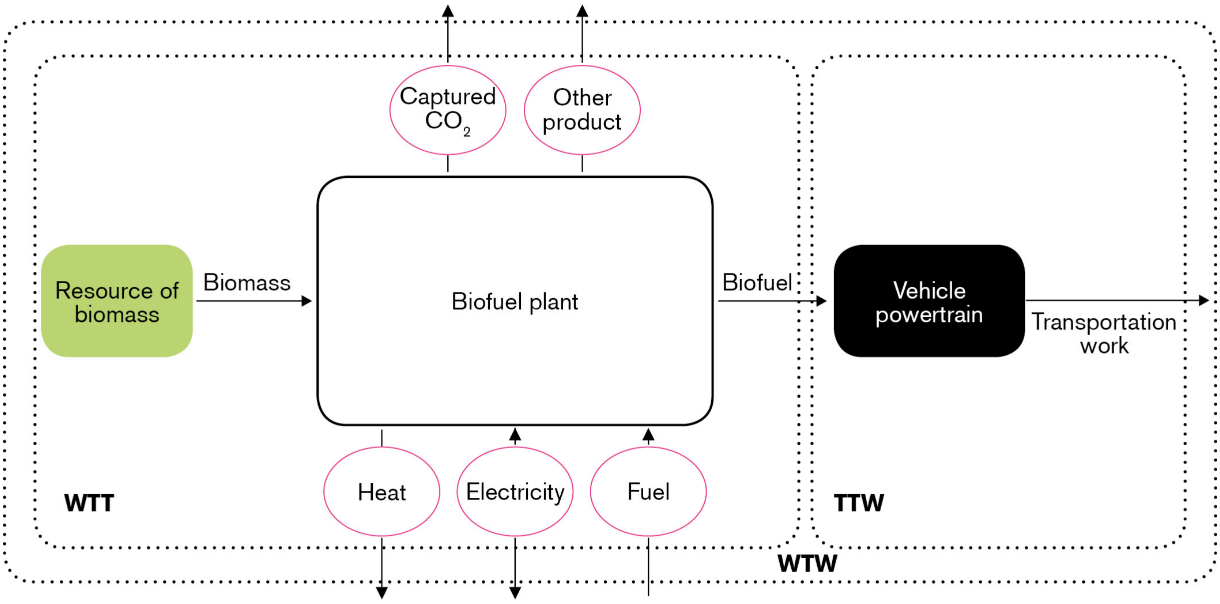

Figure 7.1 Simplified illustration of possible main energy and material flows between the main steps in a well-to-wheel (WTW) analysis of biofuels, where also the well-to-tank (WTT) and tank-to-wheel (TTW) parts are illustrated.

or on the basis of economic value. Allocation can also be avoided through system expansion or substitution, that is, expansion of the system's 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.

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]

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 (ISO 14044:2006), European Committee for Standardization.

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

7 Merrild, 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.

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

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 emphasize the importance of considering the resource that will be limiting, for example in order to reach reduction of fossil GHG[10]. 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).

8 See for example Hillman, K.M. and Sanden, B.A. et al. (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 Wetterlund E, Pettersson K. et al. (2010). Implications of system expansion for the assessment of well-to-wheel CO_2 emissions from biomass-based transportation. International Journal of Energy Research; 34(13):1136-1154.

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 and 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). Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. Biomass & Bioenergy 13(6):359-375. and Gustavsson, L. And Karlsson, Å. (2006). CO_2 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.

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 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 heat[16]. (See Chapter 8 for a thorough discussion on the use of excess heat in district heating systems.)

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]

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

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. Paris, France and 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 JM. et al. (2009) CO_2 balance and oil use reduction of syngas-derived motor fuels co-produced in pulp and paper mills 17th European Biomass Conference & Exhibition, Hamburg, Germany, 29 June – 3 July, 2009.

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 2008;36(11):4186-4197.

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

17 See for example Hillman, K.M and Sandén, B.A. (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.

The possibility of CCS could affect the CO_2 emissions of a biofuel system, or other biomass conversion systems, both directly – if CO_2 capture is possible in the production process (see Chapter 2) and the plant is located near an infrastructure for CCS – and indirectly if, for example, CCS is implemented in coal power plants (lowering CO_2 emissions from grid electricity).

The final steps in the WTW chain include distribution, dispensing and usage of the biofuels. Today oilbased 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 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 7.2 shows how the reduction of CO_2 emissions for two biofuel production processes producing DME via gasification varies dependending on assumptions about the future reference system.[19] The difference between the processes are that in Process 1 (blue bars) the production of DME is not maximized and the plant co-produces considereable amounts of electricity, resulting in a significant electricity surplus, while in Process 2 (red bars) the DME production is maximized, resulting in less produced electricity and in total an electricity deficit.[20] There is a possibility to capture and store CO_2 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 CO_2-neutral option (for example wind power).[22] As Figure 7. shows, the reduction of CO_2 emissions varies significantly depending on the assumptions about future reference transportation and electricity production systems.

Combinations that are considered to be less probable have been omitted from Figure 7.2. 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 CO_2 is not captured in the biofuel processes and in connection with motor fuels produced from coal

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, Göteborg, Sweden, and 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 commercialize such a technology see Chapter 9.

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 $CO_2/GJ_{biomass}$ in each process at a cost of 70 MJ electricity.

21 Oil (diesel):77 kg CO_2/GJ_{fuel}, Coal with CCS (FTD): 92 kg CO_2/GJ_{fuel}, Coal (FTD): 166 kg CO_2/GJ_{fuel}.

22 Coal: 201 kg CO_2/GJ_{el}, NGCC: 104 kg CO_2/GJ_{el}, Coal with CCS: 38 kg CO_2/GJ_{el}, CO_2-neutral: 0 kg CO_2/GJ_{el}.

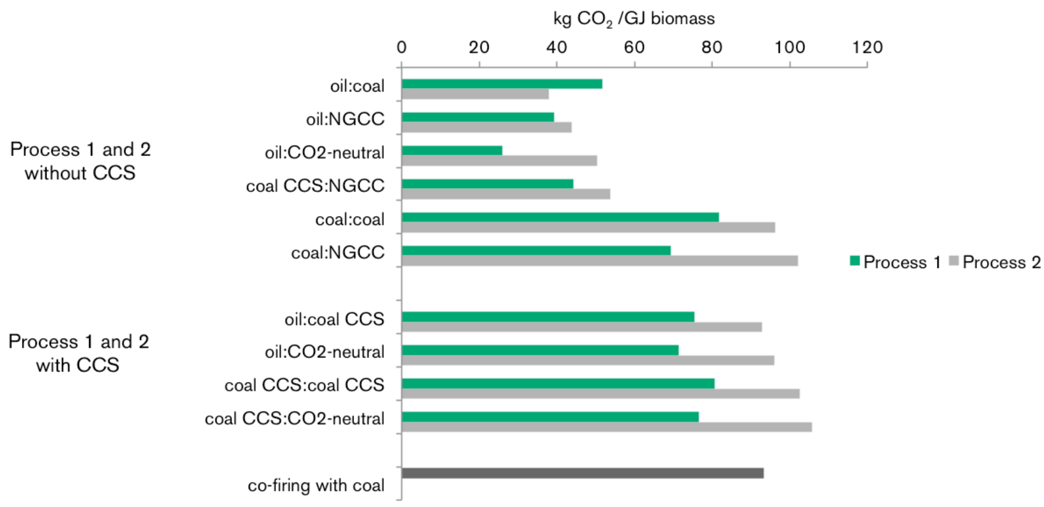

Figure 7.2. Reduction of CO_2 emissions for two biofuel production processes producing DME via gasification (see text for process descriptions). The impact of different assumptions regarding reference transportation and electricity production systems is illustrated (e.g. "oil:coal" refers to transportation based on oil and electricity based on coal). The potential CO_2 emission reduction if biomass is co-fired with coal is also shown.

since CO_2 in this cases are seperated as part of the processes. An electricity system dominated by CO_2-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 CO2neutral, a reference transportation technology based on coal (without CCS) is considered less probable.[23]

Process 1, with a surplus of electricity, benefits from a high CO_2 emitting electricity production technology, while Process 2, with a deficit of electricity, benefits from a low CO_2 emitting electricity production technology. Both processes benefit from a high CO_2 emitting transportation technology, however Process 2 are benefited to a larger extent. As can be seen in Figure 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 CO_2 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

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).

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 7., the CO_2 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 7., the reduction of CO_2 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, it should here be emphasized that reduction of global CO_2 emissions is, as stated, not the only driving force for introducing biofuels. Reducing the dependency of crude oil is also a major driving force. In a larger perspective, since it might be land available that eventually limits the simultaneous use of biomass in a multitude of high volume applications, the land use efficiency of biomass for different applications can also be compared to other types of land-use such as electricity production in solar power plants (see Figure 1.2 and Chapter 4). [24]

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 maximize the climate benefit.

24 For a comparison of area efficiency of biofuels and solar-electric propulsion, see for example Kushnir, D. and B. A. Sandén (2011). "Multi-level energy analysis of emerging technologies: A case study in new materials for lithium ion batteries." Journal of Cleaner Production 19(13): 1405-1416.

THE VALUE OF EXCESS HEAT - PROFITABILITY AND CO_2 BALANCES

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8

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 and 5). 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 CO_2 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 minimized. 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 Chapter 1, 6 and 7). 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 biomaterials, biofuel, 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 waste heat? And, how might a profitable utilization of waste heat affect different biorefinery concepts and designs as well as CO_2 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 prioritize 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 distributer 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 distributer 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 for 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 utilized 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 8.1. 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.

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

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

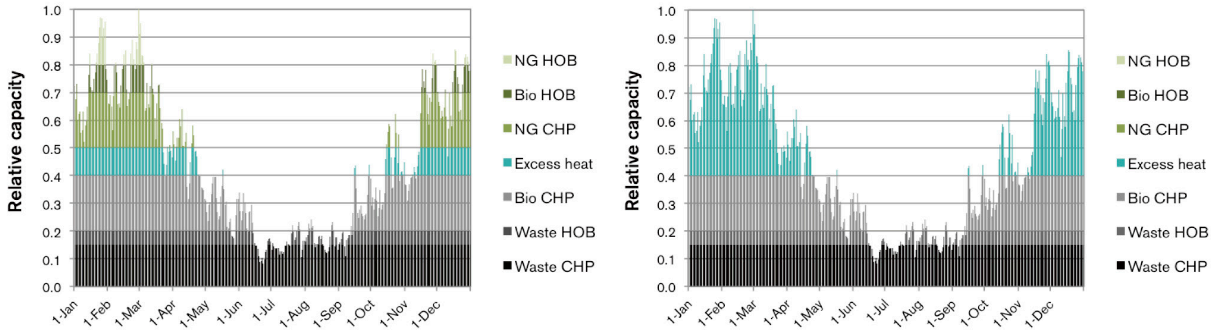

Figure 8.1 In a district heating system with low running cost of base load units it is more favourable to deliver excess heat higher up in the merit order, implying reduced utilization time due to deliveries only a limited part of the year. If the excess heat delivery capacity is large compared to the 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

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.

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 8.2. In this simplified example we consider a gasification process where 50% of the input energy is converted to biofuels and 10% to usable excess heat (the remaining 40% are losses), according to the approach used in. [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. 2003[3] where a DME plant (Dimethyl ether) is described.

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 8.3. Hence, in this example, with a rather small amount of heat being utilized, 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 waste 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 and its system settings, and the operation of a biorefinery could

2 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. Eco-traffic and Nykomb Synergetics.

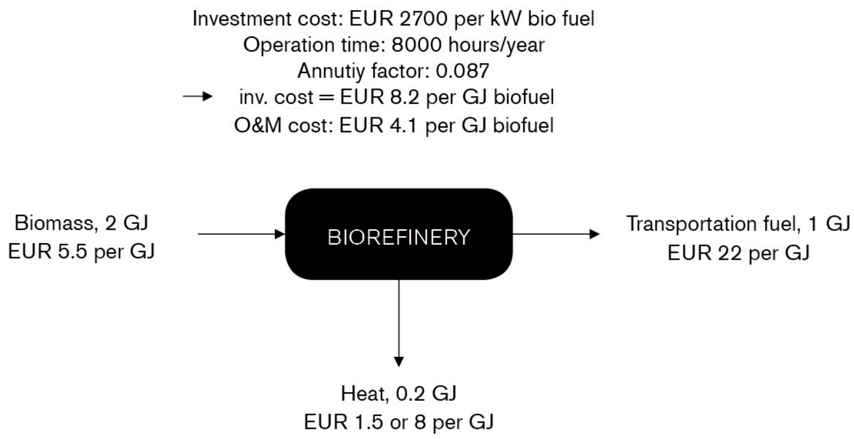

Figure 8.2 Simplification of a biorefinery, with energy flows, related energy prices as well as capital and operation costs.

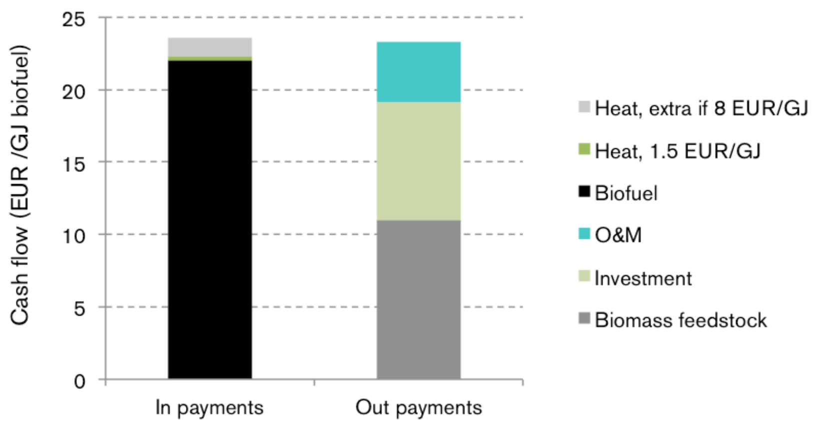

Figure 8.3 Cash flow analysis based on data in Figure 8.2

be optimised as an integrated part of a district heating system.[4]

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 CO_2 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 CO_2

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). Assessment of integration of different biomass gasification alternatives in a district-heating system. Energy, 34: 2184-2195.

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 refinery 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 CO_2 emission consequence of using steam for heat can be quantified by comparison to emissions from electricity 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 6 and reference systems in Chapter 7).

The CO_2 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 CO_2 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 8.4 and 8.5 below. Since the CO_2 emission consequences can be very different with different configurations of the district heating system, two examples are given.

In the first example we consider a typical Swedish district heating system with waste incineration as base load, heat from bio fuelled combined heat

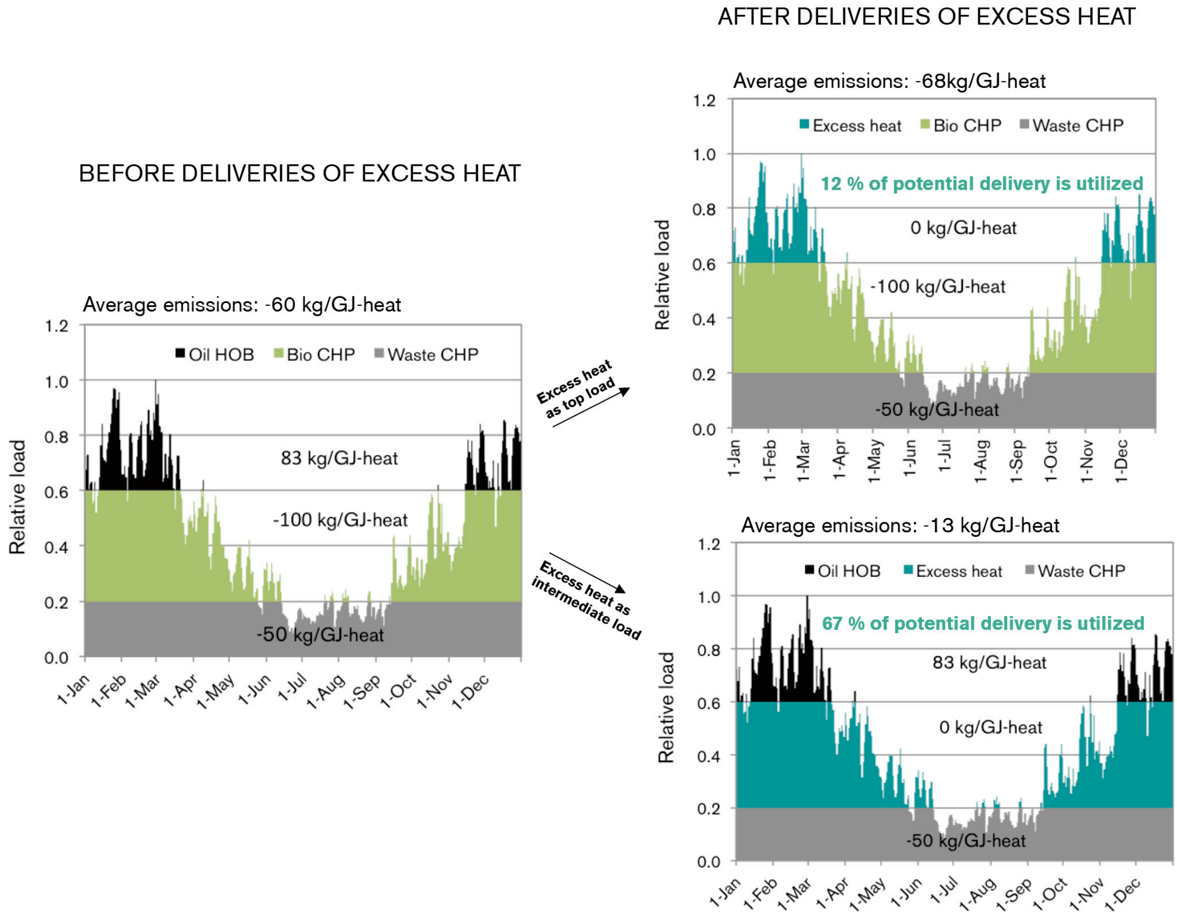

Figure 8.4 CO_2 consequences of excess heat deliveries to a typical Swedish district heating system. Emissions if excess heat is used as top load (right, above) and as intermediate load (right, below) can be compared to the case without excess heat (left).

and power plants (bio CHP) as intermediate load, and fuel oil as top load, see Figure 8.4. As can be seen in the figure, base and intermediate load production are assumed to have negative CO_2 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 7 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 CO_2 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 utilized, in this case 12 %.

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 8.4, this would lead to that 53 % of the potential heat deliveries are utilized. On the other hand, the CO_2 emissions increase when a unit with negative emission is replaced with excess heat having zero emissions. This arguing is correct if biomass is considered CO_2 neutral. The CO_2 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 CO_2 emissions related to the marginal use of biomass (see the concluding section below for some further considerations that put the numbers in figure 8.4 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 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 CO_2 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 CO_2 emission consequences of heat deliveries depend on the configuration of the district heating system and how the heat is utilized. 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, CO_2 emissions.

With this reasoning, there would be a trade-off between profitability and CO_2 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 CO_2 reduction perspective.[6]

6 e.g. Johnsson F. (editor) (2010). European Energy Pathway, Alliance for Global Sustainability (AGS), Mölndal.

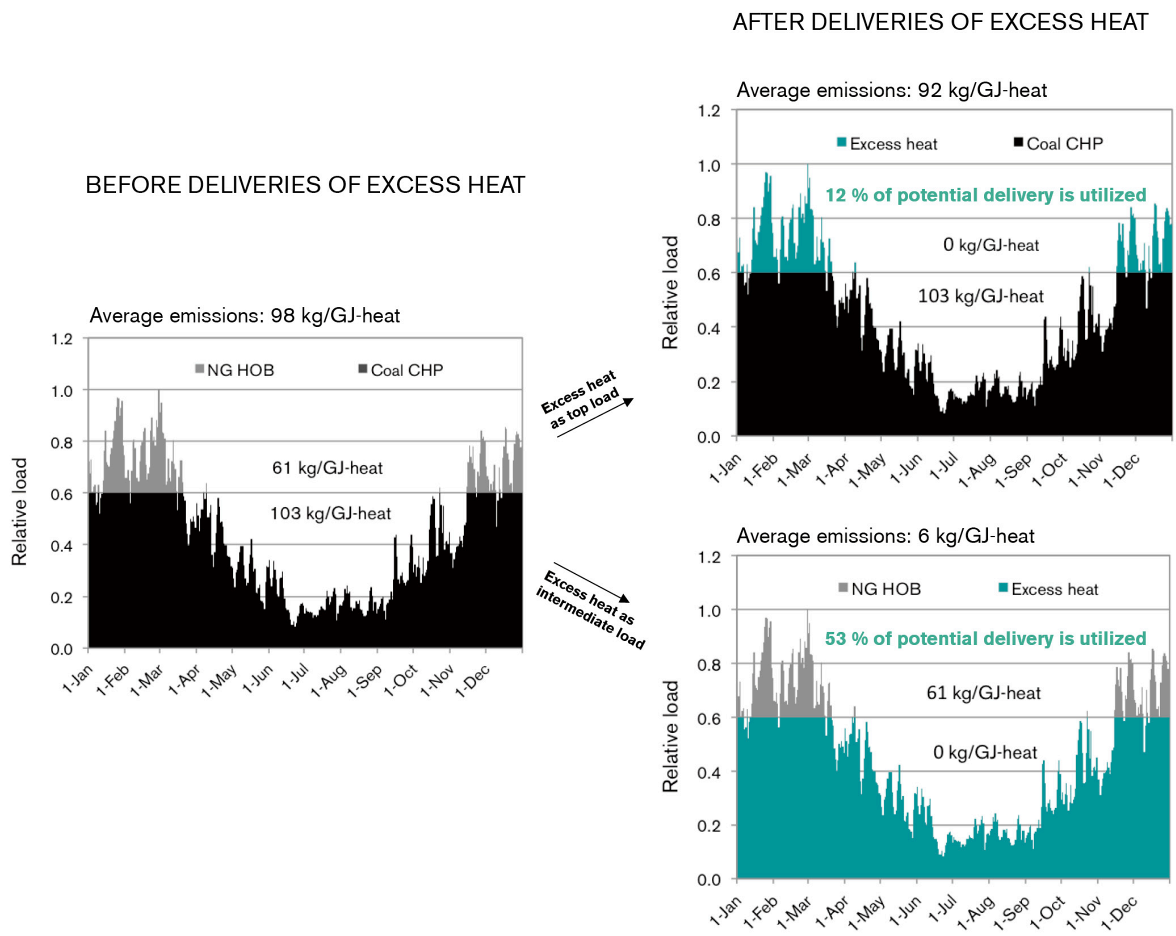

Figure 8.5 CO_2 consequences of excess heat deliveries to a fossil fuel based district heating system.

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 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, decentralized 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 maximize 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 utilized from a carbon mitigation point of view (tonnes of CO_2 mitigated), or how the resources best are utilized from a carbon cost perspective (EUR/tonnes of CO_2 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 9 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 CO_2 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 heating were contrasted[8]. Policies for CO_2 reduction and "green" 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 CO_2 intensive marginal power generation, implies minor climate benefits of transport biofuels (see also discussion on different reference systems in Chapter 7 and the example in Figure 7.2).

In two studies using the DH system of 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.

7 Fahlén E och Ahlgren EO (2009). Assessment of integration of different biomass gasification alternatives in a district-heating system. Energy, 34: 2184-2195.
8 Börjesson M och Ahlgren EO (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 & Söderström M (2010). Biomass gasification in district heating systems – The effect of economic energy policies. Applied Energy 87: 2914-2922.

CONCLUDING REMARKS

To sum up, the profitability and, especially, the CO_2 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 CO_2 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 CO_2 emission consequences when biomass is considered as CO_2 neutral and in abundant supply.

The conclusion that utilizing excess heat can have negative CO_2 consequences 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 utilize 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 utilized in other parts of the energy system, for instance for electricity or biofuel production (e.g. in a biorefinery).

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.

POLICY CHALLENGES IN REALISING BIOMASS GASIFICATION IN THE EUROPEAN UNION

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INTRODUCTION

A core technology in biorefinieries 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 paper and 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 there are nine prominent demonstration facilities, centred on three dominant technological trajectories, in the process of being realized in Austria, Finland, Germany and Sweden.

Each demonstration plant is at the heart of an alliance consisting of a wide range of firms, institutes and universities. Whereas many 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 6, Figures 6.7-6.9, on conversion efficiencies). The purpose

1 Rosenberg, N., (1996). Uncertainty and Technological Change, in: Landau, R., Taylor, T., Wright, G. (Eds.), The Mosaic of Economic Growth. Stanford University Press, Stanford, California, pp. 334-355.

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 7).

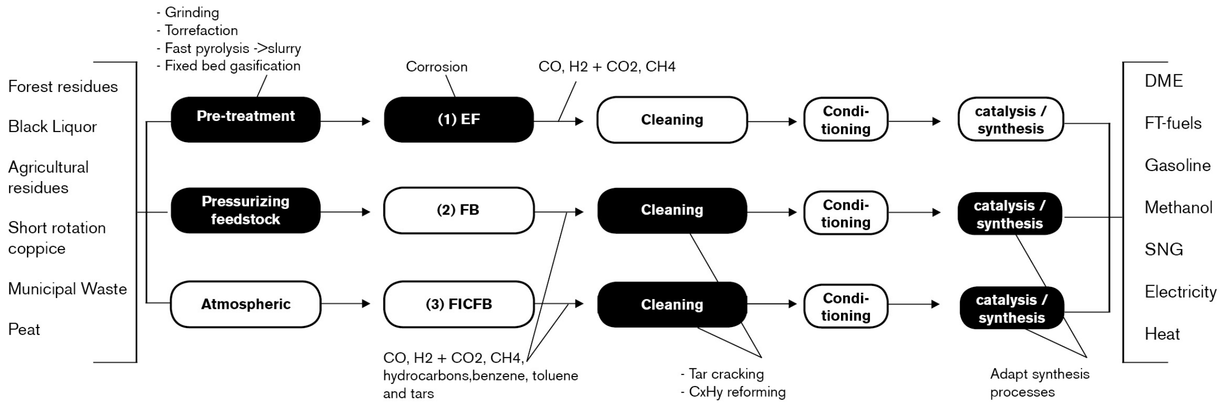

Figure 9.1 The three main trajectories for biomass gasification and main technical challenges (marked in grey and described in italics). The three main trajectories are: (1) Entrained Flow (EF) gasification, (2) Fluidized Bed (FB) gasification, and (3) Fast Internal Circulating Fluidized Bed (FICFB). Source: Hellsmark (2010).

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]

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 heating value[4]. Many types of feedstocks can, in principle, be used, e.g. municipal waste, oil, coal, natural gas 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. substitute natural gas, SNG) and methanol, see Figure 9.1.

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 9.1 where the technical challenges are marked in grey and described in italics. [5]

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

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 Higman, C., van der Burgt, M., (2008). Gasification. Gulf Professional Publishing, Burlington, USA.

5 These nine projects were identified in 2008 through an extensive literature review and interviews with industry experts. This implies that that some important but more recent projects are excluded. See Hellsmark, H. (2010). Unfolding the formative phase of gasified biomass in the European Union – The role of system builders in realising the potential of second-generation transportation fuels from biomass. Doctoral thesis, Department of Energy and Environment, Chalmers University of Technology, Göteborg.

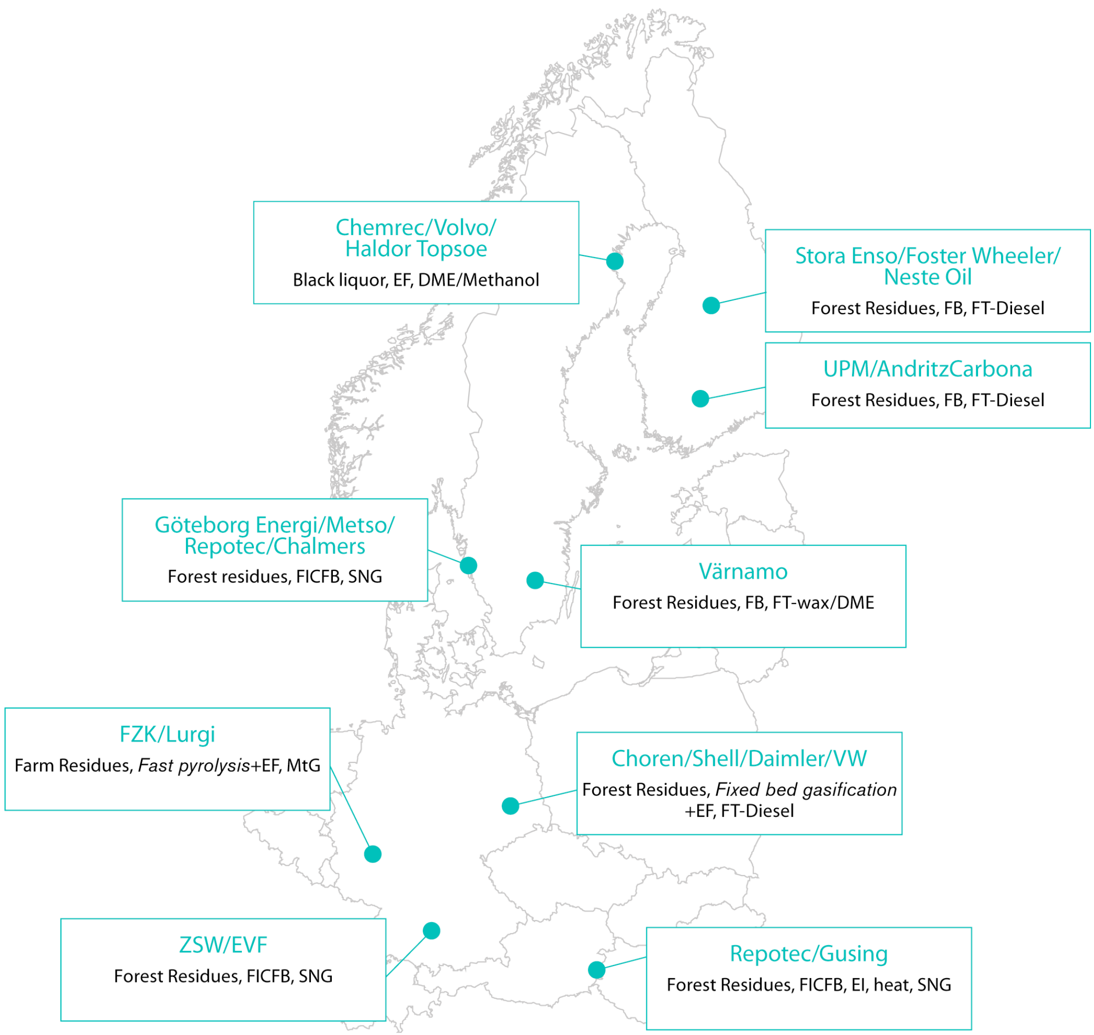

Figure 9.2 Overview of major gasification projects in Europe pursued for the production of synthetic fuels from biomass. When relevant, methods for pre-treatment are mentioned in italics. Acronyms used in the figure are: EF: Entrained Flow, FB=Fluidised Bed, FICFB=Fast Internal Circulating Fluidised Bed, SNG=Synthetic Natural Gas, DME= dimethyl ether, MtG=Methanol to Gasoline. Source: Hellsmark (2010), see footnote 5.

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 pressurized Fluidized Bed (FB) and atmospheric Fast Internal Circulating Fluidized Bed (FICFB) gasification. In the FB system, biomass reacts with a mixture of oxygen and steam. Since it is pressurized, 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. Fluidized 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 pressurized 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. [6]

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. [7] 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 equipment.

Nine such alliances are found in Figure 9.2. 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 9.1.

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 and 5), 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 all in the process of moving from the pilot stage to constructing the first demonstration units. The cost of these plants ranges from 1 to 100 MEUR. However, not all of them include demonstration of the synthesis process, see Table 9.1.

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, 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 year[8] (28 MEUR) in a demonstration plant that was constructed (but not taken in operation) in 2010 to 4 PJ per year (300 MEUR) in a pre-commercial plant (originally planned to be ready by 2012-2013)[9] and to 8 PJ per year (400 MEUR) in a commercial plant to be ready for operation by 2015.[10] 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

6 For a longer discussion of these matters, including sources, see Hellsmark, H. (2010). Unfolding the formative phase of gasified biomass in the European Union – The role of system builders in realising the potential of second-generation transportation fuels from biomass. Doctoral thesis, Department of Energy and Environment, Chalmers University of Technology, Göteborg.

7 There are also other reasons for forming alliances, such as political leverage and securing complementary products as well as funding.

8 Approximately 1.5 ktoe (tonnes of oil equivalent), 1 Mtoe equals 41.9 PJ.

9 Recent information indicates that this decision has not yet been taken which means the time-scale is shifted forward 2-3 years, at best.

10 Rudberg, J., (2008). Interview with Jonas Rudberg, CEO Chemrec, Stockholm, 2008-12-03.

Table 9.1 Industry estimates of costs and time line for the major development projects in the EU.

	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	2013	0.1PJ	75	2015-	3	150
Chalmers/Metso	2008	6	1.1	2008	6	1.1						
ZSW/EVF	2002	8	2.4	2010	10	18	2013-	10 MW	NA	2015-	3	150
Chemrec	2005	5	7	2010	5	28	2013	4 PJ	300	2015-	8	400
Värnamo				1993	18	45				2015-	8	400
Carbona/UPM	2005	6	10				2012	8 PJ	400	2015-	8	500
FW/SE/Nesté				2009	12	40	2012	4 PJ	400	2015-	8	500
Choren	1998	1	NA	2008	45	100				2015-	8	800
FZK/Lurgi	2005	0.1	NA	2008	5	4	2011	5 MW	70	2015-	8	900

Source: Hellsmark and Jacobsson (2012). 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.

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. [11] 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 9.1. [12]

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 per cent 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 years[13], 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

11 Swedish Energy Agency, 2008. Utlysning: Intresseanmälan för demonstration och kommersialisering av andra generationens drivmedel och annan energiteknik. Dnr: 410-2008-003385. Eskilstuna.

12 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 9.1.

13 The figure is a very rough estimate based on previous and similar gasification projects, see Hellsmark, H., (2010). Unfolding the formative phase of gasified biomass in the European Union – The role of system builders in realising the potential of second-generation transportation fuels from biomass. Doctoral thesis, Department of Energy and Environment, Chalmers University of Technology, Göteborg. for a longer discussion.

then take three 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.[14] 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/EC mandates a ten per cent 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. [15] On the basis on the analysis in the previous section we expect only a small share in the form of fuels from gasified biomass. [16]

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.[17]

With respect to conventional fossil based fuels, potential investors would, in the absence of a deployment policy, face very substantial market uncertainties for both the initial nine plants and for the subsequent 100 or more plants. These uncertainties are illustrated in Figure 9.3. In the figure, we distinguish between low and high cost levels (10-20 EUR/GJ) for producing synthetic fuels from biomass gasification.[18]

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 Outlook, IEA (2009) [19] 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.

14 Committee on Climate Change (2010, p. 9)) in the UK explains why public intervention must go beyond addressing negative externalities: "Investment 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."

15 Eurostat, 2012. Energy statistics, . European Commission.

16 Even though perhaps unrealistically, we assume that all of the projects in Table 1 are realized 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 per cent 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.

17 However, other market uncertainties also apply such as the size of the potential market (Chapter 3) and the availability of future biomass resources for energy purposes (Chapter 4).

18 These cost levels were provided by advocates of the different projects in Table 9.1 and Figure 9.2; they are further discussed in Hellsmark (2010).

19 IEA, 2009. World Energy Outlook. International Energy Agency, Paris.

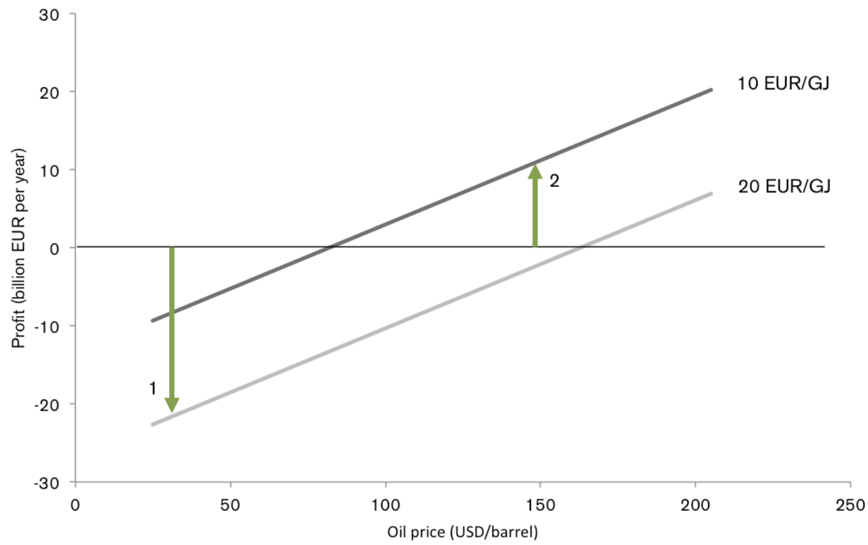

Figure 9.3 A tentative assessment of financial risk for commercially sized plants – annual losses or gains in realizing a 10 per cent market for synthetic fuels from biomass gasification by 2030 (billion EUR). Arrows 1 and 2 are discussed in the text.

Figure 9.3 provides a base for assessing the financial magnitude of the market uncertainties caused by uncertain future oil price. It points to the hypothetic annual losses (or gains) for investors if a 10 per cent market for synthetic fuels from biomass gasification (1,300 PJ per year) is realized 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 9.3).[20] 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).

In sum, there are not only substantial technical but also market related uncertainties for all the actors that need to participate to realize the potential. Moreover, these uncertainties are not of a short term character but are expected to stay for many years. Only very powerful and durable[21] 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. [22] The effectiveness of an instrument is assessed by its ability to meet a certain target, e.g. ten per cent renewable transportation fuels by 2020 or hundred per cent by 2050.

20 We here assume an exchange rate or 0.75 EUR/USD.
21 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.

22 Jacobsson, S., et al. (2009). EU renewable energy support policy: Faith or facts? Energy Policy 37, 2143-2146.

Efficiency[23], 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.[24]

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. [25]

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'. [26] This is likely to be achieved no earlier than 2020. In the next stage, a second goal for 2030 could be set at 20 per cent 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.[27]

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. [28] 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 pulp mills with chemical process technology (in contrast to mechanical). Moreover, there are joint production opportunities in the pulp and paper (Chapters 2 and 5), petro-chemical (Chapter 2) and district heating industries (Chapter 8) 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 paper and pulp industry in which

23 We here refer to economic efficiency. See e.g. Chapter 6 for a discussion of different measures of energy efficiency.
24 Verbruggen, A., (2008). Windfalls and other profits. Energy Policy 36, 3249-3251.
25 Page 473, IEA, (2008). World Energy Outlook. International Energy Agency, Paris.

26 This is broadly in line with the 450 Policy Scenario in IEA (2008) if EU maintains its share of the global biofuel market.
27 This is broadly in line with the 450 Policy Scenario in IEA (2008) if EU maintains its share of the global biofuel market.
28 Utterback, J.M., (1994). Mastering the dynamics of innovation: how companies can seize opportunities in the face of technological change. Harvard Business School Press, Boston.

the technologies (all three trajectories) can be integrated. The potential in a European market perspective is, however, quite limited. Ekbom et al. [29] (Table 7.1) 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 per cent 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 paper mills and district heating systems, 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 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 ligno-cellulosic 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 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 9.3, 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.[30] 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 discussion in Chapter 4). 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". [31] Such a double counting would, of course, mean that a 10 per cent 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

29 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. Nykomb Synergetics AB, Stockholm.

30 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 (Jacobsson et al., 2009). 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.

31 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 ... " (EC, 2009, p.26).

quite limited in comparison.[32]

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 CO_2 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.[33] 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/EC). 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.

32 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.

33 Choren, 2007. Suggestion presented on slideshow: CHOREN Stellungnahme Förderpolitik Biokraftstoffe_2007 12 engl 01, provided by Mattias Rudloff at Choren, Freiberg.

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.[34]

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.

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

34 A recurrent theme in interviews with capital goods suppliers and other firms was the lack of specialised competences in the field.

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 on their own demonstration plant in which one of these trajectories is applied to a specific context. These plants use different production processes and different feed stocks 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 per cent 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.