1

ASSESSING BIOREFINERIES

Björn Sandén
Fredrik Hedenus
Department of Energy and Environment, Chalmers University of Technology*
*Division of Environmental Systems Analysis (B. Sandén), Physical Resource Theory (F. Hedenus).
Chapter reviewers: Staffan Jacobsson Environmental Systems Analysis; Simon Harvey, Heat and Power Technology; Energy and Environment, Chalmers.

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,

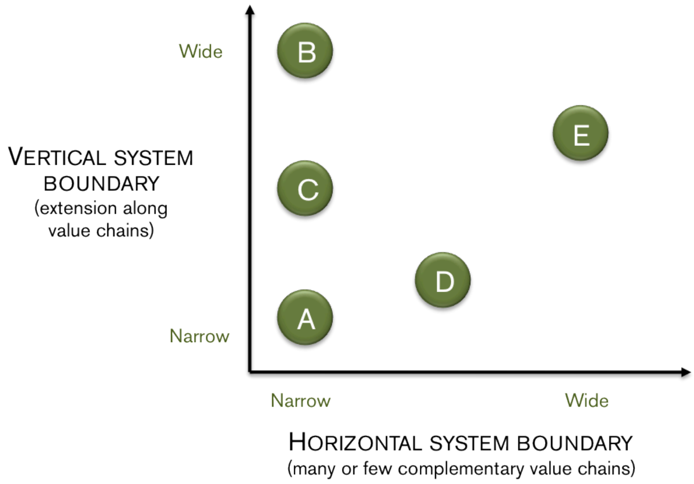

Figure 1.1 Different studies, as well as different standard methodologies, apply different system boundaries. A modelled system can encompass many or few value chains (horizontal system boundary) and smaller or larger parts of these value chains (vertical system boundary). The methodological positions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

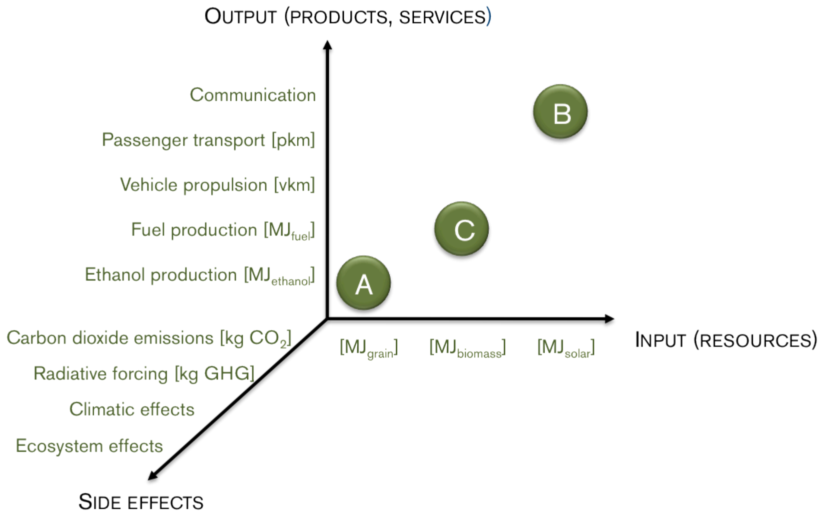

Figure 1.2 A system boundary can be more or less vertically extended towards final end use in the output dimension, towards primary resources and towards final side effects, depending on which performance measure that is relevant for the decision context at hand. The figure illustrates the example of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