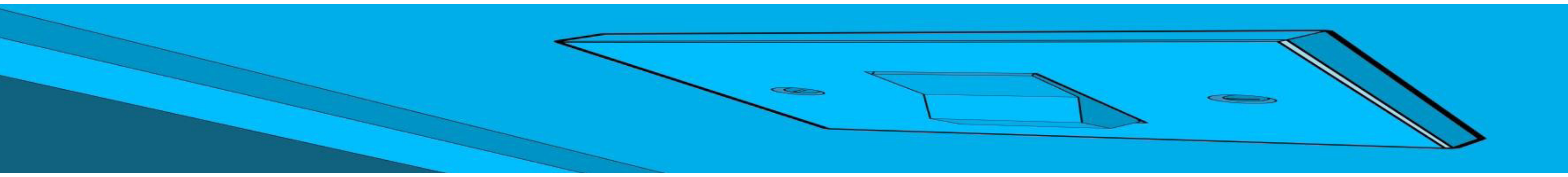

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Prioritising the best use of biomass resources: conceptualising trade-offs

Working Paper

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The UK Energy Research Centre

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Preface

This report has been produced by the UK Energy Research Centre's Technology and Policy Assessment (TPA) function. The TPA was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is useful to policymakers.

This report precedes a TPA study of some of the key issues which face the deployment of bio-energy resources in the period to 2050. The objective of this report was to examine the options for prioritising how biomass might best be used in the UK It was envisaged that this would inform the scope of the subsequent bio-energy TPA. A secondary objective was to assist DECC develop bio-energy route maps, promised under the UK's 2009 Low Carbon Transition Plan.

Acknowledgements

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Executive summary

Using biomass to provide energy services is one of the most versatile options for increasing the proportion of renewable energy in the existing system. This report reviews metrics used to compare alternative bio-energy pathways and identifies limitations inherent in the way that they are calculated and interpreted. It also looks at how companies and investors approach strategic decisions in the bio-energy area.

Bio-energy pathways have has physical and economic attributes that can be measured or modelled. These include: the capital cost, operating cost, emissions to air, land and water. Conceptually, comparing alternative pathways is as simple as selecting the attributes and metrics you consider to be most important and ranking the alternative pathways accordingly. At an abstract level there is good agreement about which features of bio-energy pathways are desirable, but there is little agreement about which performance metrics best capture all the relevant information about a bio-energy pathway. Between studies there is also a great deal of variation and this impedes comparison.

Common metrics describe *energetic performance*, *economic performance*, *environmental performance* (emissions, land and water use), and *social and ecological performance*. Compound metrics may be used to integrate multiple attributes but their highly aggregate nature may make them difficult to interpret.

Insights that may be drawn from the analysis include:

- The diversity of bio-energy feedstocks and conversion technologies means that there is unlikely to be a one-size-fits-all best use of biomass.
- In seeking to develop a strategic approach to biomass use, none of the commonly used metrics capture all pertinent information.
- Not all energy services are equally valuable. Some bio-energy applications – e.g. second generation biofuels – may be strategically important even if at current prices the *cost-per-tonne-of-carbon-saved* appears unattractive. The option value of individual bio-energy pathways and the availability of alternatives should be considered.
- Slavish adherence to a single metric – e.g. *cost-per-tonne-of-carbon-saved* – is best avoided.
- When deciding upon their strategic direction, companies and investors do not seek to find the optimum course of action from the universe of possible alternatives. Instead they look at how the acumen and assets they already have can best be turned to their advantage.
- From a strategic policy perspective, a holistic view of the merits of alternative bio-energy pathways is desirable because ongoing (and future) policy interventions play an important role in prescribing technology choices. Nevertheless, consideration should be given to whether such a view is attainable, and the extent to which it could implemented.

Contents

Acronyms and abbreviations

CHP	Combined heat and power
DDG	Distillers dried grains
GHG	Greenhouse gas
GJ	Gigajoule
IPCC	Intergovernmental panel on climate change
kWh	Kilowatt hours
LC	Ligno-cellulosic (woody) biomass
LCA	Life cycle assessment
RME	Rape methyl ester
VC	Venture capital
WUE	Water use efficiency

Introduction

Using biomass to provide energy services is one of the most versatile options for increasing the proportion of renewable energy in the existing system. Unlike wind and solar technologies which can only provide electricity and are inherently intermittent, biomass can be used to provide a continuous and steady flow of energy services. It is also the only available source of high-grade renewable heat. This versatility arises from the diversity of biomass feedstocks and conversion technologies available. It is also a consequence of the close inter-linkages with other major sectors of the economy. Wastes and residues from one sector – e.g. agriculture, food processing – may be used to provide energy services for another (Faaij, 2006). When it comes to implementing bio-energy projects, however, the existence of inter-linkages and interdependencies can prove problematic. Biomass resources are relatively abundant[1], but projects tend to be complex: feedstock prices can fluctuate dramatically, revenues are circumscribed by a bewildering array of intersecting policies (climate, waste, energy, agriculture), and some of the more sophisticated conversion technologies are unproven at scale.

It is widely accepted that future developments depend upon the economic competitiveness of bio-energy relative to other energy sources (Turkenburg, 2000). But as economic performance is effectively prescribed by policy interventions and legislation, it cannot be presumed that the existing energy markets will necessarily lead to the selection of optimal bio-energy pathways (Slade, et al., 2009a). There may also be, as some commentators have argued, a limited window of opportunity to identify optimal bio-energy system configurations prior to organic and possibly haphazard development of the sector (Dunnett and Shah, 2007).

This report examines the options for prioritising how biomass might best be used in the UK and is presented in 5 parts:

- An overview of bio-energy pathways.
- Options for measuring system performance.
- The role and limitations of Life Cycle Assessment.
- Understanding real world technology choices: theory, corporate motivations and investment strategies.
- Conclusions.

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[1] Estimates of domestic biomass resource potential between 2000 and 2030 range from ~4-11% of UK primary energy (cf 2008) depending on the rate of deployment and technical constraints envisaged (Slade, et al., 2010).

Overview of bio-energy conversion pathways

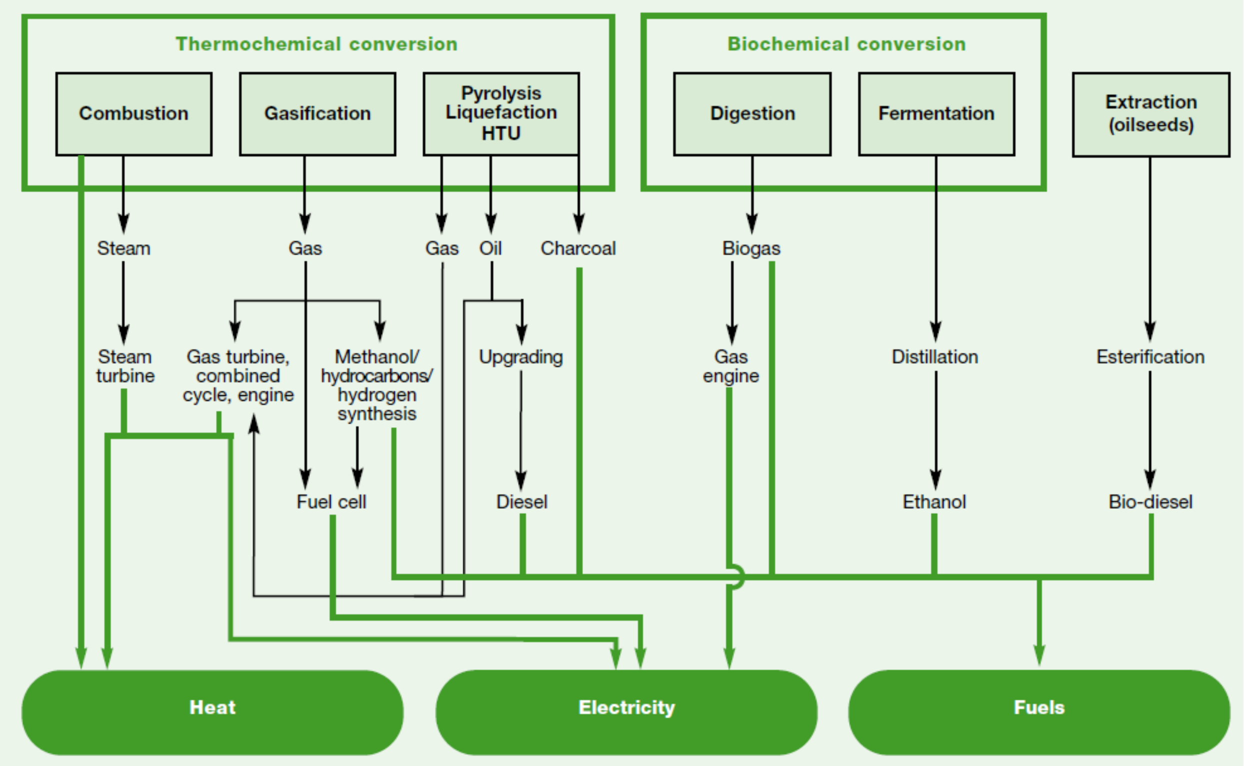
Biomass resources include an incredibly diverse range of feedstocks including dedicated energy crops, residues from agriculture and forestry, and both wet and dry waste materials: sewage sludge and municipal solid waste. Generally, drier and un-contaminated feedstocks are easier and cheaper to convert into energy carriers than wet or contaminated ones. This difference is reflected in their relative price and consequently a balance must be struck between the cost of the conversion process and the quality and price of the feedstock. It is important to note that no single conversion technology can use biomass indiscriminately in all its forms. The main biomass energy conversion pathways are shown in Figure 1.

Thermochemical pathways preferentially use dry feedstocks and include combustion, gasification and pyrolysis. Combustion involves the complete oxidation of biomass to provide heat. This may be used directly, or, on a large scale, may be used to raise steam and produce electricity. Gasification involves the partial oxidation of the biomass at high temperatures (>500°C) and yields a mixture of carbon monoxide and hydrogen (syngas), along with some methane, carbon dioxide, water and small amounts of nitrogen and heavier hydrocarbons (Hamelinck, et al., 2004). The quality of the gas depends on the temperature of the gasification process: a higher temperature process will yield more syngas with fewer heavy hydrocarbons. Syngas may be converted into a wide range of fuels and chemicals; alternatively, it can be used to produce electricity. Pyrolysis involves heating biomass in the absence of oxygen at temperatures up to 500°C and produces an energy-dense bio-oil along with some gas and char. This bio-oil is corrosive, acidic, and although in principle it could be upgraded for use as a transport fuel this would entail a significant energy penalty. Bio-oil from pyrolysis, therefore, most often receives attention as a pre-treatment and densification step that could make the long distance transport of biomass more economic (Faaij, 2006).

Biochemical conversion pathways use microorganisms to convert biomass into methane or simple alcohols, usually in combination with some mechanical or chemical pre-treatment step. Anaerobic digestion is a well established technology and is suited to the conversion of homogenous wet wastes that contain a high proportion of starches and fats – e,g. food waste. Fermentation of sugars and starches to produce alcohols using yeast is also a fully mature technology. In the future, woody biomass could potentially be used as a feedstock for both anaerobic digestion and fermentation processes, but this would require an additional pre-treatment step in order to release the sugars that these feedstocks contain.

Lastly, plant oils may be extracted mechanically, reacted with alcohols, and used as a substitute for diesel. Current and projected performance data for each pathway is presented in Annex 1.

Figure 1: Bio-energy conversion pathways



Source: Turkenburg et al (2000)

Measuring system performance

A bio-energy pathway has physical and economic attributes that can be measured or modelled. These attributes include: capital costs; operating costs; emissions to air, land and water; the quantity of feedstocks and other inputs required; the level of energy service provided etc. Attributes may also be combined to give performance metrics – e.g. the *cost per unit of energy service provided*. Conceptually, comparing alternative pathways is as simple as selecting the attributes and metrics you consider to be most important and ranking the alternative pathways accordingly.

At an abstract level there is good agreement about which features of bio-energy pathways are desirable. Hill et al (2006) summarise these features for bio-fuels, but they are equally applicable to other pathways. A viable substitute for fossil fuels, they argue, should:

- have superior environmental benefits over the fossil fuel it displace;
- be economically competitive with fossil fuels;
- be producible in sufficient quantities to make a meaningful impact on energy demands; and,
- should provide a net energy gain over the energy sources used to produce it.

Yet, when it comes to comparing individual pathways there is little agreement about which performance metrics best capture all the relevant information. Between studies there is also a great deal of variation in the technological routes considered, the metrics used, and analytical methodologies applied. Metrics are also only directly comparable for different pathways if the system boundaries are the same.

The choice of metric has important policy implications. If, for example, the policy objective were to reduce greenhouse gas emissions from feedstock production – measured as tonnes of CO_2 saved per unit energy – this might be achieved by reducing the inputs to production. De Greef (2009), however, argues that while this approach might fit with an agricultural policy based on a negative view of high productivity, the inevitable consequences are the use of much more land and water. If, in contrast, the metric used were the net GHG emission reductions per unit land, this might best be achieved by increasing inputs (fertilisers, etc.) leading to a higher productivity, high-input, high-output system.

The most commonly used metrics are described in Table 1, and can be considered to fall into five categories: *energetic performance*, *economic performance*, *environmental performance* (principally considered in terms of emissions, land and water use), *social and ecological performance*, and *compound metrics*.

Table 1: Performance metrics for comparing bio-energy pathways

Performance category	System property assessed	Metric	Closely related expressions
Energetic	Energy ratio [a]	$GJ_{in}.GJ_{out}^{-1}$	$GJ_{out}.GJ_{in}^{-1}$
Economic	Cost of service delivered	$£.GJ^{-1}$	$£.km^{-1}$ $£.litre^{-1}$ $\Delta_{ref}£.GJ^{-1}$
Environmental	Emissions per unit of service delivered	$KgCO_{2eq}.GJ^{-1}$	
	Emissions relative to a reference case	$\Delta_{ref}\ kgCO_{2eq}.GJ^{-1}$	
	Land use per unit of service delivered	$GJ.Ha^{-1}.yr^{-1}$	$Ha.yr.GJ^{-1}$
	Water use efficiency (WUE)	$Mg.GJ^{-1}$	$g_{water}.g_{drymass}^{-1}$
Social and ecological	Human welfare	• Net number of jobs created • Changes in mortality rates • Hours available to women and children for education, training or leisure • Water diverted from human use	
	Biodiversity	• Diversity and abundance of species • Compliance with conservation areas and international agreements	
	Ecosystem services	• Various proxy metrics e.g. water quality	
Compound	Economic and emissions performance	$£.TonneCO_{2\ saved}^{-1}$	
	Emissions and land use performance	$KgCO_2.Ha^{-1}.yr^{-1}$	

[a] Energy ratio metrics normally exclude the energy captured by photosynthesis from the input side of the balance.

Energetic performance metrics

Energy ratio metrics provide a measure of the efficiency of conversion from biomass to products or services. Illustrative energy balances for selected conversion technologies are shown in Table 2.

Although simple in principle, a great many factors may affect the result of an energy ratio calculation. Technology performance, for instance, is not static: it will change with the capacity of the installed plant, with the grade of fuel used, and with operational practice. Over the medium and long term there may also be improvements in the technology itself.

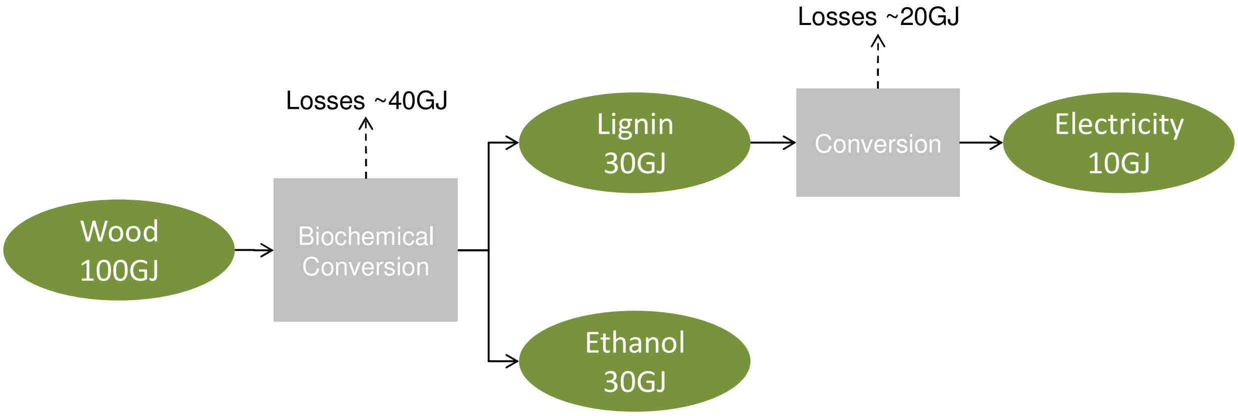
Changing the system boundaries will also change the result. The conversion of woody biomass to ethanol, shown in Figure 2, provides a simple illustration of this point. In this example 100GJ of wood is converted via a biochemical process to yield 30GJ ethanol and 30GJ lignin. The lignin may be pelleted and sold for use in small or large scale heat applications (e.g. domestic scale pellet boilers or district heating); alternatively, it may be used to generate electricity which may then be sold. If the system boundary were drawn around the ethanol and the lignin pellets, the net energy efficiency would be ~60%. If it were drawn around the ethanol and the electricity the net energy efficiency would be ~40%. What the efficiency metric fails to capture in this instance is the fact that electricity is a far more useful energy product, with a greater capacity to do useful work than low grade heat produced from simply combusting the lignin pellets. There are also practical considerations: electricity may be easier to sell than lignin pellets.

Table 2: Energy balance metrics for primary conversion technologies. *The figures shown represent the efficiency of the conversion process (fuel to vector) in isolation from the rest of the supply-chain.*

Technology	**Vector**	**Typical capacity**	**Net efficiency (LHV basis)**
Combustion	Heat	1-5 MW_{th}	70-90%
	CHP	0.1-1 MW_e	60-90% (overall)
	CHP	1-10 MW_e	80-100% (overall)
	Electricity	20-100 MW_e	20-40%
Co-combustion	Electricity	5-20MWe	30-40%
Gasification	Heat	50-250 kWh_{th}	80-90%
	CHP	0.1-1 MW_e	15-30% (electrical)
	Electricity	30-100 MW_e	40-50% (electrical)
Pyrolysis	Bio-oil	0.1-0.5MW_e	60-70%
Anaerobic digestion	Electricity	0.1-0.5MW_e	10-15%
Fermentation	Ethanol	0.3-0.75bnL.yr^{-1}	40-45%
	LC Ethanol	0.3-0.75bnL.yr^{-1}	50-60%
Extraction and esterification	RME	0.3-0.75bnL.yr^{-1}	88%

CHP: combined heat and power; RME: rape methyl ester; LC: Lignocellulosic biomass
Source: Faaij (2006)

Figure 2: The wood to ethanol production process



Using energy ratio’s to compare alternative technologies thus requires a high level of methodological consistency. While this is straight forward when comparing similar conversion technologies, it is harder to achieve when comparing dissimilar technologies or more extended bio-energy supply-chains. Dunnett (2007), for instance, argues that compiling standard energy ratios for complete supply-chains using a literature review approach is near impossible due to inconsistencies in reporting methods.

Economic performance metrics

In a rational market, opportunities are assessed in terms of their relative economic merit. This is most often expressed in terms of the cost per unit of energy service delivered. In the case of electricity production the service might be defined as the number of kWh delivered to the national grid. Alternatively, in the case of biofuels, the service might be defined as the energy content of the fuel or the number of kilometres travelled in a standard vehicle.

Comparative cost is an important and popular way of differentiating between alternative technologies. Implicit in cost calculations, however, are a whole range of detailed estimates and assumptions including:

- Capital costs
- Fuel cost (including projected cost inflation) and fuel taxes
- Operating and maintenance costs
- Waste management costs
- Decommissioning costs
- Site-specific R&D and insurance costs
- Costs of meeting emissions regulations (including possibly the cost of carbon)
- Plant lifetime (economic)
- Plant load factor
- Discount rate
- Build schedule
- Opportunities for future cost reductions with experiential learning

As with energetic metrics, a high level of methodological consistency is required (Heptonstall, 2007).

Cost assessments invariably represent a snapshot in time or are dependent on market scenarios and future price projections. Comparisons of immature technologies yield even more uncertain results. Developers of new technologies often exhibit *appraisal optimism*, whereby in the absence of data derived from commercial experience the costs of new developments are underestimated and the returns exaggerated (Gross, et al., 2007). Cost calculations may also not reflect the true economic merit of an investment, there may be external costs, welfare benefits, or consequential impacts that are difficult to estimate ex anti. Unforeseen impediments to change may also exist, including information and market barriers.

Environmental performance metrics

One of the most widely used metrics for comparing the environmental performance of bio-energy pathways is the greenhouse gas (GHG) emissions (or equivalents) per unit energy service ($KgCO_{2eq}.GJ^{-1}$). This metric may be expressed as an absolute value or relative to a reference case. The emissions burden is usually calculated using a life cycle assessment (LCA) methodology (discussed in more detail below). The advantage of this metric is that it provides an aggregate measure of whole system performance. Nevertheless, difficulties may arise when comparing pathways which produce both energy and non energy products. When this metric is quoted relative to a reference case, for example, the choice of reference will also have a significant impact on the result. For instance, the carbon savings of biomass electricity compared to gas will be far less than the savings compared to coal. For the purposes of policy formation, Edwards et al (2008) argue that this metric is of little use because the amount of GHG saved is not limited by the amount of fossil fuels there is to replace, but rather by the amount of land and money available.

The land use metric ($GJ.Ha^{-1}.yr^{-1}$) provides an insight into the strategic use of land. But, again, caution is required because if a comparison is to be meaningful the land class must be the same. More fertile land will give a better energy yield but will also be subject to a greater number of competing uses. The alternative expression relating to land use ($Ha.yr.GJ^{-1}$) is a measure of the ecological footprint of a bio-energy pathway. The intention here is to express the impact in terms of the area needed to assimilate the environmental burdens. A practical concern with the use of environmental foot printing metrics is that they do not offer policy suggestions apart from either including more land, reducing population or reducing consumption per head (Stoglehner, 2003).

Water is an important constraint on bio-energy production in many locations. When crops are grown, water is lost to the atmosphere from the plant's leaves (transpiration) and from the soil (evaporation). Water is also required for downstream processing of the biomass[2] but these downstream losses are minor when compared to those from evapo-transpiration (Berndes, 2002). Water use efficiency (WUE) metrics aim to measure the yield of biomass (or energy) per unit of evapo-transpiration, or applied water from irrigation. WUE calculations may be affected by a range of factors including: crop choice, land use practices, and the relative cost of land, water etc. The implications of a WUE calculation will also depend upon the level of water stress[3] in a given area. Similar to energy efficiency metrics, WUE calculations cannot capture all water related impacts of a bio-energy system: in the case of perennial crops, for example, potentially positive benefits may include flood prevention, erosion control, and the reduction of sediment in water courses.

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[2] In the case of electricity production water may be evaporated in cooling systems (although this may be minimised through the use of condensing systems). In the case of liquid fuels water losses may arise from a range of process steps – e.g. for syngas cleaning

[3] The level of water stress may be defined on the basis of water availability per capita ($M^3.capita^{-1}$): $<1000M^3.capita^{-1}$ = water scarcity, $<1700M^3.capita^{-1}$ = water stress, $>1700M^3.capita^{-1}$ = sufficient water (Raskin et al in (Berndes, 2002)).

Social and ecological performance metrics

Metrics for the social and ecological performance are highly subjective and in many instances are difficult to quantify. Welfare benefits, for example, might be estimated by using the *net number of jobs created* as a proxy. But because the creation of a skilled or permanent jobs might reasonably be valued more highly than an unskilled migrant jobs; calculating this metric necessitates taking a stance on the nature of the jobs created and their perceived relative value (Diaz-chavez, 2010). In developing countries the use of modern bio-energy systems may result in a time saving for women and children who would otherwise have to collect fuel. Placing a value on this time saving could provide a measure of the value of the modern system, but again this requires a subjective judgement: should time saved only be considered valuable if used for education or some other activity deemed worthwhile?

Measuring and valuing system properties such as biodiversity is similarly problematic. Direct measurement is generally more complex than simply counting the diversity and abundance of species because greater value may be placed on the presence or absence of a particular species in a particular location. To make judgements on biodiversity a diverse range of essentially descriptive indicators tend to be used. For example, floral diversity, impacts on bird life, the diversity and abundance of canopy invertebrates, impacts on soil invertebrates, etc. (Rowe, et al., 2009).

Even more abstract than biodiversity is the concept of *ecosystem services.* Considering a single aspect of the system – soil quality – proxy metrics that might be included in an ecosystem services assessment may include: soil organic carbon, soil texture, water retention and fertility.

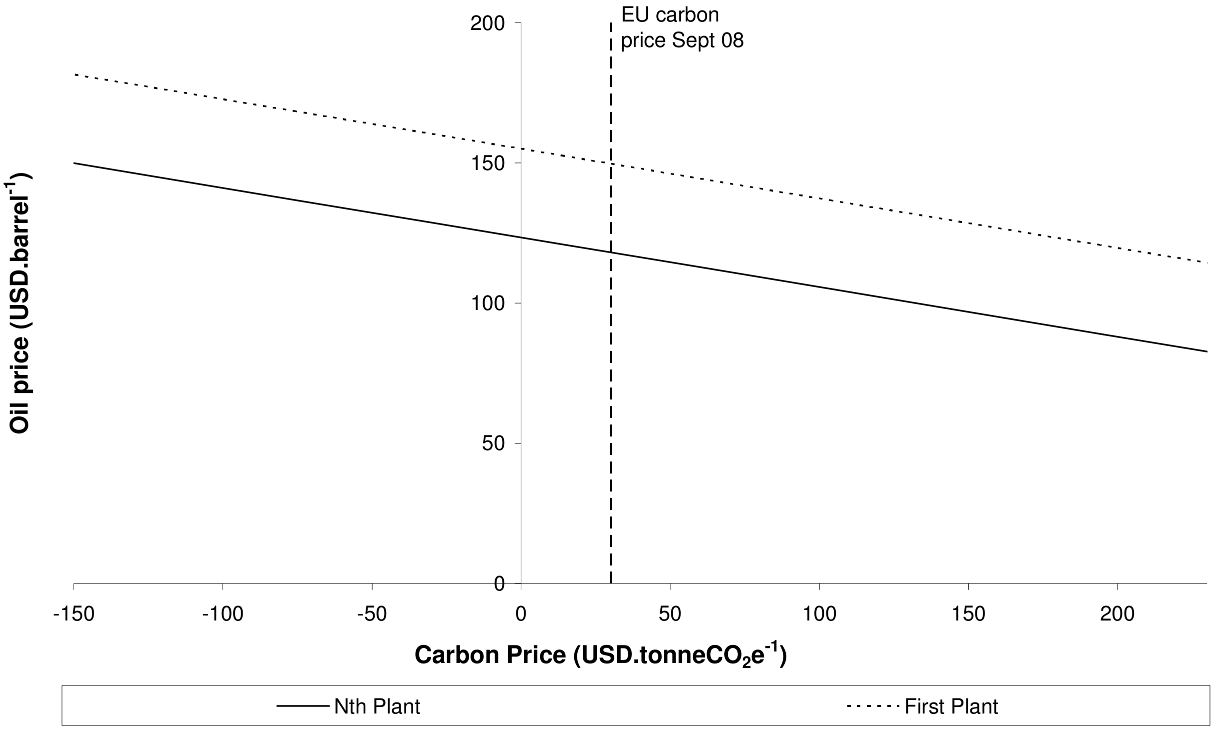
In the formulation of social and ecological metrics, ongoing monitoring tends to be implicit. For example, replacing traditional bio-energy services with cleaner alternatives that reduce indoor air pollution may reduce mortality rates. But demonstrating a causal link may take many years and require ongoing household surveys and epidemiological studies. Compliance with international conservation agreements or certification standards may be used as a proxy for impacts on the environment in general, but again, ongoing monitoring is required (Diaz-chavez, 2010).

Compound performance metrics

Compound metrics have the advantage that they can easily be related to policy goals and constraints. If, for example, the aspiration is to reduce GHG emissions at the lowest economic cost then calculating the *cost-per-tonne-of-carbon-saved* ($\text{£.TonneCO}_{2\text{saved}}{}^{-1}$) appears to be the obvious choice of metric. Likewise, if land constraints and GHG emissions are the primary concern, calculating the *emissions saving per unit area* allows technology pathways to be ranked accordingly. The limitation of these metrics lies in their aggregate nature. It is not easy to tell whether a difference between bio-energy pathways reflects a genuine relative advantage or arises as a consequence of methodological differences – e.g. the selection of a particular reference case.

Projecting the relative performance of immature technologies into the future using these metrics is also problematic as future performance is inherently uncertain. In the case of the *cost-per-tonne-of-carbon-saved* metric there is also an implicit assumption that relative prices remain static into the future. This assumption deserves to be questioned. Currently, electricity and liquid transport fuels are valued at a premium to biomass and coal that reflects their greater versatility. But if supply constraints were to increase these relative premiums may change. After all, in the transport area there are few near term substitutes for liquid fuels available and they are undoubtedly strategically important. To illustrate this point, break-even carbon and oil prices for a novel softwood-to-ethanol process are shown in Figure 3. This conversion process is effective at reducing GHG emissions (savings up to ~80% can be achieved) but the conversion is capital intensive and thus the economics of the process are relatively insensitive to the carbon price. At an oil price of 100USD.barrel^{-1}, for example, it can be seen that carbon prices in excess of 150USD.tonne^{-1} would be needed for the process to break-even. Conversely, only small changes in the price of oil relative to the price of biomass, or reductions in the cost of plant are needed to have a big impact on competitiveness. In January 2005 the price of oil was ~ 42USD.barrrel^{-1}, it increased to a peak of 143USD.barrrel^{-1} in July 2008 and is currently (March 2010) around 80USD.barrrel^{-1} (EIA, 2010). Future large swings in the price of energy products appear eminently possible, and dismissing strategically important options on the basis current prices may be imprudent.

Figure 3: Illustrative break-even carbon and oil prices for a novel stand-alone softwood-to-ethanol plant. *Assuming a constant biomass price)*



Source: (Slade, 2009)

Life Cycle Assessment

The relative environmental merit of alternative bio-energy production pathways has been the subject of many studies and much debate. Most studies have used the Life Cycle Assessment (LCA) method (or a variation upon it) to quantify the environmental burdens from bio-energy production. Although this method has been formalised by the International Standards Organisation[4], the majority of problems associated assessing the environmental performance of bio-energy pathways stem directly from limitations of the LCA method. This section introduces the principles of LCA and outlines areas of recent controversy.

The LCA method and its limitations

The LCA method provides a structured framework for identifying and quantifying energy and materials consumed, and waste released to the environment. The assessment includes the entire life cycle of the product, process, or activity. It encompasses extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal (SETAC, 1993). The argument in favour of the

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[4] Series ISO 14040

approach is that whilst traditional environmental assessment tools may overlook the problem of burden shifting or displacement, LCA ensures that environmental impacts which have been identified and reduced at one stage of the life cycle are not replaced by other, possibly greater, environmental impacts elsewhere.

The LCA methodology encompasses four phases:

- *Goal and scope definition*: sets the boundaries for the analysis, defines the level of detail and the functional basis for comparison.
- *Inventory analysis*: quantifies emissions, energy and raw materials for each process.
- *Impact assessment*: quantifies and groups effects of the resource use and emissions into a number of environmental impact categories which may be weighted for importance.
- *Interpretation*: reports the results and evaluates the opportunities to reduce the environmental impact of the product or service (De Smet, et al., 1996).

For the purposes of calculating GHG emissions metrics, many examples of LCA in the literature do not proceed beyond the inventory analysis stage. For example, the most widely cited source of comparative information on transport fuel chains is the Well-to-Wheels report by CONCAWE, JRC and EUCAR (Edwards, et al., 2006). This study focuses only on fuel production and vehicle use and estimates the Well-to-Wheels energy use and greenhouse gas (GHG) emissions for a range of future fuels and power trains.

Irrespective of whether a full or partial LCA is undertaken, the methodology has a number of limitations:

- The definition of system boundaries, the allocation of impacts, and the choice of data sources are inherently subjective.
- Good quality data may not exist, or may not be readily accessible.
- Spatial and temporal resolution is lost.
- Rebound effects, where environmental and cost efficiency improvements are cancelled out by greater consumption, are not considered (Owens, 1998, Owens, 1997).

Bio-energy systems appear highly susceptible to these shortcomings of the method and to differences in interpretation. This susceptibility arises because of the multi-scale nature of biomass supply-chains. In particular:

- Biomass feedstocks are varied in nature, low energy density, geographically dispersed, and their availability for fuel production is dependent on interactions with existing markets; moreover, data relating to agricultural practices is scarce.
- Logistics may contribute significantly to the overall environmental impact.
- Environmental and technical performance is highly dependent on the detailed process configuration and the level of integration with other systems – e.g. district heating (Slade and Bauen, 2007).

These limitations and susceptibilities are well recognised and have led to calls for greater consistency, transparency, and coherence in LCA studies (Elsayed, et al., 2003). In an attempt to compare different bio-energy pathways on a robust basis and provide the consistency and transparency demanded, a number of influential meta-studies have been conducted. These studies have re-analysed previous LCAs, drawing the system boundaries around an individual production plant and its feedstock supply-chain. From a broad UK perspective, the most comprehensive review of studies was carried out by Elsayed et al. (2003) in a report prepared for the DTI. In this report the authors generate detailed energy and emissions inventories for clearly defined bio-energy pathways, an example of which is included in Table 3.

Table 3: Midrange estimates for lifecycle GHG emissions per unit energy provision and energy ratios for selected bio-energy chains

Feedstock	Technology	Vector	kgCO2e.GJ-1	Δ_{ref} $kgCO_{2eq}.GJ^{-1}$	$GJ_{in}.GJ_{out}^{-1}$
Rapeseed	Esterification	Biodiesel	41	-46	0.437
Grain	Fermentation	Ethanol	29	-52	0.464
LC crop	Hydrolysis / fermentation	Ethanol	13	-68	-0.028
Residues	Combustion	Heat	7	-98	0.100
LC crop	Combustion	Electricity	26	-136	0.272
Residues	Combustion	Electricity	22	-140	0.309
Residues	Pyrolysis	Electricity	14	-148	0.284
Residues	Gasification	Electricity	7	-155	0.133

The reference energy service pathways used were: low sulphur diesel, petrol, oil; combustion for heat and grid pool electricity where appropriate. The assumed technological scale is 25 MWe for electricity generation, 50 kWth for heat generation and 40,000 t. yr^{-1} for biofuel production; wherein residual lignin from lignocellulosic crop to ethanol via hydrolysis and fermentation is combusted for power generation. The negative energy ratio for the conversion lignocellulosic crops to ethanol via hydrolysis and fermentation arises because energy credits are allocated to residual lignin combustion for electricity generation. In the absence of this allocation the ratio shifts to +0.249
Source: Elsayed et al (2003).

Controversies surrounding the application of LCA

Despite efforts to standardise the LCA method and apply it consistently, a lack of clarity and transparency remains. The inevitable consequence has been that successive publications have failed to inspire confidence (Dunnett and Shah, 2007). Five key uncertainties are responsible for a great deal of the inter-study inconsistency. These are:

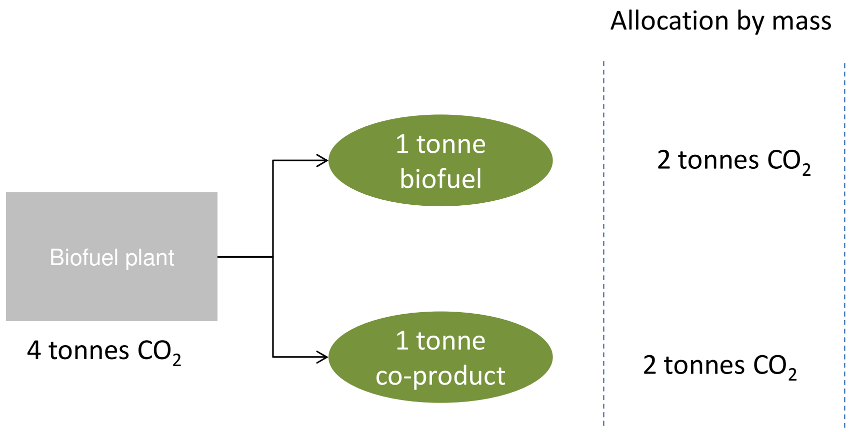
- *The inclusion of climate-active species:* While GHG equivalents (CO_2, CH_4, and N_2O) are widely accounted for, ozone depleting species (NOx and CO), reflective (SOx) and absorbing (black carbon) aerosols are often overlooked.
- *Nitrous oxide (N_2O) emissions:* The global warming potential of N_2O is some 296 times that of CO_2 over a 100 year time period. Thus, poorly characterized emissions from agriculture introduce considerable uncertainty.

- *Methods for allocating impacts to products and co-products:* Alternative methods are applied dependent on the aims of individual studies and resulting in widespread inconsistencies (considered in more detail below).
- *Soil carbon sequestration:* Benefits are highly site specific, dependent on soil type, prior land use application, and agricultural practice. Sequestration is also poorly characterized with regard to the slow rate of carbon build-up and soil saturation limits.
- *Technological performance assumptions:* Variant scale, degree of process integration, and assumed technological progress introduce further inconsistencies (Larson, 2005).

There is also an active debate about whether LCA should be limited to identifying environmental burdens and attributing them products and co-products, or whether it should be extended to consider indirect and consequential impacts, or indeed whether such an extension is even possible.

Co-products and the need for allocation. Where a bio-energy pathway produces more than one product, It is necessary to consider how the environmental impacts should be allocated (attributed) to each product. This is of particular relevance to biofuel pathways, which produce more than one product. There are a number of ways in which the effect of co-products can be taken into account. The simplest approach is to allocate a portion of the emissions to the co-product based on a physical (e.g. mass, energy content) or an economic (e.g. price) property of the product. An example of allocation by mass is shown in Figure 4.

Figure 4: Life Cycle Assessment: allocation by mass



Source: adapted from Bauen, et al., (2008)

Allocation in this way is often conceptually unsatisfying and may not fairly represent the GHG impacts of the system. For example, the co-product of wheat ethanol production is a protein rich material that is used as animal feed. Allocating impacts to this product on the basis of its energy value or mass makes little sense because its use and value doesn’t depend on its energy content.

Extending the boundaries of the carbon intensity calculation and treating the substituted product as part of the biofuel system is an alternative approach that can be more representative of the real world impacts. In the case where the co-product is animal feed that displaces Brazilian soy, for instance, then the GHG benefits from the displaced Brazilian soy might reasonably be credited to the biofuel. Yet it is not always possible to identify what product is substituted by a co-product. It may also be difficult to determine what the carbon intensity of the substituted product actually is. Consequently, most LCA practitioners recommend a flexible approach to allocation, selecting the option that best represents the system (Bauen, et al., 2008).

For an individual biomass-to-energy plant extending the system boundaries arguable provides the best reflection of the situation on the ground. Yet for the purpose of policy formation, where it is necessary to forecast and generalise the environmental impact of multiple plants in multiple locations, allocating emissions on the basis of energy content is simpler, will yield a more consistent result, and doesn't require speculation or generalisation about what products may be substituted in the future. From a policy perspective this is somewhat uncomfortable: is it defensible to decide policy priorities using one method and then monitor the impacts of the policy using another?

Consideration of consequential impacts and land-use change. In addition to the direct energy and fossil fuel inputs to a bio-energy pathway, GHG emissions may arise from consequential impacts. The most important consequential impacts are arguably direct and indirect land-use change. Direct land-use change may occur if previously uncultivated land is used to produce biomass feedstocks – e.g. if the converted land had a high carbon stock value[5] – the GHG emissions from clearance and conversion may be significant. Indirect land-use change impacts may arise if increasing demand for bio-energy feedstock increases commodity prices or displaces the production of other agricultural crops, and this, in turn, causes uncultivated land to be converted to agricultural production.

The science and convention for determining such indirect impacts is in its infancy. Nevertheless, consequential impacts have featured prominently in the debate about the merit of biofuels, and are of increasing interest in relation to other bio-energy applications. To estimate impacts from indirect land-use change the UK Renewable Fuels Agency identifies two contrasting approaches: partial equilibrium modelling (Searchinger, et al., 2008) and the use of indirect land-use change (ILUC) factors (which are calculated using an accounting methodology (Gallagher, et al., 2008) (Fehrenbach, et al., 2008)). Both have been applied to first generation biofuels to investigate possible displacement effects resulting from the use of food crops for biofuels, but the indirect effects from the increased use of forest products (and residues such as straw) have received less attention.

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[5] For instance forested land or land with peat soils would be considered to have a high carbon stock.

The IPCC provides guidance on the estimation of direct impacts (e.g. the conversion of forest or grassland to annual or perennial biofuel crops) based on climate zone, ecological zone and soil type (IPCC (2006)). In the case of by-products (e.g. straw) and managed forestry which continues to be managed (e.g. softwood in northern Europe), the direct impacts, following the IPCC's *tier-1 guidance*, are nil. If the commercial use of biomass feedstocks is modest and does not exceed the carrying capacity of existing managed forestry or waste streams, then indirect land-use-change might also reasonably be ignored. The problem for policy makers is that producing sufficient bio-energy feedstocks to supply a significant proportion of UK primary energy requires anything but a modest response (Slade, et al., 2009b).

This debate about biofuels highlights a more general issue about the importance of including consequential impacts in policy decisions: where impacts are determined relative to a reference case (counter factual) the decision about which reference case to choose needs to be sensitive to the size of the proposed change.

Understanding real world technology choices: innovation theory, corporate motivations and investment strategies

Increasing the uptake of bio-energy in the UK requires systemic technological change. To make this happen companies need to prioritise bio-energy and make the strategic decision to invest. This section is presented in two parts, firstly it looks at the theory underpinning how companies approach strategic decisions; secondly, it presents examples of companies' motivations for investing in new technology. This later section draws on work undertaken by the authors in 2009 that sought to examine companies' and investors' motivations for investing in second generation bio-fuels (Slade, 2009, Slade and Bauen, 2009).

Innovation theory

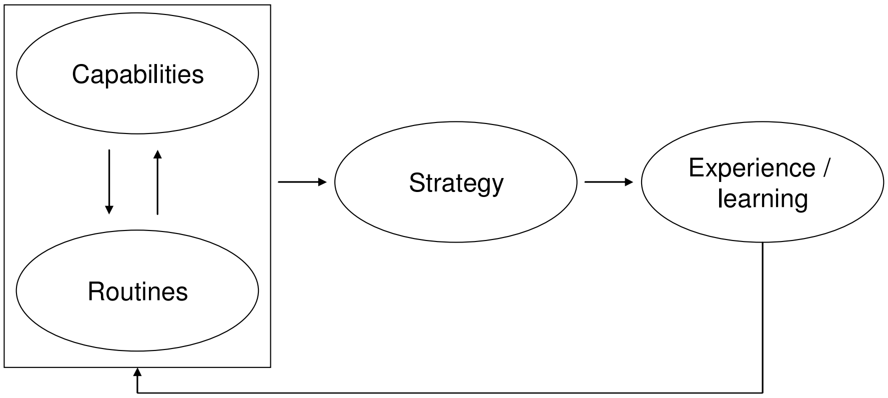
Innovation theory is the body of knowledge gleaned from previous attempts to commercialise technology and stimulate change. It can be divided into three main strands: *strategic management*, *models of technological diffusion and learning*, and *descriptions of innovation as a systemic process*. The strategic management literature is the most pertinent to this discussion as it focuses on companies' decision making processes and seeks to build a bottom-up picture of firms' individual behaviour.

The strategic management literature is underpinned by four concepts: *bounded rationality*, *organisational routines*, *capabilities* and *strategy*. *Bounded rationality* holds that companies are rational economic actors constrained by limitations of information availability, computational capacity, and time (Cyert and March, 1992, p214). *Organisational routines* are simply the dominant forms of behaviour that companies rely upon to simplify problems and make decision in the face of the uncertainty that bounded rationality entails.

Capabilities are the unique combinations of resources and competencies that distinguish a firm from its competitors and include tacit knowledge in addition to tangible and intangible assets (Penrose, 1959). *Strategy* is a broad concept. A functional definition holds that the purpose of strategy is to position a firm in the market in order to make it defensible against competition. Five determinants of competition, or forces, are widely recognised: the bargaining power of customers and suppliers, the threat of new entrants and substitute products, and the level of competition in the industry (Porter, 1983). To position itself against these forces, a firm may seek to build new capabilities (to innovate), or find niches in the market in which to exploit its existing capabilities. Examples of strategic choices include: becoming a cost leader, seeking to differentiate products in the eyes of customers, moving out of a highly competitive markets, etc. If a defensible position within the existing market cannot be found, another option remains: lobbying government to change the rules so that competition is reduced or so that existing capabilities can be exploited more profitably.

The interaction between strategy, organisational routines and capabilities is essentially dynamic. As a company pursues its strategy in the marketplace it will gain experience that will enable it to extend its capabilities and modify its routines. This relationship is summarised in Figure 5. The strategic management literature thus describes a framework for analysing a firm's decisions. It also and provides a rationale for firms to innovate and invest in new technology: investments make sense because new technologies can improve a firm's competitive position.

Figure 5: An organisational learning framework for strategy making



Adapted from Burgelman and Rosenbloom (1989)

What motivates companies?

Examining the strategies and actions of companies pursuing second generation biofuels reveals three broad motivations for interest and investment: the potential for a large market and rapid market growth, the potential to increase the profitability of existing operations, and the potential to profitably exploit existing capabilities. For larger companies the size of the market is a fundamental consideration. There are divergent views as to how the market will develop, but the key point is that it is expected to be sufficiently big to make strategic investments worthwhile, even for the larger companies. A view succinctly expressed in relation to the paper company UPM's decision to pursue both biofuels and bio-energy:

> *"The strategic question for UPM is how to make a profitable and significant business: i.e. on some time horizon there needs to be a prospect of a 1bn turnover business… even the most pessimistic estimates put the market for biofuels at ~100bn euro by 2020." (Sohlström, 2009, Executive vice president new businesses and biofuels, UPM).*

The size of the market size relative to the size of the company is also an important consideration for the international oil companies:

> *"You have to look at what we do from the perspective that [we] are a very big company. If something is not big then it has no impact on our scale." (Interview: International oil company).*

For the smaller companies the size of the market in relation to the size of the company is unlikely to be a constraint, but the potential for a large and growing market to develop is often cited as evidence that pursuing second generation biofuels is worthwhile.

The prospect of using new technology to increase the profitability of existing operations appeals primarily to companies that already have capabilities in feedstock supply and conversion processes. Existing ethanol producers, for example, describe themselves as motivated to develop and adopt technology that can add value to secondary process streams and residues such as distillers dried grains (DDG), stover and bagasse. More broadly, however, it can be seen that companies view the production of biofuels as means to expand or increase profit margins, rather than an end it itself. The following comment from a UK company specialising in grain storage and seeking to build a conventional grain-to-ethanol plant illustrates this point:

> *"The starting point was how can the value of our existing business be enhanced, not how can biofuels be provided." (Interview: Simon Wilcox, CEO, Greenspirit fuels).*

Although not primarily interested in second generation biofuels, the same company had nevertheless considered the role that they might play in the future:

> *"Incorporating lignocellulosic materials [into an existing grain to ethanol plant] would be part of a risk mitigation strategy: broadening the feedstock base and reducing exposure to volatile grain markets. Essentially it would be good insurance against peaks in the grain market." (Ibid).*

The multi-national paper company Mondi, although far bigger and operating in a completely different market, has similar priorities, emphasising the need to maximise the overall profitability, irrespective of the technology used and even the products produced:

> *"We need to look at what is the most value we can add to our feedstocks. Essentially we don't care whether we make ethanol or paper. The only real criterion is profitability. We are not wedded to any particular production process." (Interview: Claus Hirzman, Mondi Business Paper).*

A last illustration of this point is provided by Dong Energy. Dong is a Danish electricity utility that co-fires straw in coal fired power plant and began developing a straw-to-ethanol technology after experimenting with washing straw in order to reduce boiler fouling. The motivation in their case was not the production of ethanol but the production of a solid biomass product that could be co-fired more easily:

> *"In the US the talk is all about ethanol, but the production of lignin is the main driver for Dong." (Morgen, 2009, Senior manager business development and marketing - Inbicon (Dong Energy)).*

The potential to exploit existing capabilities, and in particular knowledge, appears to be a key feature in the decision making of smaller companies for whom the development and application of technology forms a significant part of their raison d'être. An example of such a company is the German gasification company, Choren:

> *"The starting point of the company was gasification – the founders had knowledge of this technology and considered it one of the good ways of converting biomass. In this sense the company was technology driven rather than selecting the best approach from a range of options." (Interview: Michael Deutmeyer, Choren).*

Other small technology developers might reasonably be viewed as similarly motivated. This focus may be deliberate – ring fencing potentially disruptive innovation in a subsidiary company is one of the management strategies proposed in the innovation literature (Christensen, 1997). Alternatively, it may simply reflect the technological capabilities which were available when the company was founded. In the UK, for example, there are three companies focusing on the application of thermophilic micro-organisms to biofuels: TMO Renewables, Green Biologics and Biocaldol. These companies share a common heritage and can trace their origins to the dissolution, in 2003, of a university spinout company called Agrol Ltd. Since going their separate ways, these companies have adopted divergent strategies: TMO is focussed on the production of ethanol from a broad range of lignocellulosic feedstocks (Curran, 2009), Biocaldol is focused on the production of ethanol from hemi-cellulose sugars (Baghaie-yazdi, 2009), and Green Biologics is focussed on improving the acetone-butanol-ethanol (ABE) fermentation (Sutcliff, 2009). All three companies, however, remain focussed on thermophiles. In line with what might be predicted from the strategic management literature, their current direction appears to have been largely determined by their initial capabilities.

What motivates investors?

Whereas companies appear to derive motivation from their existing operations and capabilities, financial investors are motivated primarily by the potential for rapid market growth and are technologically agnostic. The amount of money that financiers are prepared to invest depends on their assessment of risk: the greater the risk, the less money will be forthcoming and the greater the return they will demand. What distinguishes an investment in a new production technology from a similar investment in an established technology is the level of technical risk. Venture capital (VC) investors are the finance providers most willing to accept this risk, but their acceptance comes at a price: they demand a higher return than other investors. Moreover, the size of a typical VC investment is small when compared to the investment required to build a pilot plant or demonstration facility:

> *"VCs don't care whether the company makes chemicals or fuels provided that it has potential to grow. The fuel market is interesting because it is protected by policy. There are no equivalent policies for green chemicals.*
> *Investors are shy of demonstration projects. They are big and expensive. [Instead] Cleantech VCs have focussed on the biotech side: new bacteria, enzymes, fermentation processes etc. These are low cost companies, not much more than three scientists and a lab. Lab-scale technologies can also be sold on to the pipeline in order to realise an earlier return." (Interview: Harry Boyle, lead analyst, biofuels, New Energy Finance).*

For the venture capital investors, more important than picking a winning technology is picking a winning team:

> *"Technology is a commodity, what is more important is the ability to have the right kind of relationships. This is key." (Baruch, 2009, CMEA ventures).*

Advocates of specific technology may also be viewed with suspicion:

> *"In general technology providers are enthusiasts. Take BlueFire Ethanol for example, they are using concentrated acid technology and have better acid recovery process. They tell you that they are getting the feedstock for free; consequently the conversion process looks economic. But ultimately biomass will become a commodity." (Interview: Harry Boyle, lead analyst, biofuels, New Energy Finance).*

Strategies for investment and business development. The strategic-management literature suggests that a company's strategy – whether it should invest, how it should invest etc. – will be determined by the resources and capabilities that it has at its disposal. It is perhaps unsurprising, therefore, that the disparity in the resources available to the different companies interested in second generation biofuels gives rise to a range of strategies. These can be crudely characterised as *building a portfolio*, *picking a winner* or *keeping a watching brief*.

The oil companies are large enough to take a strategic view of both the market and the technology and build a portfolio of options. Like the financial investors they are demonstrably technology agnostic. Shell, for example, has invested in five companies spanning a range of technologies. British Petroleum (BP) have also adopted a portfolio approach as part of a proclaimed strategy to "develop an upstream biofuels business" (Mace, 2008).

The paper companies, situated at the other end of the supply-chain to the oil companies, have a clear focus the efficient use of their existing resource base but are similarly open minded when it comes to identifying the most appropriate technology. They are also large enough to hedge their bets and invest in a technology portfolio. UPM, for example, are pursuing three bio-energy concepts: gasification of forest residues followed by Fisher Tropsch, pyrolysis of forest residues to produce bio-oil, and the production of ethanol from recycled fibre. (Sohlström).

The *build a portfolio* option is unlikely to be available to smaller companies. These companies are limited in the strategies they can adopt by the resources that they can deploy. They are effectively forced to try and pick a winning option which will deliver near term results, even though they may be attracted to technologies they are unable to pursue:

> *"TMO's proposition is to offer a thermophilic organism, process design, and process guarantee. Consolidated Bioprocessing [an alternative and futuristic technology] is a wonderful vision, but we would run out of money long before we got there. Our work needs to generate a revenue stream as early as possible." (Interview: Dr Steven Martin, associate R&D director, TMO Renewables).*

The *keeping a watching brief* option is a low cost strategy, but is not entirely passive. It requires a minimal investment in the skills and information needed to make an informed decision. There is also the risk that the cost of catching up may become prohibitive:

> *"Essentially, we wish to make an informed decision whether to be an early adopter, early follower or late follower. One option is to secure privileged access to feedstock and wait. The wait option gives insight on disruptive technology, but there is always the risk that the market settles. We need to position ourselves first." (Interview: Claus Hirzman, Mondi Business Paper).*

The fact that companies (and investors) with the resources to do so are adopting a portfolio approach suggests that a winning technology for second generation biofuels has yet to emerge. Moreover, even if there were such a technology, the diversity of feedstocks and options for integration with other facilities makes it unlikely that it would fit all applications. Convergence on a small number of routes or technologies must therefore be considered unlikely. When this argument is broadened to include other bio-energy conversion pathways is seems reasonable to conclude that corporate decisions will not lead to a single preferred option.

Conclusions

This report reviews metrics used to compare alternative bio-energy pathways and identifies limitations inherent in the way that they are calculated and interpreted. It also looks at how companies and investors approach strategic decisions in the bio-energy area. The following insights may reasonably be drawn.

- The diversity of bio-energy feedstocks and conversion technologies means that there is unlikely to be a one-size-fits-all best use of biomass.
- A range of metrics are commonly used to compare bio-energy pathways but all involve a high level of subjective judgement. Methodological differences between studies are common and a general lack of transparency makes cross-study comparisons difficult.

- Metrics that aspire to measure the social and ecological impacts of bio-energy development inherently involve value judgements. They may also require ongoing monitoring.
- In seeking to develop a strategic approach to biomass use, none of the commonly used metrics capture all pertinent information. Slavish adherence to a single metric – e.g. *cost-per-tonne-of-carbon-saved* – is probably best avoided.
- Life cycle assessment is a critical tool for understanding environmental impacts, but there is an ongoing debate about the validity, transparency and applicability of the underlying assumptions. It is arguable, therefore, that the simple addition of further LCA studies will not lead to a better understanding of the issues.
- Not all energy services are equally valuable. Some bio-energy applications – e.g. second generation biofuels – may be strategically important even if at current prices the cost per tonne of carbon saved appears unattractive. The option value of individual bio-energy pathways and the availability of alternatives should be considered.
- When deciding upon their strategic direction, companies and investors do not seek to find the optimum course of action from the universe of possible alternatives. Instead they look at how the acumen and assets they already have can best be turned to their advantage. In the absence of policy intervention, it seems unlikely that corporate decisions would gravitate towards a single preferred technology.
- Even if an optimum UK bio-energy system could be identified, motivating companies to make the necessary investment decisions may be difficult or impractical.
- From a strategic policy perspective, a holistic view of the merits of alternative bio-energy pathways is desirable because ongoing (and future) policy interventions play an important role in prescribing technology choices. Nevertheless, consideration should be given to whether such a view is attainable, and the extent to which it could be implemented. An alternative strategy might be for the UK to identify and play to its strengths.

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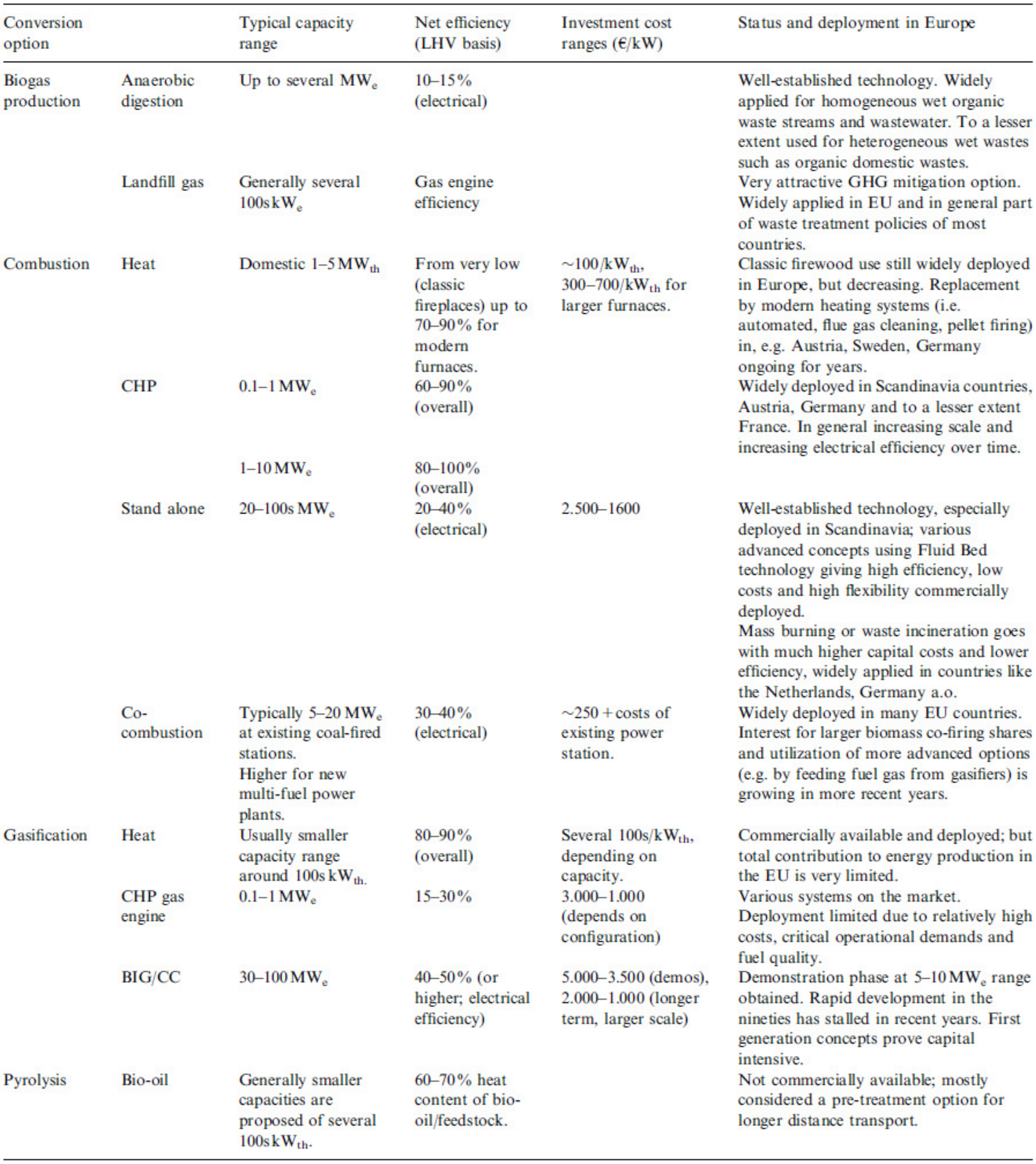
Annex 1

An overview of current and projected performance data for the main conversion routes of biomass to power and heat



Conversion option		Typical capacity range	Net efficiency (LHV basis)	Investment cost ranges (€/kW)	Status and deployment in Europe
Biogas production	Anaerobic digestion	Up to several MW_e	10–15% (electrical)		Well-established technology. Widely applied for homogeneous wet organic waste streams and wastewater. To a lesser extent used for heterogeneous wet wastes such as organic domestic wastes.
	Landfill gas	Generally several 100s kW_e	Gas engine efficiency		Very attractive GHG mitigation option. Widely applied in EU and in general part of waste treatment policies of most countries.
Combustion	Heat	Domestic 1–5 MW_{th}	From very low (classic fireplaces) up to 70–90% for modern furnaces.	~100/kW_{th}, 300–700/kW_{th} for larger furnaces.	Classic firewood use still widely deployed in Europe, but decreasing. Replacement by modern heating systems (i.e. automated, flue gas cleaning, pellet firing) in, e.g. Austria, Sweden, Germany ongoing for years.
	CHP	0.1–1 MW_e	60–90% (overall)		Widely deployed in Scandinavia countries, Austria, Germany and to a lesser extent France. In general increasing scale and increasing electrical efficiency over time.
		1–10 MW_e	80–100% (overall)		
	Stand alone	20–100s MW_e	20–40% (electrical)	2.500–1600	Well-established technology, especially deployed in Scandinavia; various advanced concepts using Fluid Bed technology giving high efficiency, low costs and high flexibility commercially deployed. Mass burning or waste incineration goes with much higher capital costs and lower efficiency, widely applied in countries like the Netherlands, Germany a.o.
	Co-combustion	Typically 5–20 MW_e at existing coal-fired stations. Higher for new multi-fuel power plants.	30–40% (electrical)	~250 + costs of existing power station.	Widely deployed in many EU countries. Interest for larger biomass co-firing shares and utilization of more advanced options (e.g. by feeding fuel gas from gasifiers) is growing in more recent years.
Gasification	Heat	Usually smaller capacity range around 100s kW_{th}.	80–90% (overall)	Several 100s/kW_{th}, depending on capacity.	Commercially available and deployed; but total contribution to energy production in the EU is very limited.
	CHP gas engine	0.1–1 MW_e	15–30%	3.000–1.000 (depends on configuration)	Various systems on the market. Deployment limited due to relatively high costs, critical operational demands and fuel quality.
	BIG/CC	30–100 MW_e	40–50% (or higher; electrical efficiency)	5.000–3.500 (demos), 2.000–1.000 (longer term, larger scale)	Demonstration phase at 5–10 MW_e range obtained. Rapid development in the nineties has stalled in recent years. First generation concepts prove capital intensive.
Pyrolysis	Bio-oil	Generally smaller capacities are proposed of several 100s kW_{th}.	60–70% heat content of bio-oil/feedstock.		Not commercially available; mostly considered a pre-treatment option for longer distance transport.

NB: Due to the variability of data all cost figures should be considered indicative only.
Source: (Faaij, 2006)

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