Sustainability Assessment of Integrated Bio-refineries

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AA	Acetic Acid
ADP	Abiotic Depletion Potential
AP	Acidification Potential
AFEX	Ammonia Fibre Explosion
CERES	Coalition for Environmentally Responsible Economics
CPRPC	Capital District Regional Planning Commission
CSL	Corn Steep Liquor
CBP	Continuous Bio-processing
CML	Centrum voor Milieuwetenschappen Leiden (Leiden Institute of Environmental Sciences, the Netherlands)
EP	Eutrophication Potential
EU	European Union
DDGS	Distillers Dried Grain Solid
DAP	Diammonium Phosphate
FAETP	Fresh water Aquatic Ecotoxicity Potential
DCFRoR	Discounted Cash Flow Rate of Return
FR	Forest Residues
GRI	Global Reporting Initiative
GHG	Green House Gas
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IChemE	Institution of Chemical Engineers
IGCC	Integrated Gasification Combined Cycle
ISO	International Standards Organization
IRR	Internal Rate of Return
LCC	Life Cycle Costing
LCA	Life Cycle Assessment
LA	Lactic acid
LUC	Land Use Change
MAETP	Marine Aquatic Ecotoxicity Potential
MESP	Minimum Ethanol Selling Price
MSW	Municipal Solid Waste
MCDA	Multi Criteria Decision Analysis
NGO	Non Governmental Organisation
NPV	Net Present Value
NNFCC	National Non-Food Crops Centre
NMVOC	Non Metallic Volatile Organic Compound
NREL	Non-Renewable Energy Laboratory
OECD	Organisation of Economic Cooperation and Development
ODP	Ozone Depletion Potential
PCI	Plant Cost Index
PM	Particulate Matter
POCP	Photochemical Oxidation Potential
PPI	Producer Plant Index
SETAC	Society of Environmental Toxicology and Chemistry
SSF	Simultaneous Saccharification and Fermentation
SHF	Separate Hydrolysis and Fermentation

TETP	Terrestrial Ecotoxicity Potential
VOC	Volatile Organic Compounds
TIE	Total Installed Equipment
TCI	Total Capital Investment
WWF	World Wildlife Fund

Abstract

Sustainability assessment of integrated bio-refineries
Temitope O Falano, University of Manchester, 2012
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Integrated bio-refineries offer a potential for a more sustainable production of fuels and chemicals. However, the sustainability implications of integrated bio-refineries are still poorly understood. Therefore, this work aims to contribute towards a better understanding of the sustainability of these systems. For these purposes, a methodological framework has been developed to assess the sustainability of different 2nd generation feedstocks to produce bio-ethanol, energy, and platform chemicals using bio-chemical or thermo-chemical routes in an integrated bio-refinery.

The methodology involves environmental, techno-economic, and social assessment of the bio-refinery supply chain. Life cycle assessment (LCA) is used for the environmental assessment. The economic assessment is carried out using life cycle costing (LCC) along side traditional economic indicators such as net present value and payback period. Social issues such as employment provision and health and safety are considered within the social sustainability assessment. The methodology has been applied to two case studies using the bio-chemical and the thermo-chemical conversion routes and four feedstocks: wheat straw, poplar, miscanthus and forest residue.

For the conditions assumed in this work and per litre of ethanol produced, the LCA results indicate that the thermo-chemical conversion is more environmentally sustainable than the bio-chemical route for eight out of 11 environmental impacts considered. The LCA results also indicate that the main hot spot in the supply chain for both conversion routes is feedstock cultivation. The thermo-chemical route is economically more sustainable than the bio-chemical because of the lower capital and operating costs. From the social sustainability point of view, the results suggest that provision of employment would be higher in the bio-chemical route but so would the health and safety risks.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning

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This degree has made me lose hair, nails, and almost my sanity in ways I cannot express. I honestly didn't see the end coming. I will like to appreciate God Almighty for the divine strength to come to the end successfully.

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1 INTRODUCTION

Fossil fuels have been and are still the major sources of energy and chemicals worldwide. The current demand of fuels for energy and chemicals is about 12 million tonnes per day and is predicted to increase by about 33% in the next 20 years (Luque et al. 2008). In addition to increasing pressure on limited reserves of fossil fuels, increased consumption of fossil fuels leads to global warming, acidification and ozone depletion, to name a few of the sustainability issues associated with fossil fuels consumption. For instance, it is widely accepted that the consumption of fossil fuels is a major contributor to greenhouse gas (GHG) emissions worldwide. Thus, there is a clear need to explore other sources of energy and chemicals.

Biomass is one such potential alternative source of energy and chemicals. Over the years, biomass resources, also known as bio-feedstock (from both plants and animals) have been converted into various fuels and chemicals, including bio-ethanol, bio-diesel, bio-gas and bio-polymers (Taylor 2008). However, the use of some bio-feedstocks such as food crops (e.g. corn and sugar cane) for fuels and chemicals production has become a contentious issue over the years. Some of the issues associated with the use of these so-called 1st generation feedstocks included competition with food production and increased food prices (Chum and Overend 2001). These and other issues have rendered the 1st generation bio-fuels and chemicals unsustainable. This has led to the exploitation of other bio-feedstock such as lignocellulosic materials (e.g. energy crops) and municipal solid waste, usually referred to as 2nd generation bio-feedstocks. They represent a potentially better alternative to the 1st generation bio-feedstocks because they avoid issues such as competition with food crops (Larson 2008).

However, processing and conversion of bio-feedstocks into various fuels and chemicals in bio-refineries is associated with other sustainability issues, including economics (Christensen et al. 2008) and feedstock availability. The need for improved performance of bio-refineries has led to the concept of integrated bio-refineries, whereby different bio-feedstocks are converted into various products including bio-fuels, bio-chemicals, electricity, and heat (Sammons Jr et al. 2008). Integrated bio-refineries offer a potential for reducing the fossil fuel demand; however, as they are still a new concept, their sustainability implications are currently poorly understood.

Therefore, this research aims to contribute towards a better understanding of the sustainability of integrated bio-refineries using 2nd generation bio-feedstocks to produce fuels, electricity, and/or platform chemicals. The following are the specific objectives of the research:

- to develop a methodological framework for the sustainability assessment of integrated bio-refineries considering environmental, economic and social aspects;
- to identify environmental, economic and social issues relevant for the bio-refinery systems and to use appropriate sustainability indicators for sustainability assessment; and
- to apply the framework to assess and compare the sustainability of integrated bio-refineries using suitable case studies and considering different 2nd generation feedstocks, production routes and products in the UK.

The main novelties of this research include:

- a generic methodological framework for sustainability assessment of integrated bio-refineries taking into account environmental, economic and social aspects.
- life cycle environmental and economic assessment as well as evaluation of social sustainability of integrated bio-refineries in the UK for bio-chemical and thermo-chemical routes and four different 2nd generation feedstocks to produce bio-ethanol, several platform chemicals and energy.

Although the sustainability assessment is focused on the UK, the methodology is generic enough to be applicable elsewhere.

The dissertation is divided into seven chapters as follows:

- Chapter 2: This chapter gives an overview of different 2nd generation bio-feedstocks, different biomass conversion technologies, and types of products that can be produced in integrated bio-refineries.
- Chapter 3: This chapter presents the methodology developed for assessing the sustainability of integrated bio-refineries. The methodology includes identifying the stakeholders and their potential sustainability issues, and defining and selecting relevant environmental, economic, and social indicators.

- Chapter 4: The analysis of the environmental, techno-economic, and social sustainability of bio-chemical refinery is presented and discussed.
- Chapter 5: Same as chapter 4 but focusing on the thermo-chemical route.
- Chapter 6: This chapter compares the environmental, economic, and social sustainability of both the bio- and thermo-chemical routes.
- Chapter 7: The conclusions and recommendation for future work are presented in this chapter.

2 AN OVERVIEW OF BIO-FEEDSTOCKS, CONVERSION TECHNOLOGIES AND BIO-PRODUCTS

2.1 Introduction

Unlike the petroleum refinery where chemicals and energy are produced from crude oil, the integrated bio-refinery uses biomass as the input. A generic flow diagram of an integrated bio-refinery is shown in Figure 2.1**.** As indicated, various bio-feedstocks are converted to chemicals, power, and fuel using either biological or thermo-chemical conversion or both. This chapter gives an overview of different bio-feedstocks, processing routes and products from integrated bio-refineries.

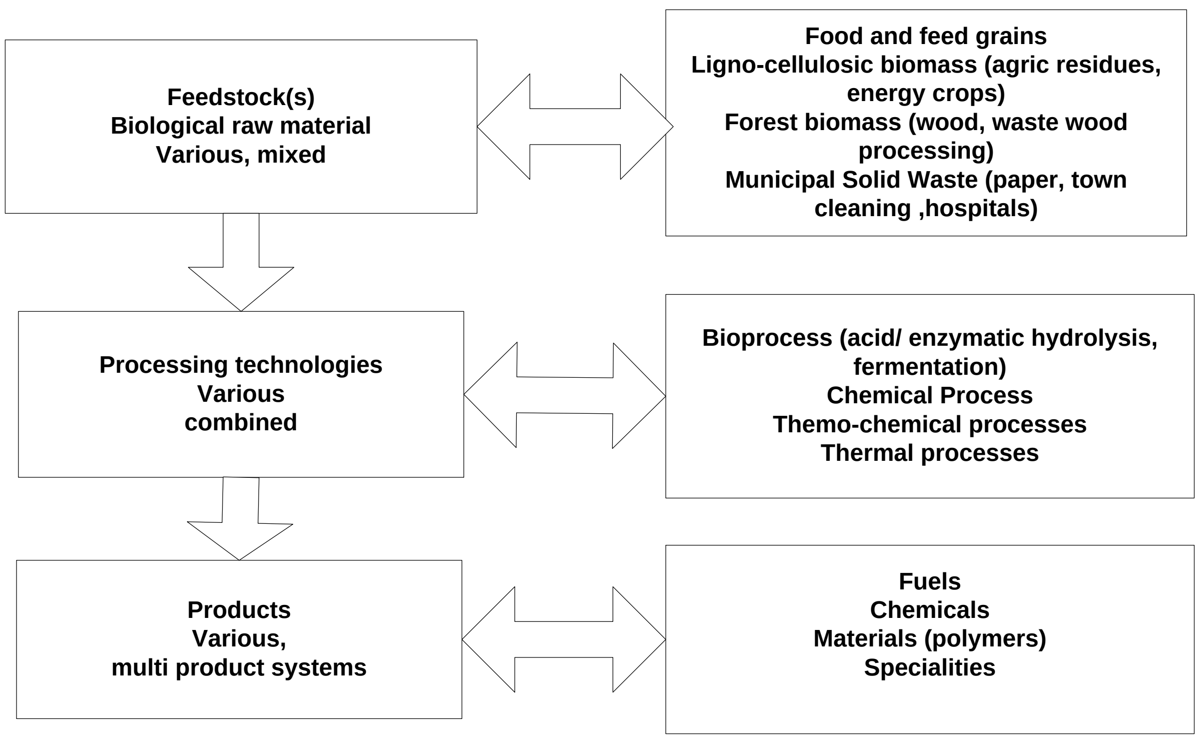


Figure 2.1 Generic diagram of an integrated bio-refinery adopted from Fernando et al. (2006) and Kamm and Kamm (2004)

2.2 Bio-feedstocks

The focus in this work is on 2nd generation feedstocks. For reference, a brief overview of 1st generation feedstocks is given below; consideration of 3rd generation (algae) is beyond the scope of this work.

The 1st generation feedstocks are starch and sugar containing materials found in mainly corn, wheat, sugar beet, sugar cane and sweet sorghum. They contain mainly cellulose and their glucose is released for fermentation either with acid or enzyme catalysed hydrolysis step. The main product from these feedstocks is bio-ethanol. The USA is the major producer of bio-ethanol from corn with a total production of about 19.8 billion litres per year. In Brazil, sugarcane is used to produce about 17.8 billion litres of ethanol per year while the EU (European Union) produces about 3.44 billion litres per year from sugar beet and starch crops (GBEP 2007). Other first generation products are bio-diesel from rapeseed, sunflower, and soybean. However, their disadvantage is competition with food prices and the land use.

The 2nd generation feedstocks are otherwise known as the lignocellulosic feedstocks. A range of feedstock sources have been identified ranging from agricultural waste to forestry feedstocks (Dunnett et al. 2008). This category of biomass is the most abundant with a yearly production of 200 x 10^9 tonnes (Zhang 2008). The United States have identified a possible production of about 1.3 billion tonnes per year of these types of feedstocks (forestry and agriculture) without interfering with land use and (Perlack et al. 2005). The various types of biomass sources available in the UK are indicated in Figure 2.2 (NNFCC 2007). As can be seen, of the total yearly amount of 26900 k tonnes, wet residues and waste wood are the most abundant sources of lignocellulosic biomass in the UK (34% and 22%, respectively). The examples of wet residues include pig slurry and silage and they are mostly used for fertilizer and biogas production. Sources of waste wood include domestic, industrial and construction and demolition waste. However, most of these are currently recycled or used by power stations. Examples of energy crops, which represent 10% of biomass in the UK, are willow, poplar, switchgrass and miscanthus. The current cultivation of miscanthus and short rotation copice is about 64,000 and 13,000 t/yr, respectively (NNFCC 2007). Dry agricultural residues (14%) are wheat straw, corn stover, barley, and oat straw, while forest residues (12%) fall into the category of logging and wood residues.

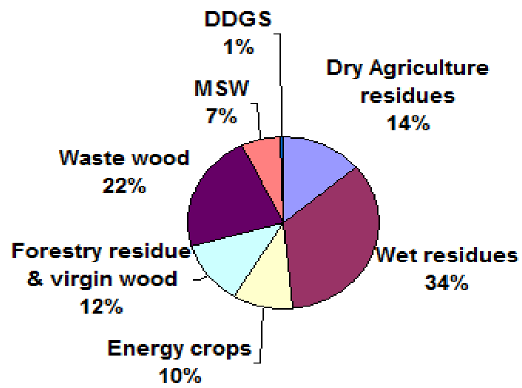


Figure 2.2 Feedstock availability in the UK (NNFCC 2007)

2.2.1 Composition and structure of lignocellulosic feedstocks

Lignocellulosic feedstocks have complex matrix structure, consisting of cellulose, hemicellulose and lignin (see Table 2.1). The major structural components are cellulose and lignin and the weight varies in different types of biomass species.

2.2.1.1 Cellulose

This is the most abundant organic material on earth and provides strength for the biomass. The cellulose, with an organic formula of $(C_6H_{10}O_5)_n$ is known to be an unbranched polysaccharide consisting of several chains of glucose linked by β-1,4-glucan. The basic repeating unit of the cellulose polymer consists of two glucose anhydride units called cellobiose unit. The glucose anhydride is polymerized into long cellulose chains that contain 5000-10000 glucose units (Mohan et al. 2006). This component of the biomass is not easy to hydrolyze and releases the glucose monomer for further polymerization (Cherubini 2010). It is only soluble in certain solvents such as aqueous *N*methylmorpholine-*N*-oxide (NMNO), CdO/ethylenediamine (cadoxen), or LiCl/*N*,*N'*-dimethylacetamide, or near supercritical water and in some ionic liquids (Swatloski, 2002;Turner, 2004).

2.2.1.2 Hemicellulose

Hemicellulose $(C_5H_8O_4)_n$ consists of short, highly branched chains of sugars, manly xylose. It contains five-carbon sugars (xylose, arabinose), six-carbon sugars (glucose, galactose and mannose) and uronic acid. It is the second most abundant organic material after cellulose. It also has an amorphous structure with reduced strength in comparison to cellulose containing both C5 and C6 sugars (Hendriks and Zeeman 2009). Hemicelluloses have lower molecular weights than cellulose. The number of repeating saccharide monomers is only ~150, compared to 5000 - 10000 in cellulose.

2.2.1.3 Lignin

Lignin is the most abundant aromatic polymer in nature, and it is the structure that makes up the woody part of the lignocellulosic biomass. It consists primarily of carbon-ring structures interconnected by polysaccharides, which are very valuable chemical intermediates. Separation and recovery of lignin structures is very difficult to accomplish (Paster et al. 2003). The compactness and complexity of lignocellulose is responsible for the strength of the plant.

Feedstock source	**Cellulose fraction**	**Hemicellulose fraction**	**Lignin fraction**
Energy crops	0.366	0.161	0.219
Crop residues	0.38	0.32	0.17
Woody biomass	0.437	0.283	0.243

Table 2.1 Composition of selected lignocellulosic feedstock (Kaylen et al. 2000)

2.2.2 Types of lignocellulosic feedstock

2.2.2.1 Energy crops

Energy crops include perennial grasses such as switch grass, alfalfa, miscanthus, and Short Rotation Crops (SRC) such as eucalyptus and poplar. Although these crops are mainly cultivated for energy purposes, they can also be used for biofuel production. Examples of these are switch grass, poplar, and miscanthus.

For instance, switch grass is a potential feedstock for biofuel production because of its high biomass productivity, adaptability to marginal land and low demand for water and nutrients (Keshwani and Cheng 2009). In addition, it has a wide range of geographic adaptation because of its well-developed root system and high water use efficiency.

Switch grass can also be integrated into farming operations due to the already existing infrastructure for planting, harvesting, and plant management practices. In agriculture, switch grass has the advantage of soil contaminants removal, high tolerance to soil characteristics, good resistance to water and wind flows and wildlife habitat (Parrish and Fike 2005). Although factors such as latitude, nutrition and type of land may affect the yield from switch grass, a typical yield is around 10-25 t/ha/yr (Balat et al. 2008). Switchgrass is widely grown in North America, from Maine to Saskatchewan in the North, from Florida to Arizona in the South, in Costa Rica and in the West Indies. Previously, it has been used as a forage crop (Keshwani and Cheng 2009), soil conservation and as an ornamental crop (Van den Oever et al. 2003). Also, it has been used for ethanol (Pimentel and Patzek, 2005; Spatari et al.; 2005; Wu et al. 2006) and for electricity production.

In addition to switch grass, other herbaceous perennials used as energy crops include alfalfa, miscanthus and reed canary grass. Alfalfa is a crop adaptable to different conditions and has a typical yield of 7 tonnes/ha of dry matter per year with existing farming practices in place (Vadas et al. 2008). Alfalfa increases the content of nitrogen and organic matter in the soil as a result of its deep roots (Vadas et al. 2008). The leaf and stem components have a high cellulose and protein content, respectively. Therefore, strategies to maximise the yield of leaf and stem is crucial to the utilisation of alfalfa in biofuel production (Sheaffera et al. 2000). Furthermore, like any other lignocellulosic biomass, improvement in cost effectiveness of biomass pre-treatment technologies is required.

Miscanthus is grown in the tropic and subtropic regions although different spices can adapt to various climatic conditions. Miscanthus requires cultivation on a good soil with adequate aqueous capacity (Lewandowski et al. 2003). Characteristics such as resistance to pest and diseases, efficient use of water and nutrients and low fertiliser requirement make it an ideal energy crop.

Short rotation woody crops are fast growing tree species such as eucalyptus, willow and poplar. When grown, these crops can be harvested once every 6-10 years with estimated annual yields of 10-15 tonnes/ha (Venedaal et al. 1999). These crops should be cultivated on moist and fertile soil as they can help growing conditions (Mitchell et al. 1999). On the other hand, retarded crop growth, difficulty in nutrient uptake and weed management practices are the implications of cultivation in poor and harsh conditions. Adequate farm management practices should also be applied as this can have an effect on soil properties (Mitchell et al.1999).

2.2.2.2 Agricultural residues

Agricultural by-products such as corn stover (leaves, stalks and cobs), wheat straw, rice straw and sugarcane baggasse have a huge potential to support and expand the biomass conversion industry in the long term. This is because they are cheap, renewable and available. However, harvesting crop residues may lead to soil erosion and poor conservation of natural resources, including water (Franzluebbers 2002; Groom et al. 2008; Lal 2006b). Retention of crop residue on the soil, on the other hand, promotes biodiversity by recycling nutrients (Lal 2006a) so that retaining up to 40% of the residue is recommended (Spatari et al. 2005; Graham 2007).

Corn stover is a major candidate for use as a bio-feedstock. It is concentrated in the US because of massive corn grain cultivation. Approximately 244 million tonnes of corn stover are recovered each year with at least 22 million tonnes originating in Indiana (Tally 2002). A small percentage is also harvested for animal feed (Kim and Dale 2008). An estimated truck delivery cost of corn stover is $0.12/dry tonne/km (Kumar et al. 2005). This price includes collecting, handling and transporting the raw material to a conversion facility. Again, this price is largely affected by the availability as well as the properties of the land (Perlack and Turhollow 2003).

Cereal straws are by-products of cereal crops such as wheat, rice, oat, and barley. In the EU and North America, about 800 million tonnes of straw a year is available (Arvelakis and Frandsen 2007). The approximate yield of straw is between 1.3-1.4 kg per kg of grain (Pan and Sano 2005). Sugar cane baggasse can be used for animal feed, paper and pulp manufacture and ethanol production. Also, it can be used for power and heat generation via combustion.

2.2.2.3 Municipal solid waste (MSW)

Cellulosic materials form about 60% of a typical MSW stream (Kalogo et al. 2007) and include kitchen waste, paper and wood. In the UK, approximately 40 million t/yr of MSW is collected (Troschinetz and Mihelcic 2009). Unlike other lignocellulosic materials, MSW is non-homogenous which makes it more difficult to process compared to other materials (Troschinetz and Mihelcic 2009). MSW like other lignocellulosic materials will require pre-treatment before it can be used as a feedstock. The application of pre-treatment methods will vary from the type of waste to achieve a high glucose yield (Li et al. 2007).

2.2.2.4 Forestry residues

Forest residue can be divided into three groups: primary, secondary, and tertiary resources. The primary resources consist of logging residues from general farm operations such as land clearing. The secondary resources are mainly wood mill residues. These residues originate from the harvest of pulpwood, saw logs and other forest products (Parikka 2004). The tertiary resources are the urban wood residues, which are waste wood from municipal solid waste, construction and demolition and industrial and commercial practices. The amount of tertiary resources in the UK is around 10.6 million t yr in the UK (NNFCC 2007). Forest residues can be utilized to manufacture a variety of products. Currently, the majority of chips and planer shavings are used in the production of paper and paper-based products. Bark is primarily ground (or pulverized) and processed for landscape uses which is sold to local customers and landscaping contractors. Sawdust, sanderdust, and mixed residues are sold for the production of energy and to the composites industry for the manufacture of particleboard and medium density fiberboard. Slabs and end trims are primarily sold to local customers for fuel consumption.

2.3 Bio-feedstock conversion technologies

The conversion technologies for producing energy and chemicals from biomass can be divided into two types: thermo-chemical and bio-chemical (Figure 2.3). This section gives an overview of the various thermo- and bio-chemical technologies and identifies the challenges, possible limitations to their advancement and gaps in the research.

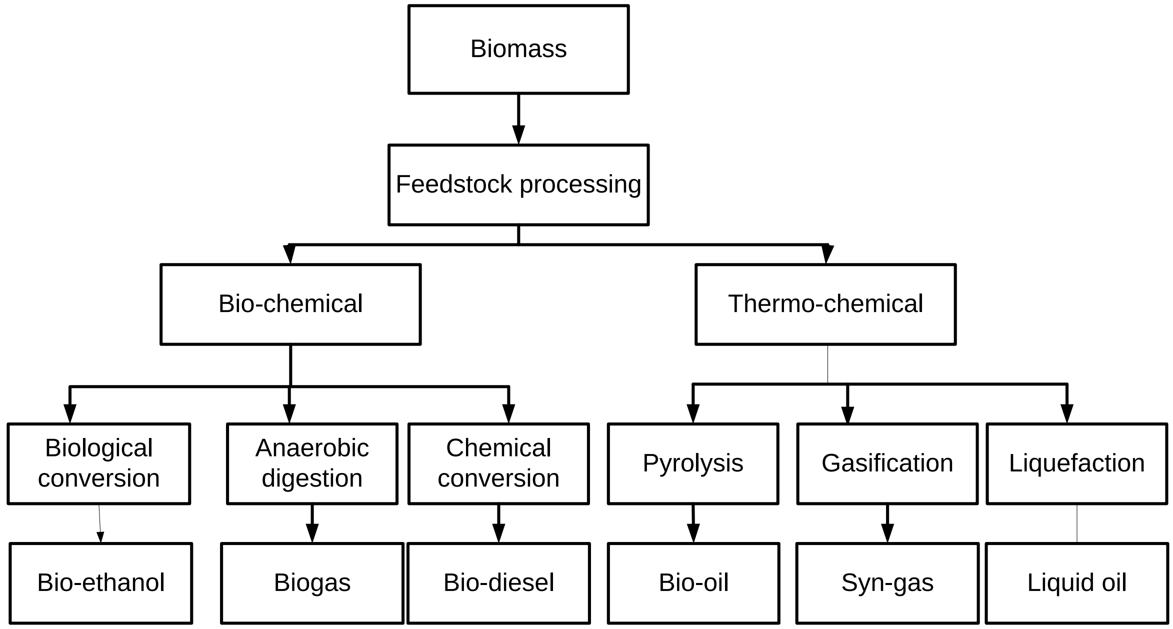


Figure 2.3 Biomass conversion routes modified from (Demirbas 2007)

2.3.1 Bio-chemical conversion

This method uses biological processes to convert biomass to energy and chemicals. The bio-chemical conversion can be divided into three types: biological conversion, anaerobic digestion and chemical conversion. Each of these conversion routes is discussed below.

2.3.1.1 Biological conversion

Biological conversion of biomass involves three steps:

1. pre-treatment and conversion of biomass to sugars ;
2. enzymatic hydrolysis using various microorganisms including yeast and fungi to ferment the biomass; and
3. processing the product into ethanol, other value-added products and electricity. These steps are described below.

1. Pre-treatment of lignocellulosic biomass

This is the first step in the production of lignocellulosic ethanol by the pre-treatment of biomass, which is vital in order to get maximum yield of glucose. The main reasons are to increase the surface area accessible for enzymes saccharification, to decrystallise the cellulose, break the lignin seal from hemicellulose and cellulose (Huang et al. 2008), decompose the hemicellulose to C5 sugars (D-xylose and L-arabinose) and soluble C6 sugars (D-mannose, D-galactose and D-glucose) and finally, to avoid the formation of inhibitors (Öhgren et al. 2007). Inhibitors are by-product chemicals obtained along with fermentable sugars within the processing chain of a bio-feedstock. They must be removed prior to fermentation as they can inactivate microorganisms, affect the pre-treatment efficiency, and slow down the rate of hydrolysis (Huang et al. 2008). There are three major groups of inhibitors: aliphatic acids (acetic, formic and levulinic acid), furan derivatives furfural and 5-hydroxymethylfurfural (HMF), and phenolic compounds (phenol, vanillin, *p*-hydroxybenzoic acid) (Huang et al. 2008).

Pre-treatment will alter the biomass structure and assist the downstream biomass processing. Without the pre-treatment, the packed cellulose structure and lignin seal remain rigid and will be resistant to enzymatic hydrolysis (Brehmer et al. 2008). A pre-treatment method should satisfy the following: (i) ensure fibre reactivity; (ii) yield pentose in non-degraded form; (iii) show no fermentation inhibitors; (iv) require less effort for feedstock size reduction; (v) require reactors of reasonable size (high solids loading); (vi) use affordable materials and lead to no solid residues (Hamelinck et al. 2005).

Figure 2.4 shows the structure of biomass before and after pre-treatment. The options available for pre-treatment are:
(i) physical (mechanical size reduction, compression milling),
(ii) physico-chemical (steam explosion, liquid hot water and ammonia fibre explosion),
(iii) chemical (base or acid), and
(iv) biological.

These options, described briefly below, have various compositions of product stream all of which proceed to the fermentation stage. Also, it is possible to combine one or more pre-treatment techniques. If physico-chemical or chemical treatment is used, biological processing is then also referred to as bio-chemical (this notation will be used later on in the case study related to the bio-chemical route; Chapter 4). The different pre-treatment techniques are shown in Figure 2.5.

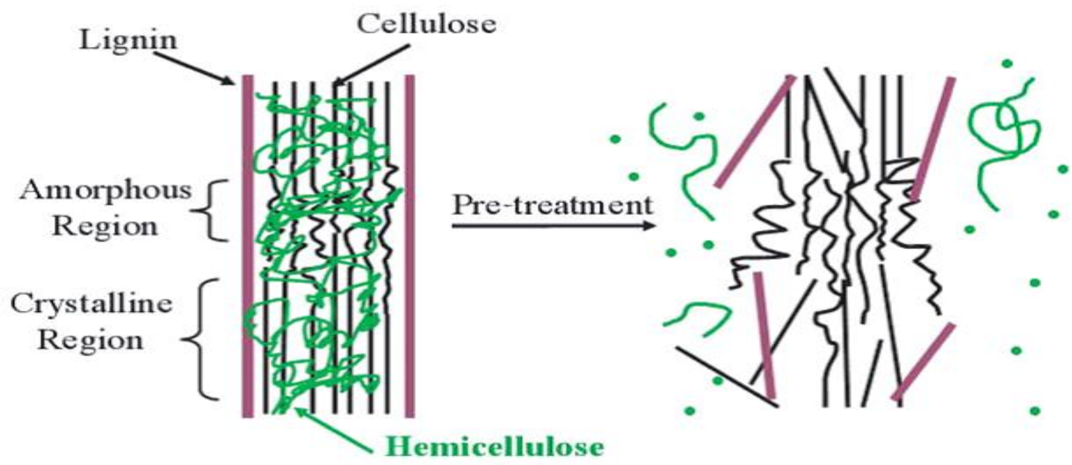


Figure 2.4 Pre treatment effect on lignocellulose biomass (Kumar et al. 2009)

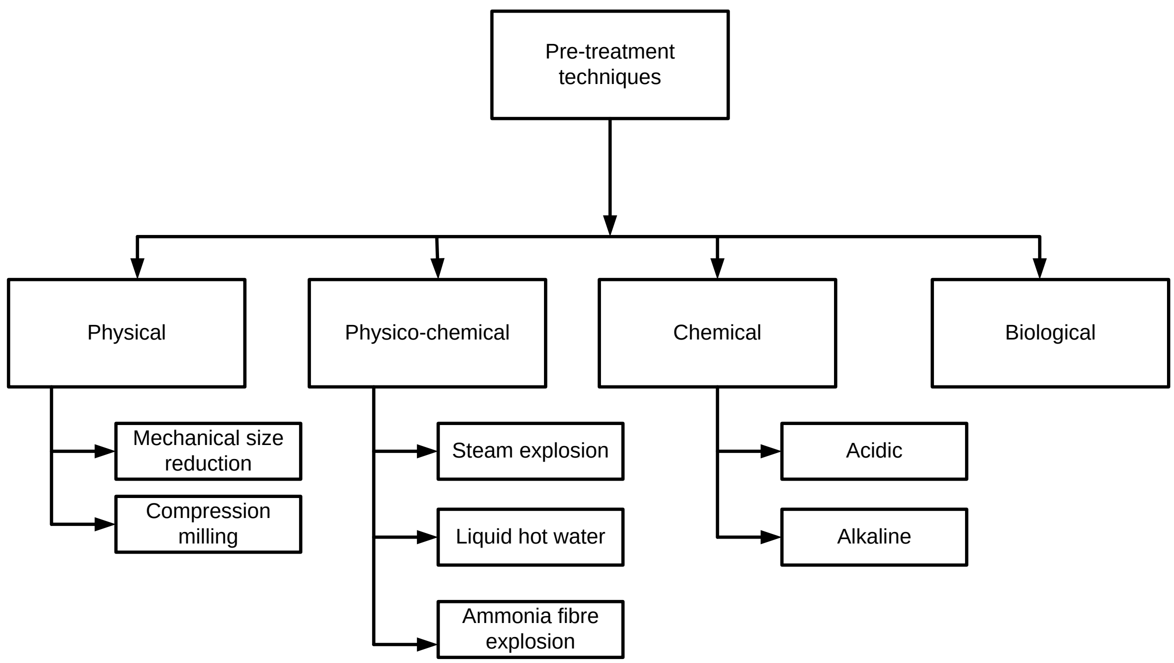


Figure 2.5 Different pre-treatment methods

(i) Physical methods reduce the size of the feedstock to ensure easy material handling for the subsequent process. In general, the aim is to improve the accessibility of cellulose to enzymes by increasing the surface area. Examples of this method are ball milling and comminution. These methods are capable of reducing the crystal structure of the feedstock. High-energy requirement, low yield, and long residence times are limitations of physical pre-treatment. Furthermore, Mosier et al. (2005) suggested that the chemical changes that occur during pre-treatment are more important than the physical disruption of the biomass.

(ii) Physico-chemical methods include steam explosion, liquid hot water and ammonia fibre explosion. The former involves the use of high pressure steam and temperatures of about 260 ^{o}C, followed by a sudden quench to atmospheric pressure (Hamelinck et al. 2005). This is to depolymerise lignin and ensure easy hydrolysis of hemicelluose (Huang et al. 2008). Although the use of steam is common for lignocellulosic materials, one important factor to consider is the production of the steam, as steam produced from fossil fuels rather than biomass could have high a environmental impact (Zhi F et al. 2003; Huang et al. 2008). Much of the research involving steam explosion pre-treatment has focused on the alteration of the lignocellulose matrix and subsequent improvement of enzymatic hydrolysis (Ballesteros et al. 2002). The use of steam explosion has been used in the Iogen demonstration plant which produces up to 2 million litres of cellulosic ethanol per year from oats, wheat and barley straw (Iogen 2004).

Another physico-chemical pre-treatment option is the liquid hot water. It uses hot water with temperatures of around 180 ^{o}C to hydrolyse the hemicellulose. Since the pH control is very important to avoid unwanted degradation products, this process is termed pH-controlled liquid hot water pre-treatment (Huber et al. 2006; Hendriks and Zeeman 2009). This approach prevents the use of acid or alkaline. Both steam explosion and pH-controlled liquid hot water treatment are classified as uncatalysed pre-treatment.

The ammonia Fibre Explosion (AFEX) pre-treatment option utilises ammonia as the medium. It involves placing the material in 1-2 kg ammonia/kg of biomass (Kumar et al. 2009). The operating pressures and temperatures are 1.4 - 3 atm and 70 - 150 ^{o}C respectively. The pressure is released swiftly after 30 mins. Although the AFEX pre-treatment effectively depolymerises the lignin (Huber et al. 2006) it does not completely solubilise hemicellulose unlike the acid pre-treatment (Sun and Cheng 2002). Due to the cost of ammonia, it is often recycled, and does not produce inhibitors that slow down the fermentation process. Using a reduced ammonia concentration solution to treat biomass is referred to as Ammonia-Recycled Percolation (ARP) (Huber et al. 2006).

(iii) Chemical treatment involves the use of chemical agents to pre-treat lignocellulosic materials and these applications have gained attention. The chemical medium can either be an alkali or acid. Acid pre-treatment could either be a dilute or concentrated acid application. The types of acid applicable are sulphuric, hydrochloric, nitric and phosphoric acid (Balat et al. 2008). Dilute acid pre-treatment involves the use of any of the named acids to convert the hemicellulose to soluble fraction and enhance enzyme digestivity (Tucker et al. 2003). Amongst others, dilute acid pre-treatment is the preferred method for pre-treating biomass. This is due to high sugar yields from the hemicellulose (Sun and Cheng 2002), low cost (Olofsson et al. 2008), lignin structure alteration with increased surface area (Huber et al., 2006) together with the prevention of the formation of inhibitors (Hendriks and Zeeman 2009). Concentrated acid is not usually used as it is corrosive and may require further neutralisation. Also, it is a costly recovery process (Wingren et al. 2003) and extra care is needed in handling. In summary, acid pre-treatment favours hemicellulose hydrolysis.

Alkaline pre-treatment can use sodium hydroxide, potassium oxide or lime (calcium hydroxide) to pre-treat bio-feedstock. Generally, they are very effective in the removal of the lignin, thereby improving accessibility of the feedstock (Lu and Mosier 2008) and producing high fermentable sugars. Alkaline pre-treatment requires mild and ambient conditions. Unlike the acid pre-treatment, alkaline pre-treatment does not produce certain intermediates that may pose a problem for subsequent processes (Lens et al. 2005).

Sodium hydroxide works well for delignification. Sharma et al. (2002) investigated the alkali pre-treatment on sunflower stalks and reported that sodium hydroxide at 0.5% (w/v) along with autoclaving for 1.5 h at 1.05 kg/cm^2 was the most effective processing condition as evaluated by the follow-up enzymatic hydrolysis. Sodium hydroxide pre-treatment is suitable for less-lignified cellulosic materials, but it has little effect on softwood with lignin content greater than 26% (Laser et al. 2009b).

Calcium hydroxide (lime) is also an effective pre-treatment chemical agent and at $0.06/kg the cheapest of all the hydroxides) (Saha and Cotta 2007). It utilises calcium hydroxide, water and an oxidising agent (air or oxygen). It is effective in lignin removal, non-corrosive, and easily recovered (Saha and Cotta 2007). Lime has been used for feasibility studies for producing ethanol and power from switchgrass (Laser et al. 2009a) and corn stover (Aden et al. 2002). The use of lime has been followed by dilute acid hydrolysis to neutralise the system.

(iv) Biological treatment requires microorganism growth on biomass to degrade lignin and hemicellulose. In addition, antimicrobial substances can be removed by biological treatment (Demirbas 2005). The cellulose is usually not attacked since it is the most resistant component to biological treatment. Examples of micro-organisms commonly used for biological treatment include the white and brown fungi, which are quite slow and ineffective thereby reducing the potential of this method (Taherzadeh and Karimi 2008). However, some of its advantages are low energy input and mild operating and environmental conditions which are needed (Hamelinck et al. 2005; Taherzadeh and Karimi 2008). Finally, chemicals are not used so the waste generated is non-toxic.

2. Hydrolysis of lignocellulose

Hydrolysis can either be chemical- or enzyme-based. Other methods include gamma ray application, which is commercially unavailable (Demirbas 2005). The chemicals can be either acidic or basic. To break down certain polysaccharides, enzymes are preferred as alternatives to degrade polymer sugars. Acid hydrolysis has been used for studies but it can corrode the fermenting organisms; hence it is not an attractive method (Olofsson et al. 2008). Enzymatic hydrolysis is preferred environmentally because it prevents the problems of chemical recovery and disposal when employed on a large scale (Taherzadeh and Karimi 2007). Though chemical hydrolysis is still effective for depolymerisation, for hemicellulose, enzymatic hydrolysis is a better choice for degradation during biomass to ethanol conversion. This is because enzyme-based hydrolysis is more cost effective than acid-based hydrolysis since it requires less utility and mild process conditions (Sun and Cheng 2002). Furthermore, enzymatic hydrolysis has the advantage of increased sugar yields with the formation of reduced degradation products (Kerstetter and Lyons 2001). The cost of enzymes has an overall effect on the economic viability of the process but in the future, this may change owing to higher volumes produced for other applications such as textiles as well as increased production efficiency (Wingren et al. 2003).

Other factors affecting hydrolysis are directly related to the individual characteristic of the lignocellulose biomass (Hendriks and Zeeman 2009). In addition, properties such as the degree of cellulose polymerisation and lignin content could limit the hydrolysis reaction and yields. To overcome this, improved enzyme activity and a reduction of steps in the process need to be developed (Hamelinck et al. 2005). Even though a great deal of work has been done to optimise the supply chain of enzyme production, this is not fully commercialised on an industrial scale due to lack of technology or bio-refinery systems (Lin and Tanaka 2006; Ogier et al. 1999) and cost of enzymes (Sims et al. 2008).

Hydrolysis of lignocelluloses can be done in two different ways:
(i) separate hydrolysis and fermentation (SHF); and
(ii) simultaneous saccharification and fermentation (SSF).
The two routes are described briefly below.

(i) Separate hydrolysis and fermentation (SHF) is performed separately from the fermentation step. The lignocellulosic feedstock is pre-treated to destroy the rigid structure and assist with further downstream processing. A part of the pre-treated biomass is used for enzyme production to alleviate fungus growth that yield cellulase enzyme, the resulting mixture (cellulose enzyme) is then added to the hydrolysis reactor. At this point, the hydrolysis is catalysed by the enzymes to form glucose. Yeast is added to the resulting mixture and is passed to the fermenter for ethanol recovery from glucose, which is later purified for pure ethanol. In SHF, the process conditions can be regulated to suit the individual feedstock ensuring flexibility. The advantage of this process is that the cellulase hydrolysis and fermentation can occur at respective temperatures. The temperatures for the cellulase hydrolysis around 45-50 ^{o}C (Wingren et al. 2003), while the latter is between 30-37 ^{o}C (Taherzadeh and Karimi 2007). On the other hand the disadvantage is the accumulation of end products resulting in a slow hydrolysis rate (Drissen 2009). Figure 2.6 summarises the above description.

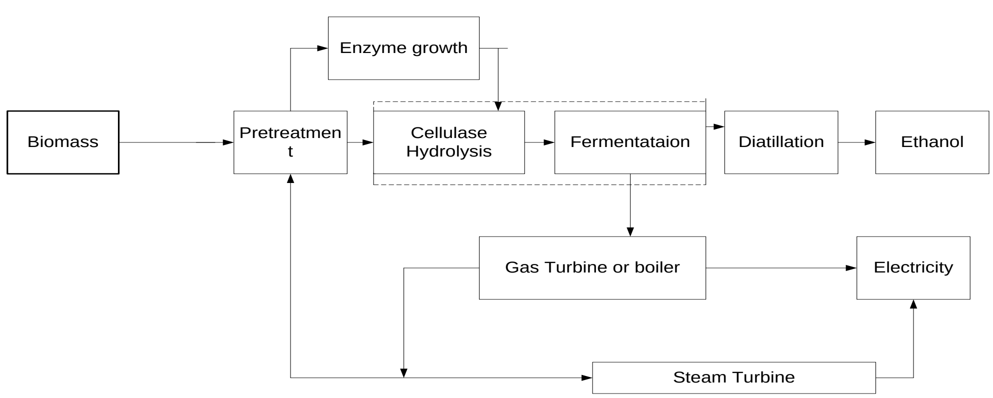


Figure 2.6 Ethanol production by hydrolysis fermentation. Modified from (Hamelinck 2006)

(ii) Simultaneous saccharification and fermentation (SSF) is similar to the SHF process, except that enzymatic hydrolysis and fermentation take place in the same vessel. The combination of yeast and enzymes in one vessel reduces the sugar build-up and hence increases the hydrolysis rates since sugar formed slows down the activity of the cellulase enzyme. In addition to this, the combination also reduces the investment cost up to 20% (Olofsson et al. 2008). Yeast cannot be reused in this system as a result of difficulty in separating lignin from yeast. The SSF process seems to be more advantageous than the SHF process from both the perspective of ethanol yield and ethanol production rate (Drissen et al. 2009). The other advantages include reduced investment cost and product inhibitors formation, lower enzyme consumption, reduced volume of reactor and short residence times.

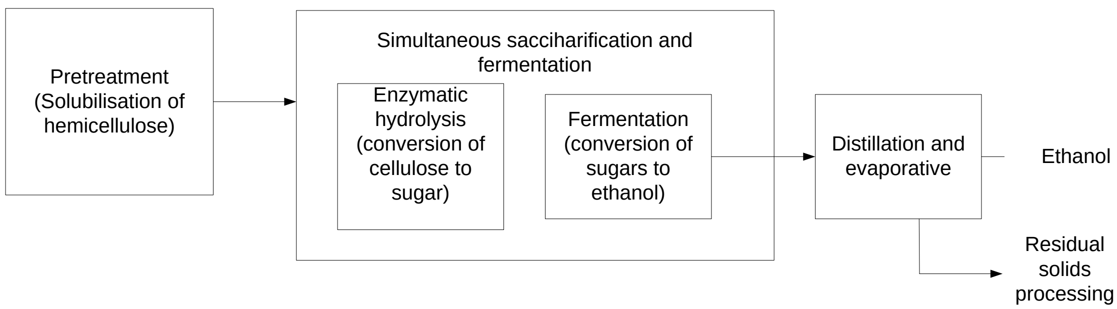


Figure 2.7 Schematic for the conversion of biomass to ethanol modified from (Hahn-Hagerdal 2006; Lin 2006)

(iii) Fermentation and product recovery involves the addition of fermenting organisms to ferment glucose to ethanol. Products from hydrolysis contain a mixture of C6 and C5 sugars. C6 sugars such as glucose are fermented with *Saccharomyces* cerevisiae (Erdei et al. 2012). This yeast is commonly used for C6 sugar fermentation because of its high bio-ethanol yield and adaptability to inhibitory compounds. C5 sugars such as xylose can be fermented with *Pachysolen tannophilus*, *Pichia stipitis* and *Candida shehate*. Xylose fermentation results in low ethanol yield (Keshwani and Cheng 2009). An alternative may be to convert xylose to xylulose (Katahira et al. 2006) which can be fermented with yeast. However, this process is not cost-effective and is the focus of R&D to develop micro-organisms capable of increasing ethanol production from pentose (Keshwani and Cheng, 2009). This can be to genetically modify the current yeast to include C5 sugar fermentation (Chandel et al. 2007).

The product recovery unit recovers the products. The fermentation broth is distilled to separate ethanol from water and a further dehydration step removes any trace amount of water. Any residual solids like lignin, unconverted cellulose and hemicellulose are burnt for power generation. Furthermore, lignin can be converted to vanillin.

2.3.1.2 Anaerobic digestion

Anaerobic digestion (AD) of biomass is a biological process that occurs in the absence of oxygen in which anaerobic bacteria are used to produce biogas from organic matter. Biogas contains about 60% methane and 40% carbon dioxide. Other products are solid and liquid residues known as digestate, which can be used to improve soil fertility. The type of feedstock used affects the quality of digestate and amount of biogas produced, as more putrescible feedstock yields more biogas. Typical feedstocks include includes paper, food and garden waste and sludge from wastewater treatment. The advantages of this method include reduction of odour, volume of waste landfilled and related land requirement. In the UK, AD is mainly used at farms.

2.3.1.3 Chemical conversion

As opposed to biological conversion, chemical conversion of biomass involves using chemical agents or reactions to convert biomass into products. The feedstocks include vegetable oil, animal fats, rapeseed, soybean and sunflower seed (Balat and Balat 2008). Transesterification of waste vegetable oil and animal fats is the most popular way of producing bio-diesel as it has high conversion rates and occurs at a relatively low temperature. Transesterification is a catalysed chemical reaction between a renewable feedstock and either methanol or ethanol to produce alkyl esters and glycerol. Factors such as temperature, water content and catalyst type affect the transesterification reaction (Al-Zuhair 2007). Commercial application of transesterification is possible and is currently practised to make a series of compounds. The reaction is shown below:

$$\mathbf{RCOOR' + R''OH \leftrightarrow RCOOR'' + R'OH}$$

The selection of catalyst determines the equilibrium shift and excess alcohol is used to shift the reaction to the right hand side and to ease phase separation of the glycerol formed. The catalyst could be acidic, alkaline or enzyme based. Acidic or alkaline catalysis is usually used because of the low cost and the shorter residence times compared to the enzyme based catalysis. Acid catalysis is used for waste vegetable oil with high fat content. Alkaline catalysis is very sensitive to any impurities in the raw material although there is a high yield of bio-diesel with a short residence time (Pang and You 2008).

2.3.1.4 Challenges for bio-chemical conversion

For the biological process to be cost effective in a bio-refinery, energy efficiency is a priority, especially in the pre-treatment process. This is because energy is required to destroy the complex structure of the lignocellulosic material, making it an energy intensive process. In addition, enzymatic hydrolysis requires optimisation in terms of cost and efficiency. The enzymes are specifically tailored to the type of raw material and pre-treatment technique. This can increase the cost of enzyme application and prevent diversity for use of different raw materials. Extensive research is needed on utilising enzymes for substrates and on improving enzyme mixtures. Companies such as Novonzymes and Genencor in the United States are currently researching into means of reducing enzymatic cost in the long term (Sims et al. 2008).

2.3.2 Thermo-chemical conversion

The thermo-chemical conversion involves the use of high temperatures and occasionally, high pressures to decompose biomass into energy, chemical and fuels. The thermo-chemical conversion can be by pyrolysis, gasification, or liquefaction.

2.3.2.1 Pyrolysis

Pyrolysis is the thermal decomposition of materials in the absence of oxygen (Yaman 2004; Mohan et al., 2006; Demirbas 2004) It converts the organic portion of the feedstock to char and volatile gases containing non condensable vapors and condensable tars which from bio-oil (Bridgwater 2004). The bio-oil formed is a low viscosity combustible product, which can be stored and transported easily. This offers the advantage of alternative fuel use after upgrading or use as a source valuable chemical and as an energy carrier (Bridgwater 2004) due to the presence of organic compounds. However, its disadvantages are that over a period of time, the viscosity increases due to polymerisation, thereby causing difficulty in phase separation and making long term storage a problem (Mohan et al. 2006). In addition to that, bio-oil is highly oxygenated. This can be reduced by applying commercially known technologies such as hydrogenation and catalytic cracking (Demirbas 2001). The char produced can be added to soil to help improve soil fertility and reduce erosion or used for process heat .

Pyrolysis has been applied to different biomass types including grass (Debdoubi 2006; Boateng 2007), woody biomass (Demirbas 2005a; Li 2005; Oasmaa et al. 2003; Oasmaa and Kuoppala 2003; Garcia-Perez et al. 2007), straw (Lee et al. 2005), bagasse (Yorgun et al. 2001) and MSW (Changkook 2007; Nurul Islam 2005). The yield and composition of pyrolysis products depend on the composition of the feedstock, the pyrolysis technique used and the operating conditions: temperature, residence time, and heating rate.

Pyrolysis can be slow or fast depending on the operating conditions and the desired final output: slow pyrolysis produces more of solid char while fast pyrolysis produces more liquid/gas. The later option is preferred for producing liquids for organic materials (Demirbas 2004).

2.3.2.2 Gasification

Gasification requires pre-treatment such as drying, screening or grinding to increase the surface area for further downstream processing. In this conversion, the biomass is decomposed in the presence of oxygen, steam or air to produce gaseous fuel (CO_2, H_2, CO, CH_4,C_2H_2, C_2H_4), trace amounts of hydrocarbons and contaminants such as char at temperatures of about 850 K - 1250 K (Bridgwater 2003). The syn-gas is then cleaned up to remove any impurities such as mercury, sulphur, or unreacted carbon using carbon beds or other purifying technologies such as the amine system. The level of impurity acceptable in the syn-gas is subject to the end use of the syn-gas. If the syn-gas is to be further catalysed into chemicals and fertilizers, then it is required to have a very low level of impurities. The recovered sulphur could be further processed into sulphuric acid.

For electricity production, the clean syn-gas could be further purified to remove CO_2, preceded by combustion in a gas turbine to generate electricity. In addition, the excess steam generated from this can be sent to a steam turbine. The combination of the above is called integrated gasification combined cycle (IGCC). Efficiency as high as 50% can be achieved using IGCC (Demirbas 2001).

For chemicals and transportation fuel production, the purified syn-gas is reacted with steam in the water gas shift reaction. Carbon dioxide, known as a diluents gas, is removed to allow downstream reaction to occur. The purified syn-gas is then passed through a catalyst that facilitates the Fisher Tropsch process, producing liquids such as methanol, ammonia, and mixed alcohols. Any unreacted syn-gas is normally burnt to generate electricity.

The purified syn-gas can also be directed to a fermentation tank where microorganisms ferment the syn-gas (Henstra et al. 2007; Datar et al. 2004). This process is known as syn-gas fermentation. Following this step, the fermented broth is further processed and separated to ethanol and other products by distillation. Micro organisms such as *Clostridium autoethanogenum, Clostridium ljungdahlii, Eurobacterium limosum, and Clostridium carboxidivorans* can be used to produce fuels and chemicals via syn-gas fermentation (Henstra et al. 2007). Advantages of this process are the mild conditions of operation, high tolerance to sulphur compounds and insensitivity to the carbon dioxide/hydrogen ratio (Datar et al. 2004).

2.3.2.3 Liquefaction

Liquefaction is the direct conversion of biomass to liquid fuels under a catalysed reaction. This involves the use of high pressure (5 to 10 Mpa) and temperatures (525-600 K) (Demirbas 2000). Factors such as pressure, reaction rate and mechanisms require adequate control to produce liquid oil. Liquefaction of biomass can be direct and indirect. Direct liquefaction involves rapid pyrolysis to produce bio-oils and/or condensable organic vapours. It requires no medium to yield liquid oil. Indirect processes are not defined as a thermo-chemical process but rather as chemical upgrade, such as Fisher Tropsch processes. The indirect liquefaction can either use alkali, acidic (Behrendt 2008 et al; Demirbas 2005b) or the glycerine medium to produce liquid oil (Demirbas 2005). Demirbas (2008) studied the effect of different ratios of alkali medium with corn stover showing that factors such as temperature and amount of alkali used are paramount criteria that determine the bio-oil produced. It was also found that the conversion yield increases with increasing alkali (Demirbas 2008).

2.3.2.4 Challenges for the thermo-chemical route

The thermo-chemical conversion is analogous to the petroleum industry today: although well established, the major challenge the process encounters is being capital-intensive. This is because of the high temperature and pressure required, which reflects in the design and materials of construction employed in the process (Öhgren et al. 2007). Moreover, tar formation is also an obstacle in the large scale commercialization of this process. It can condense and lead to blockage in pipes or clog filters, but research is underway to further utilise tar more efficiently (Sims et al. 2008). Syn-gas clean up can also be an additional drawback for commercial implementation. Gas clean up is very important as polluted off-gas can inactivate and reduce the lifetime of catalyst. There are no commercial plants available yet.

2.4 Bio-products

This section provides an overview of the types of product that can be obtained from the biomass conversion processes in integrated bio-refineries. These span fuels, platform chemicals and energy.

2.4.1 Fuels

Fuels that can be made from biomass through bio-chemical or thermo-chemical processes include ethanol, methanol, propanol, and diesel. Total worldwide bio-ethanol production is about 51 billion litres (GBEP 2007) and is expected to be the dominant fuel in the transport sector in the future (Hahn-Hagerdal et al. 2006). The main feedstocks used for the production of bio-ethanol include wheat straw and corn stover. Properties of ethanol include broader flammability limit, high heat of vaporisation and high octane number. These properties increase the efficiency of its use in car engines as a result of high compression ratio and reduced burn time (Balat et al. 2008). Bio-methanol is a poisonous gas because of its high octane rating and the gas burns invisibly (Demirbas 2007). The properties of butanol are low vapour pressure, non-sensitivity to water, reduced volatility, lower toxicity, and flammability (Qureshi and Ezeji 2008). These bio-alcohols can be produced from both 1^{st} and 2^{nd} generation feedstocks.

World bio-diesel production was 1.8 billion litres in 2003 (Demirbas 2007). Bio-diesel is produced by catalytic trans-esterification. Several feedstocks are available for the production of bio-diesel, including sunflower, peanuts, mustard seeds, soybean, canola, vegetable oils, animal fats, rapeseed and palm oil. Although the use of vegetable oils and animal fats is currently being researched (Demirbas 2007), they have high production costs (Kulkarni and Dalai 2006). The use of waste vegetable oil will reduce the cost of bio-diesel since about 60-90% of the feedstock cost is from oil (Al-Zuhair 2007).

The advantages of bio-diesel include non-flammability, non-toxicity and compatibility with standard diesel engines. Furthermore, it offers the same performance as fossil-derived diesel. Also, it has a high flash point making it less volatile and easier to transport than conventional petroleum diesel (Bozbas 2008). Table 2.2 summarises the 2^{nd} generation biofuels, their production processes and their uses.

Biofuel type	**Specific biofuel**	**Biomass feedstock**	**Production process**	**Use**
Bio-ethanol	Cellulosic bio-ethanol	Lignocellulosic	Advanced enzymatic hydrolysis and fermentation	Internal combustion engine for transportation
Synthetic bio-fuels	Biomass-to-liquids (BTL) Fisher-Tropsch diesel (FT)	Lignocellulosic	Gasification and synthesis	
Bio-diesel	Hydro-treated bio-diesel	Vegetable oils and animal fats	Trans-esterification	
Biogas	Methane gas	Lignocellulosic	Anaerobic digestion	Electricity production

Table 2.2 Production, classification and use of 2^{nd} generation biofuels. Modified from Dodds and Gross (2007) and Sims et al. (2008).

2.5 Platform chemicals

Platform chemicals serve as building blocks for the production of other chemicals. For instance, the platform chemical 3-hydroxypropianic acid can be converted to bulk chemicals such as 1, 3-propanediol, acrylic acid, acrylonitrile, methyl acrylate and acrylamide.

Recently, there have been publications investigating the production of chemicals from biomass. An example is the report by the DOE/NREL in USA published in 2004, which described the top 12 platform chemicals that can be produced from fermentable sugars through chemical or biological processes (Werpy and Petersen 2004). These chemicals and intermediate derivatives are given in Table 2.3. The intermediate derivates are building blocks for other secondary chemicals. For instance, lactic acid can be used for the production of polylactic acid (PLA) which is capable of replacing polyethylene terephthalates (PET). Nature Works LLC, a joint venture between Cargill and Dow produces PLA from corn (Vink et al. 2003), and the company is also working with Iogen and Genencor (Werpy and Petersen 2004) to use lignocellulosic biomass in the future (Saddler and Mabee 2007). Another example which was announced in 2004, is the joint venture between Tate & Lyle and DuPont to manufacture 1, 3 propanediol from corn for use in polymer fibre labelled DuPont Sorona (Black and Miller 2006).

Chemicals	**Intermediates derivatives**
1, 4 succinic acid, malic acid, fumaric acid	1,4-butanediol,tetrahydrofuran
2,5 furan dicarcoxylic acid	Succinic acid, 2,5 furandicarbaldehyde
Aspartic acid	Aminio-2,pyrolidore, aspartic anhydride
3-hydroxypropionic acid	1,3propanediol, acrylic acid, acrylonitrile. methyl acrylate, acrylamide,
Glucaric acids	Prolinol, 1,5pentanadiol
Itaconic acid	3-methyl THF, itaconic diamide
Levulinic acid	Methyltetrahydrofuran, arylic acid
Sorbitol	Lactic acid, ethylene glycol, glycerol, isosorbide
Glycerol	Glyceric acid, propanol,
Xylitol/arabinitol	Glycerol, lactic acid, xylaric acid, propylene glycol
3-hydrobutyrolactone	Acrylate-lactone

Table 2.3 Main chemicals and intermediates derivates from biomass (Werpy and Petersen 2004)

2.6 Energy

Bio-energy production can be via co-firing, gasification and pyrolysis. Co-firing refers to the process of substituting coal with a small amount of biomass (e.g. 10%) in existing power plant boilers. It is less expensive than building a new biomass power plant because it utilises much of the existing infrastructure without major modifications. Also, it helps to reduce SO_2 and NO_x emissions as a result of replacing coal with biomass. Energy can also be produced by gasification, whereby the syn-gas produced from the biomass is passed to a gas turbine which combusts the syngas at about 1200^{o}C producing steam which in turn is used to produce electricity and /or heat (Carpentieri et al. 2005). Bio-oil is the main product from biomass pyrolysis and can be usedd as a transport fuel in engines and turbines (McKendry 2002).

2.7 Summary

At present, the world's transportation sector is principally supplied by fossil fuels. However, energy consumption in this sector is drastically increasing and there are increased concerns about supply, cost and environmental issues surrounding the continuing use of fossil fuels. Utilising bio-fuels such as ethanol and others would reduce the dependency on oil and environmental impacts. Combining in an integrated refinery the production of bio-fuels with other bio-products, such as platform chemicals and energy has a potential to increase the overall sustainability of the production of these products, bringing economic, environmental and social benefits. However, presently, it is not clear which route, feedstocks and bio-products are more sustainable. As already indicated, this work represents an attempt to contribute towards this debate. The next chapter presents the methodology for sustainability assessment of integrated bio-refineries developed within the project, followed by two case studies, one looking at the bio-chemical and another at the thermo-chemical route.

3 METHODOLOGICAL FRAMEWORK FOR ASSESSING THE SUSTAINABILITY OF BIO-REFINERIES

3.1 Introduction

This chapter presents the methodology developed in this work for the sustainability assessment of integrated bio-refineries. The methodology includes identifying the stakeholders in this sector, defining, and selection of environmental, economic, and social sustainability indicators followed by a sustainability assessment.

Literature reveals that several studies have considered different sustainability issues of integrated bio-refineries. The life cycle environmental sustainability has been evaluated using life cycle assessment (LCA) by several authors (Cherubini and Ulgiati 2009; Cherubini and Jungmeier 2010; Luo et al. 2010; Zhi et al. 2003, Kemppainen and Shonnard 2005; Piemonte 2011; González-García et al.2011). Others have addressed the techno-economic aspects (Gnansounou and Dauriat 2010; Frederick Jr et al. 2008a; Klein-Marcuschamer et al. 2010; Kadam et al. 2000; Hamelinck et al. 2005; Piccolo and Bezzo 2009; Kazi et al. 2010; Mu et al. 2010). No studies have been found on social sustainability assessment of integrated bio-refineries and none of the studies have considered all three aspects of sustainability (economic, environmental and social).

3.2 Methodology

The proposed methodology for assessing the sustainability of bio-refineries is represented in Figure 3.1. The system boundary in this work is from ‘cradle to gate’, encompassing feedstock cultivation and operation of the bio-refinery and excluding the use stage of its products. Therefore, the methodology reflects this system boundary. It begins by identifying the relevant stakeholders in the industry from ‘cradle to gate’. This process helps to map out the potential interest of the stakeholders and understand any concerns they may have in relation to the industry. From this, sustainability issues along the bio-refinery supply chain are identified and appropriate indicators are then selected to measure these. The methodology is then applied on relevant case studies. Finally, the results are analysed to draw conclusions and make recommendations. These steps are described in more detail in the rest of this chapter.

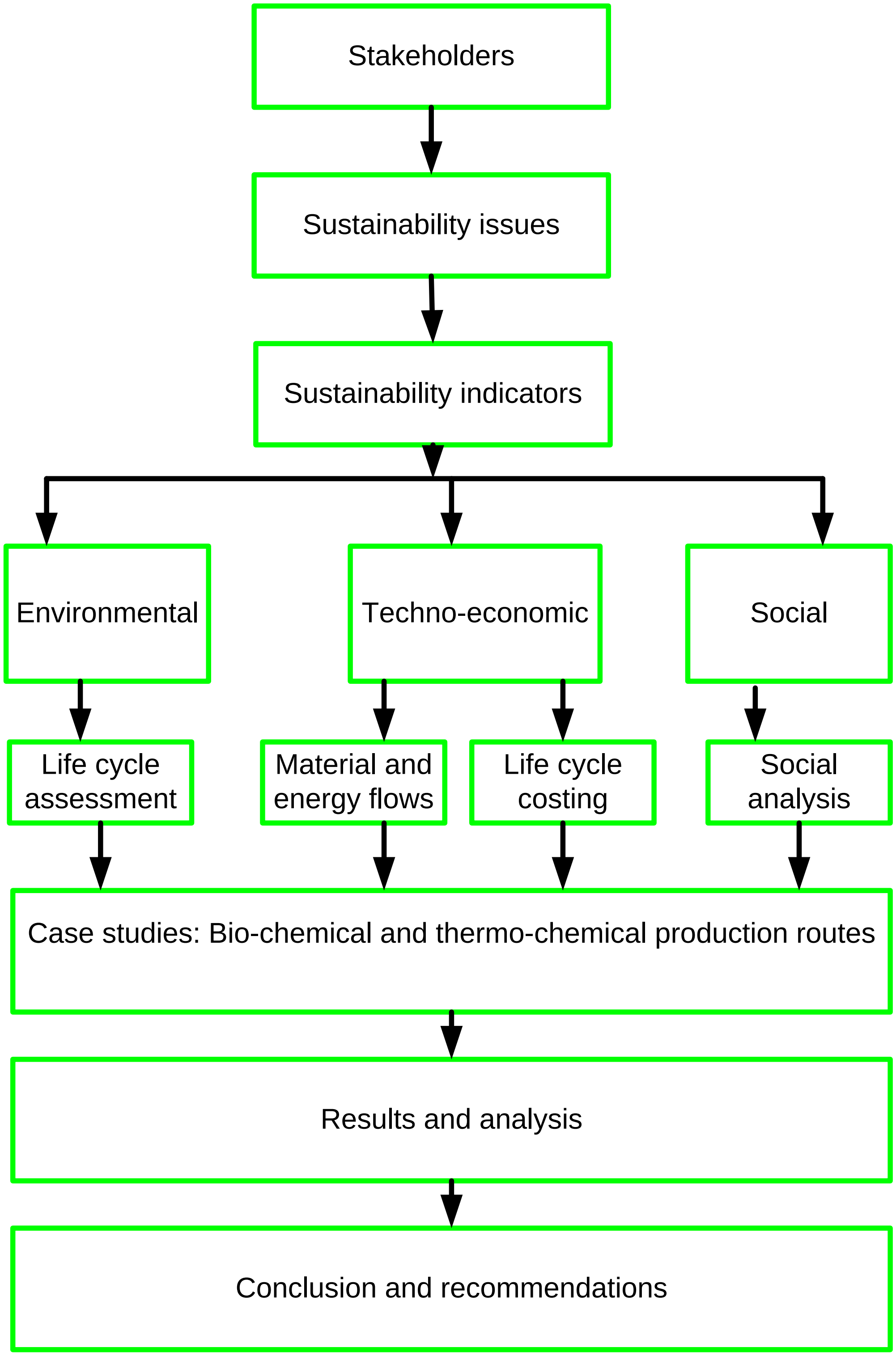


Figure 3.1 Methodology for assessing the sustainability of integrated bio-refineries

3.3 Stakeholders

Globally, the bio-based industry is large and competitive, producing a diverse range of products, including fuels and chemicals. Although fully integrated bio-refineries are not commercially available yet (Huang et al. 2008), it is envisaged that such facilities could be commercially available in the next 10-15 years, provided policy incentive and market regulations are achieved (Cherubini et al. 2009). In the US, up to $385 million has been invested in research related to the commercial implementation of integrated bio-refineries (DOE 2007). The main driving force behind the interest in this type of production is the belief that this will not only reduces greenhouse gas (GHG) emissions, but also lead to high value added products.

Owing to the complexity of its supply chain, which involves various feedstocks, processing routes and products, the industry has a diverse range of stakeholders with different sustainability interests. The stakeholders include government, suppliers, customers, local communities, local authorities, and NGOs and employees (Gold and Seuring 2010). Some of their interests are discussed below and summarised in Table 3.1

Stakeholders	**Economic**	**Social**	**Environment**
Employees	++	++	+
Suppliers	++	-	-
Investors/Refinery operators	++	+	+
Government	++	+	++
Local authorities	++	++	++
Local communities	++	++	++
Non-governmental organisations	+	++	++

++ strong interest. + some interest. – no interest

Table 3.1 Stakeholders and their potential interest in sustainability issues in bio-refinery supply chains

Employees: The total number of employees in this industry is not known as the sector is not established yet. As in other sectors, employees in this sector will be interested in good working conditions and a decent salary (Azapagic 2004). Some employees may also be interested in the environmental aspects associated with bio-refineries.

Suppliers: Suppliers in the sector would include farmers and other feedstock providers as well as those supplying chemicals and other raw materials and energy. Their primary interest is in getting the best price for their products.

Investors and refinery operators: Companies investing in and running bio-refineries will have a strong interest in economic returns on their investment. They will also have an interest in health and safety as well as environmental performance of the refinery.

Government: Government plays a major role in the success of any industry and therefore the bio-refinery sector. It takes interest in all aspect of sustainability ranging from job creation to cost and impact on the environment (Azapagic 2004). Government can provide subsidies as well as help with the investment, which is important for a fledgling sector such as this one (Annevelink et al. 2006; Azapagic 2004). Also, governments can be a significant source of funding for research and development: for example, the US government has invested about $385 million in research and for commercial implementation of integrated bio-refineries (DOE 2007). In the UK, there has been little investment in such projects to date.

On the other hand, government can also promote energy security and avoid competition with food production (Dwivedi and Alavalapati 2009). The government can maintain food prices by not diverting land for food for biofuel production. In addition, energy security can be promoted by facilitating and supporting new opportunities.

Local authorities: The local authorities play a key role in the early stages of a new development and would so in the case of a new bio-refinery. They are instrumental in implementing environmental and other regulations. In addition, they review existing legislation that may affect the plant to be built and advise as necessary (Defra and DTI 2007).

Local communities: They are interested in employment opportunities as well as the health and environmental issues associated with the new as well as existing industrial operations in their vicinity (Azapagic 2004). The local communities will be keen on avoiding nuisance such as additional traffic, noise and odour (Gold and Seuring 2010) which may occur during plant construction. Furthermore, they may also want to know if the investment will support any local community projects.

Non-governmental organisations: NGOs play a key role in preserving the environment and the well-being of communities. They can influence both governments and industry and are often the driving force behind various environmental and social activities. Some of these activities are to promote rural development and to encourage governmental support. Examples of NGOs include Green Peace and Friends of the Earth.

3.4 Sustainability issues and indicators

3.4.1 Introduction

The identification of relevant sustainability issues associated with integrated bio-refineries is crucial for the development of sustainability indicators and subsequent assessment of these facilities and their products. This section highlights some of the technical, environmental, economic and social sustainability issues relevant to the stakeholders in this sector. A life cycle approach is used throughout to understand the issues along the whole supply chain. In this study, the environmental indicators used are those used in LCA and the latter has been used as a tool to assess the environmental sustainability of bio-refineries. These indicators have been used in other LCA studies of integrated bio-refineries (Cherubini and Ulgiati 2009; Cherubini and Jungmeier 2010; Luo et al. 2010) For the economic sustainability assessment, life cycle costs have been used. This includes capital cost and operation cost. These indicators have also been used by other researchers (Gnansounou and Dauriat 2010; Gonzalez et al. 2011; Wright and Brown 2007; Laser et al. 2009c). The social indicators considered here include employment opportunities, health and safety, and local community impacts.

The sustainability issues and related indicators are discussed in more detail in the next sections. However, prior to that, a brief overview of sustainability indicators developed by other organisations and authors is provided. As there are no specific indicators for bio-refineries, these have been used as a starting point for the development of indicators in this work.

3.4.2 Existing sustainability indicators – an overview

A number of sustainability indicator frameworks have been developed by various authors and organisations. A brief overview of some of these is given below:

The United Nations Commission on Sustainable Development has developed indicators for countries to assess their progress towards sustainable development (UN 2007). These indicators provide information on social, economic environmental and institutional aspects of sustainable development. These indicators are prepared from a macro perspective and are relevant at national levels rather than for business purposes and at a project level.

The Global Reporting Initiative (GRI) framework has over 100 environmental, economic and social indicators divided in the following categories: economic, environment, human rights, product responsibility, product and service, and society (GRI 2011). While the framework considers certain parts of supply chains, it is not following the life cycle approach, thus missing on some life cycle stages, such as transport, use and final disposal of products. A number of authors have applied the GRI framework to different industries including the mining and minerals sector (Azapagic 2004), water industry (Christen et al. 2006) and the pharmacy industry (Veleva et al. 2003).

The IChemE sustainability metrics (IChemE 2002) also considers all three dimensions of sustainability. The environmental indicators include emissions, waste and effluents as well as resource use; economic indicators include investments, value, profit and tax; and the social indicators include society and workplace. However, the IChemE sustainability metrics are suitable for companies rather than for sectors, products or technologies; besides, it is specific to companies operating in the process sector. Labuschagne et al. (2005) have also developed criteria for assessing sustainability of the process industry. The proposed indicators for this research are different from the IChemE metrics as it is takes a life cycle approach and indicators are developed for each life cycle stage.

Previous authors have outlined the sustainability framework for bio-energy systems (Elghali et al. 2007; Mikkilä et al. 2009; Krotscheck et al. 2000). However, to date, there are no sustainability indicator frameworks for integrated bio-refineries. This work attempts to contribute towards the development of such a framework for the bio-refinery sector by considering environmental, economic, and social indicators alongside the technical requirements. These are discussed in turn below.

3.4.3 Proposed sustainability indicators

3.4.3.1 Environmental issues and indicators

As for other industrial activities, the environmental issues relevant for integrated bio-refineries include resource use, air, water and soil emissions, and solid waste. These are discussed below. The impacts related to these issues represent the environmental indicators used in this work. They are calculated on a life cycle basis using LCA as a tool and the CML 2001 impact assessment method (Guinee et al. 2001). The LCA methodology is outlined in section 3.4.4.

Resource use and related impacts

Resource use refers to the consumption and depletion of abiotic and biotic resources. The former includes fossil fuels and minerals and the latter land use. Apart from the area of land required for biomass cultivation (where relevant), land use change is important as it can disturb and release the carbon stored in the soil. Therefore, two indicators are used to assess the impacts of resource use: abiotic resource depletion and land use (see Table 3.2).

Emissions to the environment and related impacts

Emissions associated with a bio-refinery can come from the bio-feedstock cultivation and processing as well as from the production stage. For the bio-feedstock cultivation, activities such as fertiliser application and tillage practices produce airborne emissions can pose a threat to human life. In addition, aquatic emissions of nutrients such as N and P lead to eutrophication while atmospheric emissions of NH_3 and N_2O can cause acidification and global warming, respectively. Sawing and squaring used for waste residues can also release air emissions to the atmosphere affecting air quality and human health (Parikka 2004; Perez-Verdin et al. 2009).

Airborne emissions can also occur during the production stage. Fossil fuels used for energy production during the operation of bio-refineries together with transport emissions lead to the emission of CO_2, N_2O, CH_4, SO_2 along with heavy metals causing acidification, global warming and human toxicity. If alternative fuels such as lignin are used as a fuel, the emissions include hydrocarbons, Particulate Matter (PM) and NO_x (Paster et al. 2003).

To estimate environmental impacts related to the emissions to the environment from the bio-refinery supply chain, the following indicators are used in this work (Table 3.2): global warming, acidification, eutrophication, human toxicity potential, ozone layer depletion, photochemical smog, freshwater marine and terrestrial ecotoxicity.

Issue	**Indicator**
Resource Use	Abiotic depletion potential
	Land use
Emissions	
Greenhouse gases	Global warming potential
Acid gases	Acidification potential
Nutrients	Eutrophication potential
Ozone-layer depleting substances	Ozone layer depletion potential
Photochemical oxidants	Photochemical smog
Substances toxic to eco-systems	Freshwater ecotoxicity potential Marine aquatic ecotoxicity potential Terrestrial ecotoxicity potential

[a] Human toxicity potential is also calculated as part of LCA but is considered under social indicators.

Table 3.2 Environmental LCA indicators [a]

3.4.4 Life Cycle assessment methodology

The LCA is an environmental sustainability tool used for quantifying and identifying all the impacts from all activities from the extraction of raw materials to disposal stage (see Figure 3.2) of a product process or activity (Baumann and Tillman 2004;Azapagic et al., 2004). It is based on the mass and energy balance around the system or process of interest and emissions to the environment over the life cycle of the system, or process. This tool is used in analysing and evaluating the environmental performance of a product or process or activity to help decision makers choose amongst options and also to identify opportunities for improvement (Azapagic 1999;Azapagic and Clift 1999; Baumann and Tillman 2004).

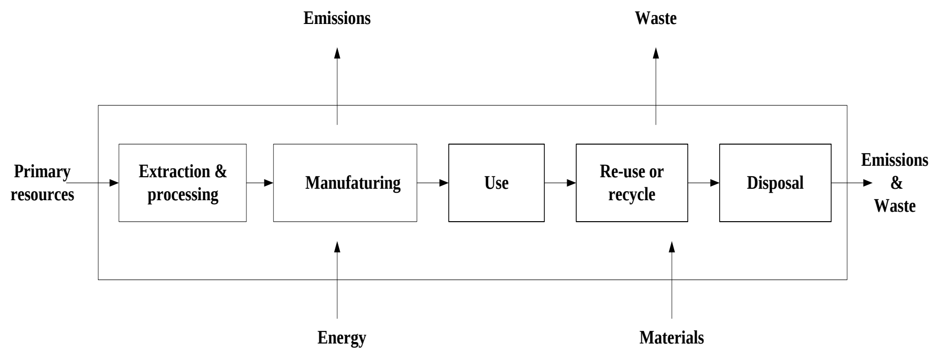


Figure 3.2 Stages in the life cycle of an activity considered by LCA (Azapagic 1999)

The LCA methodology is standardised by the ISO 14044 standard (ISO 2006). The methodology consists of four stages: goal and scope definition, inventory analysis, impact assessment and interpretation (see Figure 3.3).

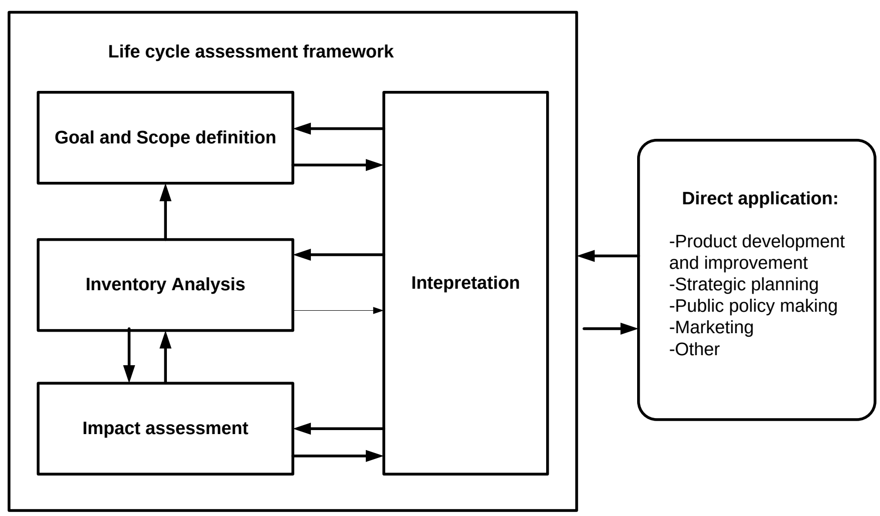


Figure 3.3 The life cycle of a product (ISO 2006)

The goal and scope phase outlines the purpose of the study, system boundaries, and the functional unit. In this study, the goal and scope of the LCA is to access and compare the sustainability of different integrated bio-refineries systems.

Inventory analysis is the next phase of LCA and involves quantifying the mass and energy, emissions to air, water and land throughout the life cycle (Azapagic et al., 2003). This consists defining the system boundaries and acquiring relevant data and if dealing with a multiple –function system, allocation may be required. In this case, the environmental burdens need to be allocated or partitioned between these different functions (ISO, 2006). The International Standards Organisation (ISO) recognises three methods for allocation:

i. avoiding allocation wherever possible by dividing the unit process into two or more sub-processes or expanding the system boundaries to include the additional functions associated with the co-products;
ii. where it is impossible to avoid allocation, the system should be defined based on the physical relationships among the functional units, i.e. the allocation should be based on how the inputs and outputs of the products or functions delivered by the systems are changed by quantitative changes; and
iii. where allocation cannot be done by physical relationships, other relationships such as economic value can be used to allocate input and output data between the co-products.

The environmental burdens across the life cycle are calculated as follows:

$$B_n = \sum_{n=1}^{N} bc_{u},_{n} x_n$$ Equation 3.1

where $bc_{u,n}$ is the relative contribution of burden x_n to impact B_n.

After the inventory analysis, comes the impact assessment. The impact assessment stage uses the results of the life cycle inventory analysis to quantify potential environmental impacts using their contributions to a set of recognised environmental impacts such as global warming and acidification. According to ISO 14044, this phase consists of four steps: classification, characterisation, normalisation and valuation.

Classification involves the aggregation of environmental burdens into their respective impact categories to indicate impacts on resource depletion, human and ecological health. The potential impacts from the burdens are aggregated in such a way that one burden can contribute to different impact. For example, VOC compounds contribute to the global warming and ozone depletion; therefore, the impacts are termed ‘potential’.

In the characterisation step, the impacts are quantified using their potency factors to indicate their contribution to the impacts. There are different methods of doing this; the two most widely used are the CML and Eco-indicator methods. The CML method developed by the Centre of Environmental Science at Leiden University in the Netherlands uses a midpoint approach for impact assessment. A quantitative modeling is done before the end of the impact pathway while the Eco-indicator is based on the damage on human health, ecosystem and resource (Marcus 2005) and is referred to as the end point approach. In this work, the CML method has been used as it is one of the most widely used in LCA impacts assessments. The LCA impact categories used are described in Table 3.3.

The characterisation is also followed by the normalisation step whereby the impacts are normalised with respect to the total impacts in a certain region or globally over a certain period of time (Azapagic et al, 2003). This step simplifies the understanding of the significance of the impacts under study. Finally, in the valuation (optional) stage, the impacts are weighed to reflect their relative importance to stakeholders or decision makers and for comparison with one another. The impacts are reduced to a single environmental impacts function as a measure if environmental performance (Azapagic et al. 2003). This is a subjective process and will depend on individual's judgment criteria. Other techniques such as cost benefit analysis, matrix and analytical hierarchy have been suggested for evaluation (Azapagic et al. 2003). The environmental impacts function EI, is expressed as:

$$EI = \sum_{k=1}^{k} w_k E_k \qquad \text{Equation 3.2}$$

where w_k is the relative importance of the impact E_k.

Finally, in the last phase of LCA, is the interpretation which evaluates the results in the previous section to reach conclusion make recommendations. ISO (2006) recommends that the interpretation stage of an LCA study should include identification of the significant issues based on the results of the LCA, an evaluation that embodies completeness, sensitivity and consistency, as well as conclusions, limitations and recommendations of the study.

Impact category	Description	Unit
Abiotic Depletion Potential (ADP)	It indicates the extraction of minerals and fossil fuels associated with the product or process. It is calculated based on the amount of known reserves and the rate of extraction. Antimony is used as the reference element for this calculation	kg Sb eq.
Acidification Potential (AP)	It measures acidification potential of acidifying pollutants, including SO_x and NO_x. SO_2 is used as a default substance to calculate the acidification potential of other pollutants	kg SO_2 eq.
Eutrophication Potential (EP)	It measures the potential of nutrients such as N and P to contribute to algae formation in aquatic and terrestrial ecosystems. It is expressed relative to PO_4	kg PO_4 eq.
Global Warming Potential	It is a measure of the potential contribution of a greenhouse gas to global warming relative to that of carbon dioxide	kg CO_2 eq.
Eco-toxicity Potential (ETP) Freshwater Aquatic Eco-toxicity Potential (FTP) Marine Aquatic Eco-toxicity Potential (MTP) Terrestrial Eco-toxicity Potential (TTP)	It measures potential impacts of toxic substances on aquatic and terrestrial ecosystems. 1,4 dichloro-benzene is used as a relative substance for this impact category.	kg DB eq.
Human Toxicity Potential (HTP)	It measures human health risks associated with toxic substances emitted into the environment. 1,4 dichlorobenzene is used as a relative substance for this impact category	kg DB eq.
Photo Oxidant Chemical Formation Potential (POCP)	It measures potential for the creation of photo-chemical (summer) smog due to the reaction of relevant chemical compounds when exposed to sunlight. Ethylene is used as a default substance	kg C_2H_4 eq.
Ozone Layer Depletion Potential (ODP)	It is a measure of the potential contribution of a substance to ozone layer depletion. CFC-11 is used as a default substance, and ODP of all other substances is calculated relative to its ODP.	kg CFC-11 eq.

Table 3.3 Impacts indicators in the CML Method (Guinée et al., 2001)

3.4.4.1 Techno-economic issues and indicators

Technical issues and indicators: Technical issues applicable to integrated bio-refineries are technology availability, capacity, efficiency, and flexibility (Charlton et al. 2009). With respect to technology availability, both bio-chemical and thermo-chemical processes have been demonstrated at a pilot scale but no commercial implementation exists yet, although feasibility work is being carried out by SUSTOIL, Iogen and other organisation (Clark and Deswarte 2008). For instance, Iogen (2004) has a demonstration plant processing 23-30 tonne per day of waste feedstock and producing about 5500 litres of bio-ethanol per day.

The capacity of a plant is dependent on the type of feedstock, location of the plant and the type of technology employed (Clark and Deswarte 2008). Efficiency of the process depends largely on its ability to utilise the feedstock for maximum recovery (yield) of products. For instance, the bio-chemical process mainly depends on efficient digestibility of the cellulose during pre-treatment and effective enzyme activity on the cellulose. Overcoming this hurdle will reduce the cost of the pre-treatment and enzyme cost, which will in turn improve the overall production cost and increase process integration efficiency (Sims et al. 2008). On the contrary, the thermo-chemical process is well proven. However, improving biomass gasification is also necessary to increase the production of syn-gas and decrease the formation of char. In addition, because of the scale of this process, it is important to reduce economic cost by increasing the magnitude of feedstock supply (Sims et al. 2008).

The flexibility refers to the ability to use different feedstock to produce a range of bio-products. As feedstock availability is of concern, the plant should be flexible enough to utilise the available feedstock and still produce the desired product. This is more achievable with the thermo-chemical than with the bio-chemical route. The reason is that the bio-chemical route requires pre-treatment and enzymes during its conversion and these vary for different feedstocks. These processes are also energy intensive and costly. On the other hand, the thermo-chemical requires drying and gasification, which are energy intensive, costly and often have low efficiencies.

Therefore, based on these technical issues, the technical indicators proposed and used in this work are (see Table 3.4)

- technology availability describes which technology is available or shows potential availability over a short term;
- technology efficiency which measures the product yield as well as energy and mass efficiency of the process (defined as the ratio of outputs to the inputs);
- process capacity is related to the plant size;
- technical flexibility relates to the degree of feedstock and product flexibility, coupled with the ability to utilise different feedstocks and produce a diverse range of products; and
- feedstock availability relates to reliable availability of the selected feedstocks.

Indicator	**Definition**
Technology efficiency	Product yield Mass and energy efficiency (ratio of inputs to outputs of energy and products, respectively)
Technology capacity	Plant size
Technology flexibility	The ability to use different feedstock to produce a range of bio-products.
Technology availability	Availability of both bio-chemical and thermo-chemical technologies.
Feedstock availability	Reliable availability of feedstocks over long term

Table 3.4 Technical indicators

Economic issues and indicators: The main economic issues for this supply chain are feedstock and capital costs (Gnansounou and Dauriat 2010; NREL 2011a&b). Feedstock costs vary depending on the type and origin. Generally, agricultural residues have lower costs compared to energy crops. Transport costs can be significant, depending on the distance travelled and the moisture content (Azapagic and Perdan 2011).

As there are no commercial bio-refinery installations, it is difficult to get estimates of capital costs. In the absence of real data, most studies estimate capital cost using design data. For example, the capital costs for the bio-chemical process have been estimated in the range from $234-422 million (Piccolo and Bezzo 2009; Kazi et al. 2010; Gnansounou and Dauriat 2010; NREL 2011a) and for the thermo-chemical process at around $300 million (NREL 2011b).

The economic assessment of 2nd generation integrated bio-refineries has been studied by other authors using common economic indicators such as capital and operating costs and in some cases Net Present Value (NPV), Internal Rate of Return (IRR) and Minimum Ethanol Selling Price (MESP) (Wright and Brown, 2007; Laser et al. 2009c; Gnansounou and Dauriat 2010; Wingren et al. 2003; Luo et al. 2010; Villegas and Gnansounou 2008; Eggeman and Elander 2005; NREL 2011b; NREL 2011a). In this work, in addition to these economic indicators, the following indicators are also used (see Table 3.5) pay back period and life cycle costs, with the latter comprising the total capital, fixed and variable operating costs over the life time of the plant. The methodology for calculating different economic indicators can be found in Appendix 1.

Issue	**Indicator**
Life cycle costs	Total capital investment
	Total fixed operating cost
	Total variable cost (feedstock and other inputs)
Return on investment	Net present value
	Internal rate of return
	Minimum ethanol selling price
	Pay back period

Table 3.5 Economic indicators

3.4.4.2 Social issues and indicators

Identifying specific social issues for this sector is difficult, as the sector is not established yet. However, some of the general social issues that apply to other industrial systems are also applicable to this supply chain. These include employment provision, health and safety, impacts on local communities and energy security. Therefore, these are the social indicators used in this work; they are summarised in Table 3.6 and discussed briefly below. Other issues such as child labour, corruption, women's rights etc., often found in developing countries, are not applicable as the focus of this study is on the UK.

Issue	**Indicator**
Employment	Provision of employment

Health and safety	Accidents and fatalities at work
	Human toxicity potential[a]
Local community impacts	Contribution to local economy
Energy security	Contribution to national energy security

[a] Calculated as part of LCA

Table 3.6 Social indicators

Employment provision**:** Provision of employment is an important socio-economic issue for any industry and therefore the bio-refinery sector. Employment opportunities exist along the whole supply chain, from agricultural activities for feedstock production, to construction and operation of bio-refineries. However, as this is an emerging sector, there are no data on the employment potential yet. Nevertheless, some parallels can be drawn with the existing related sub-sectors in the supply chain. For example, the UK agricultural sector employed up to 356,000 people in 2004 (Union 2004). The workforce is dominated by male workers (79%) and most of the jobs created in this sector are low skilled (Union 2004). The majority of employment is full-time (55 %) with 12% of people working part-time; 32 % are self employed (Boyle et al. 2010; Eisentraut 2010). A similar pattern would probably persist in terms of agricultural activities related to the provision of feedstocks for bio-refineries, particularly if agricultural waste is used as feedstock (Bryan 2011). If energy crops are used, the main employment would be related to land clearing and preparation, planting, harvesting, biomass collection and transport.

At the bio-refinery site, employment opportunities would exist for site operators, research and development personnel, supervisors and other support employees. The exact numbers would vary depending on the plant capacity but it is expected that significant employment would be provided both locally and regionally. For example, a fully operational bio-refinery in the US producing 30 million litre of bio-ethanol per year from waste wood and grass clippings is estimated to provide 380 direct and indirect jobs, including 175 construction jobs and 50 full-time positions (INEOS 2010). A similar size plant in the UK producing 30 million litres of bio-ethanol from about 100,000 tonnes of household and commercial waste will create 350 construction jobs and about 40 full time positions in the refinery (Coskata 2011).

Also, it has been estimated that the proposed US Coskata biorefinery producing 209 million litres per year of ethanol from wastes will create 300 construction jobs and 700 direct and indirect jobs related to the operation of the plant. The latter includes 125 plant operators, supervisors and engineers and about 600 indirect jobs in logging, chipping and transport (Domac et al. 2005; Willams 2010). Other studies have shown that similar employment opportunities exist in Brazil, Ireland, the European Union and some Asian countries (Domac et al. 2005).

To measure the employment provision within the bio-refinery sector, an employment indicator is proposed here expressed as the total number of person years. This indicator measures both direct and indirect employment. Direct employment involves feedstock production and transportation, construction of bio-refinery and its operation to produce products. Indirect employment refers to provision of intermediate components or products or services to the bio-refinery.

Health and safety: Similar to employment, the issue of health and safety is all pervasive and affects bio-refineries along the whole supply chain. In order to measure this, two indicators are considered here: fatalities along the supply chain and life cycle human toxicity potential (HTP). The latter is calculated as part of LCA.

The fatality rate in agriculture as recorded in 2009/10 by the Health and Safety Executive (HSE) was 8 fatalities in every 100,000 workers (HSE 2011). A total of 464 workers have died as a result of these activities in the last ten years meaning about 46 people die each year (HSE 2010). Injuries associated with feedstock production and logistics include fall from height, contact with machinery and electricity (Edwards and Nicholas 2002).

The construction of bio-refineries involves activities such as ground clearing, excavation, construction, and installation of facilities. The construction industry is one of the most hazardous sectors with a poor accident record (HSE 1998). The main cause of fatalities and injuries is contact with machinery, which in the UK leads to around 15 deaths and about 700 incidents annually (Hess et al. 2008; Laser et al. 2009a).

Human health can also be affected in many different ways along the supply chain. In the feedstock cultivation stage, health hazards include toxicity of fertilisers and pesticides and emissions of particulates due to handling of biomass. In the bio-refinery operation stage, health impacts can be due to the emissions of particulates, SO_x and NO_x from fuel combustion (Schultea and Chun 2009). Employees can also be exposed to PM used in the production process. These exposures can cause pulmonary health problems such as cancer (Roes and Patel 2007).

Local community impacts: This indicator aims to access the impacts of an integrated bio-refinery on the local community. The involvement of the local community during the planning phase of a project helps to indentify concerns and manage expectations. This interaction helps to build relationships and integrate the needs of the community and the industry. The existence of the company in the community enables a proportion of their staff to be hired from the community. The economic conditions of the community can be enhanced by improving the skills of the locals through providing training and education. Payment of taxes and royalties to the local government also help the economy.
This indicator covers the operation stage of the refinery. This is due to the fact that information on other areas may not be available due to the newness of the process. It is also suggested that the indicator be treated at the company level, since only the needs of local community is peculiar to the area where the company and bio-refinery are situated.

Energy security: This indicator can be defined as an uninterrupted and an adequate supply of energy at affordable prices (Chester 2009). An increasing attention is being paid to the issue of energy security as there are a number of growing concerns with fossil fuel depletion, imported sources of energy, high energy prices, population growth rate, energy demands from other countries, and climate change concern (EUa 2001; Asif and Muneer 2007). The issues with energy security are availability, accessibility, and affordability (Kruyt et al. 2009). All these factors are tailored to fossil resources, geological and political elements.

Fossil fuels have been and are still the major sources of energy worldwide (Demirbas 2001). The current energy demand is 41% oil, 22% gas, 16% coal, 15% nuclear and 6% renewable.(EU 2001). The UK is a major importer of energy and relies on foreign oil to meet demands thereby predicting local reserves to last for about 7 years (Asif and Muneer 2007). Switching from fossil fuels to ethanol is becoming one of the drivers of energy security.

The aim of this indicator is to assess the security of supply to minimise any risk linked to energy dependence and to evaluate the long term security of supply. To achieve this, the indicator 'contribution to national energy security' is proposed in this work.

3.5 Summary

The proposed methodology for assessing the sustainability of bio-refineries has been discussed in this chapter. The methodology involves identification of the stakeholders and sustainability issues that they may be interested in, followed by the use of a range of indicators to measure the sustainability of integrated bio-refineries. The methodology has been applied to two case studies, one considering bio-chemical and another thermo-chemical production route. This is the subject of the next two chapters.

4 CASE STUDY: BIO-CHEMICAL REFINERY

4.1 Introduction

This chapter presents the analysis of the environmental, techno-economic and social assessment of a (hypothetical) integrated bio-refinery based in the UK and using the bio-chemical route to produce a range of products. The methodologies for environmental, techno-economic and social assessment as outlined in the previous chapter are used for the assessment. The chapter starts by defining the system and stating the assumptions, followed by the analysis and discussion of the results. The results are also validated by comparing with the results of other studies and the literature where available.

4.2 System description

The life cycle of the system is outlined in Figure 4.2. The system boundaries comprise feedstock cultivation (where applicable) and transport to the refinery and feedstock processing in the refinery. The bio-refinery design is based on the model developed by the National Renewable Energy Laboratory (NREL) as reported in Aden et al. (2002). The NREL model uses corn stover as the feedstock. However, for this study, four different feedstocks suitable for the UK conditions (see Chapter 2, section 2.2) are considered: wheat straw, poplar, miscanthus and forest residue. The co-products are ethanol, acetic acid, lactic acid, and electricity. Therefore, the NREL model has been adapted for these feedstocks and outputs using the conversion efficiencies and the composition of each feedstock. Table 4.1 shows the feedstock composition. As can be seen, forest residue has the highest cellulose content while wheat straw has the lowest. This in turns affects the products from each feedstock. The calculations carried out in this study for each feedstock and the outputs can be found in Appendix 2.

Feedstock composition (%)	Wheat straw (Cherubini and Ulgiati, 2009)	Poplar (Wooley et al., 1999)	Miscanthus (De Vrije et al., 2002)	Forest residue (Vassilev et al., 2010)
Cellulose	34.6	42.67	38.2	44.1
Xylan	19.2	19.05	19	9.3
Arabinan	2.35	0.79	1.8	1.5
Galactan	0.75	0.24	0.4	2.0
Mannan	0.31	3.93	3.1	8.6
Lignin	16.8	27.44	25	27.4
Ash	10.2	1	2	0.9
Extractives	12.9	0.03	7.9	3.4
Acetate	2.24	4.64	1.8	2.8
Moisture content (%)	11	50	15	70
Ultimate analysis				
C %	43.9	50.9	48.1	52.7
H %	5.3	6.0	5.4	5.4
O %	39.8	41.9	42.2	41.1
N %	0.6	0.2	0.5	0.7
S %	0.2	0.1	0.1	0.1
LHV (MJ/kg)	17.8	18.7	17.2	16.37

Table 4.1 Feedstock composition and characteristics

The plant comprises the following processes: feedstock handling and pre-treatment, saccharification and fermentation, product recovery, boiler and wastewater treatment. These are described briefly below.

Feedstock handling and pre-treatment: The feedstocks are transported to the plant by trucks. Once in the plant, the materials are stored and later reduced in size. The feedstocks are cut, washed, and transported internally by conveyors to the shredding equipment before entering the pre-treatment process. In the pre-treatment stage, the feedstocks are treated with dilute sulphuric acid at high temperature (190^{o}C) to dissolve the hemicellulose to soluble sugars, namely xylose, arabinose, and galactose. Table 4.2 shows the hydrolysis reactions of the hemicellulose component of the feedstock and the percentage converted to products. The acid hydrolysis also librates inhibitors such as acetic acid and furfural which can be toxic to the fermentation microorganisms. After the pre-treatment, the resulting material is flash cooled; this enables the removal of the inhibitors. At this stage, the acetic acid is separated via the adsorptive membrane (Binbing et al. 2006). The resulting material is washed and pressed to separate the liquid portion of the hydrolyzate. The liquid portion is then neutralised and detoxified with lime. Gypsum, which is formed as a by-product, is filtered and sent offsite to landfill.

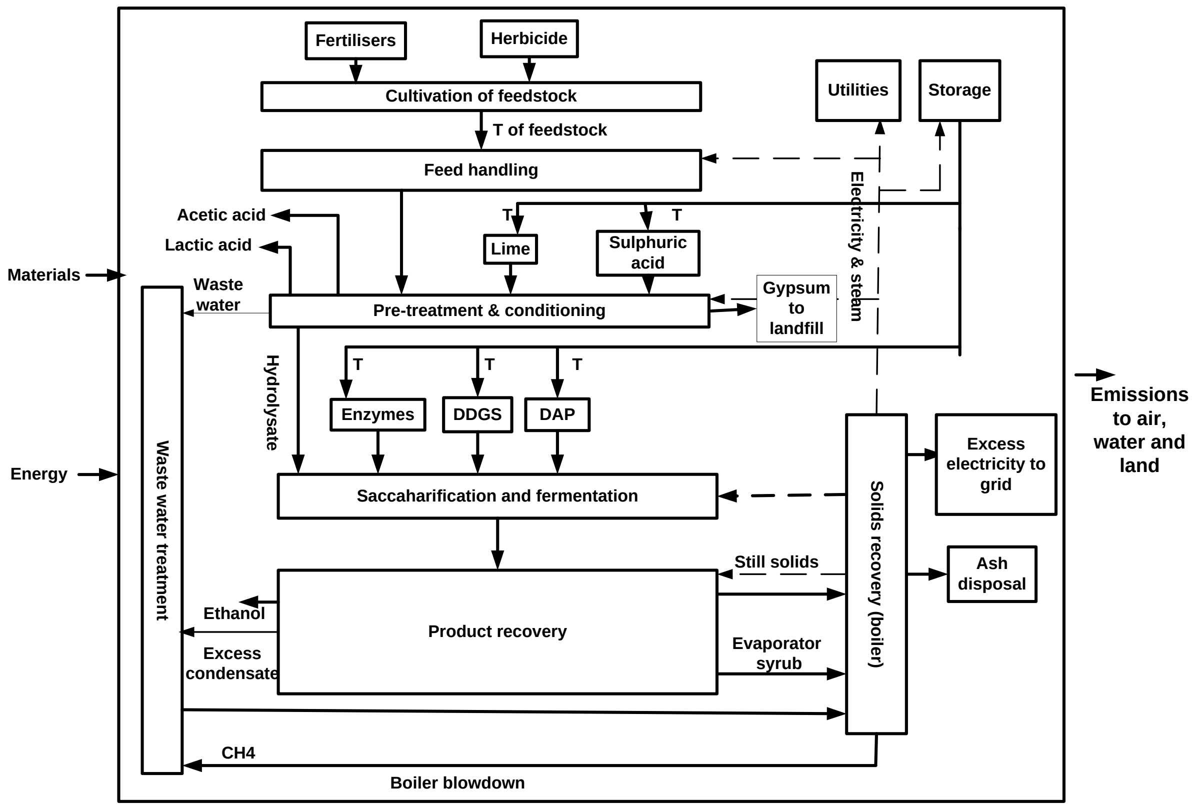


Figure 4.1 Life cycle diagram of the bio-chemical refinery considered in this study [DDGS – Distillers Dried Grain Stillage; DAP – Dammionium Phosphate; T- Transport]

Reaction	**Reactant**	**Fraction converted to product**	**Equation no.**
Xylan + nH_20 → Xylose	Xylan	85%	(1)
Arabinan + nH_20 → Arabinose	Arabinan	75%	(2)
Galactan + nH_20 → Galactose	Galactan	75%	(3)
Mannan + nH_20 → Mannose	Mannan	75%	(4)
Acetate → Acetic acid	Acetate	100	(5)

Table 4.2 Pre-treatment reactions (Aden et al. 2002).

Saccharification and fermentation: In this stage, collections of enzymes are used to assist the saccharification of cellulose to glucose. These include endoglucanases for polymer size alteration, exoglucanases for crystalline cellulose hydrolysis and B-glucosidase for cellobiose hydrolysis to glucose. The resulting glucose and other sugars are fermented to ethanol by *Z.mobilis*. This bacteria is capable of glucose fermentation to ethanol. Other hemicellulose sugars such as mannose and galactose are also fermented. *Escherichia coli* is capable of utilizing glucose and xylose as substrates to produce lactic acid (Dien et al., 2002). Table 4.3 lists the series of reactions taking place at this stage.

Reaction	**Reactant**	**Fraction converted to product**	**Equation no.**
Cellulose + H_2O → 2 Glucose	Cellulose	100%	(6)
Glucose → 2 Ethanol + 2 CO_2	Glucose	90%	(7)
Glucose + 2 H_2O → 2 Glycerol + O_2	Glucose	0.4%	(8)
Glucose + 2 CO_2 → 2 Succinic acid + O_2	Glucose	0.6%	(9)
Glucose → 3 Acetic acid	Glucose	1.5%	(10)
Glucose → 2 Lactic acid	Glucose	0.2%	(11)
3 Xylose → 5 Ethanol + 5 CO_2	Xylose	85%	(12)
3 Xylose + 5 H_2O → 5 Glycerol + 2.5 O_2	Xylose	0.3%	(13)
Xylose + H_2O → Xylitol + 0.5 O_2	Xylose	0.46%	(14)
3 Xylose + 5 CO_2 → 5 Succinic acid + 2.5 O_2	Xylose	0.9%	(15)
2 Xylose → 5 Acetic acid	Xylose	1.4%	(16)
3 Xylose → 5 Lactic acid	Xylose	0.2%	(17)

Table 4.3 Fermentation reactions (Aden et al. 2002).

Product recovery: Ethanol recovery is accomplished via a two-column distillation and molecular sieve adsorption. In the first column (known as the beer column), the feed is pre-heated with flash vapours from the pre-treatment unit, and further heated through exchange with bottoms from the first distillation column. This process removes any CO_2 and about 90% of water from the fermentation vents to recover ethanol. The ethanol is removed from the side stream as a vapour and fed to the second column. Overhead vapour from the second column is fed to a molecular sieve adsorption unit that produces 99.5% pure ethanol. Bottoms from the distillation unit containing unconverted insoluble materials are dewatered by a pressure filter and sent to the boiler unit for combustion.

Boiler Unit: This unit burns various by–products from the system to produce electricity and steam for the process and for sale. It utilises three streams of waste: methane gas from anaerobic digestors, residual lignin, and concentrated syrup from the evaporator. Methane gas is produced from the treatment of waste water. The residual lignin is from the unutilised lignin portion of the feedstock and waste water stream is concentrated to high soluble solids known as concentrated syrup. The unit produces steam at 103.1 atm and 510 ^oC which is fed to a multistage turbine generator. Steam is extracted at various conditions as process heat to meet the process requirements. The turbine generates electricity, which is used by the plant, and the surplus electricity is sold to the grid. This unit is self-sufficient with respect to energy demand. Sulphur dioxide, carbon monoxide, and nitrogen oxides are assumed to be emitted at a rate of 0.68 kg/MWh, 0.31 kg/MWh and 0.31 kg/MWh, respectively (Aden et al. 2002).

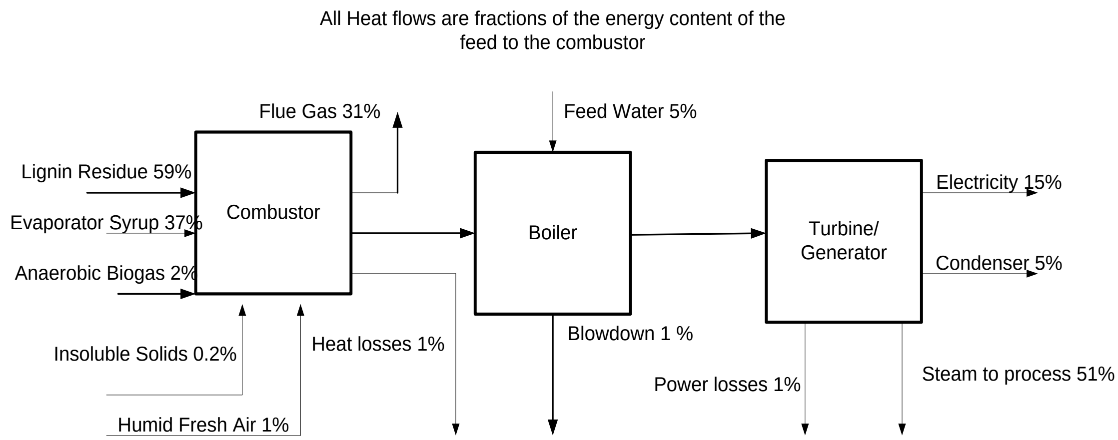


Figure 4.2. Energy balance around the boiler (Aden et al., 2002)

Figure 4.2 shows the energy balance around the boiler. The total energy available to export to the grid is the total electricity produced minus the amount required by the plant.

Waste water treatment plant: This unit treats used water for reuse in the plant. The stream includes waste water from the pre-treatment unit, non-recycled condensate, boiler blow down, is initially screened to remove large particles. This is followed by anaerobic and aerobic digestion to digest organic matter in the stream. A stream of biogas is a by-product of this (anaerobic digestion), and is used in the boiler for combustion. The aerobic digestion produces a clean water stream that is reused in the system.

4.3 Environmental sustainability assessment

The environmental sustainability of the bio-chemical refinery has been assessed by carrying out an LCA as presented and discussed in the following sections.

4.3.1 Goal and scope definition

The objective of this study is to assess the environmental sustainability of a bio-chemical integrated refinery, which produces bio-ethanol as the main product with acetic acid, lactic acid, and electricity as co-products. As mentioned previously, the feedstocks considered in this study are wheat straw, poplar, miscanthus and forest residue. They are chosen as most suitable and promising feedstocks for the UK conditions. The analysis is carried out for two functional units:

i) the operation of the plant for one year; and

ii) 1 litre of ethanol co-produced with the other products.

The first functional unit considers the impacts from the system as a whole without allocating the impacts between the co-products while the second includes the co-products allocation to enable comparisons of these products with their equivalents but produced in alternative systems .

The system boundary is from "cradle to gate", the latter representing the refinery gate. As shown in Figure 4.1 the life cycle stages considered include feedstock production, feedstock transportation and production of different products. Therefore, the use phase of the products as well as their distribution is excluded from this study. The impacts from construction and decommission of the refinery are also excluded from this study as typically the infrastructure impacts for industrial installations add little to the overall impacts.

4.3.2 Inventory analysis

The feedstocks are assumed to be grown in the UK and transported 100 km to the refinery. The same transport distance is assumed for the other materials used in the system. This is a normal practice in LCA in the absence of real transport data.

It is assumed that the refinery operates 24 hours a day and a total of 335 days in a year

(Luo et al. 2010). All the process conditions used in the plant are the same as defined by Aden et al. (2002).

The input and output data for the bio-refinery are summarised in Table 4.4. As mentioned previously, these are based on the NREL study (Aden et al. 2002). The modelling has been carried out by fixing the amount of ethanol being produced and then calculating the respective amounts of feedstock demand (see Table 4.4) based on their respective compositions discussed in the previous section.

The life cycle inventory data for wheat straw and forest residue are from the Gabi (PE 2007) and the Ecoinvent 2.0 (Ecoinvent 2007) databases and the data for poplar and miscanthus are from GEMIS (2004). The background data for the other materials are also from the GABI (PE 2007) and the Ecoinvent databases (Ecoinvent 2007). The LCA data for enzymes are not available in any of the databases but data for the greenhouse gas emissions have been found in the literature and used here (Maclean and Spatari 2009).

	Wheat straw		Poplar		Miscanthus		Forest residue	
	kg/hr	t/yr	kg/hr	t/yr	kg/hr	t/yr	kg/hr	t/yr
Inputs								
Biomass (wet)	112,968	908,262	97,000	779,880	104,000	836,160	99,000	795,960
Water consumption	238,631	1,918,593	204,901	1,671,524	219,688	1,586,397	209,126	1,681,373
Enzymes	7,863	63,218	6,751	54,028	7,238	57,888	6,890	54,672
Lime	2,759	22,182	2,369	18,492	2,540	20,100	2,418	19,296
Sulphuric acid	3,784	29,748	3,250	25,728	3,484	28,011	3,317	26,535
Distiller Dried Grains Solid (DDGS)	1,504	12,060	1,292	9,648	1,385	10,452	1,319	10,452
Diammonium Phosphate (DAP)	189	1,519	162	1,302	174	1,398	166	1,334
Outputs								
Ethanol	24,000	192,960	24,000	192,960	24,000	192,960	24,000	192,960
Acetic acid	3,181	25,567	5,144	41,357	2,523	20,100	3,390	27,255
Lactic acid	396	3,183	345	2,773	354	2,846	314	2,524
Electricity (MWh)	24	171,192	19	156,333	20	160,800	19	156,333
Gypsum	8,314	66,732	7,139	57,397	7,654	61,104	6,550	52,662

Table 4.4 Summary of data for the bio-chemical refinery

Since this is a multi-output system, the method for allocating the environmental impacts between the co-products is important as it can affect the results. For the functional unit “operation of the system for one year”, no allocation is needed as the results are reported for the system as a whole. For the functional unit “production of 1 litre of ethanol with other co-products”, following the ISO 14040/44 methodology (ISO 2006a&b), system expansion has been used to credit the system for co-producing the other products assuming most common alternative ways of producing these co-products. Thus, acetic acid is assumed to be produced from acetaldehyde, butane, and electricity from the UK grid; these data have been sourced from the Ecoinvent database. Due to a lack of LCA data, “unspecified organic chemical” is assumed for lactic acid production. While this means that the results for lactic acid may be either over or underestimated, due to its relatively low amount, the effect on the results may not be significant.

In addition, economic allocation has also been carried out to gauge the effect on the results.

4.3.3 Impact assessment and interpretation

The environmental impacts have been estimated using the CML 2001 method (Guinee et al. 2001). The results are first presented for the whole system operated over one year, followed by the second functional unit (production of 1 litre of ethanol).

4.3.3.1 Functional unit: Operation of the system over one year

The total annual impacts of the bio-chemical refinery for all the feedstock options considered are presented in Figure 4.3. As can be seen, overall the impacts from the system using forest residue are the lowest and wheat straw the highest. This is discussed below; the full results can be found in Appendix 3.

Note that the results for the human toxicity potential (HTP) are reported together with the rest of the LCA results as this impact is calculated as part of the LCA study. However, as this impact strictly speaking represents a social rather than an environmental impact, in the methodology developed in this work, HTP is included in the social sustainability assessment. Therefore, a reference is also made to it later, in the section on social sustainability assessment.

Abiotic Depletion Potential (ADP):

The total ADP of the bio-refinery is in the range of 264-481 t Sb eq./yr for different feedstocks. The system using forest residue has the lowest while the system with wheat straw has the highest ADP. The feedstock is the highest contributor adding to the total impact from 27% for forest residue to 56% for wheat straw. Up to 60% of this contribution for all four feedstocks is from the use of oil in the farm machinery and about 30% from natural gas. Other raw materials such as lime, sulphuric acid, DAP and DDGS cause the remaining ADP with other inputs and transport being insignificant.

Acidification Potential (AP):

The total estimated AP is 1322, 848, 899 and 725 t SO_2 eq./yr for wheat straw, poplar, miscanthus and forest residue feedstocks, respectively. In the case of wheat straw, about 44% of the total is from feedstock cultivation. Major burdens from wheat straw cultivation are ammonia, nitrogen oxides and sulphur dioxide emissions to air, contributing about 27.2%, 14.1% and 6.1%, respectively. The second largest contributor to the total AP for the system with the wheat straw feedstock is sulphuric acid production (31%) and the boiler unit. This is mainly due to sulphur dioxide emissions to air which accounts for 32.2% and 11.3%, respectively. For poplar and miscanthus, sulphuric acid production is the major contributor, which accounts for 42% of the AP while the feedstock and the boiler unit contribute about 23% and 24% to the total AP, respectively. In the case of the forest residue feedstock, sulphuric acid production is also the main 'hot-spot' accounting for 50% followed by the boiler unit which contributes to 30% of the total AP, while the contributions from the feedstock are relatively small (9%). SO_2 from sulphuric acid production is the major burden for AP for all feedstock cases.

Eutrophication Potential (EP):

As shown in Figure 4.3, the EP of bio-refinery with wheat straw is 833 t PO_4 eq./yr, while for the other feedstocks it ranges from 38 for forest residue to 87 t PO_4 eq./yr for miscanthus. The main reason for the significant difference between wheat straw and the other feedstocks is the cultivation of wheat and the related impact allocated to straw. The cultivation stage accounts for 96% of the total EP for the wheat straw, mainly due to nitrate emissions which in turn contribute around 71% to the total EP from cultivation. Other contributors are the boiler with 1.2%, with the rest from the pre-treatment and fermentation materials. For poplar and miscanthus, about 66% of EP are from the feedstock; ammonia, nitrous oxide and nitrogen oxides emissions contribute 18%, 17.6% and 16.1%, respectively, to this. For these feedstocks, the boiler unit contributes about 12% to the total EP. For the forest residue feedstock, most of the total EP of 38 t PO_4eq./ yr is caused by the nitrogen oxides emissions from the boiler unit (42%), a further 31% is from the cultivation of forest residue feedstock.

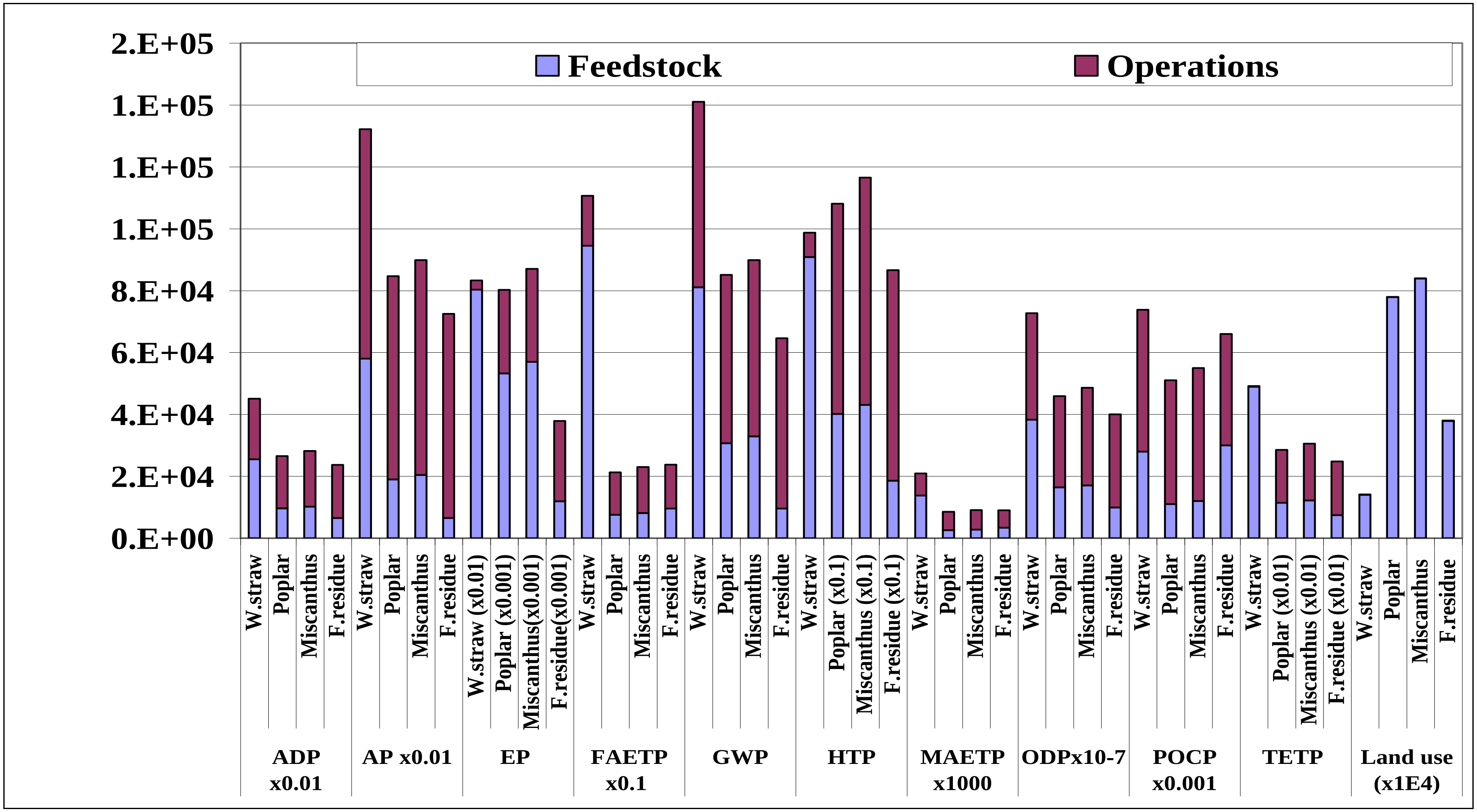


Figure 4.3. Total annual environmental impacts from the bio-chemical refinery

[All units in t/yr, except for land use which is in m^2.yr. ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP; Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity; HTP; Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP; Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential]

Freshwater Aquatic Ecotoxicity Potential (FAETP):

This impact is estimated at 11,000 t DCB eq./yr for wheat straw and about 2,000 t DCB eq./yr for the other feedstocks. Like the other impact categories discussed above, the highest contributor for the wheat straw option is the cultivation stage, which contributes 85% of the total FAETP. The most significant burdens are emissions to agricultural soil (50.1%) and emissions to freshwater (32%). For poplar, miscanthus and forest residue, the contributions of the feedstock and sulphuric acid to FAETP are about 35% each. The main burdens are nickel (42%) and vanadium (21%) emissions to fresh water.

Global Warming Potential (GWP):

The bio-refinery with forest residue as a feedstock has the lowest GWP at 64 kt CO_2 eq./yr. The use of wheat straw results in highest GWP (141 kt CO_2 eq.), while the GWP of the system with poplar and miscanthus are 85 and 89 kt CO_2 eq./yr, respectively. It should be noted that this impact only considers the fossil carbon and the biogenic carbon is excluded throughout the system. For the forest residue option, about 50% of the total GWP is from the enzymes used for fermentation, and DAP and DDGS used in the biomass hydrolysis. The pre-treatment stage and the feedstock related activities contribute about 30% and 15% of the total GWP, respectively. For poplar and miscanthus, 36% of the total GWP is from the cultivation stage mainly due to the carbon dioxide and nitrous oxide emissions, which contribute 15% and 21%, respectively. The other main contributors for GHG emissions for poplar and miscanthus options are the pre-treatment stage (8%) and the fermentation and hydrolysis materials (38%). In the case of wheat straw, 57% of the total GWP is due to the GHG emissions associated with cultivation (mainly carbon dioxide and nitrous oxides from agricultural activities). The remaining impact is from the production of other raw materials used in the system. Energy use does not contribute to this impact as the system is energy self-sufficient. The contribution of transport and waste management to the total GWP for all the feedstocks is about 5%.

Human Toxicity Potential (HTP):

The total HTP of the system is in the range of 8,658 – 98,706 t DCB eq./yr, with the lowest impact for the forest residue and the highest for the wheat straw. For the latter, about 92% of this impact is attributable to the feedstocks. Emissions of heavy metals to agricultural soil (mainly chromium) and pesticides emissions (mainly isoproturon) to agricultural soil are the major burdens, accounting for 52% and 26% of the total feedstock impacts. For both poplar and miscanthus options, feedstock, sulphuric acid and DAP production are accountable to about 37%, 34% and 18% of HTP, respectively. The major burdens from poplar feedstock are emissions of chromium and nickel to air. The main burdens from the sulphuric acid production are chromium and arsenic emissions to air. In the case of forest residue, main contributors are the feedstcok and sulphuric acid production accounting for about 20% and 43%, respectively, to the total HTP.

Marine Aquatic Ecotoxicity Potential (MAETP):

The MAETP associated with the operation of an integrated bio-refinery in a year is estimated at about 100 Mt DCB eq./yr for wheat straw while for other feedstocks it is about 8 Mt DCB eq./yr. For the wheat straw option, the contribution of cultivation is about 65% to the total impact, while fermentation materials (DAP and DDGS) are responsible for 20% of the total impact. The major burden from the farming of crops includes hydrogen fluoride emissions to air, which is accountable for 39% of feedstock emissions. For the poplar and miscanthus, the contributions of pre-treatment and fermentation materials (lime, sulphuric acid,DAP and DDGS) and cultivation of crops are about 65% and 30% of the total MAETP, respectively. Finally, for the forest residue, the contributions of pre-treatment and fermentation materials and cultivation of crops is 63% and 37%, respectively.

Ozone Depletion Potential (ODP):

The ODP for the bio-refinery system is 7, 4.5, 5, and 4 kg R11 eq./yr for wheat straw, poplar, miscanthus and forest residue feedstock, respectively. In the case of wheat straw, about 55% of the ODP occurs as a result of wheat straw cultivation due to the emissions of non–methane volatile organic compounds (NMVOC) such as halon 1301 and 1211.Other contributors are lime and DDGS with about 15% each. The contribution of the feedstock to the total ODP for poplar and miscanthus is about 36%, while for forest residue it is about 24%. Lime and DDGS contribute about 45% to the total ODP for poplar and miscanthus while for forest residue 50% of the total ODP is from lime and DDGS.

Photochemical Ozone Creation Potential (POCP)

The POCP of 74 t ethane eq./yr is highest for the wheat straw feedstock. For the other feedstocks, this impact is in the range of 52-66 t ethane eq./yr with the lowest POCP found for the poplar option. About 40% and 30% of the total POCP emissions are from the life cycles of wheat straw and sulphuric acid. For poplar and miscanthus, about 20% is from feedstock cultivation while about 35% is from sulphuric acid. In the case of forest residue, the feedstock contributes 45% while the sulphuric acid adds a further 25% to the total POCP. In all cases, the boiler contributes an average 20% to the total. The main burden from the sulphuric acid production is sulphur dioxide emissions to air. Air emissions from the boiler unit such as sulphur dioxide, carbon-monoxide and nitrogen oxides are other contributors to this impact.

Terrestrial Ecotoxicity Potential (TETP):

The total TETP ranges from 249 t DCB eq./yr for forest residue to 45 kt for wheat straw. The latter is very high compared to the other options and this is largely due to the cultivation stage (99%). This is due to the method used to allocate the impacts between wheat and straw - in the Ecoinvent database, which is used for these data, the allocation for TETP is based on the metals content in straw, hence most of the TETP impact is allocated to straw. In the case of forest residue, the sulphuric acid contributes 37% and feedstock 30% of the total impacts. For miscanthus and poplar, about 40% of the total TETP is from the feedstock and 32% is from the sulphuric acid production. Chromium and vanadium emissions to air account for 16% and 14% of the feedstock burdens, respectively. Similar burdens are also associated with sulphuric acid production

Land Use:

The land occupation for forest residue is about $3.7x10^8$ $m^{2}\cdot yr$ and about 99% of that is from the land needed for the feedstock. This is because the total forest area is allocated to wood production and its products and waste while other functions of wood such as recreation activities are not accounted for (Werner et al. 2007). For the straw, the land use is estimated at 1.41 $x10^8$ m^2 yr and with the majority of the land requirement (99%) being for the agricultural land. Poplar and miscanthus a total land use of about $7.8x10^8$ $m^{2}\cdot yr$

and 8.4x10^8 m^2·yr, respectively with the majority from feedstock.

4.3.3.2 Functional unit: 1 litre of ethanol

This section discusses the impacts for the functional unit of one litre of ethanol produced with other co-products. Both the results using system expansion and economic allocation are presented, respectively. As mentioned in section 4.3.2, in the former case, the system is credited with the avoided burdens for the co-products using the system expansion approach. For economic allocation, the prices for each co-product have been used as allocation factors.

1. System expansion

These results are shown in Figure 4.4. For the detailed results, see Appendix 3.

Abiotic Depletion Potential:

This impact is negative for all four feedstock options, indicating a saving in abiotic resources. The ethanol from poplar is the best option with ADP of -4.84 g Sb eq./l ethanol. This is mainly due to the higher amount of the acetic acid produced (because of the higher acetate content) and the associated credits for its production. Miscanthus is the worst option but still saves -3.25 g Sb eq./l ethanol.

Acidification Potential:

Ethanol from wheat straw has the highest AP of 2.36 g SO_2 eq./l ethanol. The AP for ethanol from poplar, miscanthus and forest residue is estimated at -0.09, 0.34 and -0.35 g SO_2 eq./l ethanol, respectively. Credits from the production of electricity account for about 80% of the total avoided burdens from co-products in all cases.

Eutrophication Potential:

Wheat straw has the highest EP of about 3 g PO_4 eq./l ethanol. The lowest EP is -0.042 g PO_4 eq./l ethanol for poplar feedstock. Credits for electricity and acetic acid production contribute 50% each across all the feedstocks.

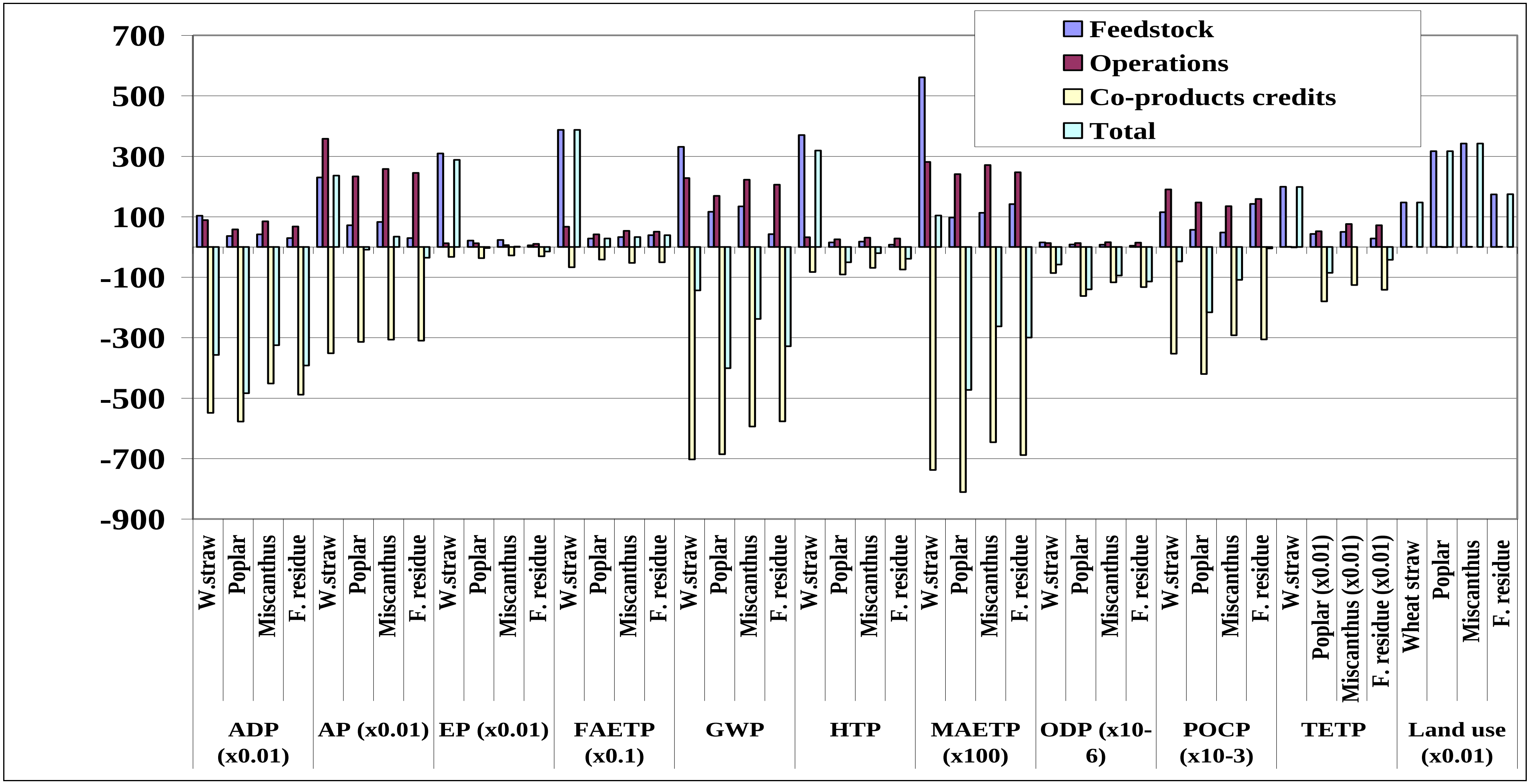


Figure 4.4. Environmental impacts of ethanol for system expansion

[All units in g/l ethanol, except for land use which is in m^2.yr. Credits: acetic acid - production from butane; lactic acid – average organic chemicals; electricity – UK grid (45% of natural gas, 28% coal and 18% nuclear (DECC, 2010b)). ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP; Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity; HTP; Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP; Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential]

Global Warming Potential:

The total GWP per litre of ethanol ranges from -401 to -144 g CO_2 eq./l ethanol for forest residue to wheat straw, respectively. From these, the feedstock contribution is about 331 g for wheat straw and about 43 g for forest residues. The total co-product credits are 703, 686, 594, 577 g CO_2 eq./l ethanol for the wheat straw, poplar, miscanthus and forest residue, respectively. This is mainly due to the credits for electricity production which range from 400-550 g CO_2 eq./l ethanol for different feedstocks. Wheat straw produces the highest amount of electricity, due to high amount of solids and lignin and other waste stream burnt to produce electricity. This is followed by miscanthus, poplar and then forest residue

Human and Eco-toxicity Potentials:

The total FAETP and HTP of ethanol from wheat straw is around 33 g and 320 g DCB eq. per litre of ethanol, respectively. Most of the impacts are from the feedstock cultivation stage. The total co-products credit is about 12.55 and about 83 g DCB eq. per litre of ethanol for FAETP and HTP, respectively. Ethanol from poplar has the lowest FAETP and HTP with a result of about -8.33 and -50.8 g DCB eq/l ethanol, respectively. Ethanol from miscanthus has a total of -1.87 and -20.50 g DCB eq/l ethanol for FAETP and HTP respectively, while ethanol from forest residue has -2.51 and about -39 g DCB eq/l ethanol for FAETP and HTP respectively.

The MAETP is highest in the case of ethanol from wheat straw and lowest in the case of ethanol from poplar. About 60% of the total co-product credit is from electricity production.

Ozone Layer Depletion Potential:

Wheat straw has the highest feedstock impact (0.015 mg) while others are in the range of 0.0043-0.0083 mg R11/l ethanol. The average total plant emission is about 0.055 mg for all feedstocks. For all feedstocks, the total ODP is negligible indicating a saving.

Photochemical Oxidant Creation Potential:

The average co-product credit for all four feedstocks is about 0.35 g ethene eq/l ethanol. The feedstock emissions is highest for the forest residue with about 0.14 g/l, followed by wheat straw with 0.12 g/l while others are about 0.05 g/l of ethanol.

Ethanol from wheat straw has the highest TETP of 198 g DCB eq./l ethanol, mainly due to the impacts associated with feedstock production. Heavy metals emissions to agricultural soil from wheat straw contribute about 98% to the feedstock emissions. The total TETP for ethanol from other feedstocks is less than 1 g DCB eq./l ethanol.

Land Use:

At 3.17 m^2.yr per litre of ethanol, land use is highest for the miscanthus. The best option is wheat straw 1.47 m^2.yr.

2. Economic allocation

The results for the economic allocation are shown in Table 4.5. The economic allocation factors are indicated in Table 4.5. As can be seen, most of the emissions are allocated to ethanol, followed by electricity. A brief overview of the results is given below; for the full results, see Appendix 3. Overall, a similar trend in the environmental impacts is noticed as for the system expansion with ethanol from forest residue and poplar being the best options and wheat straw the worst. With respect to the land use, miscanthus is again the worst option and wheat straw the best.

Economic allocation	Wheat straw (%)	Poplar (%)	Miscanthus (%)	Forest residue (%)
Ethanol	85	84	87	87
Electricity	7	6	6	5
Acetic acid	6	9	5	7
Lactic acid	2	2	2	1
Total	100	100	100	100

Table 4.5 Economic allocation ratios for different feedstock options

[Prices assumed: Ethanol: £808/t (ICIS 2012); Electricity: £0.069/kWh (DECC 2011); Acetic acid: £407/t (ICIS 2012); Lactic acid: £1027/t (NNFCC 2010).]

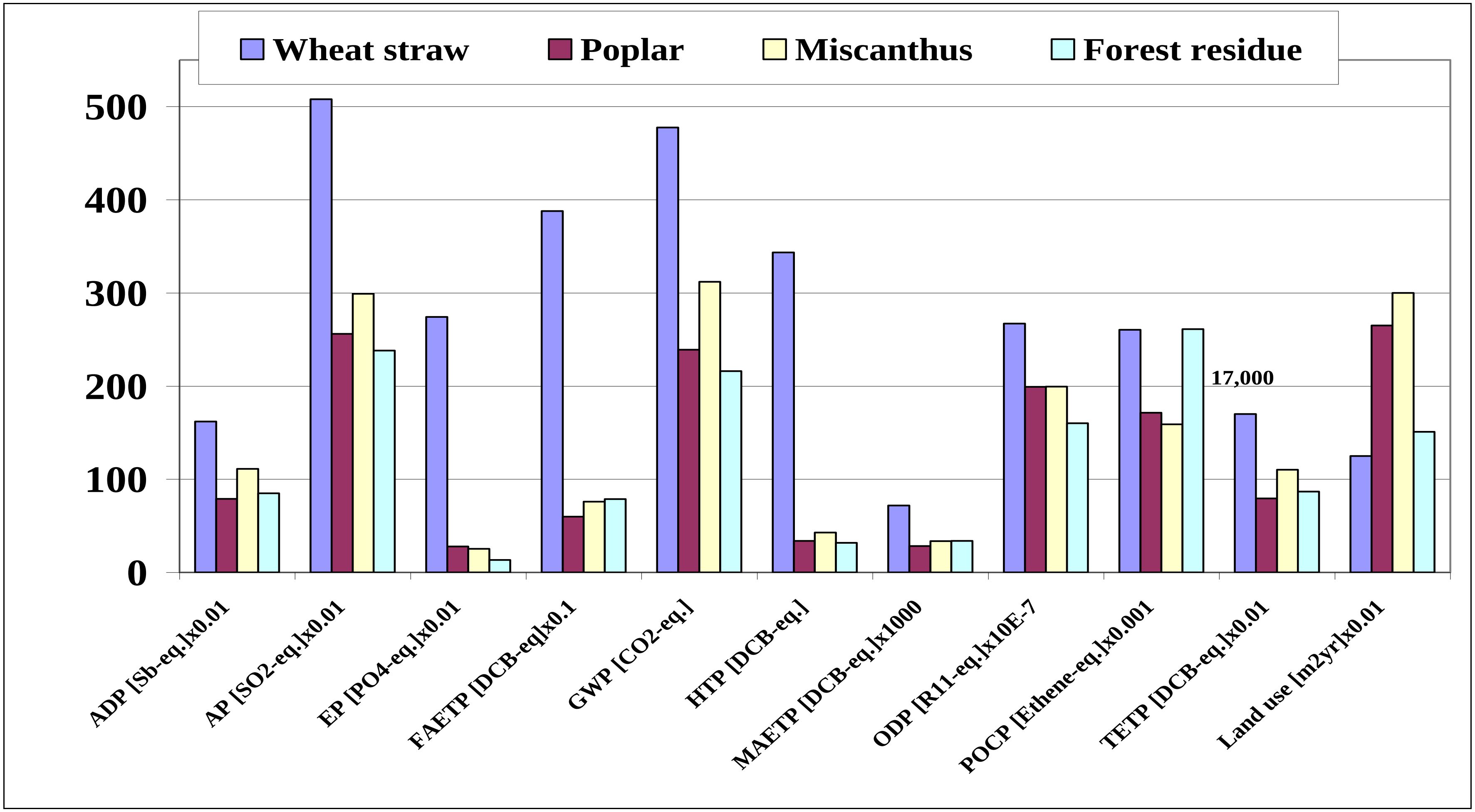


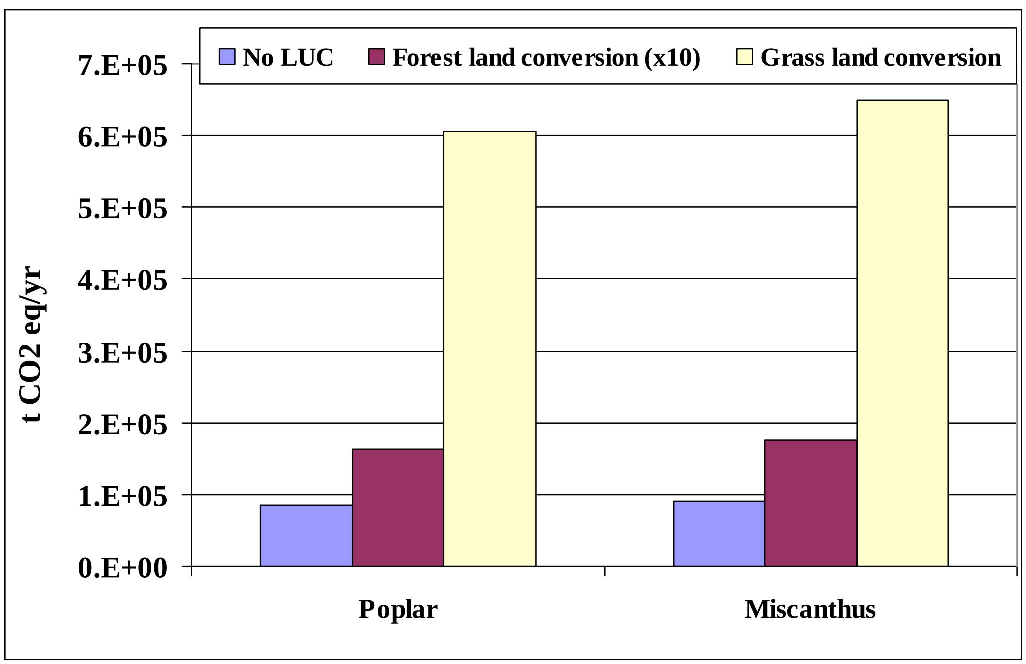
Figure 4.5. Environmental impacts of ethanol for economic allocation [All units in g/l ethanol except for land use which is in m^2.yr.]

4.3.4 Land use change

This section considers the effect of possible land use change on the GWP results. Potentially, this only applies to two types of feedstock here: poplar and miscanthus. The following assumptions have been made:

- GHG emissions of 20 t CO_2 eq./ha/yr of as a result of forest land conversion into land used for cultivation of poplar and micanthus (assuming the use for 'perenials') (BSI, 2011); and
- GHG emissions of 6.7 t CO_2 eq. /ha/yr as a result of grassland conversion into forest land (BSI, 2011).

Figure 4.6 shows the result of possible effect on land use change on the GWP. When forest land is converted to land used for poplar and miscanthus cultivation, there is an increase of about 95% in the GWP compared to the case with no land-use change. If the land use is changed from grassland to cultvation of 'perenials', the total GWP increases by about 85%. Therefore, the results are very sensitive to the land use change and this aspect must be taken into account with any future development of bio-refineries.



[LUC-Land Use Change]

Figure 4.6 Impact of land use change on GWP

4.3.5 Comparison of results with other studies

As already mentioned, few other LCA studies are available in literature, and particularly those that go beyond estimations of GWP. Only two such studies have been identified and they focus on switchgrass and wheat straw (Cherubini and Jungmeier 2010 & Cherubini and Ulgiati 2009). Those results are compared with the results found in this study in Figure 4.7 for the functional unit 'operation of the system for one year'. As shown, the results for the wheat straw obtained in this study are slightly higher than the corresponding literature study. Arguably, the agreement of the results is quite good across the impacts (except for the TETP), given quite different assumptions on the inputs and co-products in the two studies.

Direct comparison between the switchgrass and poplar is not possible as they are quite different species albeit both being energy crops. Nevertheless, for reference, they are compared in the graph indicating that the impacts from the poplar system are lower than for poplar the switchgrass except for the GWP. It is not clear where the main differences come from, but it is possible that they are not only due to the cultivation but also due to processing differences. For example, the current study assumes pre-treatment with the sulfuric acid and lime while the literature study is based on uncatalysed steam explosion.

Figure 4.8 compares the GWP per litre of ethanol from wheat straw and poplar feedstock obtained in this study with that conducted by Mu et al. (2010). As can be seen, there is a good agreement of the results. The differences arise mainly due to different co-product credits which are slightly higher in the current study due to the acetic and lactic acid which was not considered in their study. Thus, they credited the system for electricity only assuming the US national grid (as opposed to the UK grid assumed for the electricity credit in the current study). Furthermore, the authors did not consider the GWP from the enzyme life cycle.

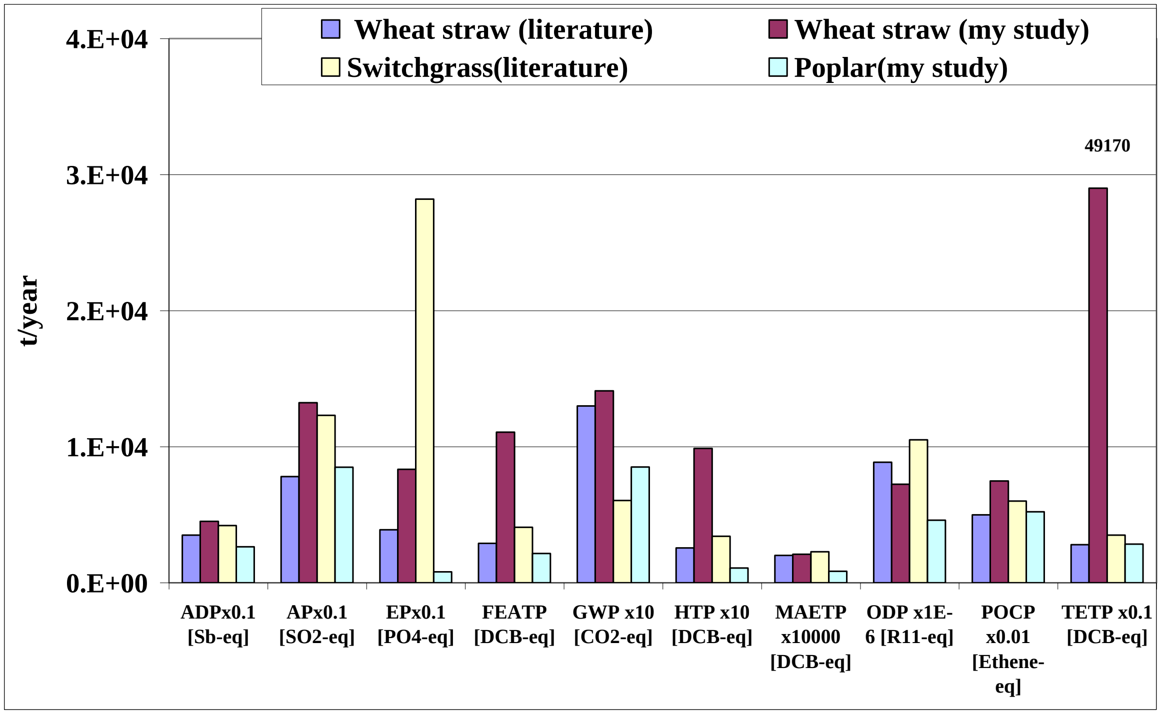


Figure 4.7 .Comparison of environmental impacts for the wheat straw and poplar feedstocks found in this study with literature (Cherubini and Jungmeier 2010 & Cherubini and Ulgiati 2009)

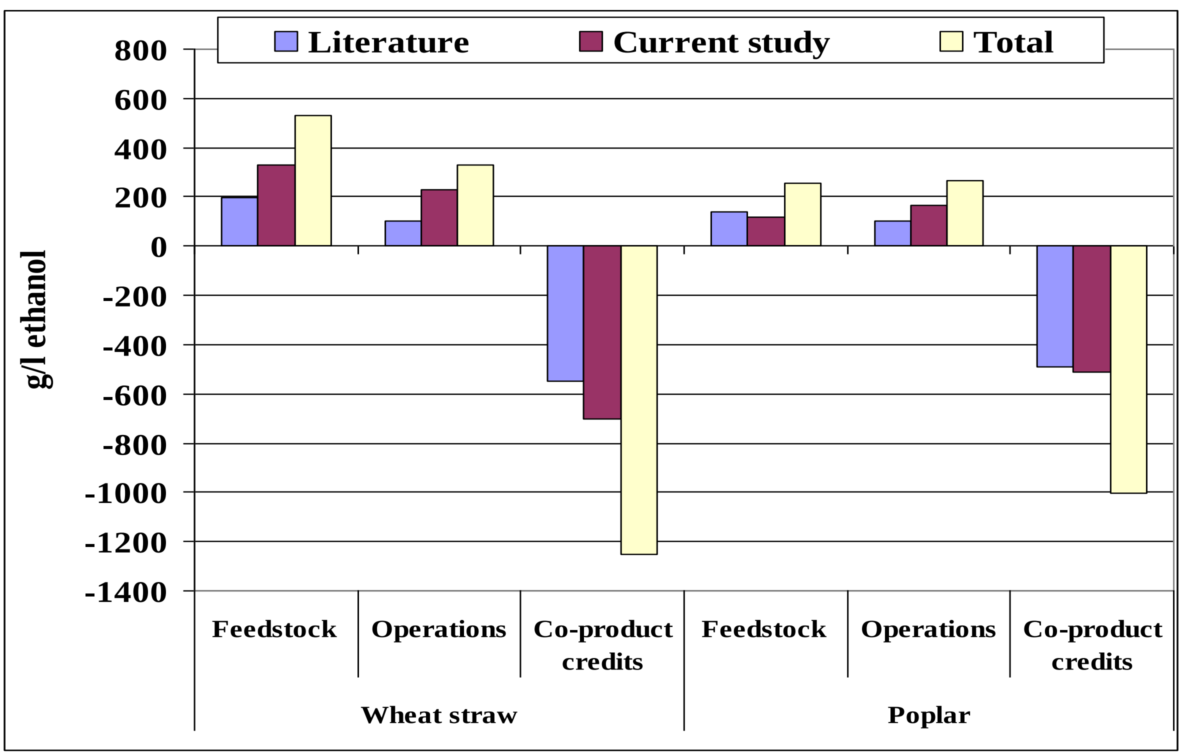


Figure 4.8. Comparison of GWP for the wheat straw and poplar for the current study with literature data (Mu et al. 2010)

4.3.6 Comparison of bio-refinery with fossil-based refinery

This section compares the life cycle environmental impacts of the integrated bio-chemical refinery and its products considered in this study with the impacts from the fossil-based refineries producing the same products but at different sites (i.e. not as a part of an integrated refinery).

The LCA data for the fossil-derived products are taken from the Ecoinvent (2007) database and the following production routes/data have been assumed:

- ethanol from ethylene;
- acetic acid from acetaldehyde/butane;
- electricity from the UK grid; and
- lactic acid – average data for organic chemicals.

To compare them with the bio-refinery products, the same amounts of the fossil-derived products have been assumed. The results are shown in Figures 4.9-4.12 for the functional unit ‘operation of the system for one year’. As can be seen, for all the bio-feedstock options, the bio-refinery products have lower impacts than their fossil-derived alternatives except land use. The exception is wheat straw, which has high expect AP, HTP, and TETP, which is due to the emissions from the feedstock cultivation.

Therefore, it can concluded that, for the assumptions made in this study, producing the range of products from the feedstocks considered here in an integrated bio-chemical refinery is environmentally more sustainable than producing the same products using fossil resources.

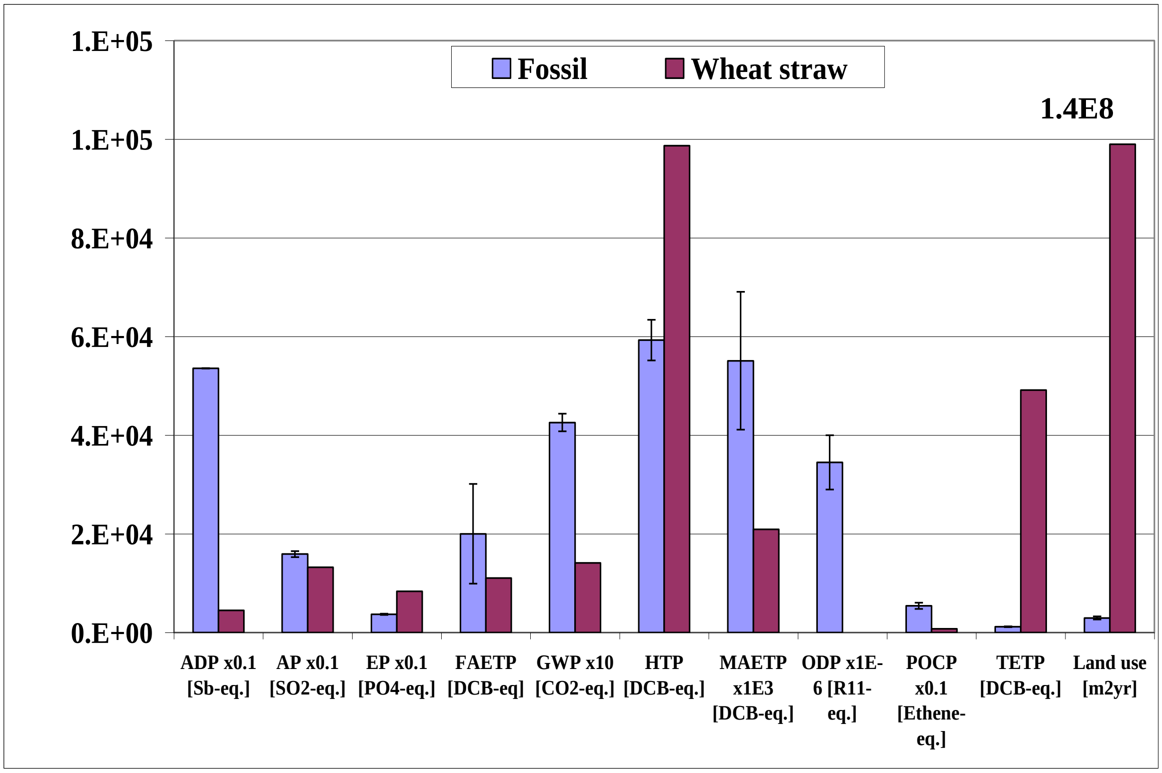


Figure 4.9. Comparison of impacts for the bio-refinery products using wheat straw and the equivalent fossil-based products [All units in tonnes/year except for land use which is in m^2.yr]

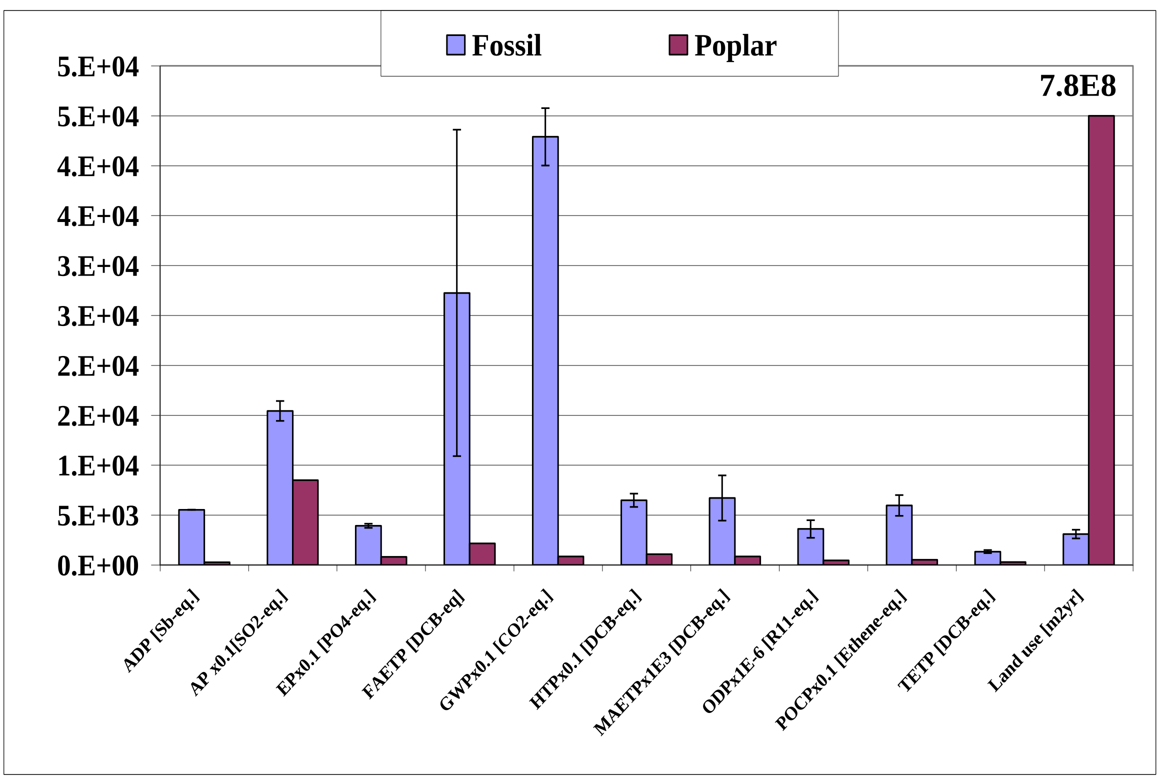


Figure 4.10 Comparison of impacts for the bio-refinery products using poplar and the equivalent fossil-based products. [All units in tonnes/year except for land use which is in m^2.yr]

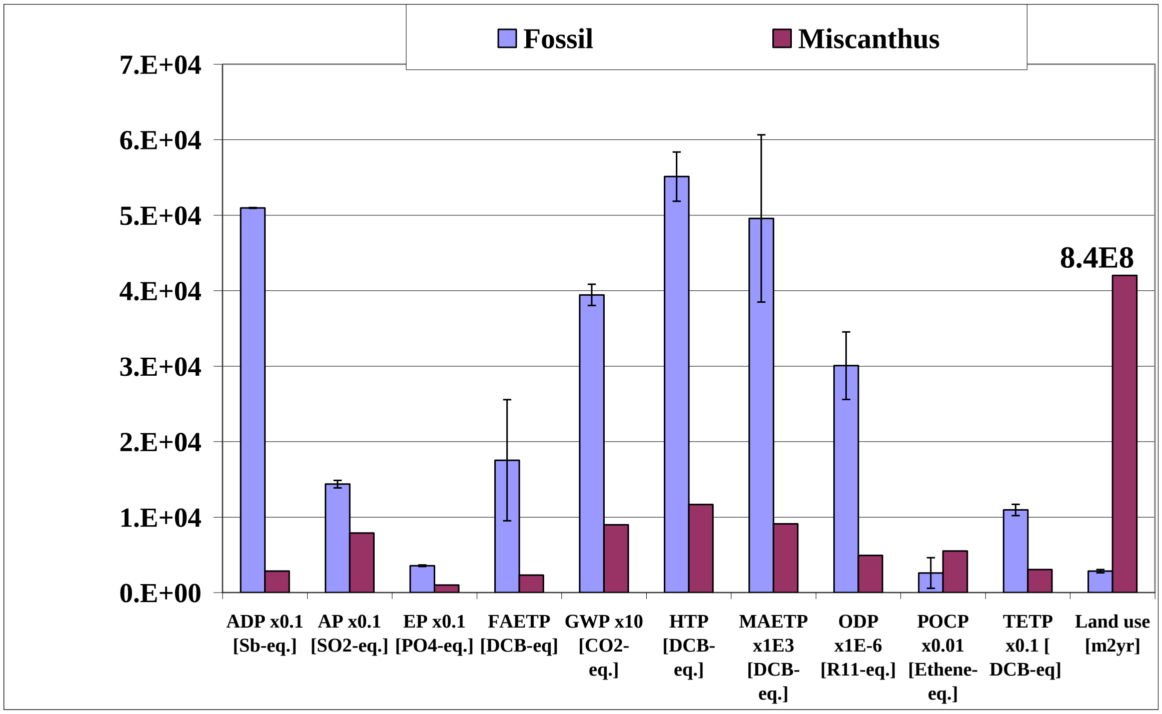


Figure 4.11 Comparison of impacts for the bio-refinery products using miscanthus and the equivalent fossil-based products. [All units in tonnes/year except for land use which is in m^2.yr]

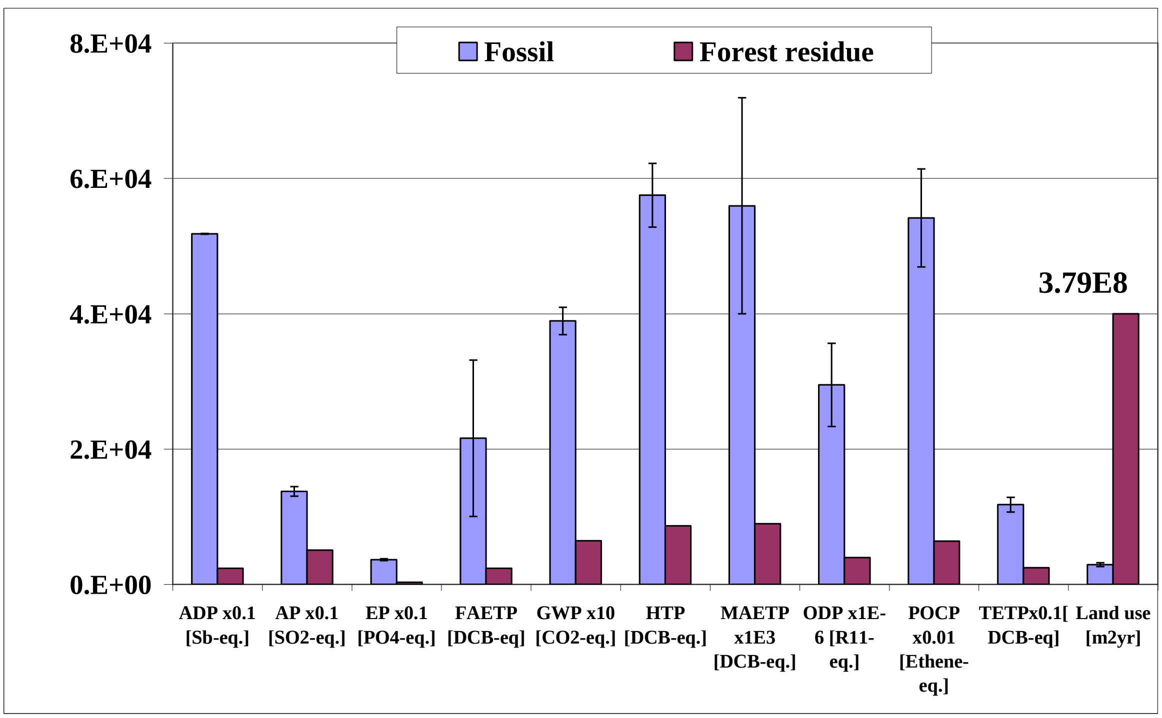


Figure 4.12 Comparison of impacts for the bio-refinery products using forest residue and the equivalent fossil-based products. [All units in tonnes/year except for land use which is in m^2.yr]

Figure 4.13, compares the results per litre of ethanol using system expansion with the impacts ofethanol made from ethylene. As can be seen, all the impacts are higher for the latter with the exception of EP, HTP, and TETP from wheat straw. Land use is also higher for wheat straw and forest residue.

If instead of system expansion, economic allocation is applied to the co-products from the 2nd generation bio-feedstocks (see Figure 4.14), a similar trend is noticed, except that ethanol from wheat straw, in addition to the above impacts has higher AP impacts.

If acetic acid from 2nd generation feedstocks is compared to that from butane/ acetaldehyde (see Figure 4.15), all the impacts are higher for the latter. An exception to this is ethanol from wheat straw which has higher TETP. A similar trend is noticed with lactic acid (see Figure 4.16) with all the impacts being higher for fossil-derived lactic acid (assuming the average LCA data for organic chemicals.

Therefore, it can concluded that per litre of , for the assumptions made in this study, producing the range of products from the feedstocks considered here is environmentally more sustainable than for all feedstocks with the exception of wheat straw due to agricultural activities.

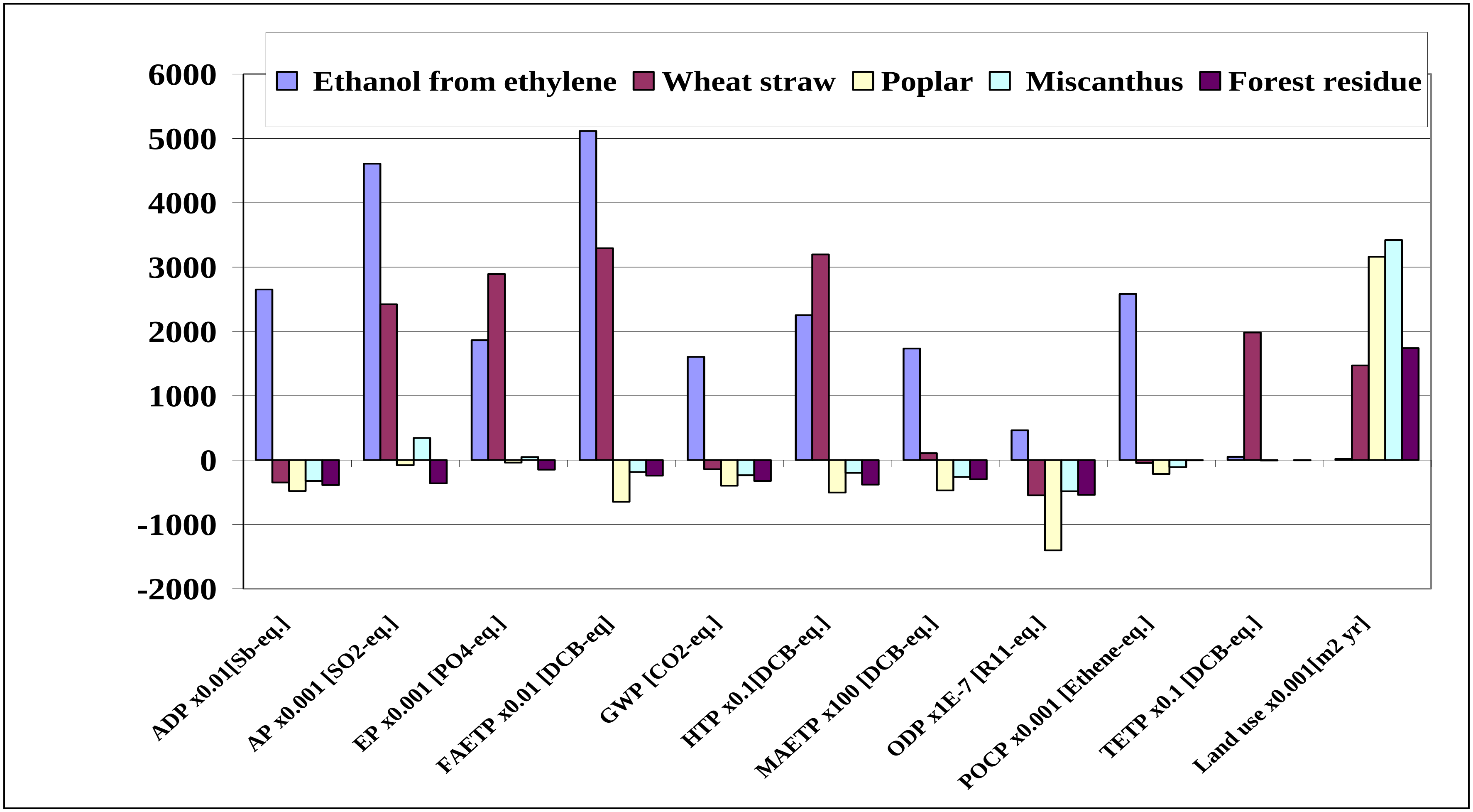


Figure 4.13 Comparisons of impacts of ethanol from 2nd generation feedstocks with ethanol from ethylene (using system expansion) [All units in g/l except for land use which is in m^2.yr]

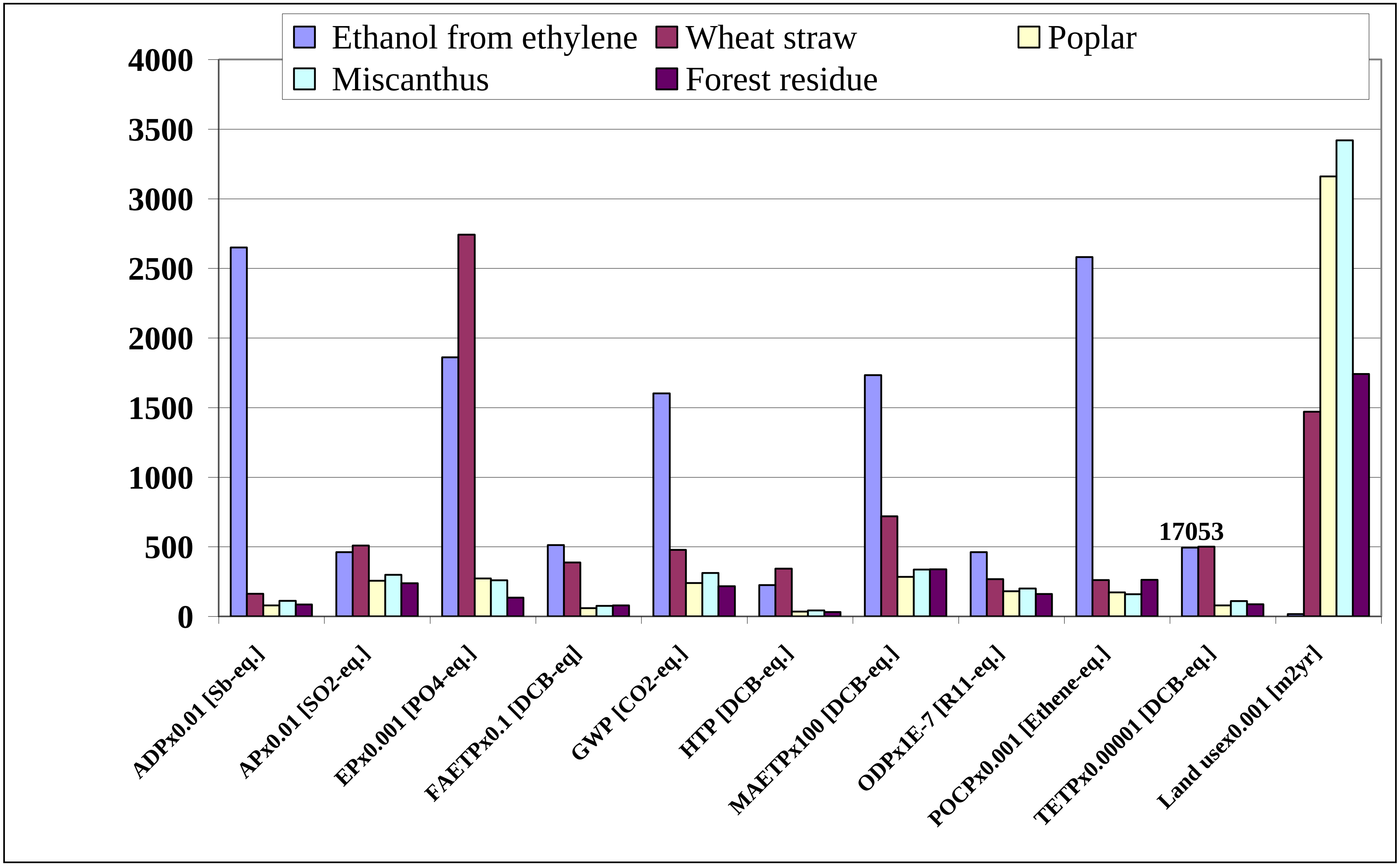


Figure 4.14 Comparisons of impacts for the bio-refinery with ethanol from ethylene (using economic allocation) [All units in g/l except for land use which is in m^2.yr].

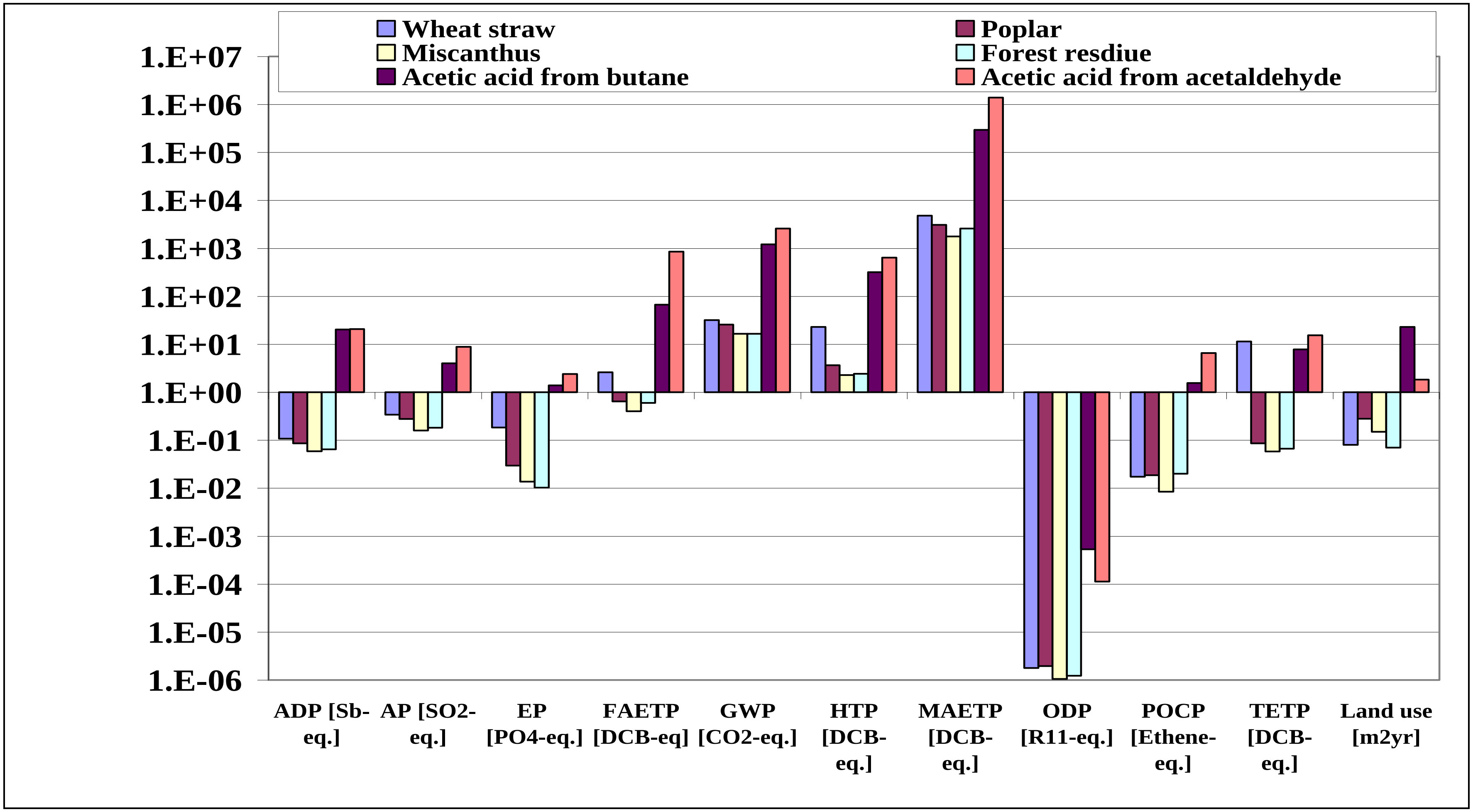


Figure 4.15 Comparisons of impacts allocated to acetic acid (produced in the bio-refinery) with acetic acid made from butane and acetaldehyde [All units in g/l except for land use which is in m^2.yr]

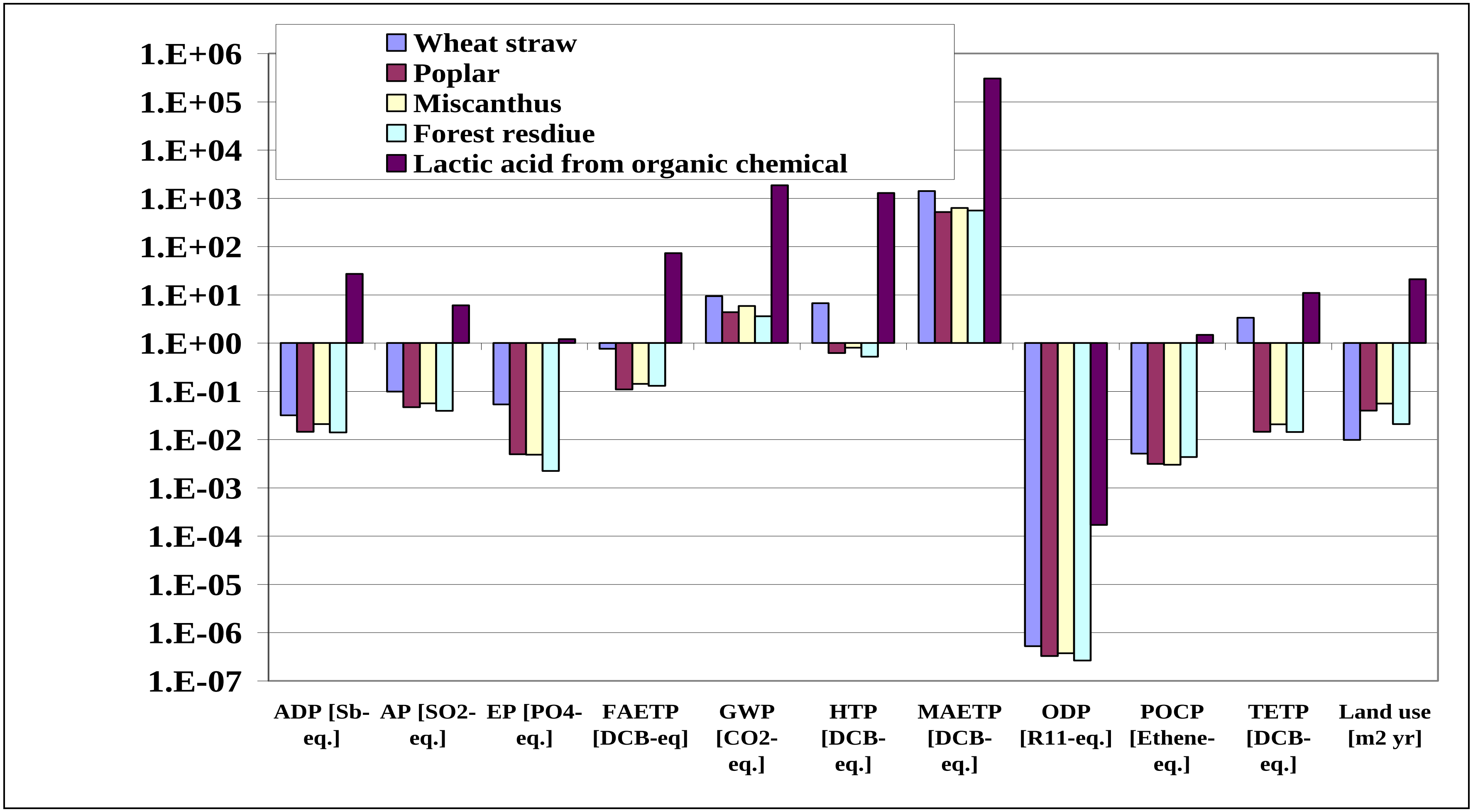


Figure 4.16 Comparions of impacts allocated to lactic acid (produced in the bio-refinery) with lactic acid from organic chemicals [All units in g/l except for land use which is in m^2.yr]

4.3.7 Comparison of ethanol from 1st and 2nd generation feedstocks

In this section, the LCA results of ethanol from 2nd generation feedstocks obtained in this study are compared with the LCA impacts of ethanol from two 1st generation feedstocks: wheat grain and sugar beet. These feedstocks are selected because both are grown in the UK and the production of ethanol from these feedstocks is emerging (NNFCC, 2007; British Sugar 2010). The data for ethanol from wheat grain and sugar beet are taken from CCaLC (2011) and Froteinis et al. (2011), respectively.

As shown in Figure 4.17 and 4.18, the impacts of bio-ethanol from wheat and sugar beat are considerably higher than from any of the 2nd generation feedstocks considered in this study (the two figures show the results for system expansion and economic allocation for the 2nd generation ethanol obtained here, respectively). Exceptions to this are EP, FAETP, and TETP for which sugar beet has a lower impact than wheat straw.

Therefore, it is clear that ethanol from 2nd generation feedstocks (considered here) is environmentally more sustainable that ethanol from 1st generation feedstocks such as wheat and sugar beet.

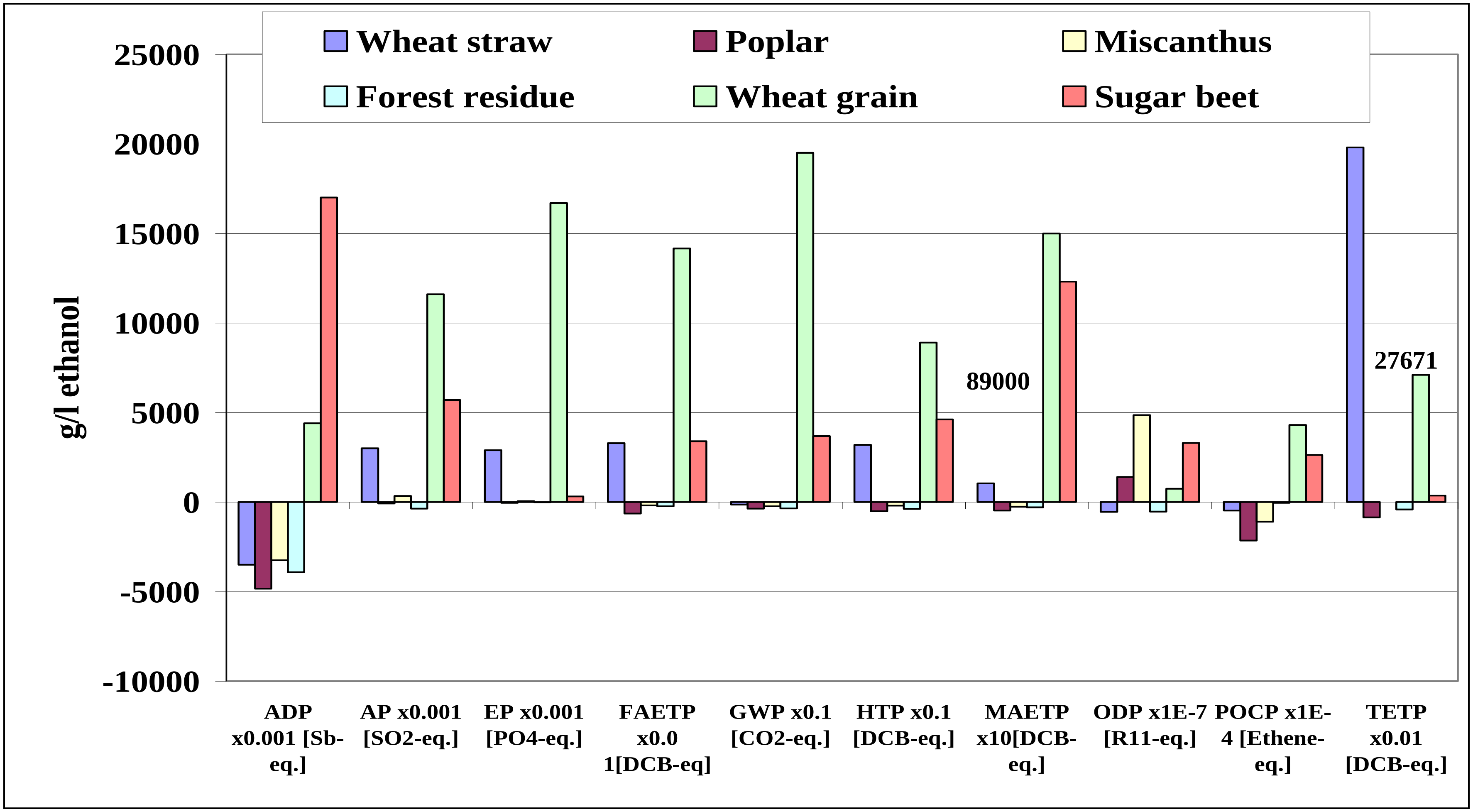


Figure 4.17 Life cycle impacts of ethanol from 1st and 2nd generation feedstocks using system expansion

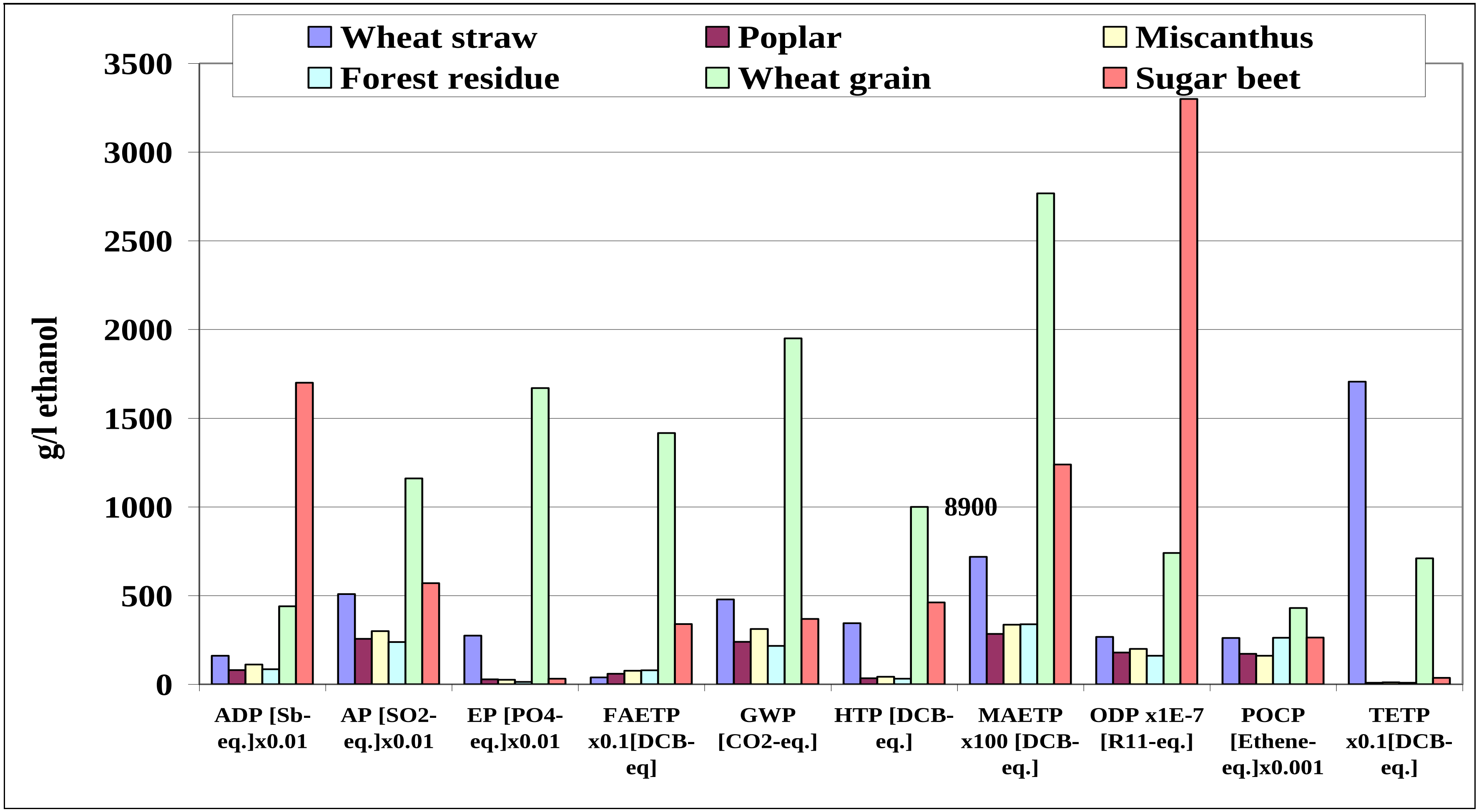


Figure 4.18 Life cycle impacts of ethanol from 1st and 2nd generation feedstocks using system economic allocation for the latter

4.3.8 Comparison of ethanol from 2nd generation feedstocks with petrol

The LCA results of ethanol using the 2nd generation feedstocks considered here are compared to petrol. The comparison is carried out for two system boundaries: 'cradle to gate', as assumed throughout this work and from 'cradle to grave'. The latter is important as the majority of the impacts for petrol occur in the use stage. For reference, comparison with 1st generation ethanol (from wheat and sugar beet) is also shown for the 'cradle to gate' system boundary. The comparison in all cases is on the basis of the energy content in the fuel. The LCA data for petrol (unleaded and low sulphur) are taken from Ecoinvent (2007). The data for the use stage of ethanol are also from Ecoinvent and they have been added to the 'cradle to gate' environmental impacts estimated in this study.

4.3.8.1 Comparison from 'cradle to gate'

As indicated in

Figure 4.19 using system expansion, the impacts from 'cradle to gate' from 2nd generation ethanol are lower for all impact categories than for petrol. The exception to this is ethanol from wheat straw, which has higher AP, EP, FAETP, HTP, and TETP; as discussed before, this is due to the agricultural activities. A similar trend is noticed if economic allocation is used (see Figure 4.20) except that ethanol from wheat straw, in addition to the above impacts, also has higher GWP than petrol.

Therefore, arguably, based on the results obtained here, production of ethanol from wheat straw is not an environmentally sustainable choice compared to petrol production. However, as the main impacts occur in the use stage, it is important to consider the full life cycles of both fuels. This is discussed in the next section.

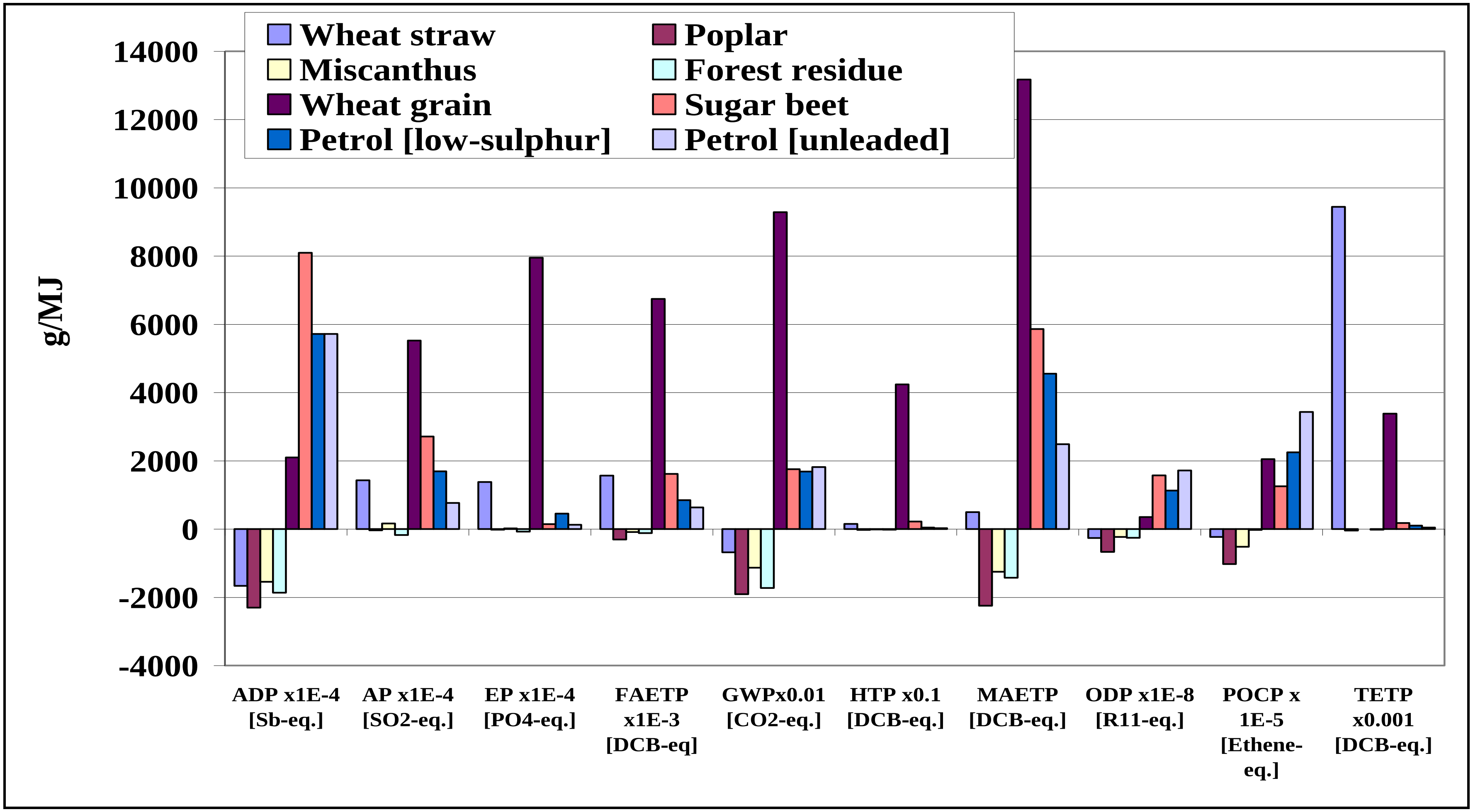


Figure 4.19 LCA impacts of ethanol from 2nd generation feedstock using system expansion compared with petrol and 1st generation ethanol (system boundary: from 'cradle to gate')

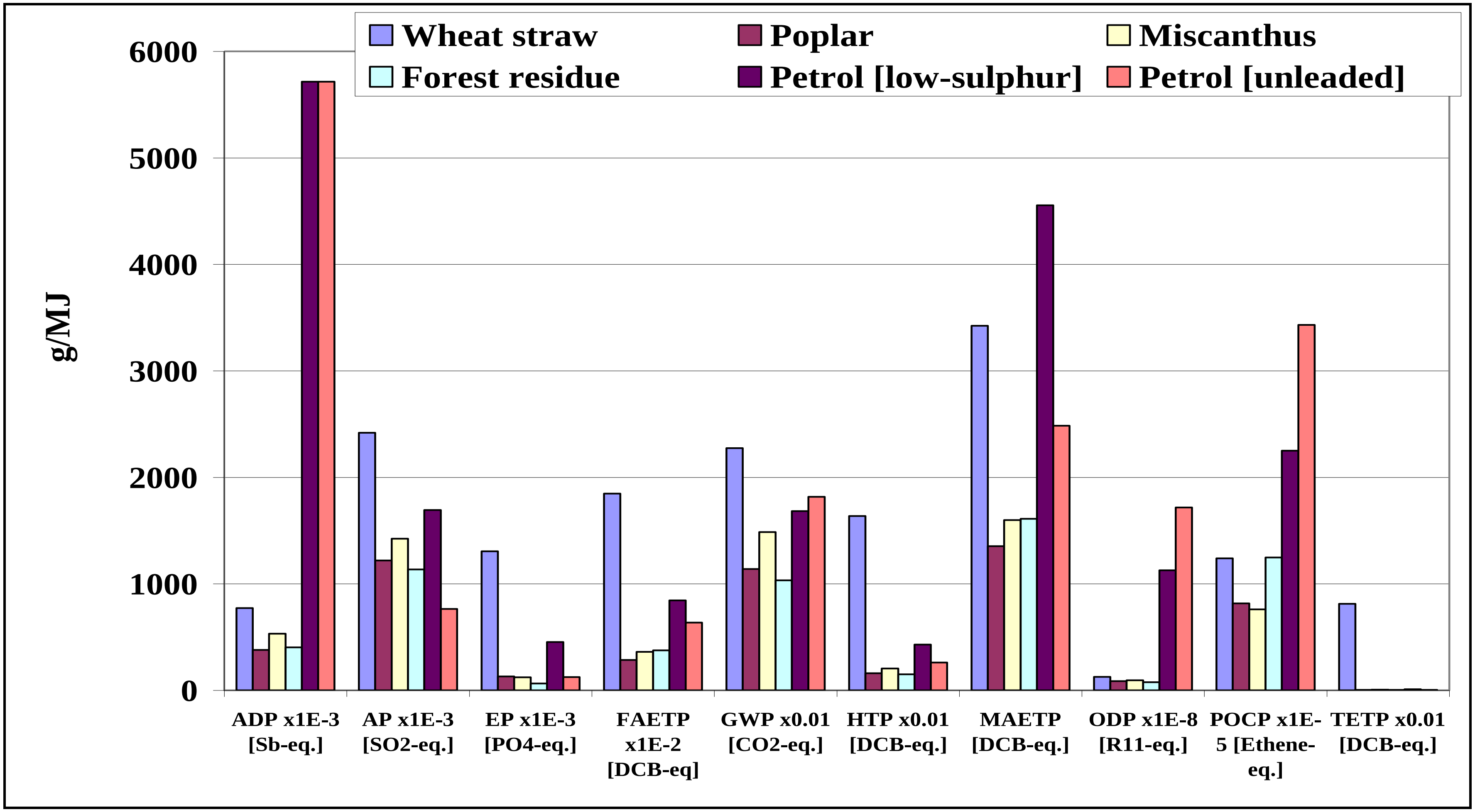


Figure 4.20 LCA impacts of ethanol from 2nd generation feedstock using economic allocations compared with petrol and 1st generation ethanol (system boundary: from 'cradle to gate')

4.3.8.2 Comparison from 'cradle to grave'

In this section, the impacts are considered from 'cradle to grave'. As pure ethanol is not used in the UK, two mixtures are considred: 15 % vol of ethanol from biomass mixed with 85% vol of petrol and 4 % vol of ethanol from biomass with 96% vol of petrol. The emissions from tyre abrasion are also included as it was not possible to separate them out from the emissions associated with combustion of the fuel.

As seen in Figure 4.21 and Figure 4.22, using system expansion, all the impacts from 'cradle to grave' from pure petrol are higher than from mixture of petrol and the ethanol produced from the 2nd generation biomass. The exception to this are AP, EP FAETP, and TETP for ethanol from straw which are higher than for pure petrol. A similar trend is noticed if economic allocation is used (see Figure 4.23 and Figure 4.24), except that ethanol from wheat straw, in addition to the above impacts, also has also a slightly higher GWP and than pure petrol. It is also interesting to note that the difference in GWP between the pure petrol and the mix with bio-ethanol is rather small which suggests that larger proportion of bio-ethanol in petrol would be required for more significant savings of GHG emissions.

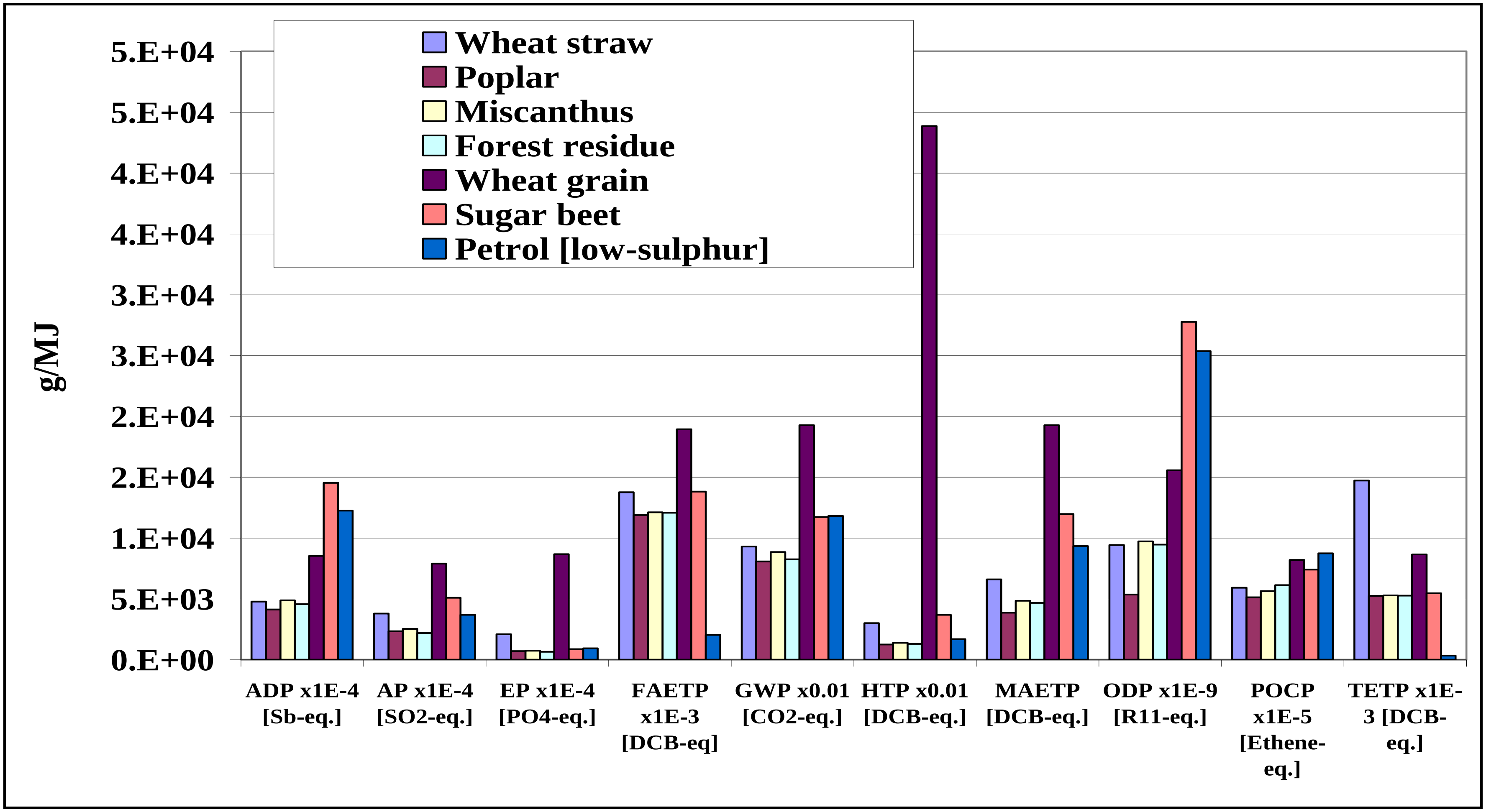


Figure 4.21 Comparison of environmental impacts of pure petrol with the petrol/ethanol mixture (85%/15%) for different 2nd and 1st generation feedstocks (system expansion; system boundary: from 'cradle to grave')

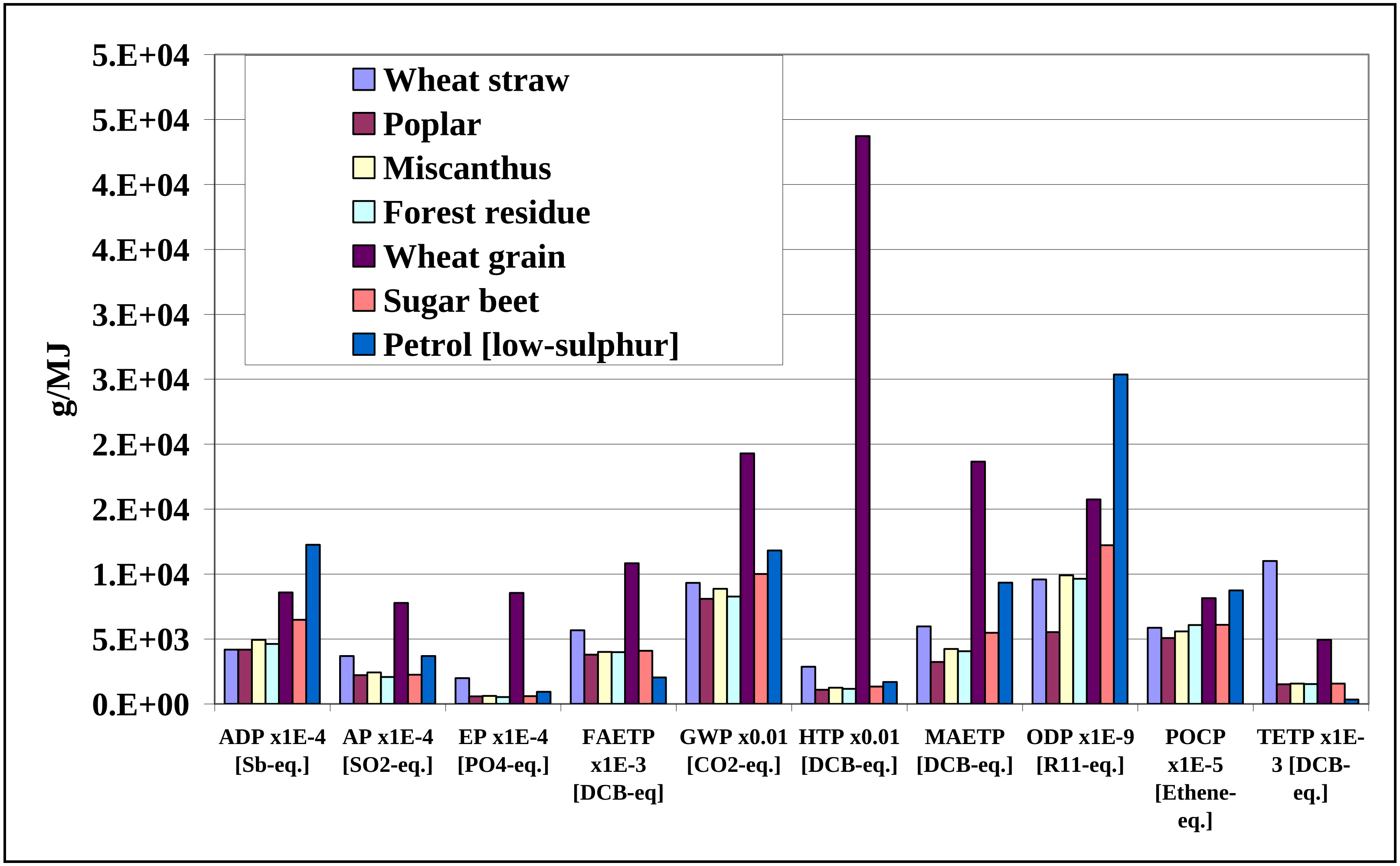


Figure 4.22 Comparison of environmental impacts of pure petrol with the petrol/ethanol mixture (96%/4%) for different 2nd and 1st generation feedstocks (system expansion; system boundary: from ‘cradle to grave’)

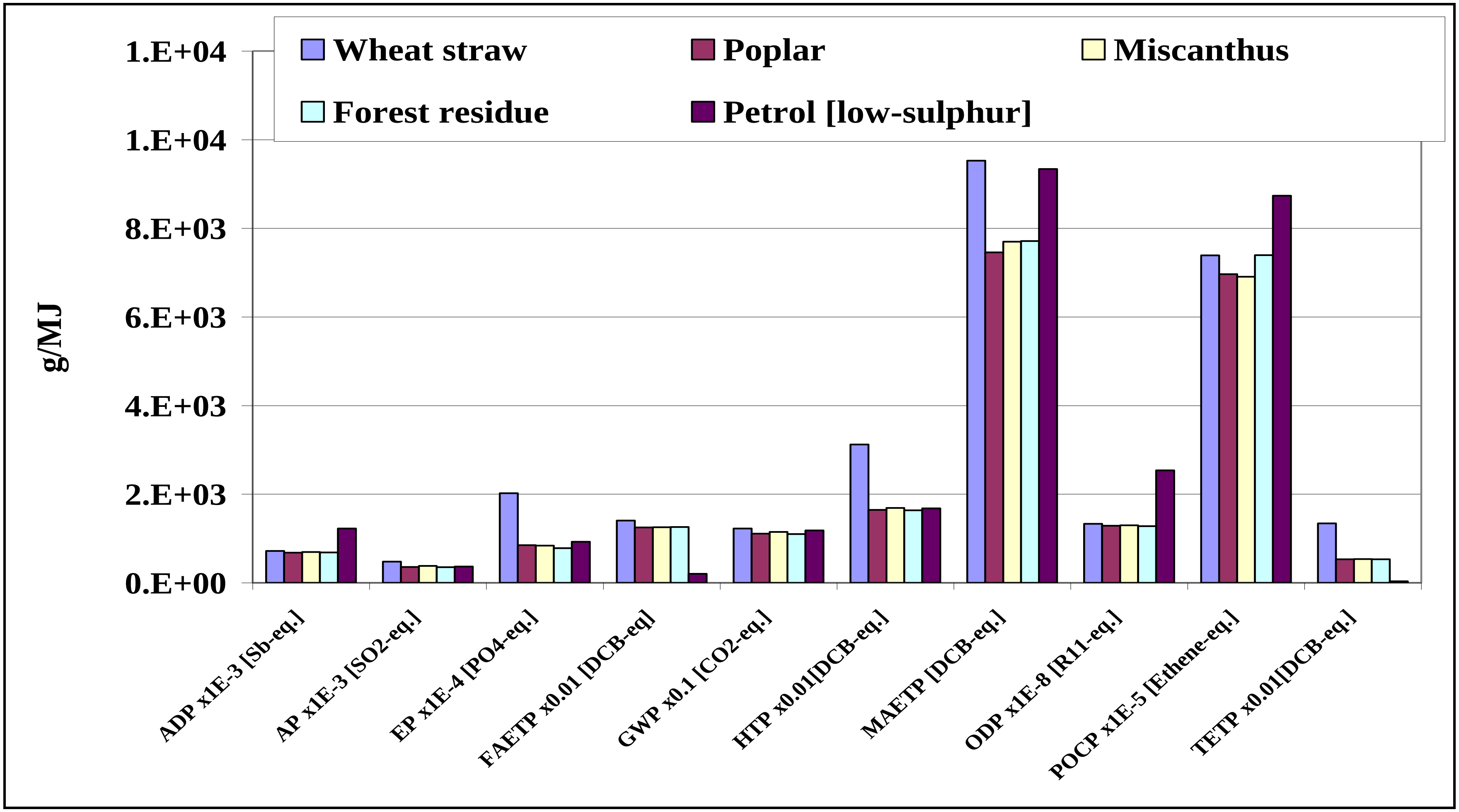


Figure 4.23 Comparison of environmental impacts of pure petrol with the petrol/ethanol mixture (85%/15%) for different 2nd generation feedstocks (economic allocation; system boundary: from 'cradle to grave')

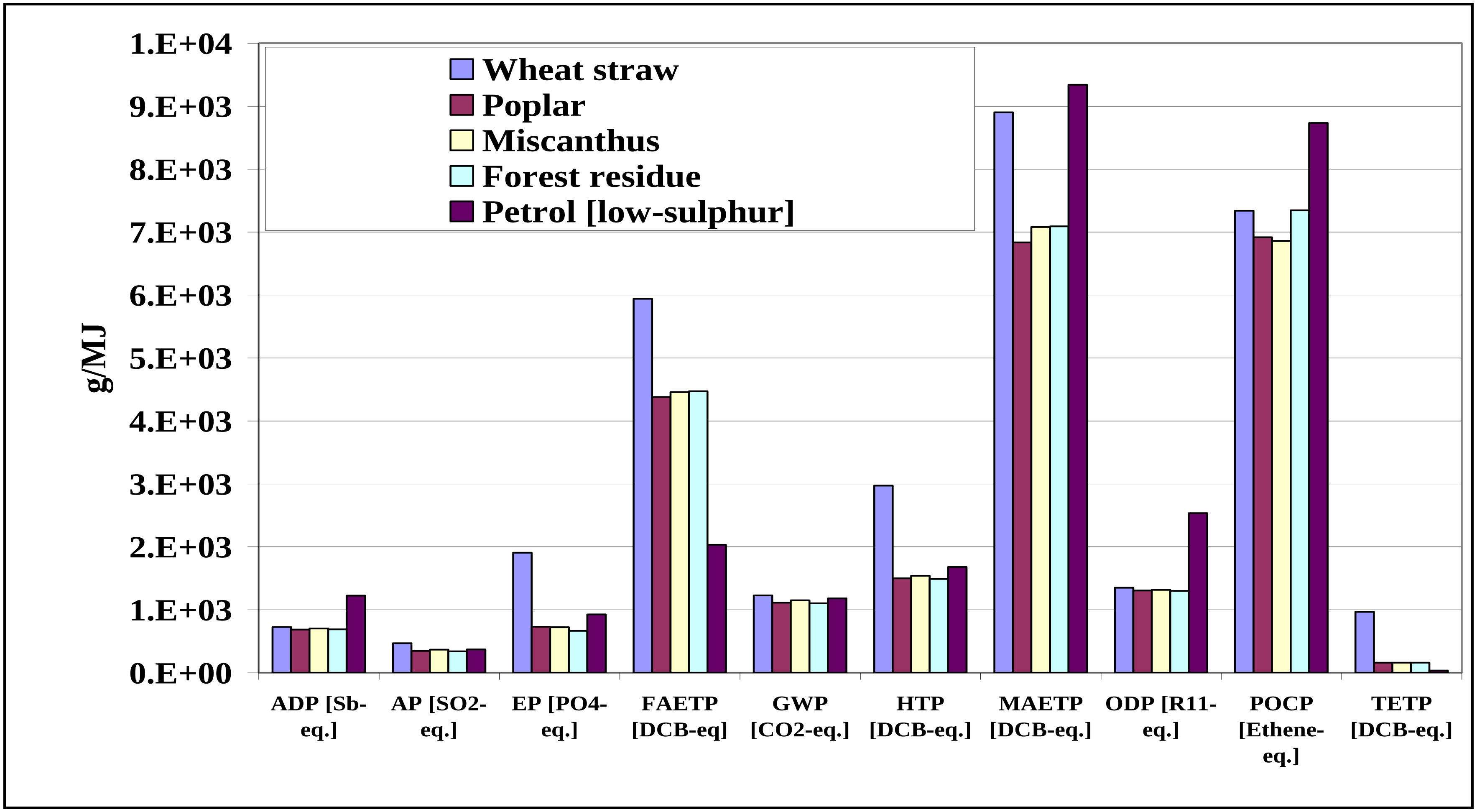


Figure 4.24 Comparison of environmental impacts of pure petrol with the petrol/ethanol mixture (96%/4%) for different 2nd generation feedstocks (economic allocation; system boundary: from 'cradle to grave')

4.4 Techno-economic sustainability assessment

The results of the techno-economic assessment are obtained using the indicators discussed in Chapter 3. The technical indicators that have been quantified are technology efficiency (product yield and mass and energy efficiency) and plant capacity. The remaining two - feedstock flexibility and technology availability – are not quantitative indicators so no further analysis is provided beyond the fact that integrated bio-chemical refineries have limited flexibility as each feedstock requires a different enzyme that they are not available on a commercial scale yet.

The economic indicators comprise life cycle costs (capital and operating), net present value (NPV), internal rate of return (IRR), minimum ethanol selling price (MESP) and payback time. The results are presented in Table 4.6 and discussed in turn below.

As can be seen, the yield of ethanol per tonne of feedstock increases in the order of wheat straw<miscanthus<forest residues<polar. Poplar has the highest ethanol yield because it has high cellulose content. The ethanol yield from wheat straw has been reported in various studies as between 225 - 292 l/t (Gnansounou 2010; Mu 2010). In this study the ethanol yield from wheat straw is assumed at 266 l/t. Similarly, with poplar feedstock, the ethanol yield is reported as 349 l/t by Gnansounou and Dauriat (2010) and in this study it is 311 l/t. There are no reported values for the ethanol yield of forest residue and miscanthus from previous authors.

Energy efficiency is defined as the ratio between energy output (ethanol and other co-products) and energy input (feedstock). The energy content of feedstocks, ethanol and co-products are estimated using their respective lower heating values. For the ethanol output only, the energy efficiency is 32% for wheat straw, 36% for poplar, 35% for miscanthus, and 40% for forest residue. These figures increase when the other co-products are also considered in the output. In the latter case, the energy efficiency is in the range of 34-43% (see Table 4.6).

The mass efficiency, calculated as the ratio of the amount of ethanol to the amount of feedstock, is highest for poplar (24.7%) and lowest for wheat straw (21.2%). When the co-products are included (acetic and lactic acid), this goes up slightly to 25%-33%.

Using the above results for the yield and efficiencies, and assuming the fixed capacity of the plant (245 Ml/yr of ethanol) for all four feedstocks, the required biomass treatment capacity ranges from 779 kt/yr for poplar to 908 for wheat straw.

		Wheat straw	**Poplar**	**Miscanthus**	**Forest residue**
Technical indicators	**Unit**				
Ethanol yield	l/t	266	311	290	305
Energy efficiency (ethanol)	%	32	35	34.7	40
Energy efficiency (ethanol & co-products)	%	34	39	38	43
Mass efficiency (ethanol)	%	21.2	24.7	23.07	24.2
Mass efficiency (ethanol & co-products)	%	23	33	25	27.9
Biomass treatment capacity	kt /yr	908	779	836	795
Plant capacity (ethanol production)	Ml/yr	245	245	245	245
Economic indicators					
Total feedstock cost	£M	29	47	50	23.8
Total transport cost	£M	10.2	8	9.6	9.1
Feedstock cost	£/t	32	58	58	30
Feedstock cost	£/l ethanol	0.1	0.19	0.17	0.08
Total capital investment	£M	297	259	276	262
Total variable costs	£M/yr	50.08	64.09	69.62	41.31
Variable operating cost	£/l ethanol	0.174	0.22	0.248	0.145
LCC	£M	3977	4243	4446	3529
LCC	£/l ethanol	16.2	17.3	18.1	14.4
NPV	£M	116	99	28	179
IRR	%	15.2	15.04	11.4	18.72
MESP	£/t ethanol	649	673	770	560
Pay back time	Years	13.2	13.34	21	10.23

Table 4.6 Results of the techno-economic assessment of the bio-chemical plant

For the economic assessment, the data to calculate the capital costs were obtained from the Black & Veatch study (as quoted in NNFCC, 2007) and the NREL (2011a) study. In addition, vendor quotations and the costs were used as given in Table 4.7. The UK Plant Cost Index (PCI) was used to escalate the prices from 2007-2012 (see Table 4.8). Table 4.9 shows the costs of consumables used by the plant. The producer plant index (PPI) by the US Department of Labour has been used to escalate the cost of chemicals to 2012 (CDRPC 2007). The reference production capacity of the bio-chemical refinery is 245 million litres per year of ethanol along with the various quantities of the co-products (see Table 4.6).

Feedstock costs for different feedstock are assumed as follows: £32 per tonne for wheat straw (Copeland and Turley 2008), £30 per tonne for forest residue (DECC 2010a), £58 per tonne each for miscanthus and poplar (ADAS 2008). The transport cost is assumed at £0.11/km.tonne (Huang et al., 2009).

Total installed equipment cost (TIE)	
Indirect cost	
Engineering and supervision	8% of TIE
Legal expenses	2% of TIE
Construction and contractors fee	15% of TIE
Project contingency	10% of TIE
Working capital	15% of TIE
Total capital investment (TCI)	TIE + indirect cost
Variable cost	
Raw materials & energy	
Fixed cost	
Maintenance	7% of TCI
Operating labour	15% of product cost
Laboratory cost	15% of operating Labour
Operating supplies	15 % of maintenance cost
Supervision	10% of operating Labour
Local taxes	2% of TCI
Insurance	1% of TCI
Plant overhead	60% of (operating labour + supervision +maintenance)

Table 4.7 Assumptions for capital and operating costs (Peters et al. 2003)

Year	PCI
2001	115.5
2002	111.7
2003	112.1
2004	116.9
2005	122.9
2006	127
2007	130
2012	144

Table 4.8 UK Plant cost index (PE 2007)

Consumable	Cost (£/tonne)	Source
Sulphuric acid	114	NNFCC (2007)
Lime	115	NNFCC (2007)
Enzymes	64.46	NNFCC (2007)
Diamoniuim phosphate	199	NNFCC (2007)
DDGS	101	Frederick (2008b)
Cooling water chemicals	1412	Frederick (2008b)
Boiler feed water chemicals	1457	Frederick (2008b)
Wastewater chemicals	2.57	Frederick Jr et al. (2008b)
Gypsum and ash disposal	14	Frederick (2008b)

Table 4.9 Cost of consumables used in the bio-chemical refinery

Parameter	Assumption
Discount rate	10%
Plant life time	30 years
Tax rate	30%
Working capital	15 % of fixed capital investment
Construction period	3 years
Project life	30 years
Investment path	20 % in the first year, 30% in the second year and 50% in the third year
Tax rate	30%
Depreciation	Straight line method

Table 4.10 Parameters used for discounted cash flow calculations

The profitability of the plant was estimated using the discounted cash flow rate of return (DCFRoR) to estimate the NPV, IRR and PBP. These were estimated using the LCC and revenues from the products. The assumptions for DCFRoR are listed in Table 4.10. The results of the economic assessment are given in Table 4.6

The capital costs are estimated between £260-300 M and the total LCC are around £4 billion with the lowest for forest residue (£3.5b) and highest for miscanthus (£4.4b). The LCC per litre of ethanol is about £14 for forest residue and about £18 for miscanthus. As shown in Figure 4.25, the main contributors to the total costs are feedstock, labour and capital costs. The feedstock cost contribution is about 22% for wheat straw and forest residue while for poplar and miscanthus it is about 35%. Capital costs contribute around 23% for wheat straw and forest residue and around 19% for the other two feedstocks. The average labour and maintenance cost is about 20% and 15%, respectively for all the feedstocks. The contribution of consumables and transport is around 8% each.

For the assumed plant life of 30 years, forest residue has the highest total NPV of £179 M and miscanthus the lower (£28 M). This difference is due to a high variable cost with miscanthus as against other feedstcoks (See Table 4.6).

The IRR, which is defined as the discount rate at which the NPV is zero (breakeven point), is 15.2%, 15.04%, 11.4% and 18.72% for wheat straw, poplar, miscanthus and forest residue, respectively. The higher the IRR, the more desirable it is to undertake the project; thus, the bio-refinery using forest residue is the most favorable project in terms of economic benefits. The MSEP is the selling price of ethanol at which the NPV is zero. For instance, ethanol from forest residue can be sold for as low as £560 per tonne. This is the shortest breakeven point and the highest of 7.4 years is for miscanthus.

Therefore, based on the techno-economic analysis, forest residue appears to be the most sustainable feedstock option for the bio-chemical refinery.

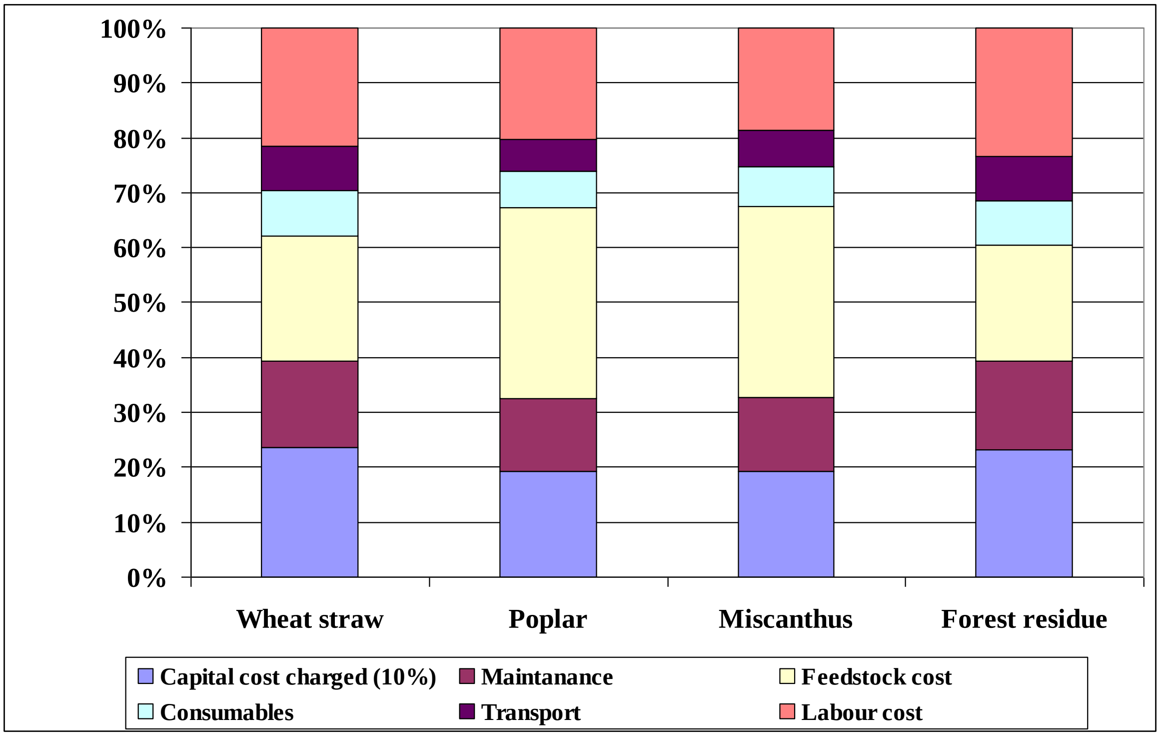


Figure 4.25 Contribution of different life cycle stages to the total costs of the bio-chemical refinery

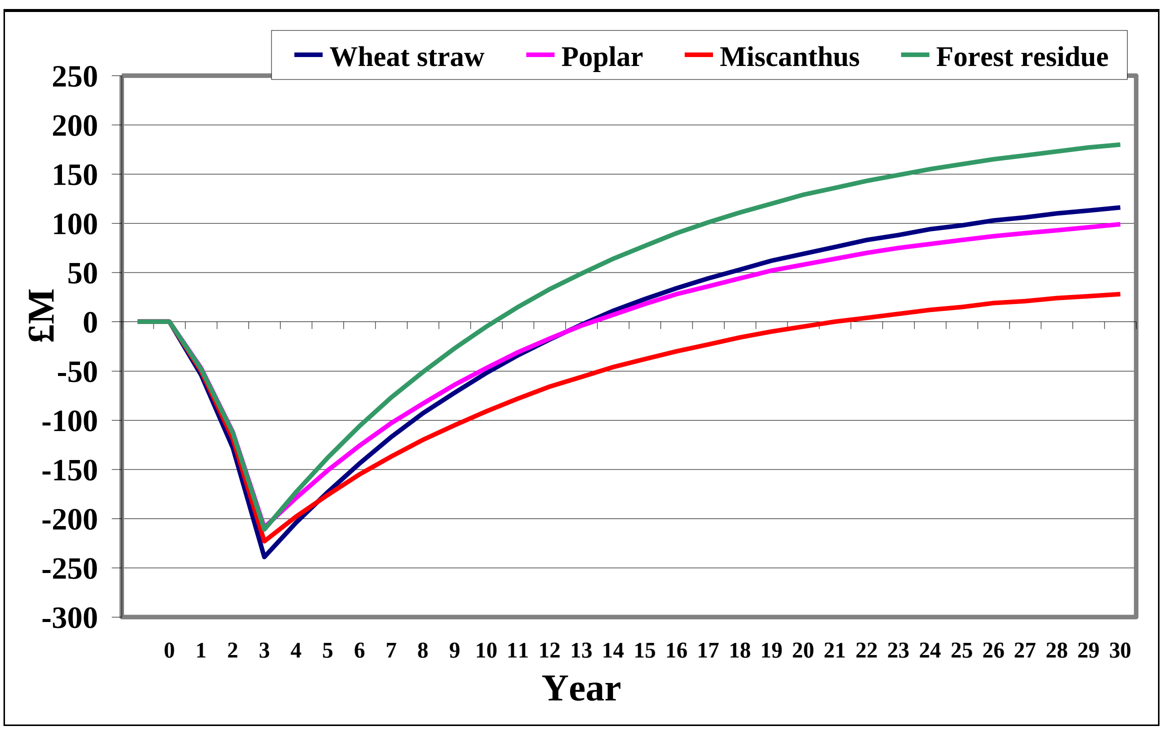


Figure 4.26 NPV values over the life time of the plant showing the break-even point

4.4.1 Comparison of the economic assessment with other studies

The number of studies on economic aspects of ethanol production from 2nd generation feedstock is limited. This is mainly due to the lack of large scale commercial facilities. Most studies have considered the bio-chemical conversion following the NREL study, which estimated the total capital cost at £123 million using corn stover (NREL, 2011a). The values found by other authors are quite different, although based on the same NREL study and using the same methodology – these are listed in Table 4.11. As can be seen, for the same feedstock (corn stover) and similar capacities, the capital costs range from £46-342 M The equivalent values estimated in this study are around £300 M; however, direct comparison is not possible due to different feedstocks used and the capacities of the plants. Nevertheless, these values fall within the range of the values reported by other authors.

Source	Production cost (£/l)	Capital Cost (M£)	Feedstock	Scale (dry tonne/day)	Ethanol yield (l/t)	Notes
(NREL, 2011a)	0.17	123	Corn stover	2200	337	Dilute acid pre-treatment, SSCF process, electricity co-product.
(Kazi et al., 2010)	1.16	235	Corn stover	2200	270	Varying pre-treatment options and downstream process assumptions
(Huang et al., 2009)	N/A	N/A	Aspen, Poplar, Cornstover, Switchgrass	2200	311-416	Dilute acid pre-treatment
(Laser et al., 2009b)		342	Switch grass	5000	439	AFEX pre-treatment, CBP process, varying process conditions
(Gnansounou and Dauriat, 2010)	0.35-0.48	175-193	Straw, Eucalyptus, Poplar, Switchgrass,	1760-2200	262-315	Dilute acid pre-treatment
(Sendich et al., 2008)	0.23-0.32		Corn stover	2200	262	AFEX pre-treatment, SSCF process, varying process conditions
(Bals et al., 2011)	0.46	46	Corn stover	850	292	AFEX pre-treatment, varying pre-treatment conditions
(Piccolo and Bezzo, 2009)	0.35	220	Hardwood	2200	281	Dilute-acid pre-treatment, varying financial inputs
(Luo et al., 2010)	0.37	242	Corn stover	1700	195-277	Dilute acid pre-treatment, varying feed compositions and process conditions
(Gonzalez et al., 2011	0.325	193	Softwood and Hardwood	1295	273-285	Green liquor pre-treatment

AFEX-Ammonia Fiber Explosion, CBP-Consolidated bio-Processing,SSCF-Simultaneous Saccharification and Co-fermentaion

Table 4.11 Techno-economic studies of bio-chemical refinery adapted from (NREL, 2011a)

4.4.2 Sensitivity analyses for the economic sustainability

A sensitivity analysis was performed for the forest residue option as the most profitable option to find out how the NPV might change with the main parameters such as feedstock and capital costs as well as the minimum ethanol selling price. The results are shown in Figure 4.27 and Figure 4.28. As can be seen in Figure 4.27 as the cost of feedstock increases, the NPV goes down and at about £75/tonne, the NPV becomes zero. Increasing the cost beyond this value makes the plant operated at a loss. The cost assumed for forest residue in this study is £30/t, which means that the current cost would need to go up by 2.5 times before the NPV becomes zero. The variable costs would increase by 50%. If, on the other hand, the feedstock costs were to half compared to the current price, the variable costs would also half while the NPV would increase by about 25%.

In Figure 4.28 capital cost, transport costs as well as MESP are varied +/-20% compared to the current results. As indicated, the MESP has the highest impact on NPV, followed by the capital cost; the transport cost has a small effect on NPV.

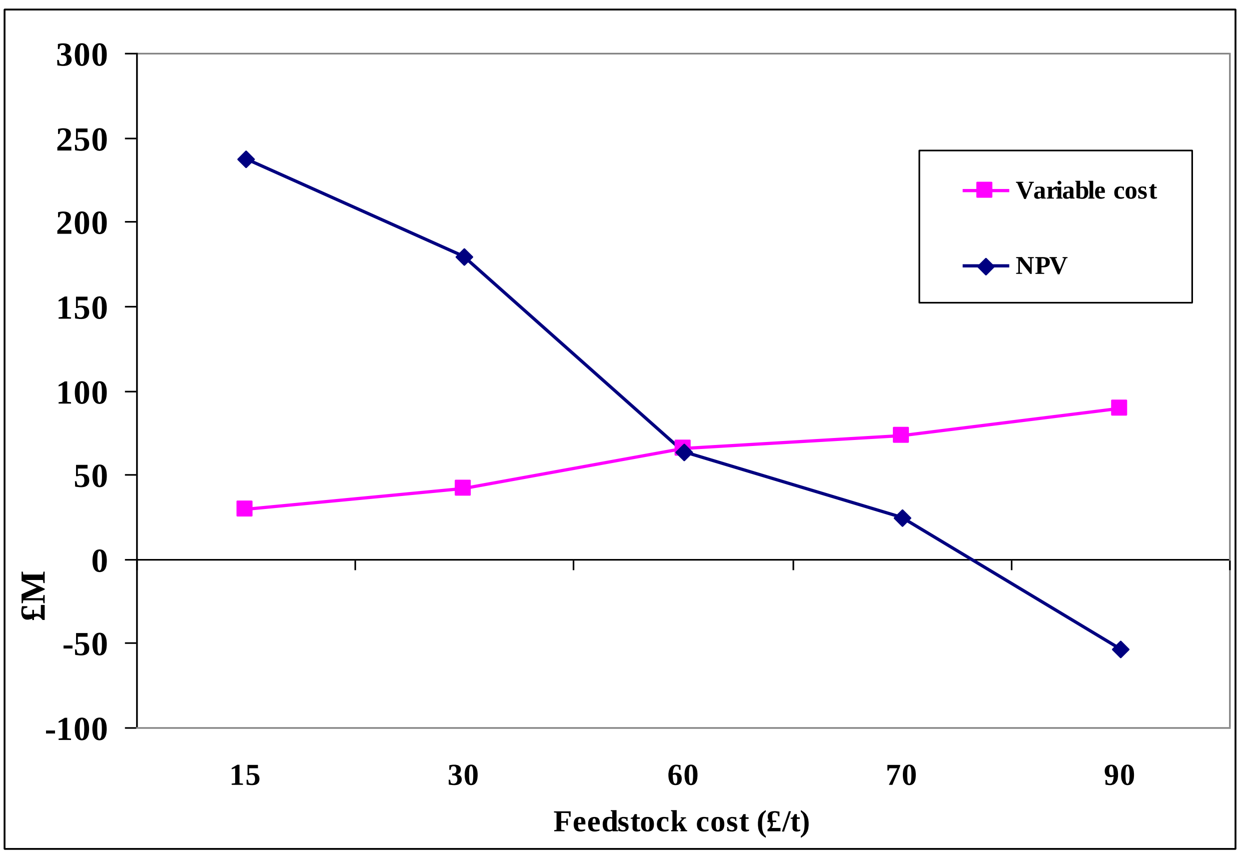


Figure 4.27 Influence of feedstock costs on NPV and variable costs

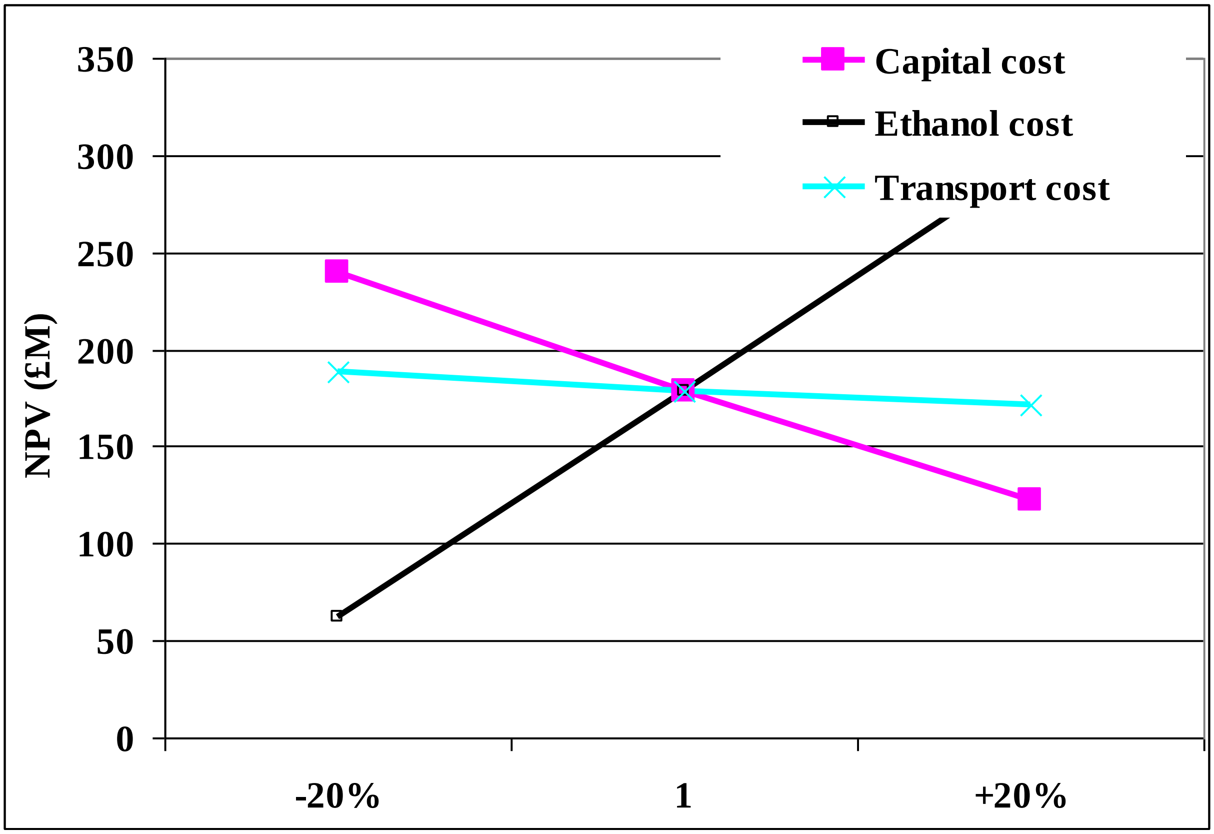


Figure 4.28 Influence of minimum ethanol selling price, transport and capital costs on NPV

4.5 Social sustainability

The social sustainability of the bio-chemical refinery is discussed below, using the following indicators defined in Chapter 3: employment provision, health and safety, local community impacts and energy security.

4.5.1 Employment provision

Employment is provided in each stage in the bio-refinery system, including feedstock cultivation and plant operation. The estimated employment figures for the cultivation stage are given in Table 4.12. As shown, forest residue provides the highest employment opportunities (1067 person years) related to logging of forestry residue. Wheat straw has the lowest labour requirements (358 person years).

Feedstock	Wheat straw	Poplar	Miscanthus	Forest residue
Total quantity (t/yr)	908,262	779,880	836,160	795,960
Labour requirement (FTE/t) (NNFCC,2012)	0.000438	0.000945	0.000852	0.00188
Estimated total employment (person years)	**397**	**736**	**715**	**1067**

[a]Full time equivalent

Table 4.12 Employment provision in the feedstock cultivation/provision stage

In the bio-refinery, employment is provided for operators and other support employees. From RFA (2012), Abengoa estimated a total employment of 65 full time staff for a 25 million gallons of ethanol per year. From this, it is estimated that the operation of the plant size considered here will require an estimated 169 person years FTE.

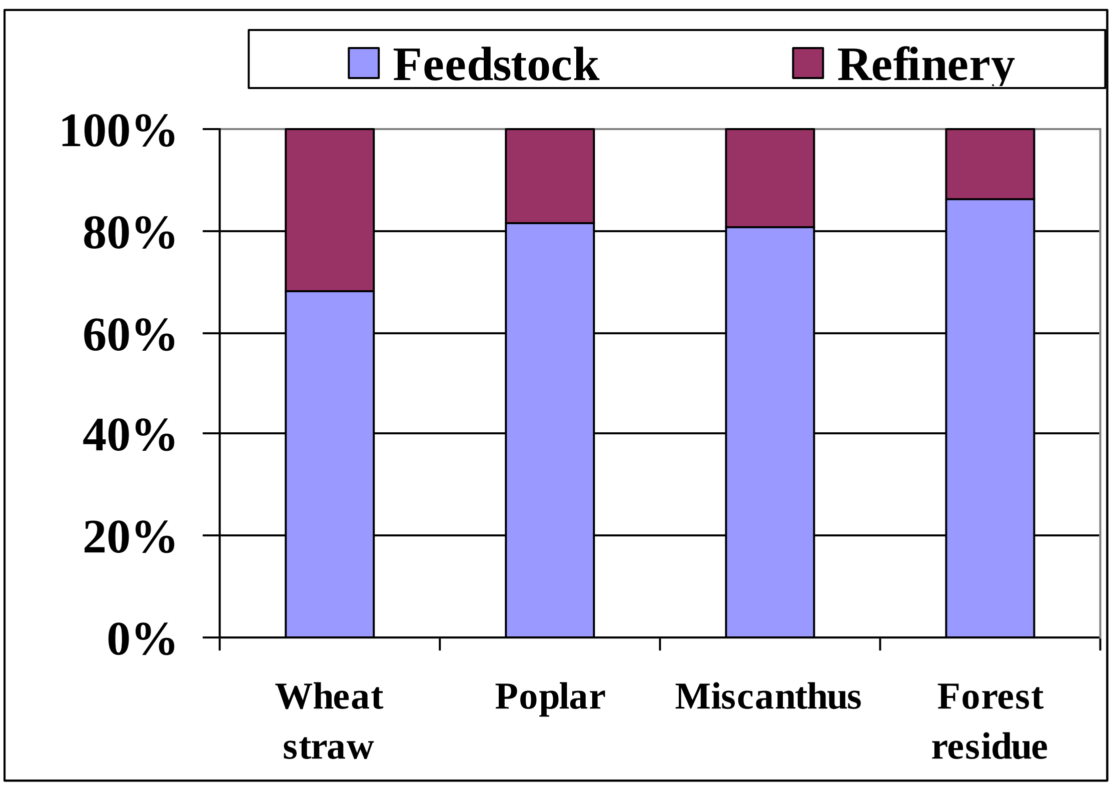


Figure 4.29 Feedstock cultivation and refinery operation employment contribution

Therefore, as indicated in Figure 4.29, the total employment estimated at 566 person years for wheat straw, 905 for poplar, 884 for miscanthus and 1236 for forest residue, respectively. The majority of the jobs (80%) is provided in the feedstock provision stage.

4.5.2 Health and safety

The health and safety is assessed using two indicators: human toxicity potential (HTP) estimated as part of LCA and number of fatalities at work. As shown in section 4.3.3, wheat straw has the highest HTP (98 kt DCB eq./yr) while the other three feedstock have a much lower impact (8.6-11 kt). This is largely due to the emissions of heavy metals and pesticide emissions to soil in the cultivation of wheat.

Based on the data by the UK Health and Safety Executive of 8 deaths per 100,000 workers last year in agriculture (HSE 2011a), the average number of deaths for the feedstock provision stage is estimated at 0.045, 0.072, 0.071 and 0.098 for wheat straw, poplar, miscanthus and forest residue, respectively.

As there are no operating bio-chemical refineries, data on worker fatalities do not exist. However, given that the type of the operation is similar to that of the chemical sector, the statistics for the latter has been used to estimate possible fatalities in the bio-refinery sector. HSE (2011b) reports a rate of about 19 fatalities per 100, 000 workers in the chemicals sector. therefore, using these data, the average number of deaths for 169 workers in the refinery is estimated at 0.0321. Therefore, the total potential fatalities for the chemical bio-refinery from ‘cradle to gate’ are 0.077, 0.104, 0.103, and 0.13 for wheat straw, poplar, miscanthus and forest residue.

4.5.3 Local community impacts

The impacts on the local community can occur at both the feedstock provision and plant operation stages. The type and extent of the impact will depend on the specific location and size of the operations. For example, the feedstock provision may include land clearing and change of land use, increase in local transport and agricultural activities but can also stimulate rural development and employment opportunities. Building and operation of the bio-refinery may have similar impacts on the local community. Given that the analysis here is based on a hypothetical system, it is not possible to carry out a more specific analysis of the impacts on local communities beyond noting that these are important for sustainability of any and therefore this system and must be assesses carefully on a case by case basis.

4.5.4 Energy security

Ethanol production from biomass has a potential to contribute towards improved energy security in the UK by displacing the need for the equivalent amount of fossil fuels. As all four feedstock options produce the same amount of ethanol in the case study considered here, they all have the same potential to contribute towards improved energy security by avoiding the need for about 200 kt of petrol.

4.6 Summary

This chapter has presented the environmental, techno-economic and social assessment of the bio-chemical refinery system comparing four different feedstocks. Their comparison in terms of their ranking for each sustainability aspect considered is given in Table 4.13. The total score is the addition of all the best options '1' for a particular feedstock category. The simple ranking method used suggests that forest residue represents the most sustainable option scoring 16 and miscanthus the least sustainable option, scoring 1. A similar analysis has been carried out to assess the sustainability of the thermo-chemical refinery. This is presented in the next chapter.

Indicator	Wheat straw	Poplar	Miscanthus	Forest residue
Environmental				
Abiotic Depletion Potential (ADP)	4	2	3	1
Acidification Potential (AP)	4	2	3	1
Eutrophication Potential (EP)	4	2	3	1
Freshwater Aquatic Eco-toxicity Potential (FAETP)	4	1	2	3
Global Warming Potential (GWP)	4	2	3	1
Human Toxicity Potential (HTP)	4	2	3	1
Marine Aquatic Eco-toxicity Potential (MAETP)	4	2	3	1
Ozone Layer Depletion Potential (ODP)	4	2	3	1
Photo Oxidant Chemical Formation Potential (POCP)	4	1	2	3
Terrestrial Eco-toxicity Potential (TETP)	4	2	3	1
Land use	1	3	4	2
Techno-economic				
Ethanol yield	4	1	3	2
Mass efficiency	4	1	3	2
Energy efficiency	4	2	3	1
Plant capacity				
Life Cycle Costs (LCC)	2	3	4	1
Net Present Value (NPV)	2	3	4	1
Internal Rate of Return (IRR)	2	3	4	1
Minimum Ethanol Selling Price (MESP)	2	3	4	1
Payback period	2	3	4	1
Social				
Employment provision	4	2	3	1
Safety (fatalities)	1	3	2	4
Local community impacts	NA	NA	NA	NA
Energy security	1	1	1	1
Total score	3	6	1	16

Table 4.13 Ranking of feedstock options for different sustainability criteria (1: best option; 4: worst option)
[Contribution to energy security is the same for all feedstocks]

5 CASE STUDY: THERMO-CHEMICAL REFINERY

5.1 Introduction

The environmental, techno-economic and social assessment of a UK based hypothetical thermo-chemical refinery is presented in this chapter. The chapter starts by defining the system and stating the assumptions, followed by the analysis and discussion of the results. The results are validated by comparing with other studies where available.

5.2 System description

The thermo-chemical study is based on the model of thermo-chemical process developed by the National Renewable Energy Laboratory (NREL) (Phillips et al. 2007). The life cycle of the system is outlined in Figure 5.1. These include feedstock cultivation, and transport to the refinery and feedstock processing in the refinery. The model developed by NREL used poplar as the feedstock. However, similar to the bio-chemical study, four different feedstocks were used (See Chapter 4) wheat straw, poplar, miscanthus and forest residue. The co-products are ethanol, propanol and butanol. Therefore, the NREL model has been adapted for these feedstocks and outputs using the ultimate analysis of each feedstock (see Table 4.1). In addition, the system diverts about 28% of the syn gas produced to generate electricity for the plant.

The plant comprises of the following processes: feedstock handling and drying, gasification, gas clean up and conditioning, alcohol synthesis and separation, boiler and utilities. The system flow diagram is shown in Figure 5.1 and they are described briefly below.

Feedstock handling and drying:

The feedstocks are dried to a moisture content of 5% with flue gas from other areas of the plant.

Gasification

In this section, the dried woody biomass is converted to syngas and char using steam as the fluidising medium. Heat for the endothermic gasification reactions is supplied by circulating a hot medium between the gasifier vessel and the char combustor. In this case the medium is synthetic olivine, which is used as a heat transfer solid for various applications. A small amount of MgO must be added to the fresh olivine to avoid the formation of glass-like bed agglomerations that would result from the biomass potassium interacting with the silicate compounds. Without MgO addition, the potassium will form glass and this will cause the gasifier bed to become hard and sticky. The benefit of MgO addition makes the potassium form a higher melting point char that is formed is combusted and used to reheat the olivine. Other ash and sand particles are removed with a cyclone.

Gas cleanup:

In this process, the syn gas is cooled, quenched and tars are reformed in a tar reformer unit. The water gas shift reaction also occurs in the reformer. The syngas is reacted with tar reforming catalyst in an entrained flow reactor. The tar reformer operates at 890^{o}C and the energy needed is provided from the heat generated by the hot catalyst and combustion of additional syngas and unreacted gases from the alcohol synthesis reactor in the regenerator. The hot reformed syngas is cooled through heat exchange with other process streams and scrubbed with water to remove impurities like particulates, ammonia, halides, and recalcitrant tars. The wastewater is treated in a wastewater treatment facility. After heat recovery, the remaining low-quality heat in the flue gas from the catalyst regenerator is utilized for feedstock drying.

Alcohol synthesis:

In this stage, the syngas is further compressed and heated to about 300^{o}C. The heated syngas is then passed across a bed of molybdenite catalyst for conversion into alcohol. The product gas containing the alcohols is cooled and separated from the unconverted syngas. The hydrogen sulphide and carbon dioxide are removed from the syngas by an acid gas removal unit. Sulphur is also removed to avoid contamination of the catalyst.

Alcohol separation:

The crude mixed alcohol is degassed and dried. The resulting product is separated to a mixture of ethanol, propanol, and methanol using molecular sieve to dry ethanol and distilled to the required concentration. Any methanol and water mixture is recycled back to the alcohol synthesis unit. The system is self-sufficient in terms of electricity. This is achieved by diverting about 28% of the unconverted syngas through turbo expanders, which are used to generate energy as required by the plant. A steam generator is used to generate steam for all processes. All process units in the plant are indirectly fed with steam except the gasifier for which steam is directly injected into the process.

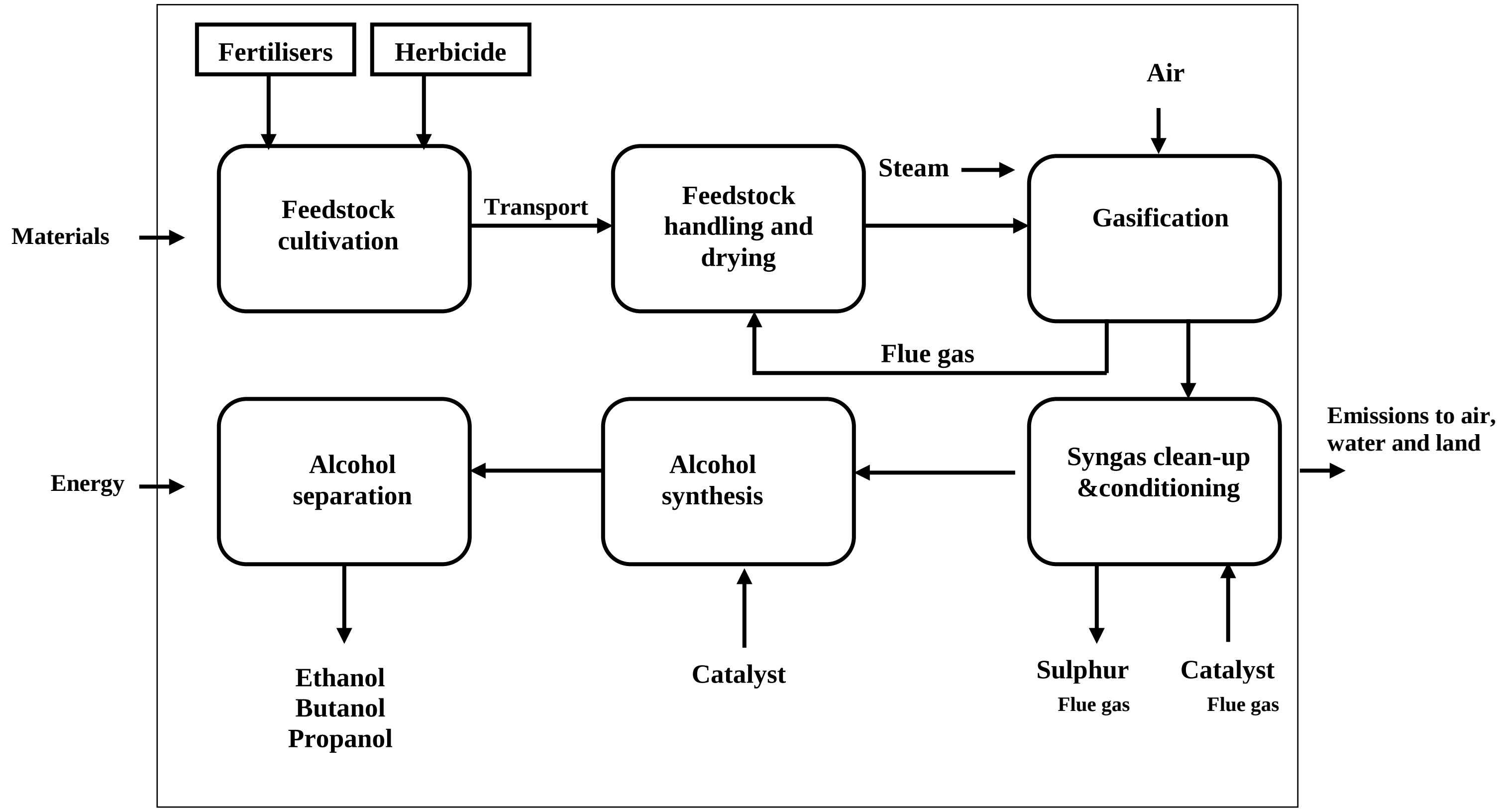


Figure 5.1.Life cycle diagram of the thermo-chemical refinery considered in this study adapted from (Phillips et al.2007)

5.3 Environmental sustainability assessment

5.3.1 Goal and scope definition

The goal of this study is to assess the environmental sustainability of a thermo-chemical integrated refinery, which produces bio-ethanol as the main product with butanol and propanol as co-products. The analysis is carried out for two functional units:

(i) the operation of the plant for one year , and

(ii) 1 litre of ethanol coproduced with the other products.

The operation of plant for one year considers the impacts from the system as a whole while the second functional unit includes allocation of co-products. This enables comparisons of these products with their equivalent but produced in alternative systems.

The system boundary is defined as “cradle to gate”, the gate being the refinery gate. As shown in Figure 5.1, the life cycle stages considered include feedstock production, feedstock transportation, and production of different products. The use phase and distribution of the products are excluded from this study. The impacts from construction and decommission of the refinery are also excluded from this study as typically the infrastructure impacts for industrial installations add little to the overall impacts.

5.3.2 Inventory analysis

Similar to the bio-chemical study, the feedstocks are assumed to be grown in the UK with an assumed distance of 100 km. It is assumed that the refinery operates 24 hours a day and a total of 335 days in a year.The input and output data for the thermo-refinery are summarised in Table 5.1. These are based on the model developed by NREL (Phillips et al. 2007). The ultimate analysis of the four different feedstocks was inputed in the ASPEN and the products were calculated based on a fixed amount of ethanol output.

The life cycle inventory data for wheat straw and forest residue feedstock are obtained from the Gabi (PE 2007) and the Ecoinvent 2.0 databases Ecoinvent (2010) while the data for poplar and miscanthus are taken from GEMIS (GEMIS 2004). The background data for the other materials are also extracted from GABI (PE 2007) and Ecoinvent 2.0 (Ecoinvent 2007). The materials and energy balance flows for the thermo-chemical conversion route are taken from the study conducted by (Phillips et al. 2007), see Table 5.1.

The allocation procedures used have been described in Section 4.3.2. For this study, the life cycle system is expanded to include credits from the system co-producing the other products assuming alternative ways of producing these co-products. For these purposes, propanol is assumed to be produced from propene and butanol from propylene. The data have been sourced from the Ecoinvent database (Ecoinvent 2010).

Inputs								
	Wheat straw		Poplar		Miscanthus		Forest residue	
Thermo-chemical conversion	kg/hr	t/yr	kg/hr	t/yr	kg/hr	t/yr	kg/hr	t/yr
Biomass (wet)	106,250	853,848	95,834	770,232	102,083	820,723	93,750	753,348
MgO	22	176	3.63	29	11	88	3.6	29
Olivine	224	1,800	243	1,953	234	1,881	243	1953
Synthesis catalyst (molybdenite)	1.9	15	1.1	8.8	1.1	8.8	1.1	8.8
Tar reforming catalyst (cerium oxide)	0.9	7.2	0.9	7.2	0.9	7.2	0.9	7.2
Oxidiser for sulphur recovery	242	1,945	131	1,053	156	1,254	128	1,029
Outputs								
Ethanol	24,568	196,980	24,937	200,196	24,568	196,980	24,418	196,320
Butanol	401	3,224	405	3,256	390	3,135	396	3,183
Propanol	3,199	25,719	3,234	25,728	311	25,012	3166	25,454
Sulphur	102	820	54	434	64	514	53	426
Sand and ash	638	5,129	1228	9648	342	2,749	1,207	9,648

Table 5.1 Summary of the data for the thermo-chemical refinery

5.3.3 Impacts assessment and interpretation

The results are first presented for the whole system operated in a year followed by the second functional unit (production of 1 litre of ethanol). The environmental impacts have been estimated using the CML 2001 method (Guinee et al. 2001).

5.3.3.1 Functional unit: Operation of the system over one year

The total annual impacts of the thermo-chemical refinery for all feedstock are presented in

Figure 5.1 Amongst all feedstocks, forest residue has the least while wheat straw has the highest impacts. A full set of results can be found in Appendix 4. Note that the results for the human toxicity potential (HTP) are reported together with the rest of the LCA results as this impact is calculated as part of the LCA study. However, as this impact strictly speaking represents a social rather than an environmental impact, in the methodology developed in this work, HTP is included in the social sustainability assessment. Therefore, a reference is also made to it later, in the section on social sustainability assessment.

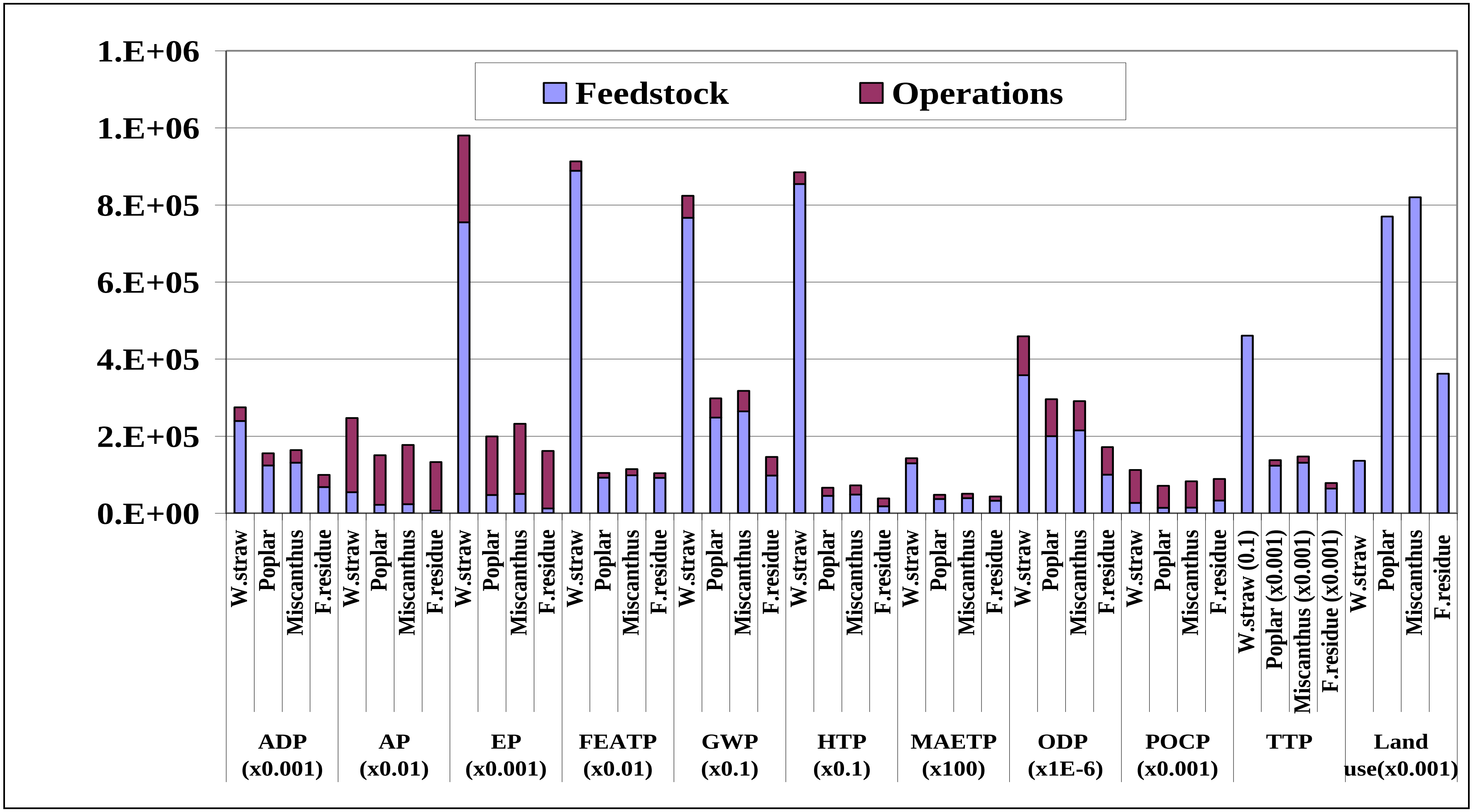


Figure 5.2. Total annual environmental impacts from the thermo-chemical refinery

[All units in t/yr, except for land use which is in m^2.yr. ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP; Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity; HTP; Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP; Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential]

Abiotic Depletion Potential (ADP):

The total ADP is in the range of 99-274 t Sb-eq. The feedstock is the highest contibutor to the total ADP and the results ranges from 48%-86% for forest residue and wheat straw. Major contributors to this are oil and natural gas, 68% an 24%, respectively. Other raw materials account for the rest.

Acidification Potential (AP):

Majority of the AP is as a result NO_x (60%) and SO_2 (26%) released during flue gas combustion while about 20% of the total AP is associated with the feedstock production. The total estimated AP of thermo-chemical refinery across all the feedstocks is between 1300-1800 t SO_2 eq./yr.

Eutrophication Potential (EP):

Figure 5.2 shows the impact on eutrophication by the different feedstock used expressed as PO4 eq per year of production. As shown in Figure 5.2 the system with wheat straw has the highest EP while the system with forest residue has the lowest impact. Nitrate emissions are responsible for EP from the wheat straw production stage, and a further 17% from gasification unit. The system with forest residue shows that about 80% is from the gasification unit. For system with miscanthus and poplar s, about 65% of the EP are from the char combustor stage.

Freshwater Aquatic Ecotoxicity Potential (FAETP):

The FAETP of poplar, miscanthus, and forest residue is estimated at about 1,000 t DCB eq./yr. For these feedstocks, about 85-90% of the total FAETP is from the feedstock cultivation and this is mainly dominated by nickel (46%), and cobalt (13%). The system with wheat straw is calculated at about 9,000 t DCB eq./yr, and the total feedstock contribution is about 88% to the total FAETP. The most significant burdens are emissions to agricultural soil (47%) and emissions to fresh water (17%).

Global Warming Potential (GWP):

The GWP result is as follows: the large contribution from wheat straw is primarily due to emissions from the feedstock stage mainly carbon dioxide and nitrous oxides. The contribution from poplar and miscanthus feedstock cultivation is about 85% of total GWP with carbon dioxide and nitrous oxide contributing 15% and 21%, respectively. The other source of GHG emissions is from the transport. The thermo-chemical refinery with forest residue option has the lowest GWP at 14 kt CO_2 eq./yr, from this, about 65% of the total GWP is from the feedstock related activities while about 30% is from transport. It should be noted that this impact only considers the fossil carbon and the biogenic carbon is excluded throughout the system.

Human Toxicity Potential (HTP):

Emissions of heavy metals to agricultural soil (mainly chromium) and pesticides emissions (mainly isoproturon) to agricultural soil are the major burdens, accounting for 48% and 24%, respectively of the total wheat straw production. The system with forest residue has the lowest HTP. The feedstock and feed handling stage accounts for 50% and 35% of the total HTP, respectively. For poplar and miscanthus option, feedstock and the feed handling stage production are accountable for about 70%, and 20% of the total HTP, respectively.

Marine Aquatic Ecotoxicity Potential (MAETP):

The total MAETP is estimated at 14,245 kt DCB eq./yr for wheat straw feedstock and about 5,000 kt DCB eq./yr for other feedstock. For the wheat straw option, the contribution of the feedstock cultivation is about 90% of the total MAETP as a result of hydrogen fluoride emissions to air. For miscanthus and poplar systems, 76% of the total MAETP is from feedstock production. With forest residue, about 75% of the total MAETP is as a result of feedstock production. Major burden associated with feedstock cultivation is hydrogen fluoride emissions to air.

Ozone Depletion Potential (ODP):

The estimated ODP of 4 kg R11 eq./yr for wheat straw option is mainly caused by feedstock cultivation. Emissions of non-methane organic compounds (NMVOC) such as halons 1301 and 1211 are the main contributors to this impact (58% and 15% of the total ODP, respectively). The ODP of poplar, miscanthus, and forest residue is about 2 kg R11 eq./yr and majority of the impact is from the feedstock cultivation contributing about 73%, 73% and 58 %, respectively. Other contributor is the transport system.

Photochemical Ozone Creation Potential (POCP):

The system with poplar and miscanthus have a total POCP of about 70 and 80 t ethene eq./yr, respectively. The major burdens are NOx and SO_2 from the feed handling stage. Forest residue has a total POCP of about 88 t ethene eq./yr with about 55% from the feed handling stage and 35% from the feedstock cultivation stage. Finally, wheat straw has a total impact of about 115 t ethene eq./yr. From this, the feedstock contribution is about 25% while the feedstock handling stage is 70%.

Terrestrial Ecotoxicity Potential (TETP):

The total TETP is about 150 t DCB eq./yr for poplar and miscanthus. The poplar and miscanthus have similar results with about 90% of the total TETP from the feedstock. Chromium and vanadium emissions of heavy metals to air account for 10% and 6%, of the feedstock burdens, respectively. The major contributor to the forest residue total TETP is 81% from the feedstock production. About 99% of the total TETP for wheat straw is associated with the crop production stage. Emissions of heavy metals to agricultural soil and air account for almost all TETP results.

Land Use

The total land use is highest with miscanthus (7.7×10^8 m^2 yr) and lowest with wheat straw (1.36×10^8 m^2yr). Majority of this is as a result of feedstock cultivation, which contributes about 95%.

5.3.3.2 Functional unit: 1 litre of ethanol

This section discusses the impacts for the functional unit of one litre of ethanol produced with other co-products. Both the results using system expansion and economic allocation are presented, respectively. As mentioned in section 5.3.2, in the former case, the system is credited with the avoided burdens for the co-products using the system expansion approach. For economic allocation, the prices for each co-product have been used as allocation factors.

1. System expansion

These results are shown in Figure 5.3. For the detailed results, see Appendix 4

Abiotic Depletion Potential:

The total ADP from all the feedstocks is about -4.5 g Sb.eq/l ethanol. Co-products credits from propanol are high in this category due to savings from non-renewable energy sources such as crude oil and natural gas.

Acidification Potential:

The total AP results with the avoided burden are in the range of 4-8 g SO_2 eq./ l ethanol. The total co-product credits from all the feedstock is about 1.5 g SO_2 eq./l ethanol. Feedstock and plant operations contribute to this impact. Forest residue has the least AP while wheat straw has the highest.

Eutrophication Potential:

The total EP per litre of ethanol is in the range 0.4-4 g PO_4 eq./ l ethanol, with wheat straw being the highest and forest residue being the lowest. The total credit from co-products from all feedstocks is about 0.25g PO_4 eq./l ethanol.

Global Warming Potential:

The total GWP per litre of ethanol ranges from -361- to -96 g CO_2 eq./l ethanol for forest residue to wheat straw, respectively. The total co-product credit is about 420 gCO_2 eq./l ethanol for all the feedstocks. This is mainly due to the credits from propanol production (approx 400 g CO_2 eq./l ethanol).. The feedstock contribution to GWP of 1 litre ethanol is 305, 95, 120, and 39 g CO_2 eq. for wheat straw, poplar, miscanthus, and forest residue, respectively

Human and Ecotoxoicty Potentials

The total FAETP, TETP, and HTP are all negligible for all the feedstocks with the exception of wheat straw. The main reason is due to the high feedstock emissions from wheat straw cultivation, which is about 10 times more than the other feedstocks. Hence, the total feedstock and plant operations emission outweighs the total credits from the co-products. The total MAETP for all feedstock is negligible. In these impact categories, the credits from the co-products are higher than the sum of the feedstock and operation emissions.

Ozone Depletion Potential:

Wheat straw has the highest feedstock impact (0.014 mg) while others are in the range of 0.0043-0.0088 mg R11/l ethanol. The average total plant emission is about 0.0033 mg for all feedstocks. For all feedstocks, the total ODP is negligible indicating a saving.

Photochemical Oxidant Creation Potential:

The average co-product credit for all four feedstocks is about 6.8 g ethene eq/l ethanol. The feedstock emissions is highest in forest residue with about 0.13, followed by wheat straw with 0.11 g ethene /l ethanol while others are about 0.03g ethene. For all feedstocks, the total POCP is negligible indicating a saving.

Land Use

Miscanthus has the highest total land use of about 3.2 m^2 yr while wheat straw is the least with 1.34 m^2 yr

2. Economic allocation

The results with the economic allocation are shown in Figure 5.4. The economic allocation ratio for the thermo-chemical process is about 80%, 2 % and 18% for emissions allocated to ethanol, butanol and propanol, respectively. Similarly, to the bio-chemical study, most of the emissions are allocated to ethanol, followed by propanol. A brief overview of the results is given below; for the full results, see Appendix 4. Overall, a similar trend in the environmental impacts is noticed as for the system expansion with ethanol from forest residue and poplar being the best options and wheat straw the worst. The cost assumed for proponal is £1345/tonne (ICIS 2012) while butanol is £1323/tonne (ICIS 2012).

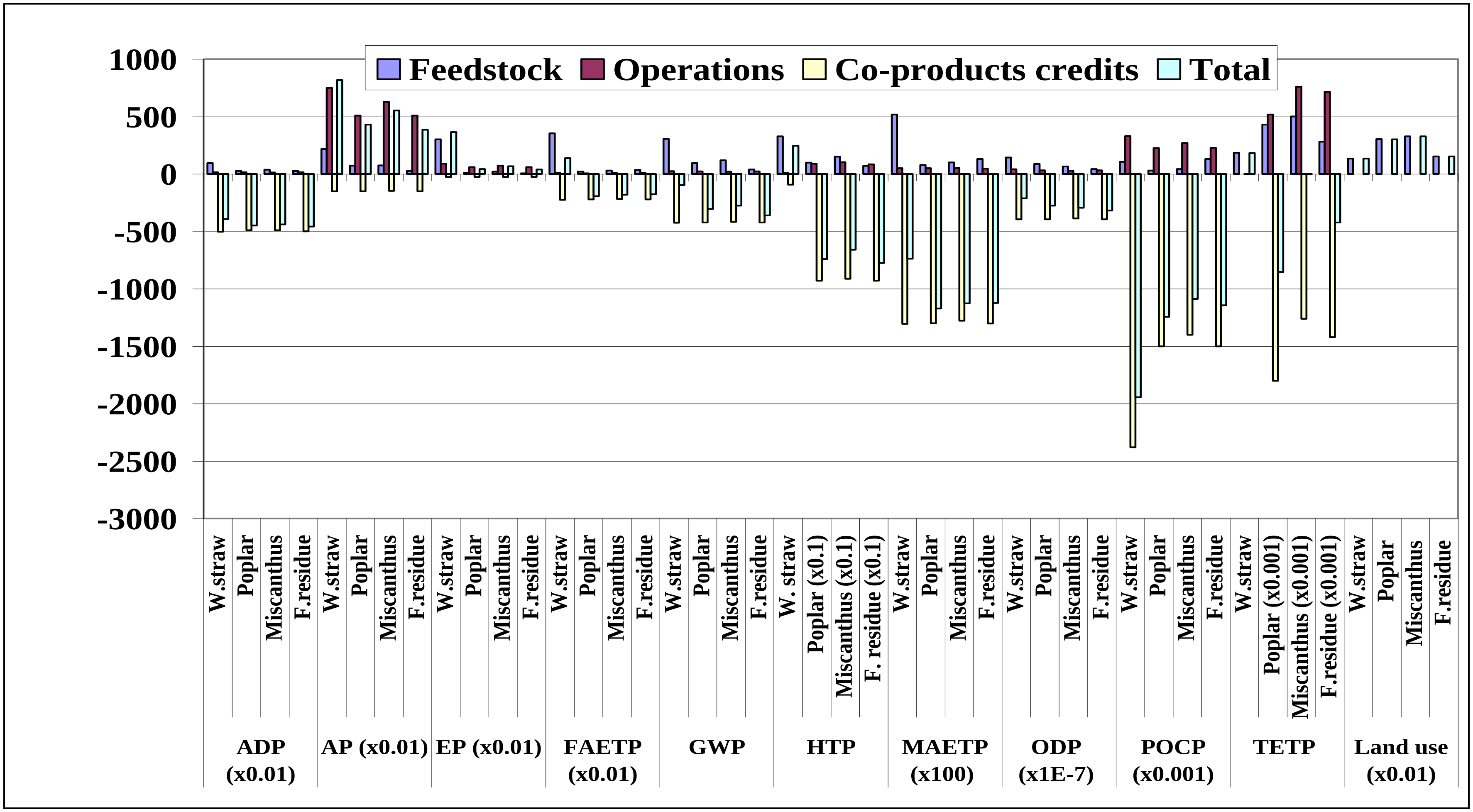


Figure 5.3. Environmental impacts of ethanol for system expansion (g/l)-

[All units in g/l ethanol, except for land use which is in m^2.yr. Credits: Propanol –production from propene and butanol form propylene. ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP; Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity; HTP; Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP; Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential**]**

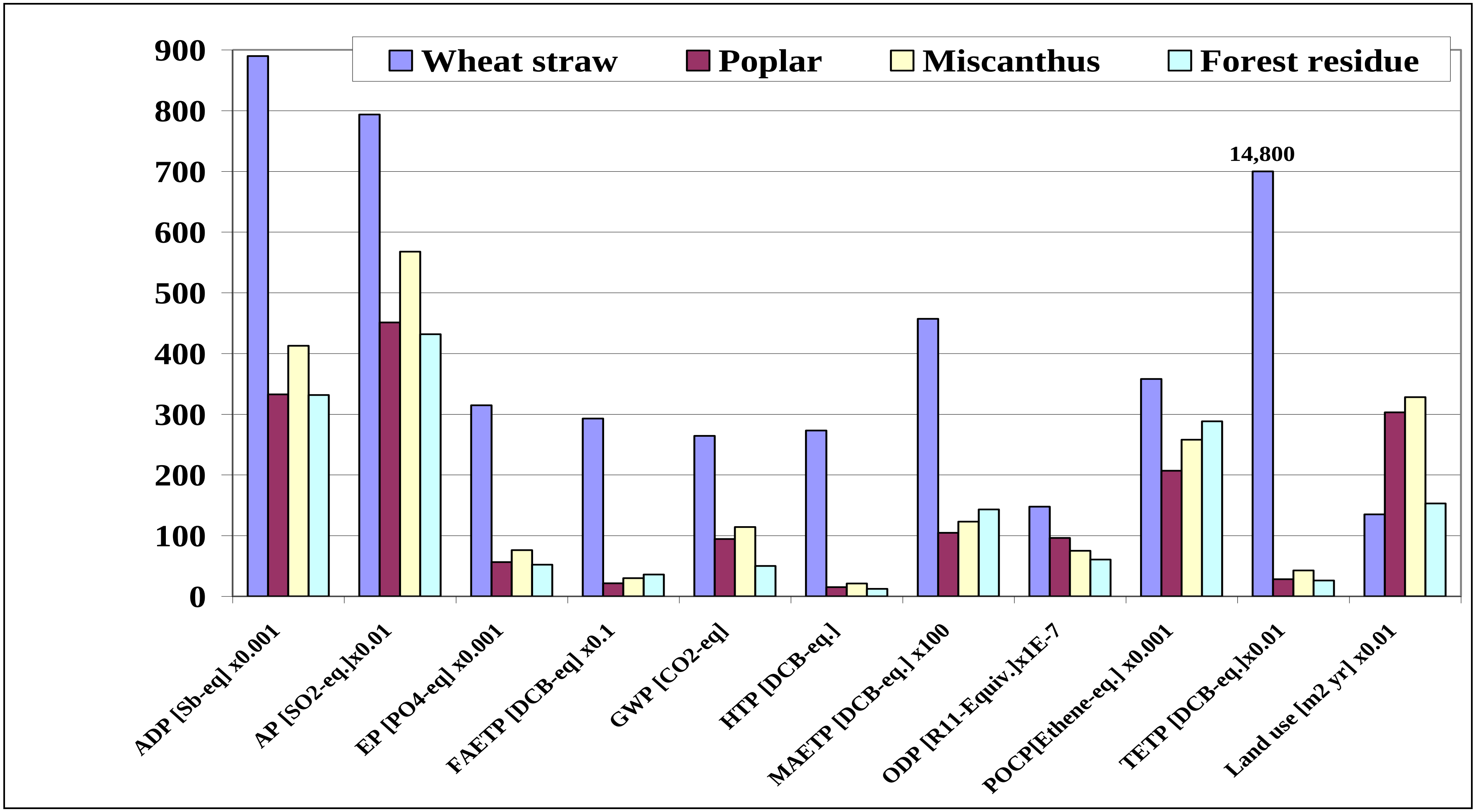


Figure 5.4. Environmental impacts of ethanol for economic allocation [All units in g/l ethanol except for land use which is in m^2.yr.]

5.3.4 Land use change

This section considers the effect of possible land use change on the GWP results. Potentially, this only applies to two types of feedstock here: poplar and miscanthus. The following assumptions have been made, similar to the bio-chemical study.

- GHG emissions of 20 t CO_2 eq./ha/yr of as a results of forest land conversion into land used for cultivation of poplar and micanthus (assuming the use for 'perenials') (BSI, 2011); and
- GHG emissions of 6.7 t CO_2 eq. /ha/yr as a result of grassland conversion into forest land (BSI, 2011).

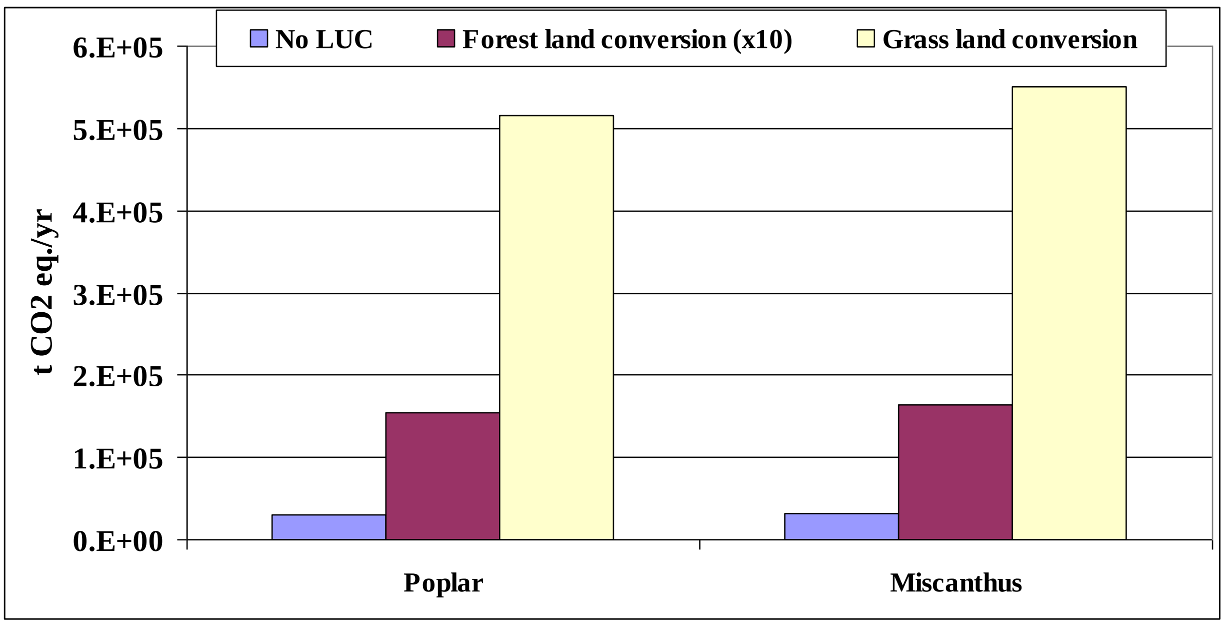


Figure 5.5 Impact of land use change on GWP

Figure 5.5 shows the result of possible effect on land use change on GWP results. When forest land is converted to land used for poplar and miscanthus cultivation, there is an increase of about 98% in the GWP compared to the case with no land use change. However, if the land use is changed from grassland to cultivation of 'perenials', the total GWP increases by about 95%. In both land use change cases, the results are sensitive to the GWP results and must be considered in any future development of thermo-chemical refineries.

5.3.5 Comparison of results with other studies

This section compares the LCA results of this study with other LCA studies on ethanol from 2nd generation feedstocks via the thermo-chemical route. Literature on thermo-chemical LCA studies is rather limited as compared to bio-chemical studies. The study by Mu et al. (2010) compared the GHG, emissions of ethanol from a range of feedstocks using the thermo-chemical conversion. The system was credited for propanol and butanol production similar to this study. The results for this study are about 25% higher than the study by Mu et al. (2010) with the exception of poplar, which is about 15% less in this study. The authors were not transparent about the quantities of propanol and butanol, however, the difference in the plant co-product credit is about 17%, and this is small.

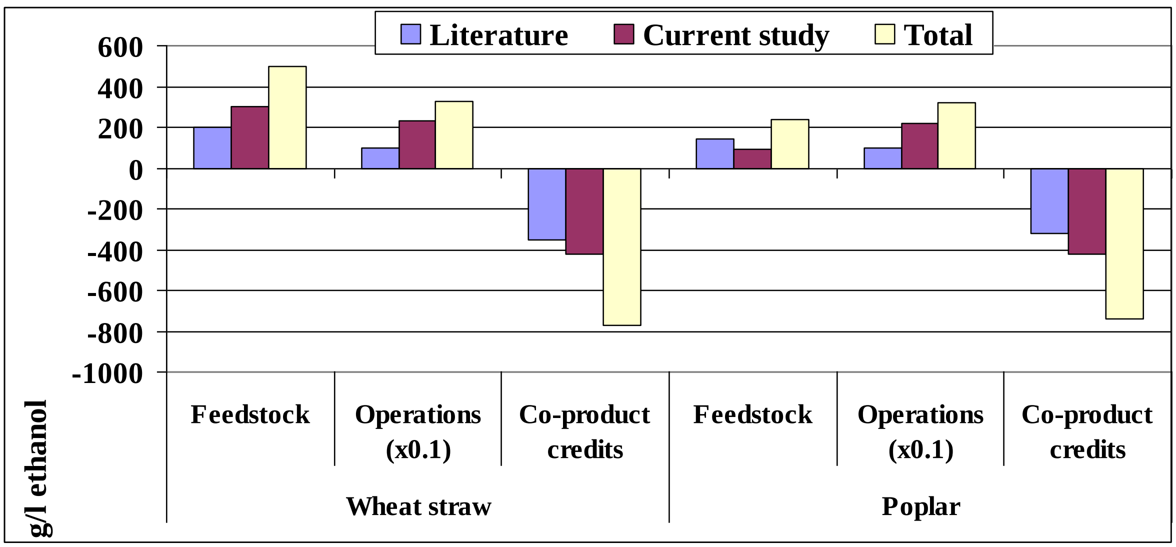


Figure 5.6 . Comparison of GHG emissions for the wheat straw and poplar thermo-refinery and literature (Mu et al.2010)

5.3.6 Comparison of thermo-chemical refinery with fossil- based refinery

This section compares the results of the life cycle environmental impacts of a thermo-chemical refinery in addition to its products with the environmental impacts from the fossil-based refineries producing the same products differently. The inventory data for fossil derived products were taken from the Eco-invent (2007) database and the following production routes have been assumed:

- ethanol from ethylene;
- propanol from propene;
- butanol from propylene;

To enable this comparison, equal amounts of products have been assumed for both the thermo-refinery and the fossil –derived refinery. These are shown from (Figure 5.7-5.10). As can be seen, all of the thermo-refinery bio-feedstock options have lower impacts in all categories than their fossil-derived alternatives expect with AP and land use. This due to the emmisons of flue gas from the gasification unit. Other additional exception is with wheat straw feedstock, which has higher impacts in EP, TETP, and HTP. This is due to emissions from the feedstock cultivation.

Therefore, it can concluded that, for the assumptions made in this study, producing the range of products from the feedstocks considered here in an integrated thermo-chemical refinery is environmentally more sustainable than producing the same products using fossil resources.

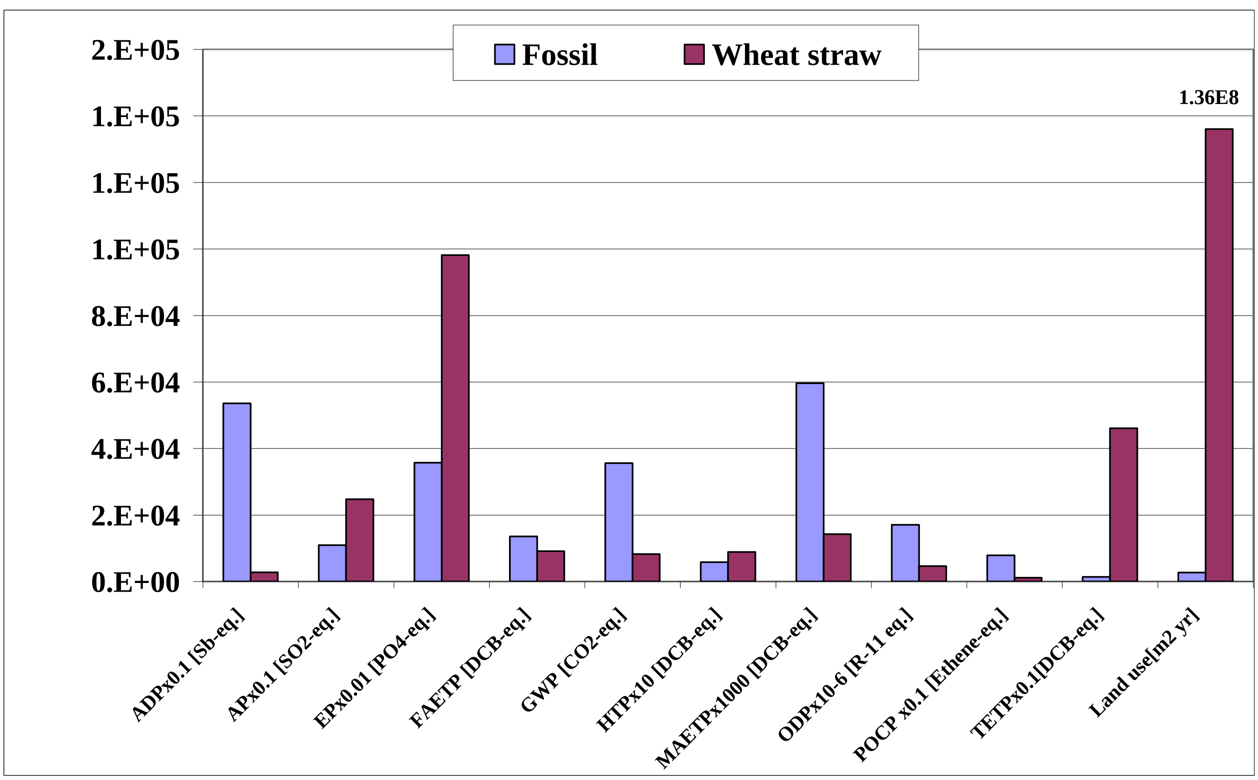


Figure 5.7. Comparison of impacts for the thermo-refinery products using wheat straw and the equivalent fossil-based products [All units in tonnes/year except for land use which is in m^2.yr]

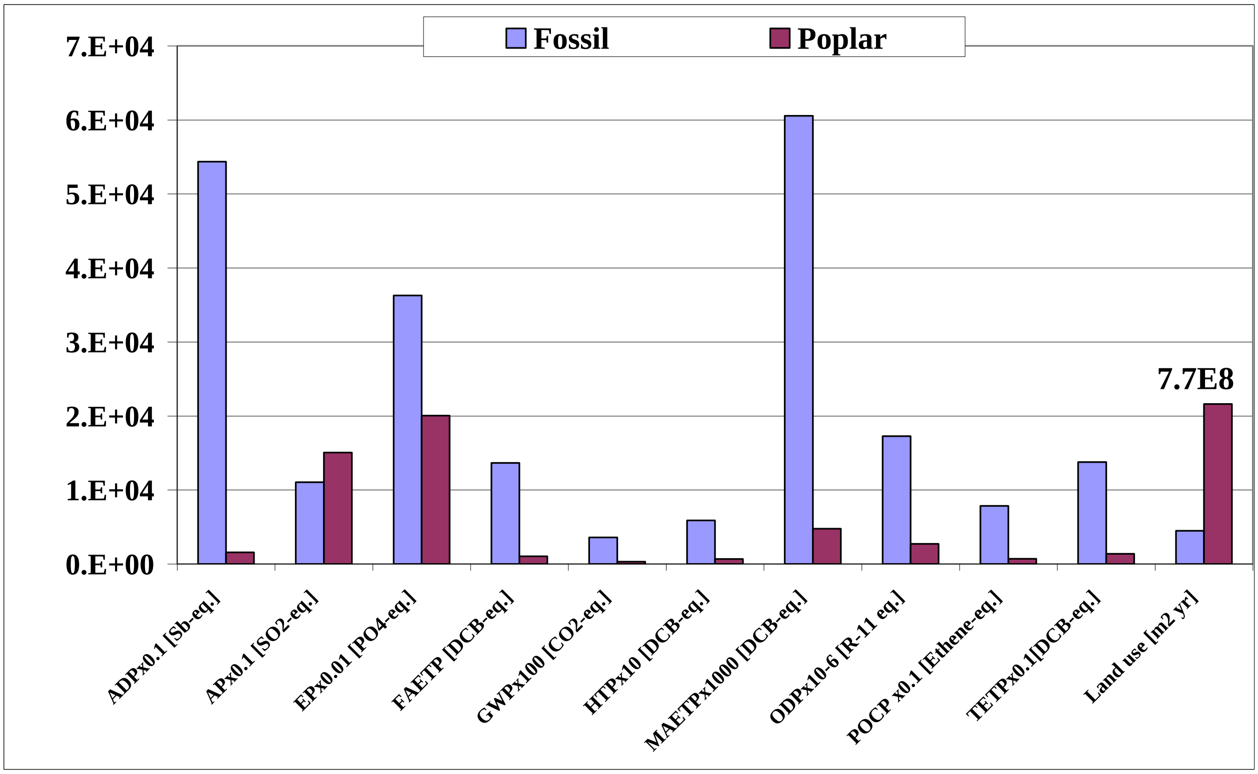


Figure 5.8. Comparison of impacts for the thermo-refinery products using poplar and the equivalent fossil-based products[All units in tonnes/year except for land use which is in m^2.yr]

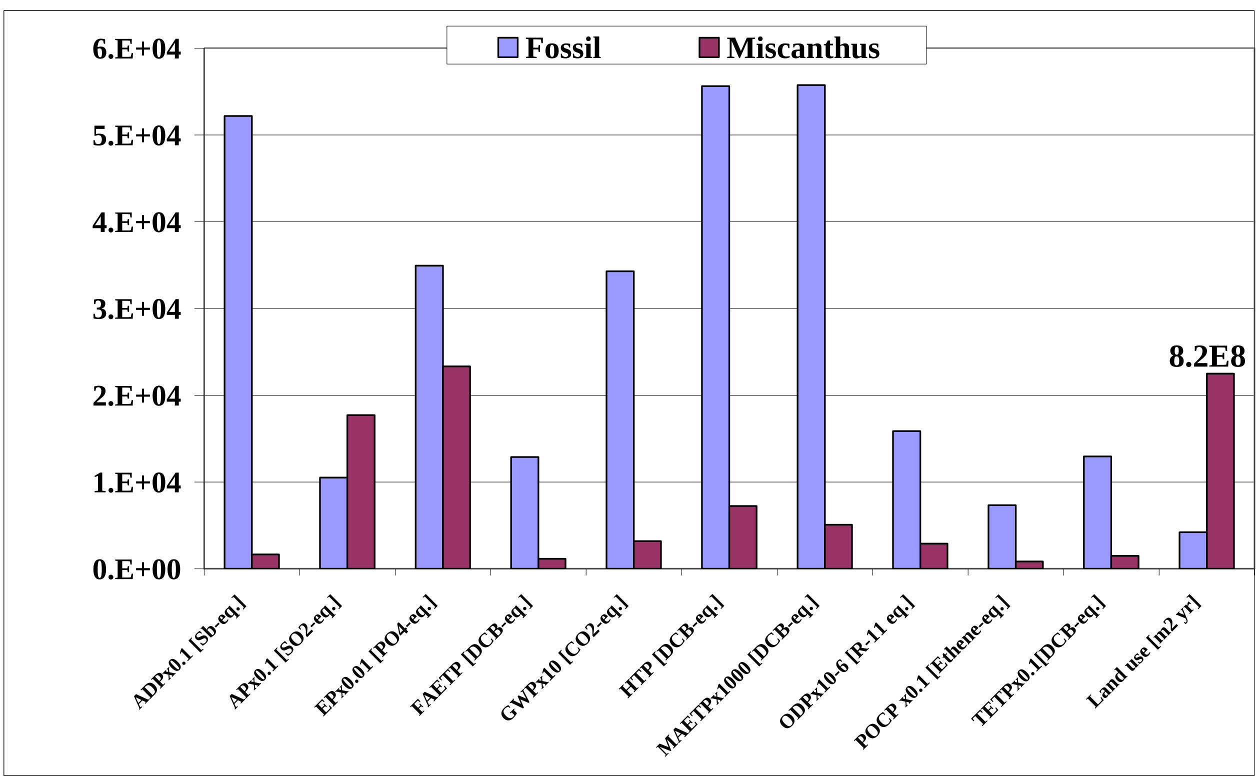


Figure 5.9 Comparison of impacts for the thermo-refinery products using miscanthus and the equivalent fossil-based products. [All units in tonnes/year except for land use which is in m^2.yr]

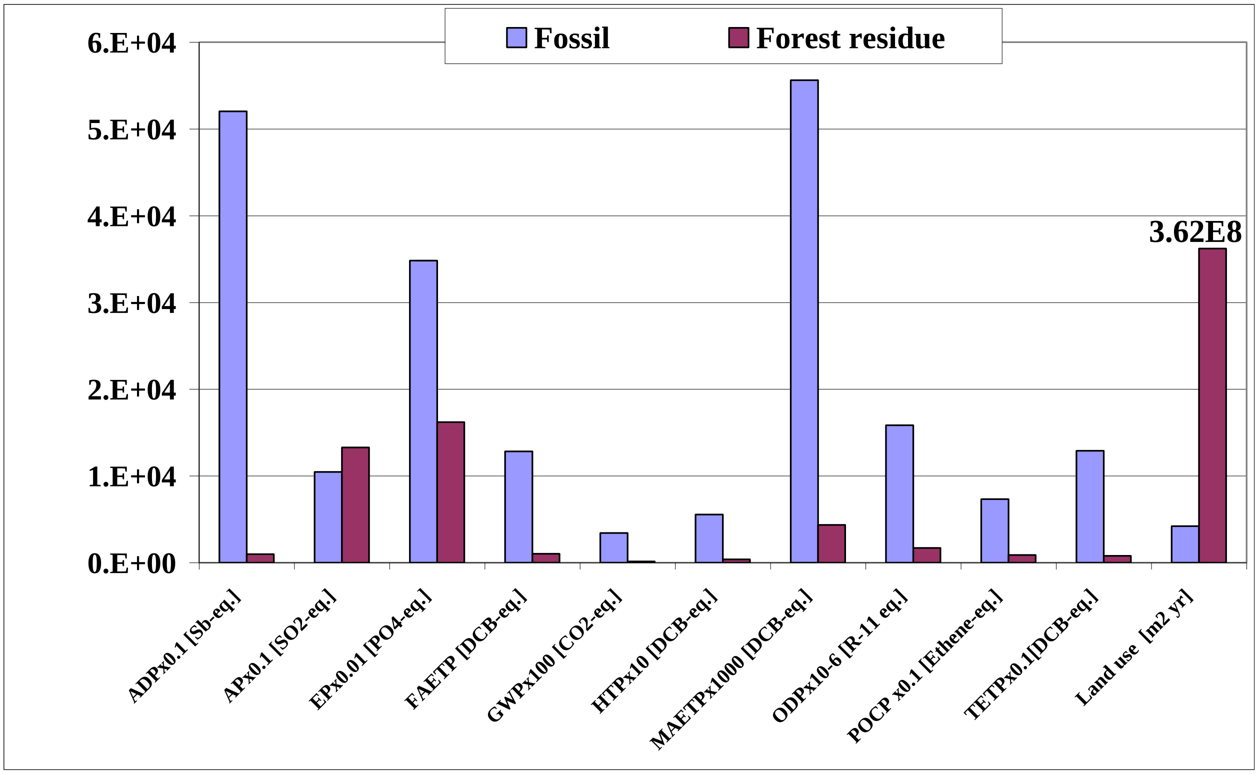


Figure 5.10 Comparison of impacts for the thermo-refinery products using forest residue and the equivalent fossil-based products

The results of the products from the thermo-chemical refinery were compared with the results if they were sourced from fossil sources. In Figure 5.11, when the results were compared based on system expansion, all impacts from ethanol from ethylene were higher than the 2nd generation bio-feedstocks with the exception of AP, EP, HTP, and TETP from wheat straw. Land use is also higher for wheat straw and forest residue than from ethanol from ethylene. The result is similar for economic allocation (see Figure 5.12).

When the result of propanol (see Figure 5.13) is compared, all impacts from propene were higher than ethanol from 2nd generation bio-feedstocks. An exception to this is ethanol from wheat straw has higher TETP. A similar trend is noticed with butanol from propylene (Figure 5.14), however, all impacts are higher for the alternative fossil source.

Therefore, it can concluded that, for the assumptions made in this study, producing the range of products from the feedstocks considered here is environmentally more sustainable than for all feedstocks with the exception of wheat straw due to agricultural activities.

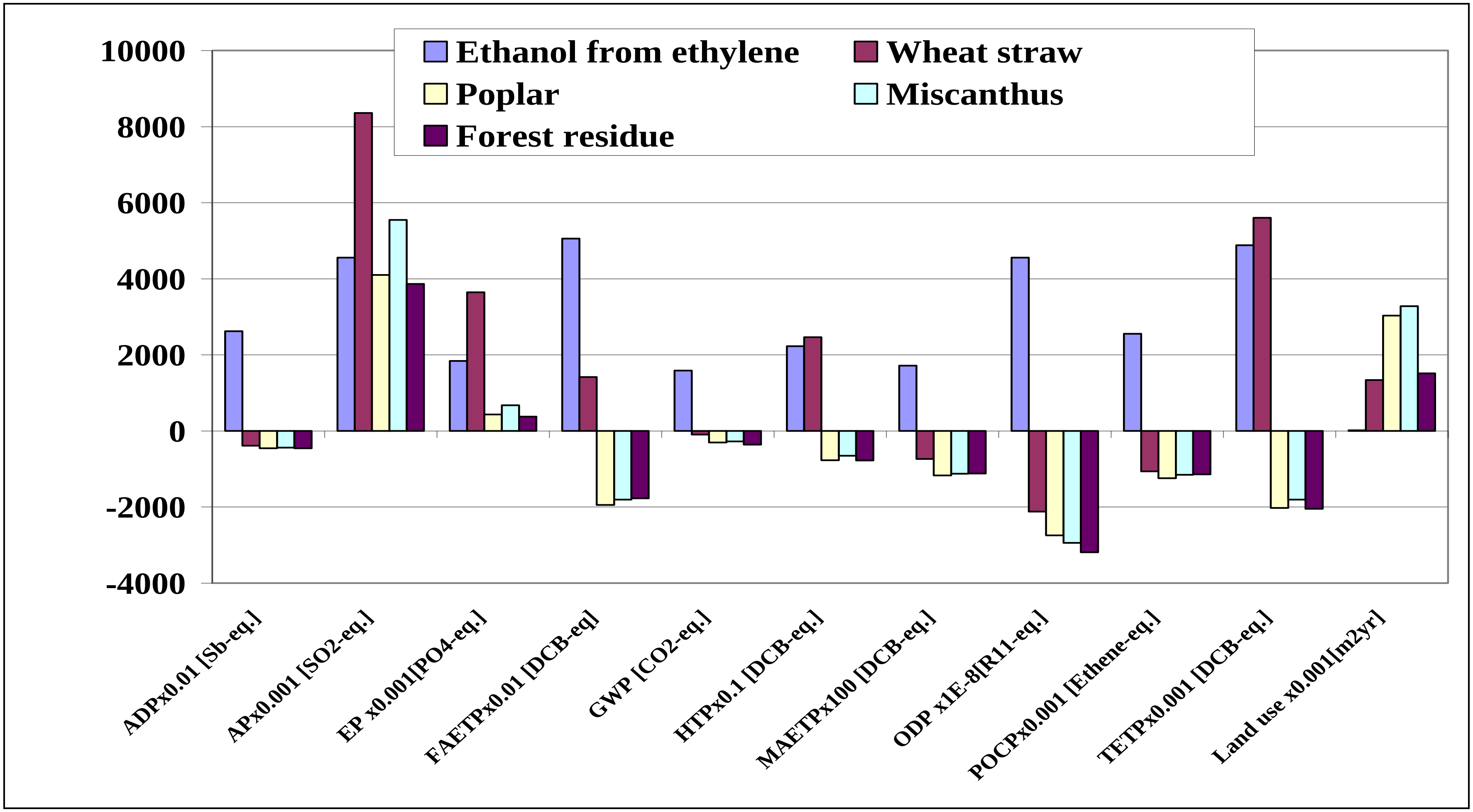


Figure 5.11 Comparisons of impacts of ethanol from 2nd generation feedstocks with ethanol from ethylene (using system expansion) [All units in g/l except for land use which is in m^2 yr]

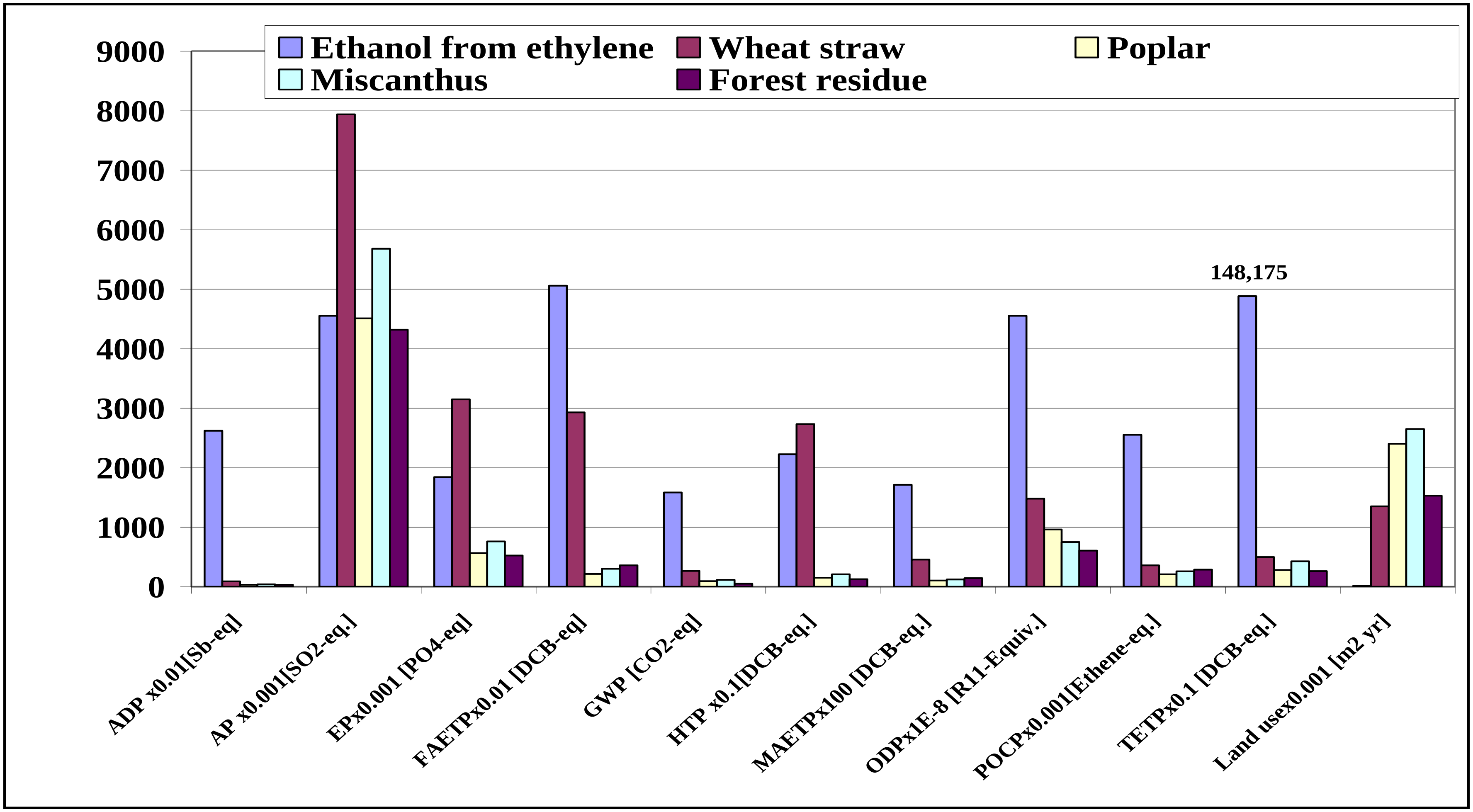


Figure 5.12 Comparisons of impacts for the thermo-refinery with ethanol from ethylene (economic allocation)
[All unit in g/l except for land use which is in m^2 yr]

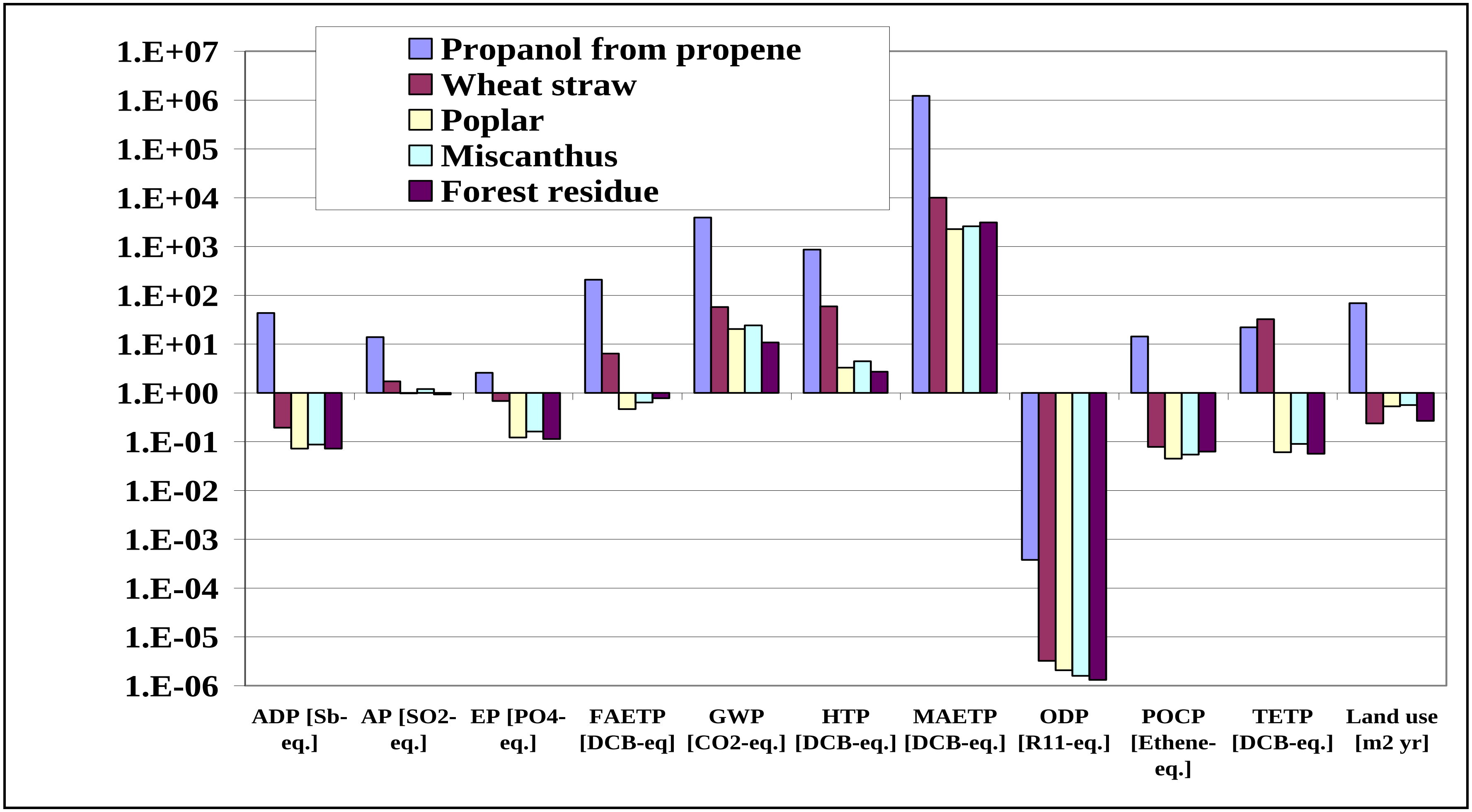


Figure 5.13 Comparisons of impacts allocated to propanol (produced in the thermo-chemical refinery) with propanol made from propene [All units in g/l except for land use which is in m^2 yr]

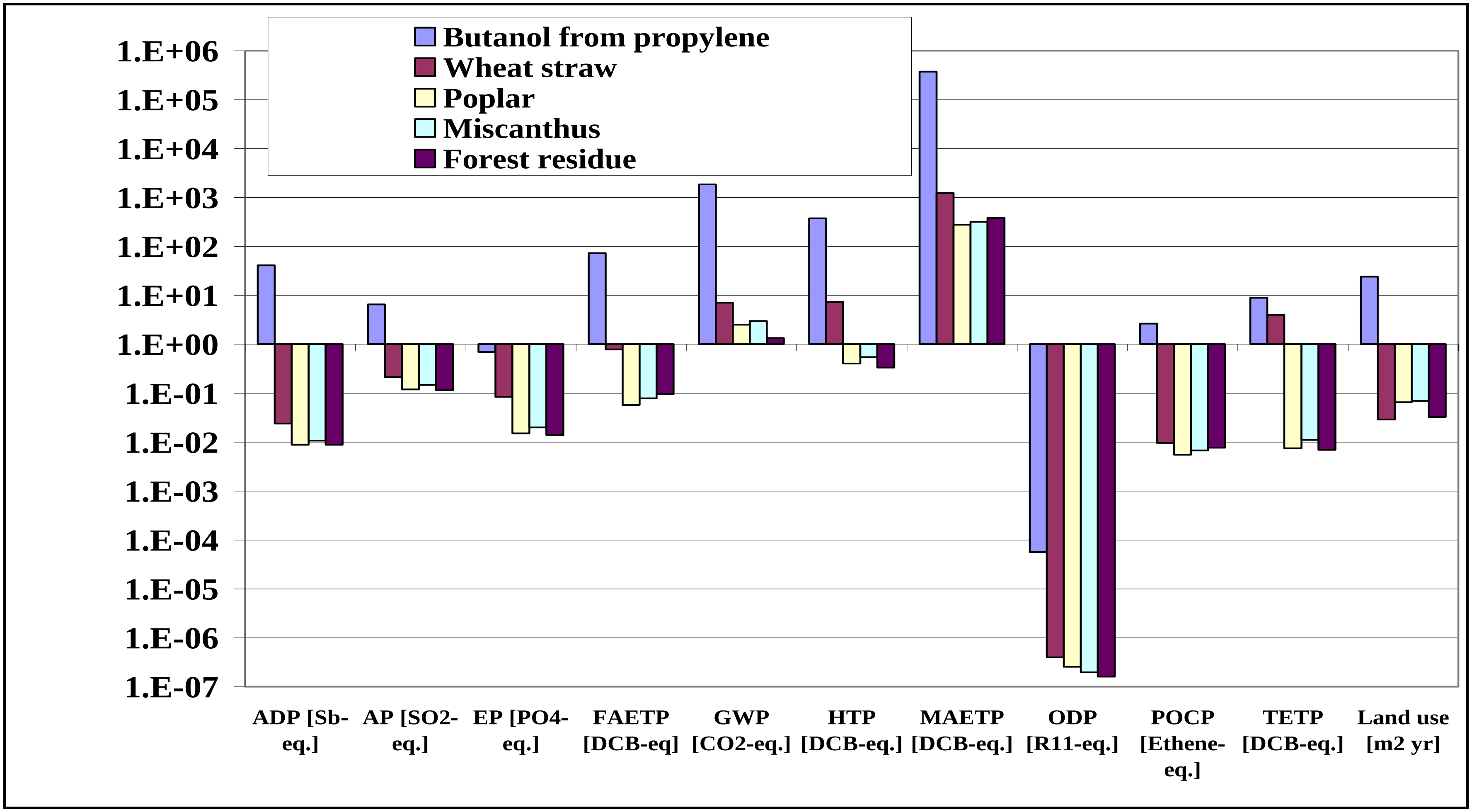


Figure 5.14 Comparisons of impacts allocated to butanol (produced in the thermo-chemical-refinery) with butanol made from propylene [All units in g/l except for land use which is m^2 yr]

5.3.7 Comparison of ethanol from 1st and 2nd generation feedstock

In this section, the LCA results of ethanol of this study are compared with LCA impacts of ethanol production from wheat grain and sugar beet. These feedstocks are selected for the same reason as mentioned in section 4.3.7 and the data sources are the same. As seen, it can be clearly seen that the impacts of bio-ethanol from 1st generation feedstocks are considerably higher than the bio-ethanol from 2nd generation feedstocks. As shown in Figure 5.15 and Figure 5.16, all impacts are lower for 2nd generation feedstock .

Therefore, it is clear that ethanol from 2nd generation feedstocks (considered here) is environmentally more sustainable that ethanol from 1st generation feedstocks such as wheat and sugar beet.

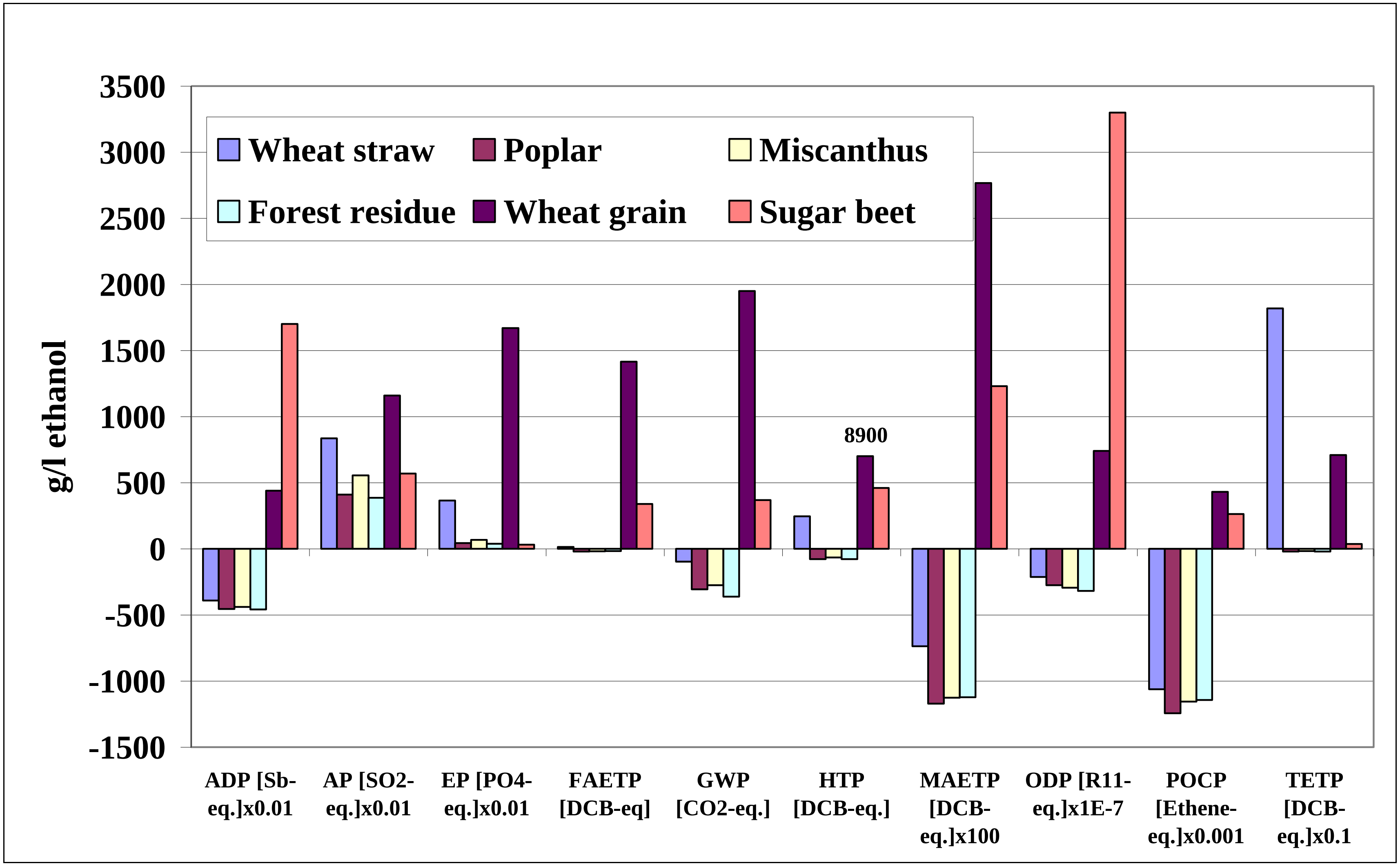


Figure 5.15 Life cycle impacts of ethanol from 1st and generation feedstocks using system expansion

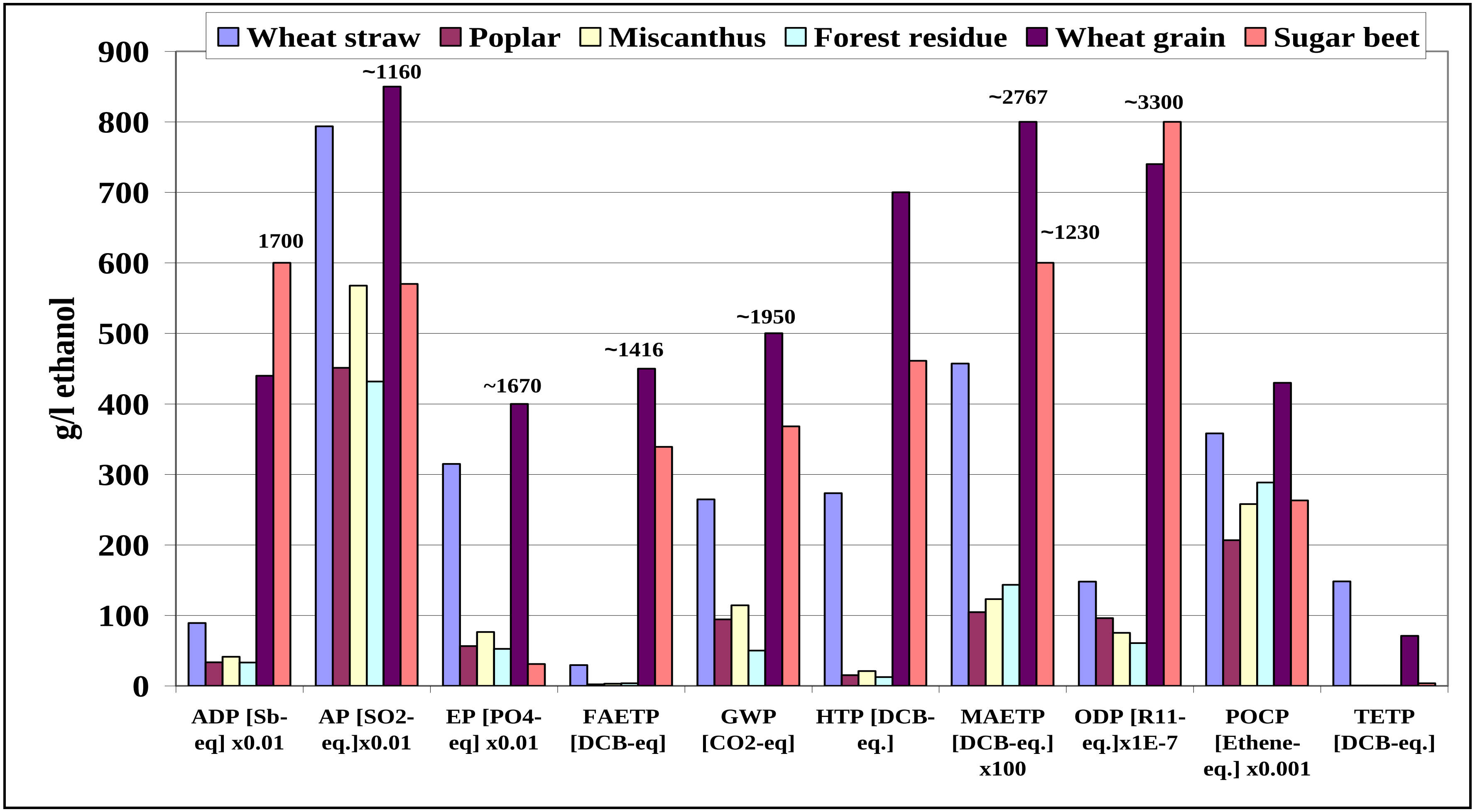


Figure 5.16 Life cycle impacts of ethanol from 1st and 2nd generation feedstocks using system economic allocation for the latter

5.3.8 Comparison of ethanol from 2nd generation feedstocks with petrol

Similar to the bio-chemical study, the LCA impacts are compared for 'cradle to gate' and 'cradle to grave', the later includes the use phase of petrol. The comparison in all cases is on the basis of the energy content in the fuel. The LCA data for petrol (unleaded and low sulphur) are taken from Ecoinvent (2007). The data for the use stage of ethanol are also from Ecoinvent and they have been added to the 'cradle to gate' environmental impacts estimated in this study

5.3.8.1 Comparison from cradle to gate

As shown in Figure 5.17, The AP and EP results from all four feedstocks considered in the 2nd generation refinery were higher than the petrol production LCA results. This is due to high NO_x and SO_2 emissions associated with the thermo-refinery. All other impact categories with the exception of TETP and HTP are higher for the wheat straw system only. The high HTP is as a result of high feedstock emissions. In Figure 5.18, where economic allocation is used, there is a similar result, in addition to the above impacts, ethanol from wheat straw has higher FAETP, This is mainly due to feedstock contribution.

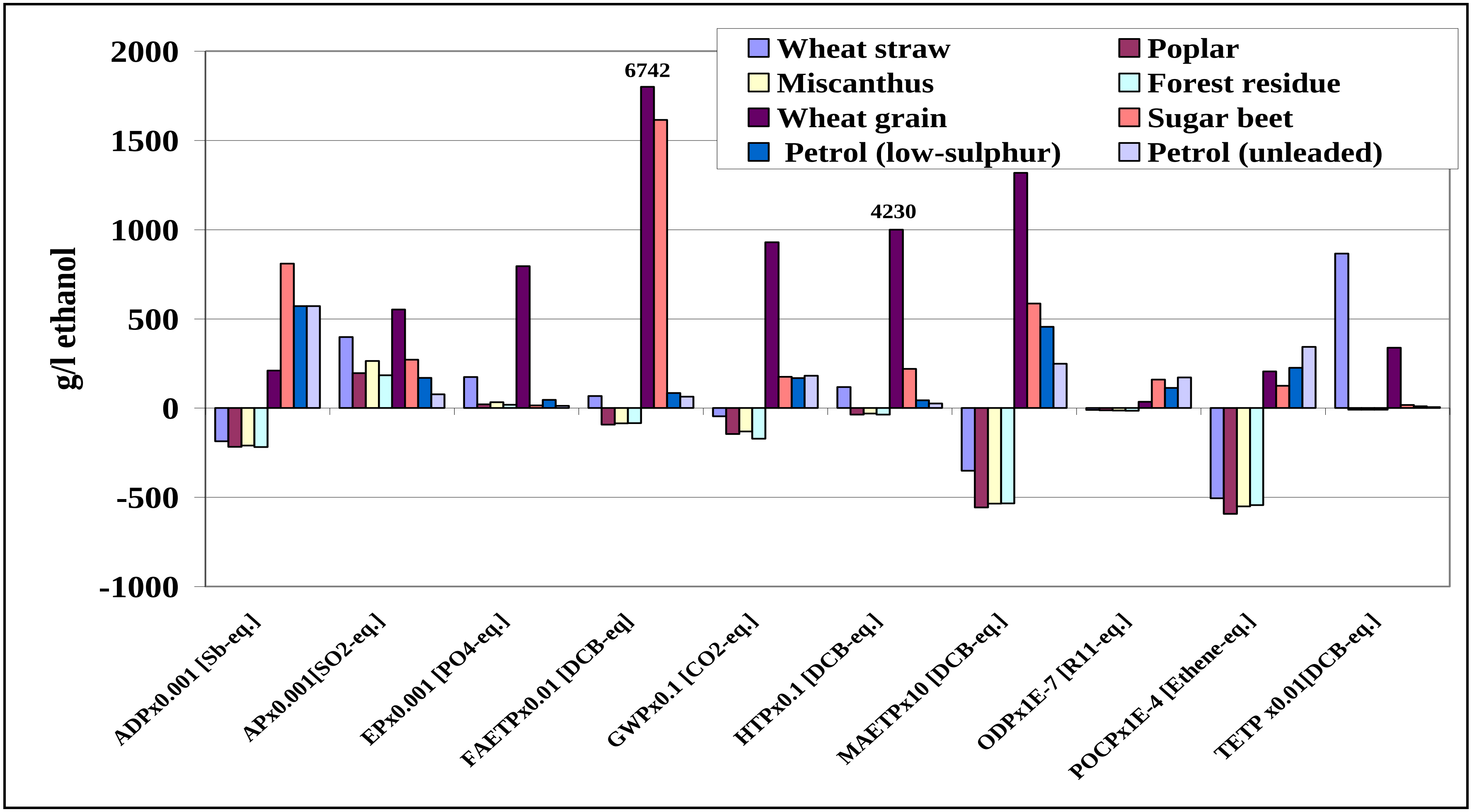


Figure 5.17 LCA impacts of ethanol from 2nd generation feedstock using system expansion compared with petrol and 1st generation ethanol (system boundary: from 'cradle to gate')

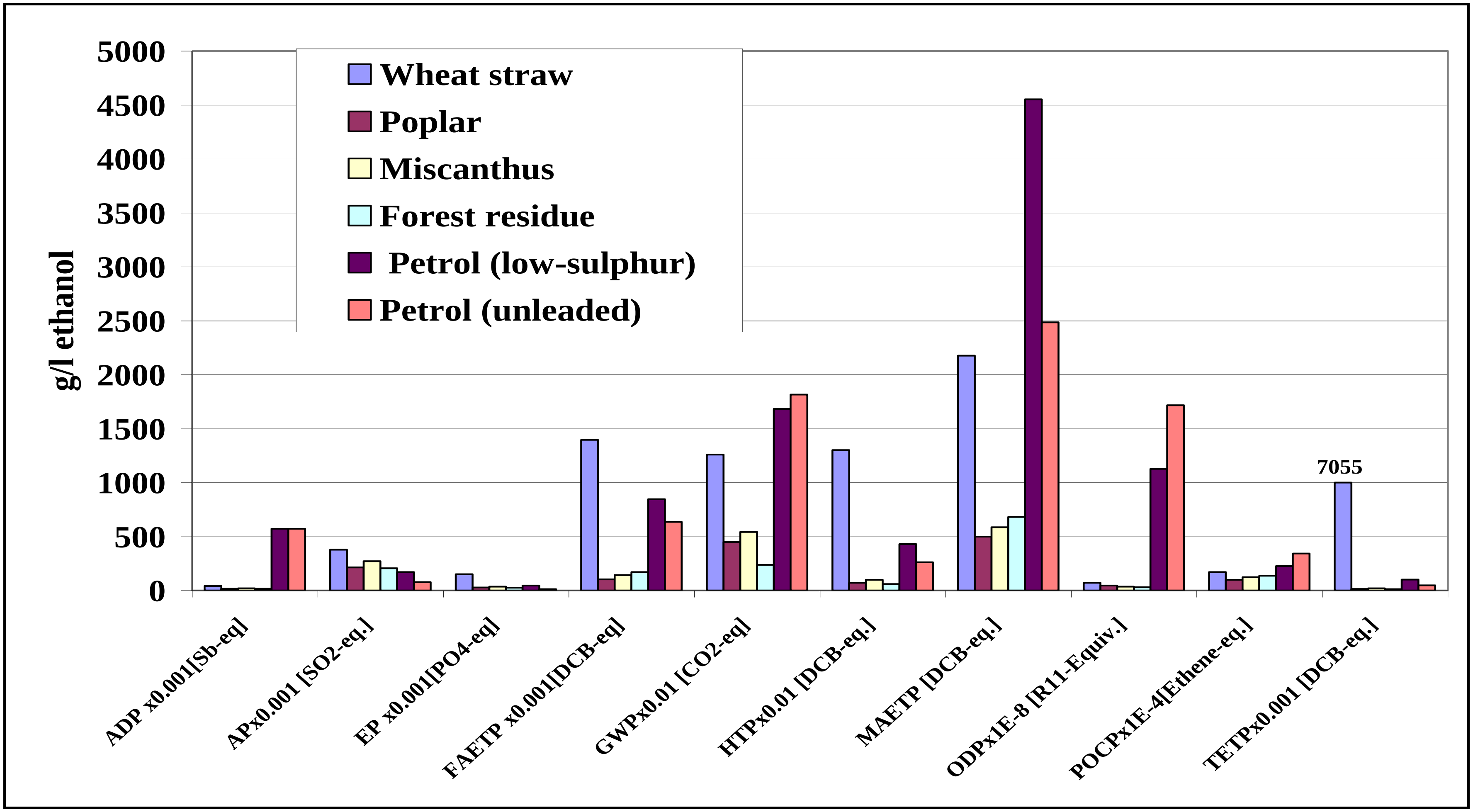


Figure 5.18 LCA impacts of ethanol from 2nd generation feedstock using economic allocations compared with petrol and 1st generation ethanol (system boundary: from 'cradle to gate')

5.3.8.2 Comparison from 'cradle to grave'

In this section, the impacts are considered from 'cradle to grave'. The combustion of petrol considered here is 15 % vol of petrol from biomass mixed with 85% vol of ethanol and 4 % vol of ethanol from biomass mixed with 96% vol of petrol. Please note that results include emmisons from tyre abrasion.

As seen in Figure 5.19 and Figure 5.20 using system expansion, all the impacts from 'cradle to grave' for petrol are higher than 2nd generation biomass except AP, EP, FAETP, and TETP. Ethanol from wheat straw exhibit higher impacts in all of the above and HTP. The same result is noticed if economic allocation is used (see Figure 5.21 and Figure 5.22)

All the 2nd generation bio-feedstocks have higher AP, EP, TETP, and FAETP as compared to petrol use in cars. In addition to these impacts, wheat straw has higher HTP and TETP results. These results are because of feedstock cultivation. In conclusion, the use of wheat straw as a feedstock is not environmentally sustainable.

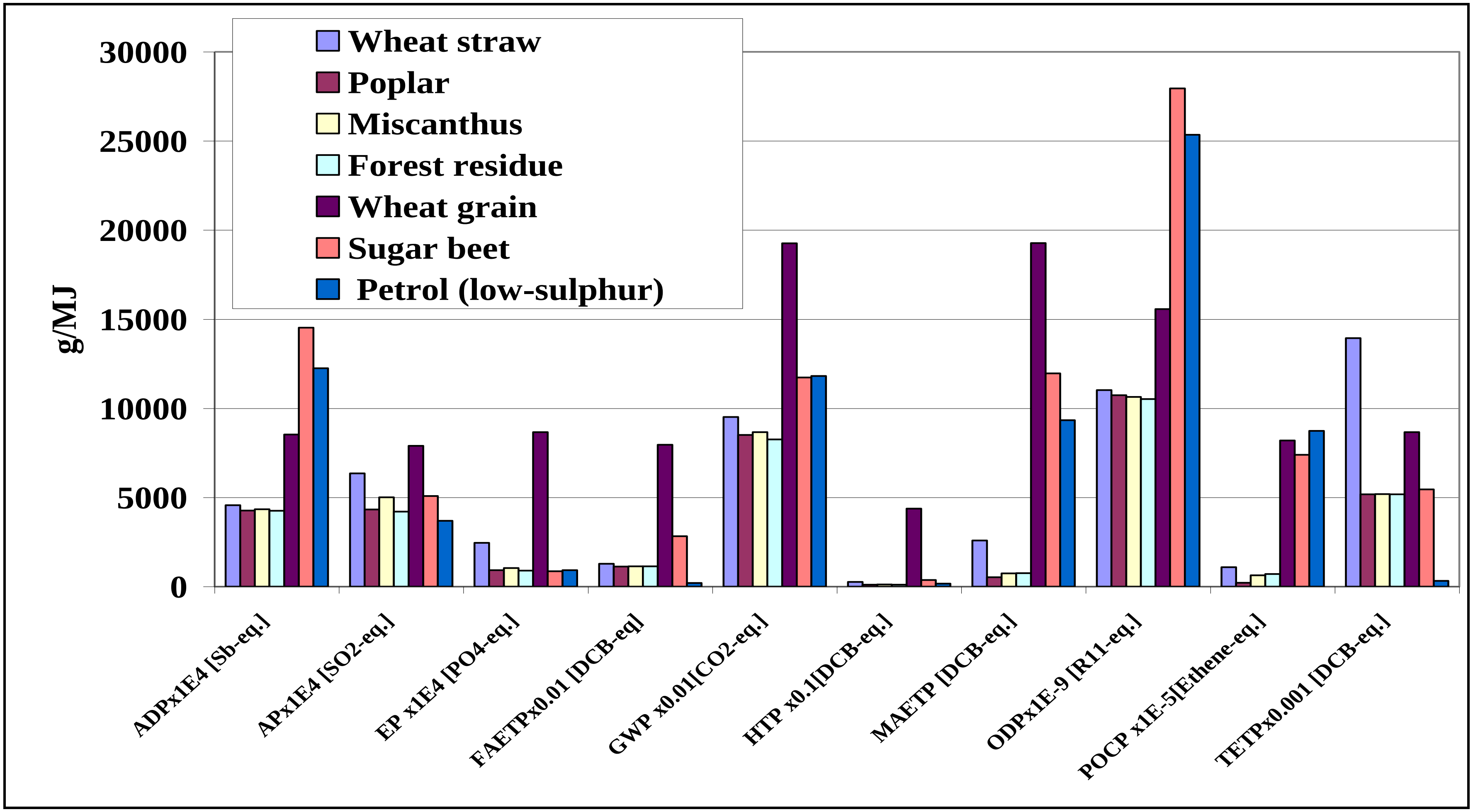


Figure 5.19 Comparison of environmnetal impacts of pure petrol with the petrol/ethanol mixture (85%/15%) for different 2nd and 1st generatin feedstocks (system expansion; system boundary: from 'cradle to grave')

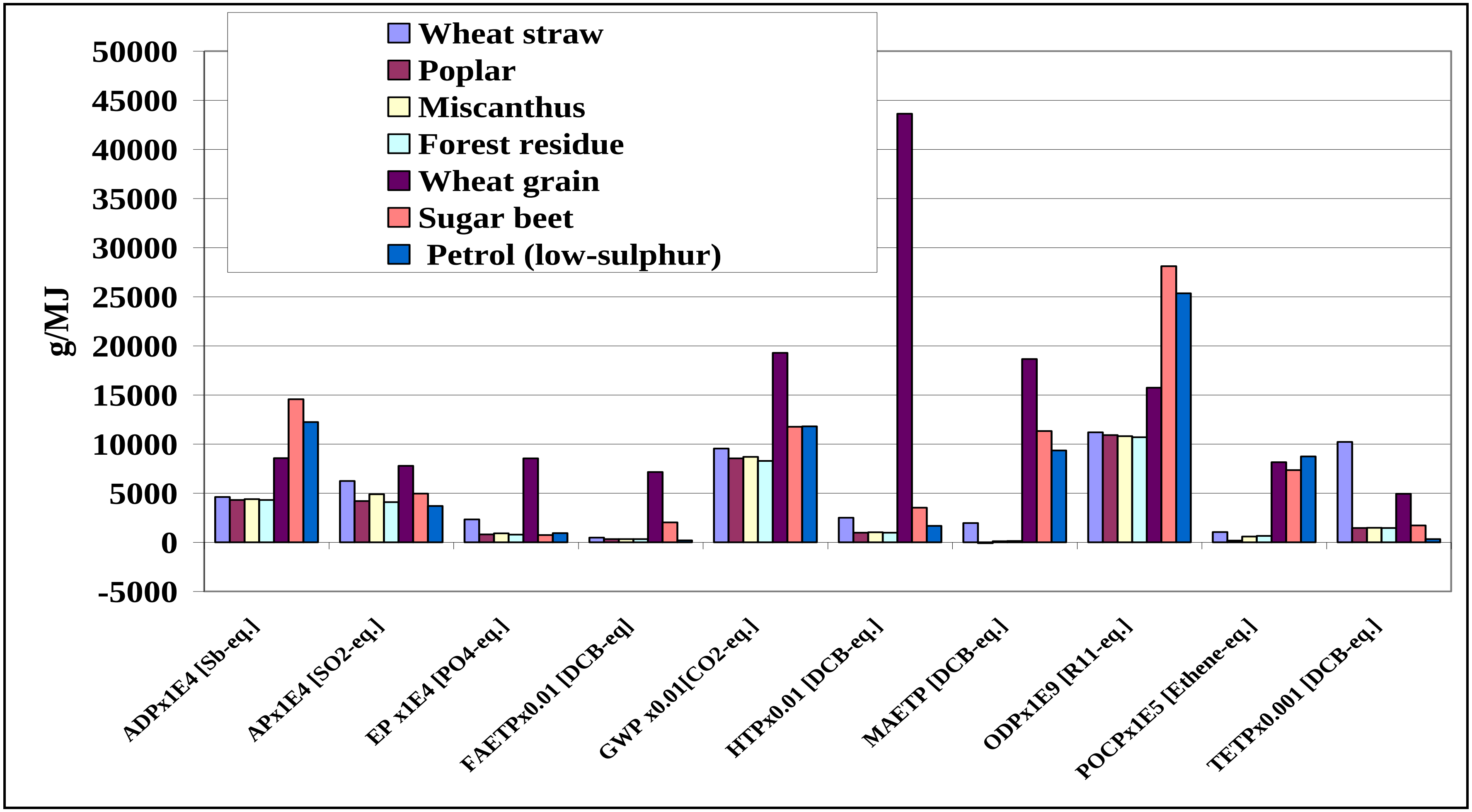


Figure 5.20 Comparison of environmnetal impacts of pure petrol with the petrol/ethanol mixture (96%/4%) for different 2nd and 1st generatin feedstocks (system expansion; system boundary: from 'cradle to grave')

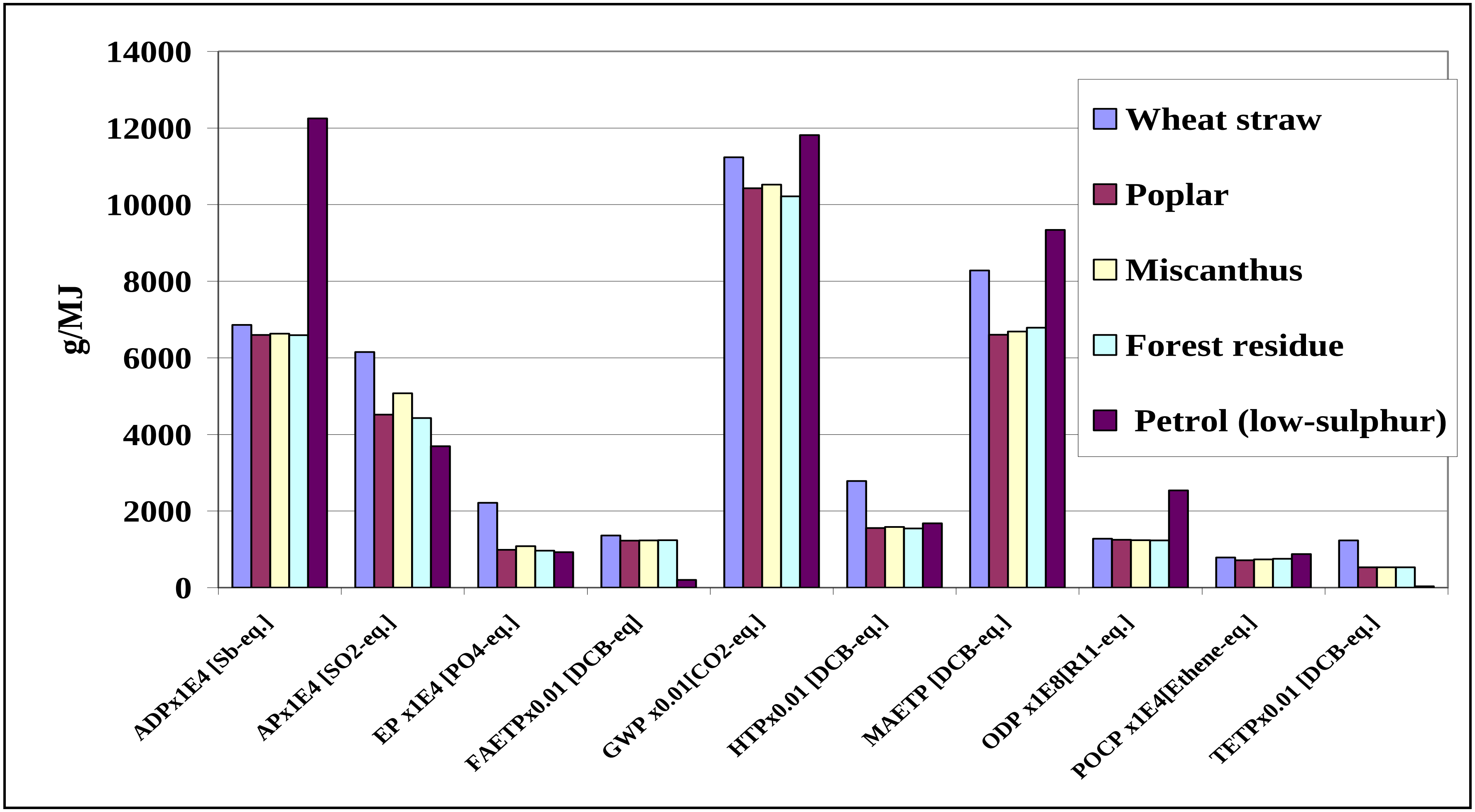


Figure 5.21 Comparison of environmnetal impacts of pure petrol with the petrol/ethanol mixture (85%/15%) for different 2nd generation feedstocks (economic allocation; system boundary: from 'cradle to grave')

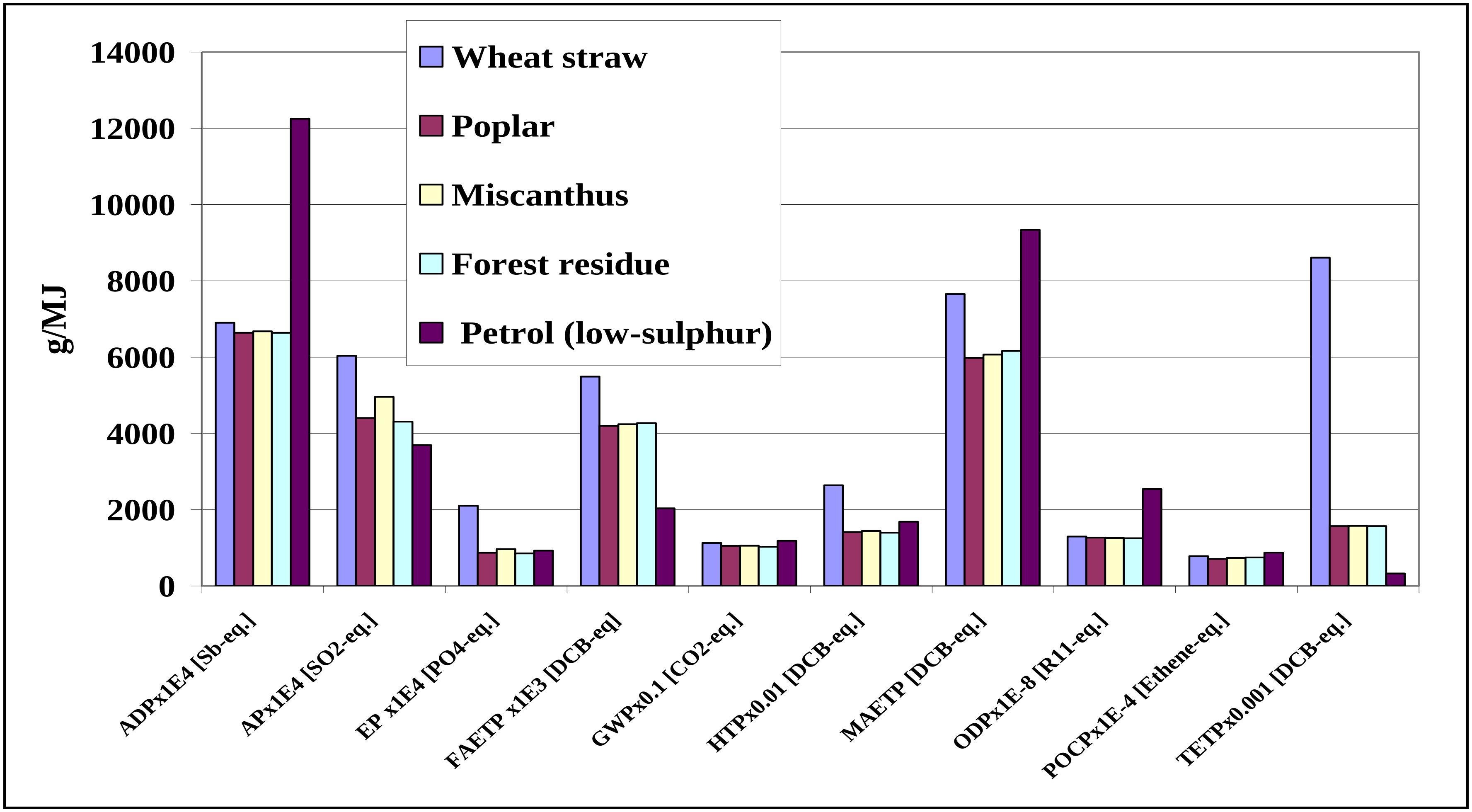


Figure 5.22 Comparison of environmnetal impacts of pure petrol with the petrol/ethanol mixture (96%/4%) for different 2nd generation feedstocks (economic allocation; system boundary: from 'cradle to grave')

5.4 Techno-economic sustainability assessment

The results of the techno-economic assessment are obtained using the indicators discussed in Chapter 3. The technical indicators that have been quantified are technology efficiency (product yield and mass and energy efficiency) and plant capacity. The remaining two - feedstock flexibility and technology availability – are not quantitative indicators so no further analysis is provided beyond the fact that integrated thermo-chemical refineries have the flexibility with different feedstock and that they are not available on a commercial scale yet.

The economic indicators comprise life cycle costs (capital and operating), net present value (NPV), internal rate of return (IRR), minimum ethanol selling price (MESP) and payback time. The results are presented in Table 5.2 and discussed in turn below.

As seen, the yield of ethanol per tonne of feedstock increases in the order of wheat straw<miscanthus<poplar<forest residue. The ethanol yield from wheat straw and poplar has been reported in previous thermo-chemical studies as between 270-283 l/t and 283-349 l/t, respectively (Mu et al., 2010; Gnansounou and Dauriat 2010). This study reports 289 l/t and 325 l/t for wheat straw and poplar, respectively. There is currently no reported ethanol yield data for forest residue and miscanthus.

The energy efficiency for an ethanol output only, is as follows 35% for wheat straw, 37% for poplar, 35% for miscanthus, and 43% for forest residue. These figures increase when the other co-products are also considered in the output. In the latter case, the energy efficiency is in the range of 40-50% for all feedstocks (see Table 5.2 below). The mass efficiency is also calculated for all the feedstocks and both poplar and forest residue have a mass efficiency of 26% while wheat straw has the lowest (23%). When co-product are added (propanol, butanol) this goes up slightly to 25-30 %

Using the above results for the yield and efficiencies, and assuming the capacity of the plant (250 Ml/yr of ethanol) for all four feedstocks, the required biomass treatment capacity ranges from 770 kt/yr for poplar to 854 kt/yrfor wheat straw.

		Wheat straw	Poplar	Miscanthus	Forest residue
Technical indicators	**Unit**				
Ethanol yield	l/t	289	325	293	326
Energy efficiency (ethanol)	%	35	37.2	37.4	42
Energy efficiency (ethanol & co-products)	%	40	43.8	40.9	50
Mass efficiency (ethanol)	%	23.1	26	24	26
Mass efficiency (ethanol & co-products)	%	26.5	29.8	24.7	29.8
Biomass treatment capacity	kt /yr	854	770	820	753
Ethanol production capacity	Ml	250	254.6	250.3	248
Economic indicators					
Total Feedstock cost	£M	27.3	47	49	22.6
Total Transport cost	£M	9.6	7.9	9.3	8.5
Feedstock cost	£/l	0.087	0.148	0.158	0.073
Total capital investment	£M	246	230	244	225
Total variable cost	£M/yr	38.23	55.71	59.51	32.11
Variable operation cost	£/l	0.125	0.176	0.191	0.104
LCC	£M	3531	3977	4126	3222
LCC	£/l	14	15	16	13
NPV	£M	282	236	180	340
IRR	%	23.02	22.6	19.3	27.5
MESP	£/t ethanol	432	498	568	353
Pay back time	Years	8.15	8.42	10.82	6.5

Table 5.2 Results of the techno-economic assessment of the thermo-chemical plant

For the economic assessment, the data to calculate the capital costs were obtained from the Black & Veatch study (as quoted in NNFCC 2007) and the NREL (2011b) study. In addition, vendor quotations and the costs were used as given in Table 5.3. The UK Plant Cost Index (PCI) was used to escalate the prices from 2007-2012 (see Table 4.8). Table 5.3 shows the costs of consumables used by the thermo-chemical plant. The producer plant index (PPI) by the US Department of Labour has been used to escalate the cost of chemicals to 2012 (CDRPC 2007). The reference production capacity of the thermo-chemical refinery is about 250 million litres per year of ethanol along with the various quantities of the co-products (see Table 5.2). Feedstock costs for different feedstock are the same as assumed for the bio-chemical study.

Consumable	**Cost (£/tonne)**	**Source**
Magnesium oxide	259	(NREL, 2011b)
Olivine	121	(NREL, 2011b)
Tar reformer catalyst	27.7	(NREL, 2011b)
Alcohol synthesis catalyst`	46.5	(NREL, 2011b)
Boiler feed water chemicals	0.7746	(NREL, 2011b)
Cooling water chemicals	1412	(Frederick Jr et al., 2008b)
Solids disposal	23	(Frederick Jr et al., 2008b)
Make up water	0.8 £/m^3	(NNFCC 2007)
LOCAT chemicals	289/ton sulphur produced	(NREL, 2011b)

Table 5.3. Cost of consumables used in the thermo-chemical refinery

The economic indicators such as NPV, IRR, and PBP were estimated using the discounted cash flow rate of return (See Table 4.10). The full results of the economic assessment can be found in Table 5.2.

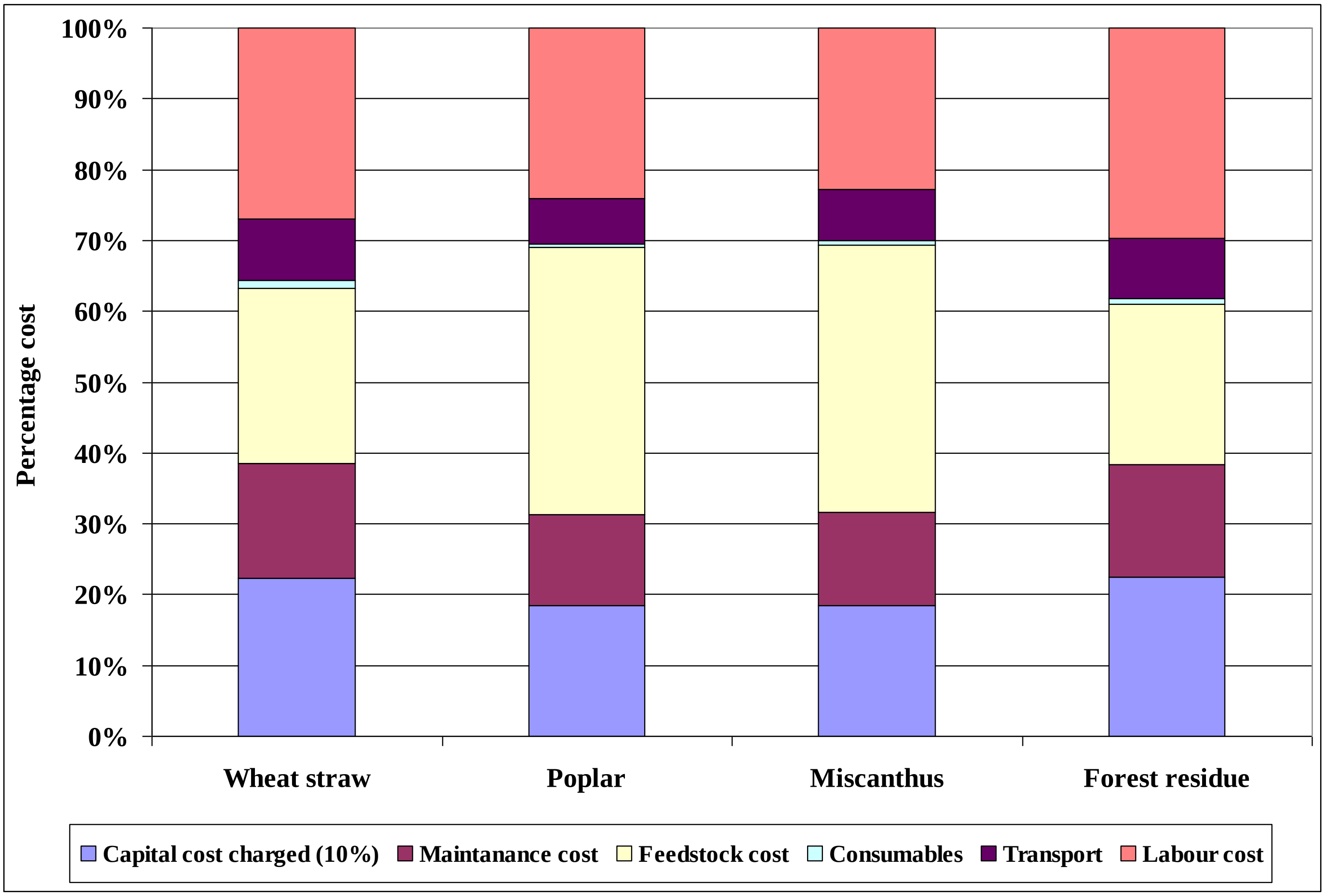


Figure 5.23 Contribution of different life cycle stages to the total costs of the -chemical refinery

The estimated total LCC is around £4 billion with the lowest for forest residue (£3.2b) and the highest for miscanthus (£4.1b). The main contributors (see Figure 5.23) to the total cost are feedstock and labour cost. The feedstock cost contribution is about 25% for wheat straw and forest residue and 37% for poplar and miscanthus. The average labour cost for all feedstock is about 25%. Other minor contributors are capital cost (average is 20%). The contribution of consumables is minimal (1%) to the total cost.

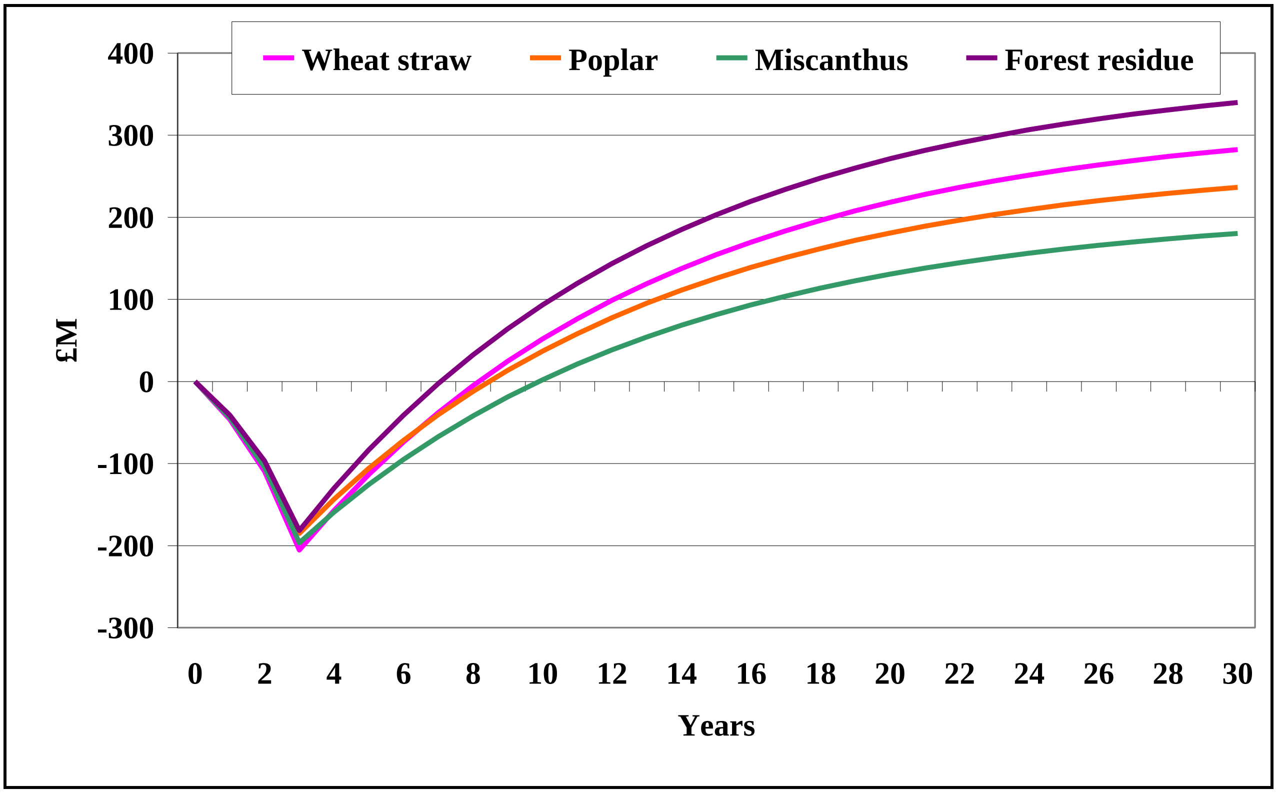


Figure 5.24 NPV values over the life time of the plant

NPV, IRR and PBP are indicators used for assessing the economic profitability of the plant. Forest residue has the highest NPV and IRR of £340M and 27%, respectively. Figure 5.24 shows the graph of the total NPV for all feedstocks over the life time of the plant. The higher the IRR, the more desirable it is to undertake the project. The MESP and PBP are £353 and 3 years, respectively for the forest residue option. In this case, the thermo-refinery using the forest residue option is the most favorable project in terms of economic benefits. The thermo-refinery with miscanthus option has the least NPV (£180M) and IRR (19.3%) and the highest MESP (£568) and PBP (9 years). This is mostly due to the high unit cost of miscanthus feedstock and lower net cash flow.

Therefore, based on the techno-economic analysis, forest residue appears to be the most sustainable feedstock option for the thermo-chemical refinery.

5.4.1 Comparison of the economic assessment with other studies

The cost data of thermo-chemical plant from second generation feedstock is rather limited. The economic results of the thermo-chemical case studies are validated against other similar literature studies. Wright and Brown (2007) compared the capital cost of different of thermo-chemical plant. In this analysis, the Fischer-Tropsch plant is more expensive than all other types of thermo-chemical plants such as methanol and hydrogen fuel systems. This is due to additional equipment cost for the F-T process for syn gas conversion. Frost et al. (2009) calculated the project investment of a thermo-chemical plant to be £136 M for a plant capacity of 275 Ml. The total installed equipment cost in this study is between £140-154 M depending on the plant capacity.

5.4.2 Sensitivity analyses for the economic sustainability

Similar to the bio-chemical refinery, a sensitivity analyses was carried out for the most profitable scenario, forest residue for NPV changes with feedstock cost, capital cost and minimum ethanol selling price.,

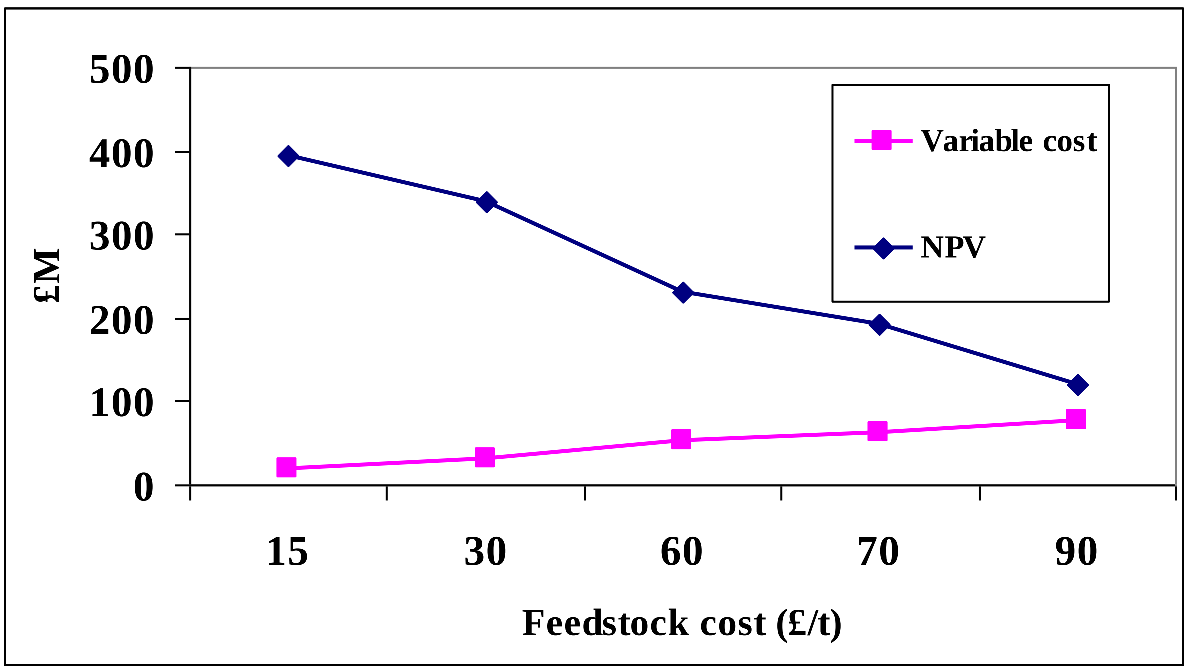


Figure 5.25 Influence of feedstock costs on NPV and variable costs

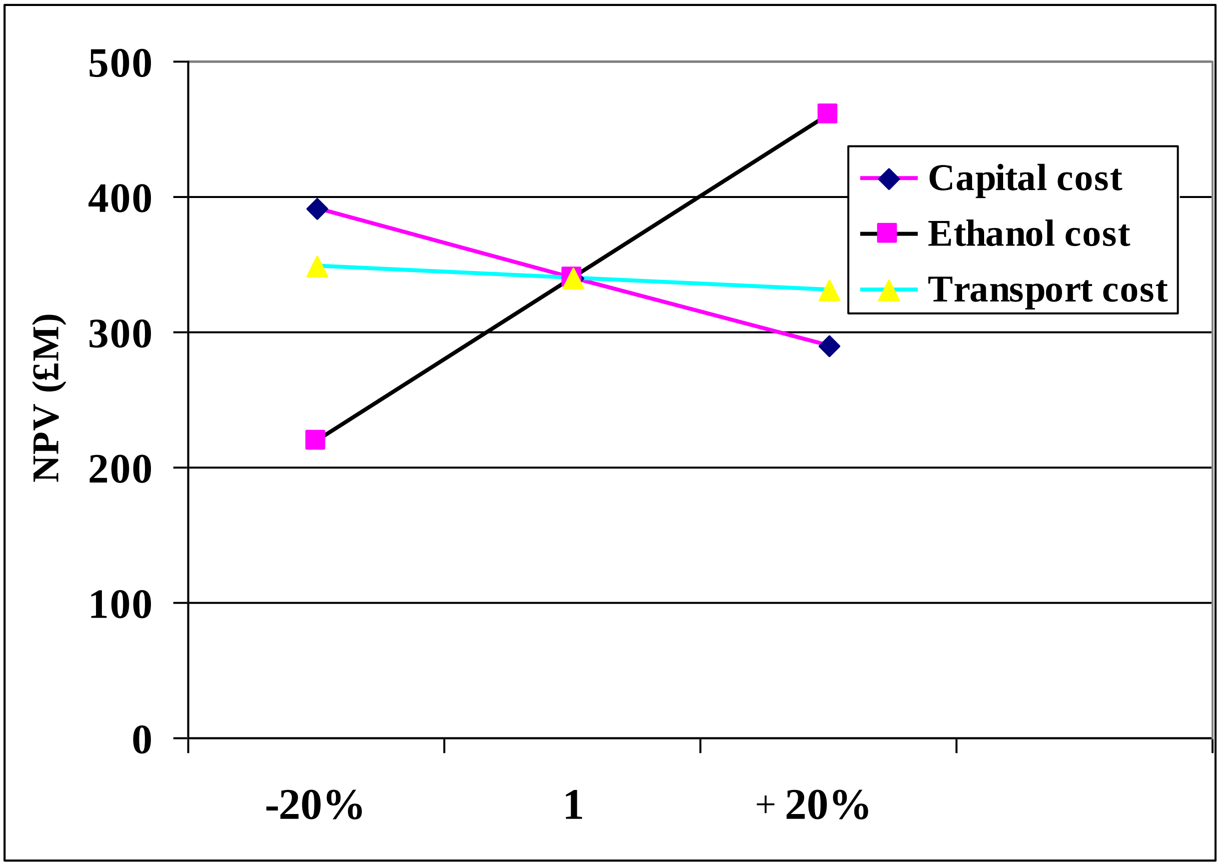


Figure 5.26 Influence of minimum ethanol selling price, transport and capital costs on NPV

A similar trend is noticed here, in Figure 5.25, at a cost feedstock cost of about £95, the NPV becomes zero. This means the feedstock cost would need to increase up to 3.2 times before the plant can start to operate at a loss and the variable cost would increase by about 60%. If the reverse happens, and the feedstock cost is reduced to half, the NPV increase by about 30% while the variable cost would be about 38% less.

In Figure 5.26, capital cost, transport costs as well as MESP are varied +/-20% compared to the current results. As indicated, the MESP has the highest impact on NPV, followed by the capital cost; the transport cost has a small effect on NPV.

5.5 Social sustainability

The social sustainability of the thermo-chemical refinery is discussed below, using the following indicators defined in Chapter 3: employment provision, health and safety, local community impacts and energy security.

5.5.1 Employment provision

The total estimated employment figures for the cultivation stage are given in Table 5.4. From this table, wheat straw requires the least labour requirement (386 person years) while forest residue provided the most employment (989 person years) over an annual plant requirement.

Feedstock	Wheat straw	Poplar	Miscanthus	Forest residue
Total quantity (t/yr)	853,848	770,232	820,723	753,348
Labour requirement (FTE/t)	0.000438	0.000945	0.000852	0.001341
Estimated total employment (person years)	**386**	**727**	**699**	**989**

Table 5.4 Employment provision in the feedstock cultivation/provision stage

Other employment opportunities are provided for technical and other support staff. Since there are no data on thermo-chemical refinery due to lack or planned operational plants (NNFCC 2012). The employment data provided by the bio-chemical plant has been assumed (RFA 2012). The plant operation requires about 171, 174, 171, and 170 full time jobs for wheat straw, poplar, miscanthus, and forest residue, respectively. Therefore, the total life cycle employment is about 562 902, 870, 1180 person years for wheat straw, poplar, miscanthus and forest residue, respectively. Figure 5.27 shows that majority (80%) of the employment is provided at the feedstock cultivation stage.

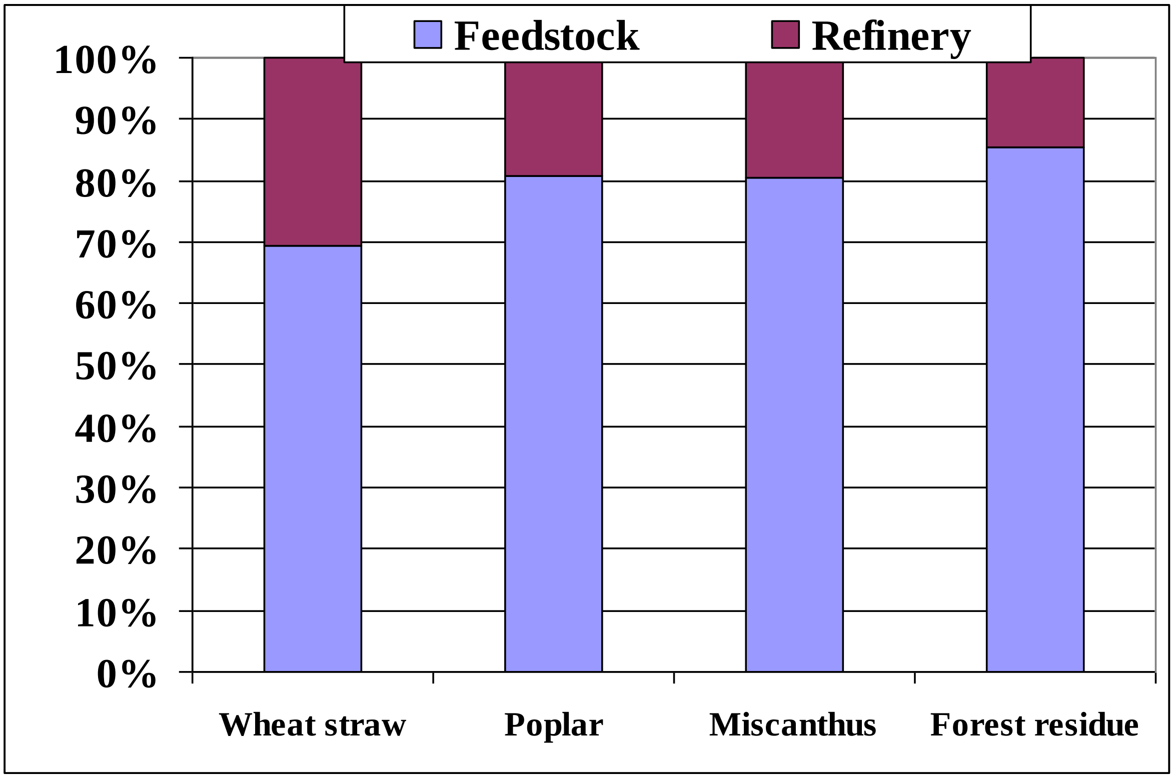


Figure 5.27 Feedstock cultivation and refinery operation employment contribution

5.5.2 Health and safety

This is also assessed using HTP, estimated as part of LCA and the number of fatalities at work. As discussed in section .5.3.3, wheat straw has the highest HTP (88 kt DCB eq.) while others are between 4-7 kt. This is due to heavy metals and pesticide emissions to soil in wheat cultivation.

The data provided by the UK Health and Safety Executive is estimated at 8 deaths per 100,000 workers (HSE 2011a) have been used to estimate the average number of deaths for the feedstock provision stage to be 0.03,0.058, 0.055,0.079 for wheat straw, poplar, miscanthus and forest residue, respectively.

Data from the chemical sector have been used to estimate the fatalities for the plant. This is appropriate, as the operation is similar (19 death per 100,000 workers). The average death at the refinery is 0.032, 0.033, 0.032, and 0.032 for wheat straw, poplar, miscanthus and forest residue, respectively. Therefore, the total potential fatalities for the thermo-refinery from 'cradle to gate' are 0.062, 0.091, 0.087, and 0.11 for wheat straw, poplar, miscanthus and forest residue, respectively.

5.5.3 Local community impacts

For explanation on the impacts on local community, see section 4.5.3

5.5.4 Energy security

Similar to the bio-chemical studies, ethanol production from the four different biomass has a potential to contribute towards improved energy security in the UK by displacing the need for the equivalent amount of fossil fuels. They all have the same potential to contribute towards improved energy security by avoiding the need for 199-203 kt petrol.

5.6 Summary

The sustainability of the thermo-chemical refinery is presented in this chapter comparing four different feedstocks. Table 5.5 shows their comparisons for different sustainability aspect. Similar to the bio-chemical process, the total score represents the total addition of the best options ‘1’ for a particular feedstock. In summary, the results suggest that, similar to the bio-chemical refinery, forest residue represents the most sustainable option and miscanthus is the least sustainable, scoring respectively 17 and 0.

Indicator	Wheat straw	Poplar	Miscanthus	Forest residue
Environmental				
Abiotic Depletion Potential (ADP)	4	2	3	1
Acidification Potential (AP)	4	2	3	1
Eutrophication Potential (EP)	4	2	3	1
Freshwater Aquatic Eco-toxicity Potential (FAETP)	4	1	2	3
Global Warming Potential (GWP)	4	2	3	1
Human Toxicity Potential (HTP)	4	2	3	1
Marine Aquatic Eco-toxicity Potential (MAETP)	4	2	3	1
Ozone Layer Depletion Potential (ODP)	4	2	3	1
Photo Oxidant Chemical Formation Potential (POCP)	4	1	2	3
Terrestrial Eco-toxicity Potential (TETP)	4	2	3	1
Land use	3	1	2	4
Techno-economic				
Ethanol yield	4	2	3	1
Mass efficiency	4	2	3	1
Energy efficiency	4	2	3	1
Plant capacity	1	3	2	4
Life Cycle Costs (LCC)	2	3	4	1
Net Present Value (NPV)	2	3	4	1
Internal Rate of Return (IRR)	2	3	4	1
Minimum Ethanol Selling Price (MESP)	2	3	4	1
Payback period	2	3	4	1
Social				
Employment provision	4	2	3	1
Safety (fatalities)	1	3	2	4
Local community impacts	NA	NA	NA	NA
Energy security	2	1	3	4
Total score	2	4	0	17

Table 5.5 Ranking of feedstock options for different sustainability criteria

6 SUSTAINABILITY COMPARISON OF BIO-CHEMICAL AND THERMO-CHEMICAL REFINERIES

6.1 Introduction

This chapter compares the bio-chemical and thermo-chemical refineries on their environmental, techno-economic and social sustainability, using the results presented in the previous two chapters. Since the two systems produce different products, the comparison is per litre of ethanol, first using the system expansion, followed by the economic allocation.

6.2 Comparison on environmental sustainability

6.2.1 Comparison based on system expansion

The two refinery systems are compared in Figure 6.1 for the four feedstocks considered in this study. Overall, for all the feedstocks, the thermo-chemical refinery is environmentally more sustainable for eight out of eleven impact categories than the bio-chemical: they are [1]ADP, FAETP, HTP, MAETP, ODP POCP, TETP and land use. The thermo-chemical refinery is better for these systems because of lower use of feedstock and better yields. The bio-chemical option is better for AP, EP, and GWP. This is due to the higher credits from electricity production.

Therefore, if all the impacts are assumed to have equal importance, the thermo-chemical bio-refinery appears to be more environmentally sustainable. However, it is unlikely that all the impacts would be considered equally important. For example, one of the main drivers for ethanol from biomass is the need to reduced the greenhouse gas emissions. Therefore, if only GWP is considered, the bio-chemical route is better than the thermo-chemical route. This is because of the associated credits from electricity production.

[1] [ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP; Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity; HTP; Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP; Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential]

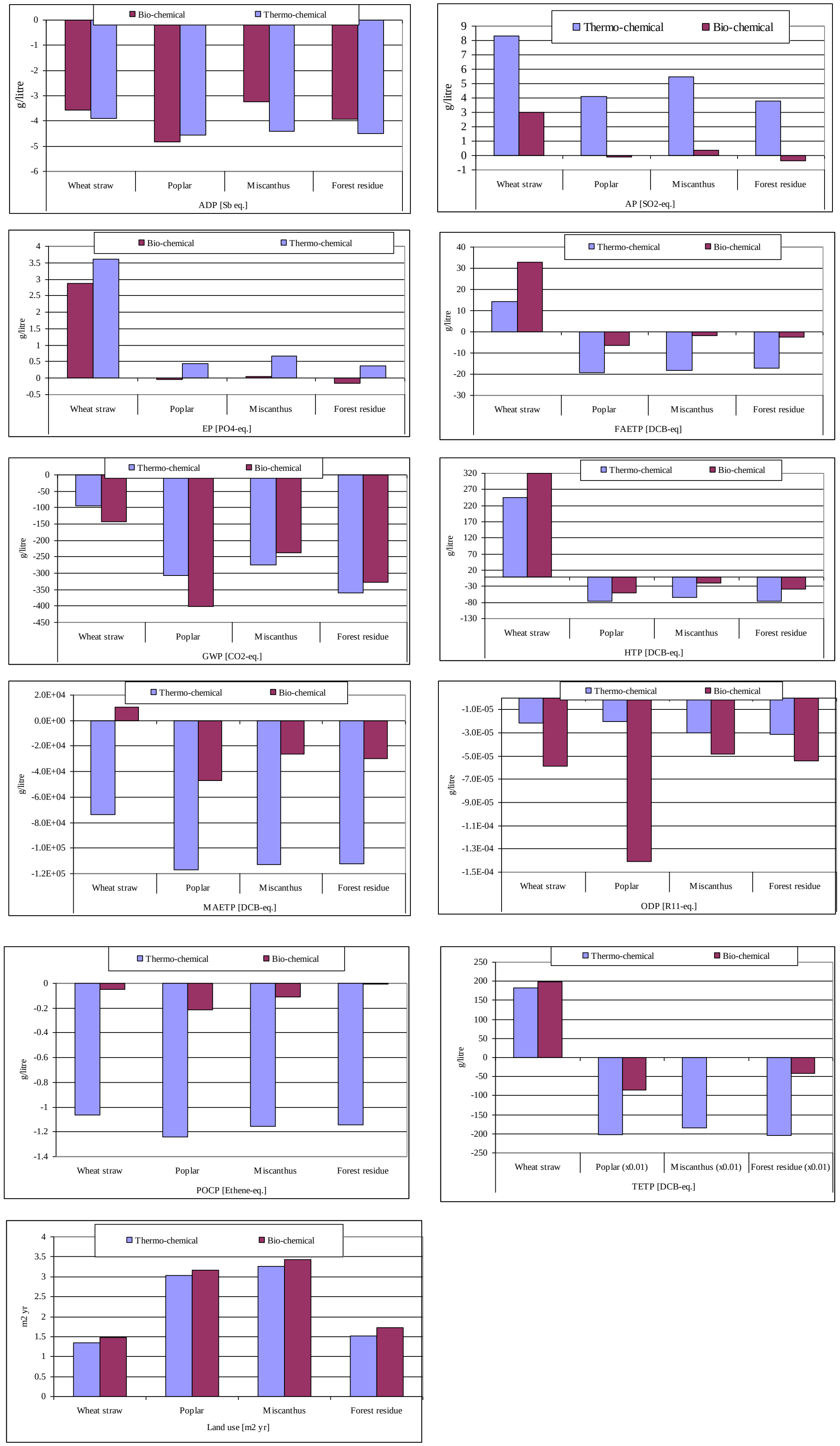


Figure 6.1 Comparison of environmental sustainability of bio-chemical and thermo-

chemical refineries per litre of ethanol (system expansion)

6.2.2 Comparison based on the economic allocation

These results using economic allocation are compared in Figure 6.2. As indicated, the thermo-chemical refinery is now a better option for nine out of eleven impact categories: ADP, FAETP, HTP, GWP MAETP, POCP, ODP, TETP and land use.

The bio-chemical option is better for AP, and EP. This is due to the lower process emissions compared to the thermo-chemical, which has higher AP and EP and a result of flue gas emissions from the gasification unit. Thus, like system expansion, economic allocation also points towards the thermo-chemical refinery as an environmentally better option.

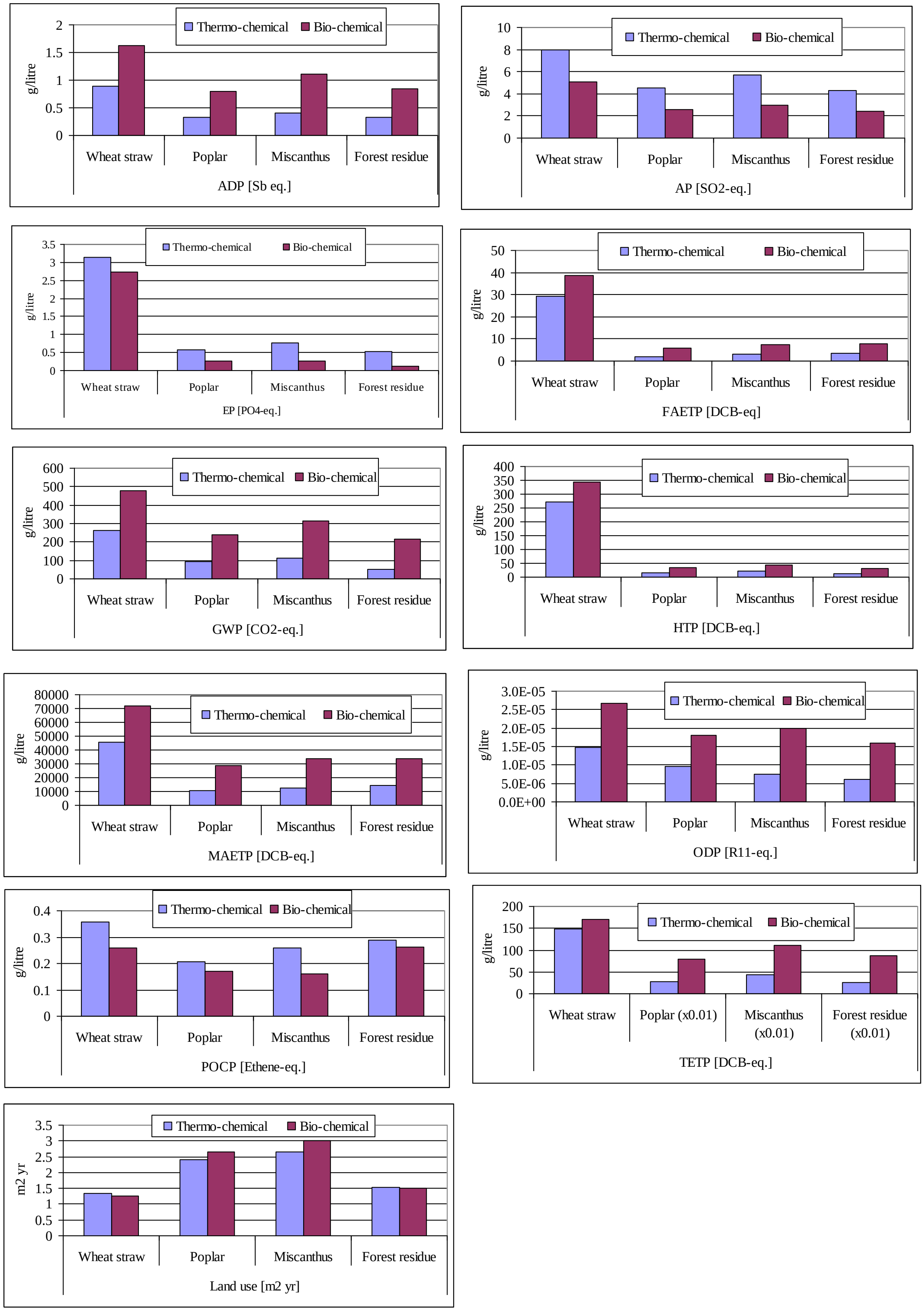


Figure 6.2 Comparison of environmental sustainability of bio-chemical and thermo-chemical refineries per litre of ethanol (economic allocation)

6.3 Comparison of techno-economic sustainability

The techno-economic sustainability of the two routes is compared in Figure 6.3.and 6.4; these results are discussed below.

Efficiency: The ethanol yield and mass and energy efficiency of the thermo-chemical process are higher than the bio-chemical process (see Figure 6.3) because it utilises the whole component of the feedstock for the products. The bio-chemical route on the other hand, only utilises the cellulose and the hemicellulose components of the feedstock. The energy efficiency is also higher in the thermo-chemical process than in the bio-chemical process. This is due to higher energy ratio of ethanol and co-products to the feedstock. However, the difference is overall not very high. For example, the yield for poplar and forest residue in the thermo-chemical route is about 4% higher than for poplar (the best option) in the bio-chemical refinery. The differences in the mass and energy efficiencies are even smaller – up to 3%.

Plant capacity: The plant capacity in both cases is less than 855 kt per year. This would require 753-853 t/yr of feedstocks for the thermo-chemical and 700-836 t/yr for the bio-chemical plants. The issue here might be feedstock availability rather than plant capacity although the latter may be limited by biomass transport and storage facilities.

In the UK, the estimated potential for the feedstocks considered here are (NNFCC, 2010):

- wheat straw: 1.8 M t/yr;
- poplar: 711 t/yr;
- miscanthus: 861 t/yr; and
- forest residue: 1.2 M t/yr.

As the thermo-chemical system requires lower use of feedstcok than the bio-chemical route, there is sufficient feedstock for both routes with the exception of the poplar. This will be needed to be sourced from elsewhere eg other countries or other feedstcok considered. Poplar required in the bio-chemical system is about 1.2% higher than the thermo-chemical system. This means that although, both refineries require a significant amount of feedstock and the thermo-chemical process requires less, but the difference is small (~5%).

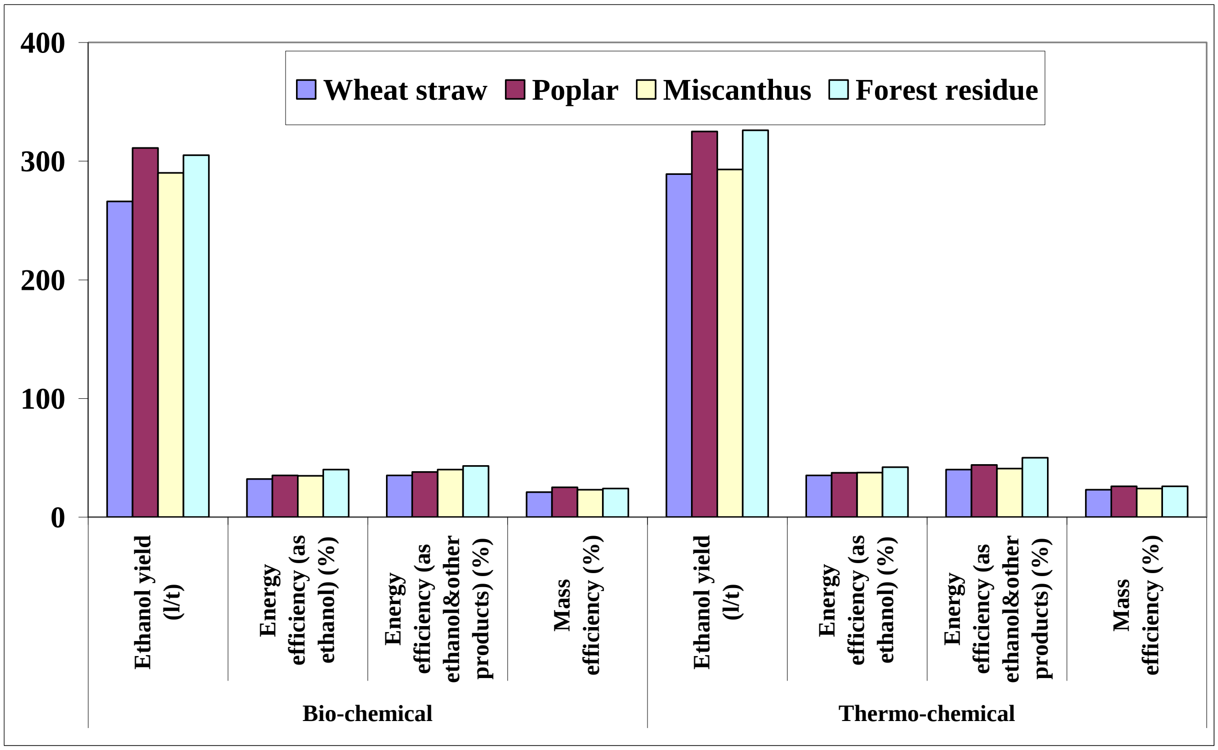


Figure 6.3 Comparison of technical performance of bio- and thermo-chemical refineries per litre of ethanol

Plant flexibility: The bio-chemical plant is less flexible as it requires different pre-treatment techniques for various kinds of feedstock. In this study, the dilute acid pre-treatment has been used for all the feedstocks considered. However, certain feedstocks are better suited to certain conversion processes. For instance, agricultural residue are better utilised via the bio-chemical route while woody biomass is more suited for the thermo-chemical route. The thermo-chemical route can utilise any feedstock type.

Technology availability: Both bio- and thermo-chemical refineries remain unproven at full commercial scale due to significant technical and economic barriers yet to be overcome. However, there exist a few bio-chemical facilities utilising 2nd generation feedstock at the pilot and demonstration scales. For example, TMO uses bacteria to ferment a variety of feedstock such as wheat straw, newspapers, and MSW to produce fuel ethanol (DUNSFOLD 2008). After a successful trial run for a year, plans are underway for a commercial facility. INEOS Bio is also building a plant that utilises biodegradable household and commercial waste to produce biofuel and bio-energy in the North East, UK (INEOS Bio 2010). In summary, most technologies remain at pilot stage and none is commercialised yet. In the UK, it appears that the bio-chemical technology is becoming increasingly popular compared to the thermo-chemical process as observed, for example, through the development of the TMO and INEOS Bio processes.

Costs and profitability: The costs and profitability results are compared in Figure 6.4. As can be seen, the capital costs and LCC (Life Cycle Cost) for the thermo-chemical refinery are lower while the NPV (Net Present Value) and IRR (Internal Rate of Return) are higher compared to the bio-chemical system. However, the two systems cannot be compared directly as they produce different co-products. Therefore, comparison is made here only for the economic indicators for which it is possible to convert to per litre basis.

The average MESP (Minimum Ethanol Selling Price) is slightly lower for the thermo-chemical process (£462/l) than in the bio-chemical process (£638/l) due to a higher ethanol yield from the thermo-chemical process. This in turns yields higher co-product credits than in the bio-chemical process. In addition, the average life cycle cost of ethanol per litre is also lower (£14.50) in the thermo- than in the bio-chemical system (£16.50).

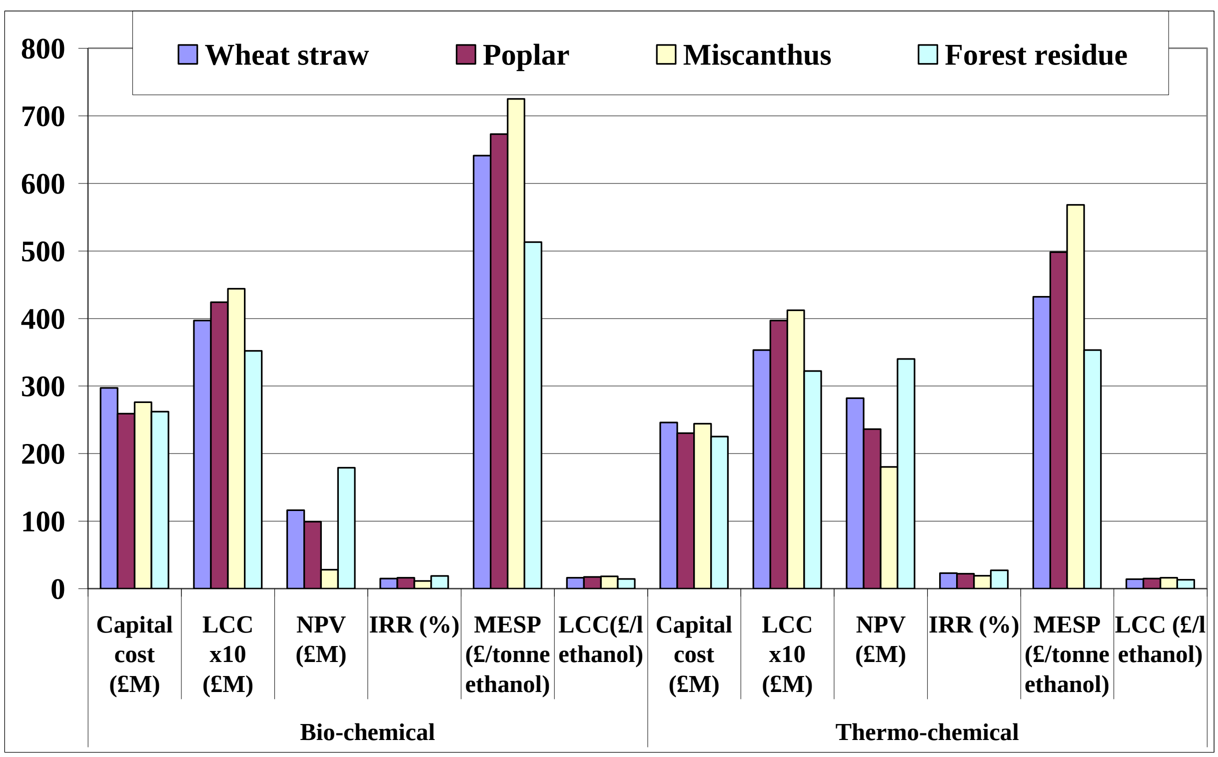


Figure 6.4. Comparison of the economic sustainability of the bio-chemical and thermo-chemical refineries

6.4 Comparison of social sustainability

Table 6.1 compares the bio-chemical and thermo-chemical routes for the social sustainability indicators considered in this study. The total employment for feedstock cultivation required for the bio-chemical is higher than that for the thermo-chemical plant. However, the HTP (Human Toxicity Potential) is also higher for the bio-chemical than the thermo-chemical system. This is due to the higher capacity required for the bio-chemical plant to produce the same amount of ethanol. The total number of fatalities, calculated based on the number of employees, is similar for both systems.

Case studies	**Bio-chemical**				**Thermo-chemical**			
Social impact (per litre ethanol)	Wheat straw	Poplar	Miscanthus	Forest residue	Wheat straw	Poplar	Miscanthus	Forest residue
Total Employment (person years)	$2.3x10^{-6}$	$3.6x10^{-6}$	$3.6x10^{-6}$	$5.0x10^{-6}$	$2.2x10^{-6}$	$3.5x10^{-6}$	$3.4x10^{-6}$	$4.7x10^{-6}$
HTP (t DCB eq.)	$4x10^{-4}$	$4.4x10^{-5}$	$4.7x10^{-5}$	$3.5x10^{-5}$	$3.5x10^{-4}$	$2.5x10^{-5}$	$2.9x10^{-5}$	$1.53x10^{-5}$
Accidents record	$3.1x10^{-10}$	$4.2x10^{-10}$	$4.2x10^{-10}$	$5.3x10^{-10}$	$1.2x10^{-10}$	$2.3x10^{-10}$	$2.19x10^{-10}$	$3.2x10^{-10}$

Table 6.1 Comparison of social sustainability of the bio-chemical and thermo-chemical refineries

As local community impacts are location and company specific, it is not possible to compare the two options for this impacts.

Finally, with respect to energy security, both processes have the overall potential to contribute to energy security and to replace about 200 kt of petrol per year.

6.5 Summary

The environmental, techno-economic, and social sustainability of the bio- and the thermo-chemical systems have been compared in this chapter. Their comparison is summarised in the table below. Overall, the thermo-chemical refinery appears to be a more sustainable option across all the feedstocks assuming equal importance of all the sustainability criteria. The bio-chemical option is more sustainable for the AP, EP, plant capacity and employment provision. In reality, it is unlikely that all the criteria would be considered equally important. However, even so, the thermo-chemical system would still be emerge as the best option as it is overall best economically as well as environmentally, with little difference for the social criteria. Thus, arguably, the thermo-chemical refinery using forest residue is the most sustainable option overall.

	Wheat straw		Poplar		Miscanthus		Forest residue	
	Bio-chemical	**Thermo-chemical**	**Bio-chemical**	**Thermo-chemical**	**Bio-chemical**	**Thermo-chemical**	**Bio-chemical**	**Thermo-chemical**
Environmental								
Abiotic Depletion Potential (ADP)	2	1	1	2	2	1	2	1
Acidification Potential (AP)	1	2	1	2	1	2	1	2
Eutrophication Potential (EP)	1	2	1	2	1	2	1	2
Freshwater Aquatic Eco-toxicity Potential (FAETP)	2	1	2	1	2	1	2	1
Global Warming Potential (GWP)	1	2	1	2	2	1	1	2
Human Toxicity Potential (HTP)	2	1	2	1	2	1	2	1
Marine Aquatic Eco-toxicity Potential (MAETP)	2	1	2	1	2	1	2	1
Ozone Layer Depletion Potential (ODP)	1	2	2	1	2	1	2	1
Photo Oxidant Chemical Formation Potential (POCP)	2	1	2	1	2	1	2	1
Terrestrial Eco-toxicity Potential (TETP)	2	1	2	1	2	1	2	1
Land use	2	1	2	1	2	1	2	1
Techno-economic								
Ethanol yield	2	1	2	1	2	1	2	1
Mass efficiency	2	1	2	1	2	1	2	1
Energy efficiency	2	1	2	1	2	1	2	1
Plant capacity	1	2	2	2	1	2	1	2
Life Cycle Costs (LCC)	2	1	2	1	2	1	2	1
Net Present Value (NPV)	2	1	2	1	2	1	2	1
Internal Rate of Return (IRR)	2	1	2	1	2	1	2	1
Minimum Ethanol Selling Price (MESP)	2	1	2	1	2	1	2	1
Payback period	2	1	2	1	2	1	2	1
Social								
Employment provision	1	2	1	2	1	2	1	2
Safety (fatalities)	2	1	2	1	2	1	2	1
Local community impacts	NA	NA	NA	NA	NA	NA	NA	NA
Energy security	NA	NA	NA	NA	NA	NA	NA	NA

Table 6.2 Ranking of feedstock and technology options for different sustainability criteria

7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This research has developed a framework for the sustainability assessment of integrated bio-refineries taking into account environmental, techno-economic, and social aspects. The methodology has been applied to the UK conditions for the assessment of different 2^{nd} generation bio-feedstocks. These have been selected because a market opportunity has risen for biofuels in the UK from the obligation on fuel suppliers to ensure 5% of road vehicle is from sustainable sources. Lignocellulosic ethanol can contribute towards this achievement.

The objectives of this research have been met in that:

- A methodological framework has been developed to evaluate the sustainability of integrated bio-refineries.
- The application of the methodology has been tested on two substantive case studies of bio-chemical and thermo-chemical processing of four different feedstocks to produce ethanol and a range of co-products.

The main conclusions from this work are summarised below. This is followed by recommendations for future work.

7.1 Conclusions

7.1.1 Bio-chemical refinery

The main conclusions from the sustainability assessment are as follows (see Chapter 4 for details):

- The environmental sustainability assessment indicates that the forest residue is the most sustainable option and wheat straw is the worst option.
- As a way of example, producing 192 t of ethanol per year, generates 141 kt CO_2 eq. using wheat straw and 64 kt CO_2 eq.using forest residue. Per litre of ethanol, this is equivalent to -144 and -327 g CO_2 eq., respectively.
- When the system is credited for the co-products, most impacts become for all feedstocks except wheat straw indicating that they have been saved by not

having to produce these products in fossil-based systems.

- When the impacts between the co-products are allocated on an economic basis, about 85% of the total GWP is allocated to ethanol, while 7%, 6% and 2% is allocated to electricity, acetic acid and acetic acid, respectively.
- Total capital cost of the bio-chemical refinery is estimated at £297; 259; 276; and 262 million for wheat straw, poplar, miscanthus and forest residue, respectively.
- The total life cycle cost per litre of ethanol is lowest for forest residue (£14.4) and highest for miscanthus (£18.1).
- The employment provison is highest with forest residue and lowest with wheat straw while the fatalities record is highest with forest residue and lowest with wheat straw
- Overall, it can be concluded that the forest residue the most sustainable feedstock for the bio-chemical refinery.

7.1.2 Thermo-chemical refinery

The main conclusions from the sustainability assessment of the thermo-chemical system are as follows (see Chapter 5 for details):

- The environmental sustainability assessment indicates that the forest residue is the most sustainable option and wheat straw is the worst option.
- As a way of example, producing 192 t of ethanol per year, generates 82 kt CO_2 eq. using wheat straw and 14 kt CO_2 eq.using forest residue. Per litre of ethanol, this is equivalent to -95 and -361 g CO_2 eq., respectively.
- When the system is credited for the co-products, most impacts become negative for all feedstocks except wheat straw indicating that they have been saved by not having to produce these products in fossil-based systems.
- When the impacts between the co-products are allocated on an economic basis, about 80% of the total GWP is allocated to ethanol, while 2.2%, and 17.4% is allocated to butanol and propanol, respectively.
- Total capital cost of the bio-chemical refinery is estimated at £246; 230; 244; and 225 million for wheat straw, poplar, miscanthus and forest residue, respectively.

- The total life cycle cost per litre of ethanol is lowest for forest residue (£13) and highest for miscanthus (£16).
- The employment provision is highest with forest residue and lowest with wheat straw while the fatalities record is highest with forest residue and lowest with wheat straw
- Overall, it can be concluded that the forest residue the most sustainable feedstock for the thermo-chemical refinery.

7.2 Bio-chemical vs thermo-chemical refinery

- Environmentally, the thermo-chemical option is more sustainable than the bio-chemical across all the impacts with the exception of AP, EP and GWP.
- From an economic point of view, the thermo-chemical refinery has a high NPV, IRR and payback time and low capital costs compared to the bio-chemical refinery.
- From the social point of view, there is little difference between the two options considered.
- Overall, the thermo-chemical option appears to be more sustainable than the bio-chemical option.
- However, as both technologies are developing and the assessment has been made on a theoretical basis, the results and the conclusions should be treated as tentative.
- Further work is required in many areas to provide further estimates of sustainability assessment of integrated biorefineries; some recommendations for further work follow.

7.3 Recommendations for future work

The following are suggestions for future work:

- The methodological framework proposed here should be developed further to include other sustainability indicators, particularly related to social sustainability.
- Other environmental assessment methods could be used for LCA and the results compared.
- Other feedstocks should also be considered, including MSW.

- Detailed modelling and optimisation of the bio-refineries should be carried out to minimise the environmental impacts and economic costs.
- Further data collection should be carried out to ensure more reliable estimates.
- Multi-criteria decision analysis should be carried out with the stakeholders using the proposed indicators to find out how the choice of the options might be affected by stakeholder preferences.

8 REFERENCES

DUNSFOLD, (2012) www.dunsfoldpark.com/dunsfold-park/news/uk-s-first-cellulosic-ethanol-plant-completes-first-year-of-operation.html, accessed 30 June 2012

ADAS, (2008) Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities. UK.

ADEN, A., RUTH, M., IBSEN, K., JECHURA, J., NEEVES, K., SHEEHAN, J. & WALLACE, B. (2002) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. National Renewable. Energy Laboratory. United States

ALAKANGAS, E., KERANEN, J., FLYKTMAN, M., JETSU, P., VESTERINEN, P., TUKIA JAAKKO, V. & JAMK, J. K. (2010) Biomass resources, production,use,processing and logistics in Central Finland-analysis of the current status. *BIOCLUS-Developing research and innovation environment in five european regions in the field of sustainable use of biomass sources.* Finland, 245438.

ANNEVELINK, E., DE JONG, E., VAN REE, R. & ZWART, R. W. R. (2006) First workshop on the possibilities of biorefinery concepts for the industry. Netherlands.

ANTIZAR-LADISLAO, B., & TURRION-GOMEZ, J. L., (2008) Second-generation biofuels and local bioenergy systems.Biofuels, bioproducts and biorefning 2(5), 455-469.

ARVELAKIS, S., & FRANDSEN, F. J., (2007) Melting behavior of ashes from the co-combustion of coal and straw. *Energy & Fuels,* 21(5), 3004-3009.

ASIF, M., & MUNEER, T., (2007) Energy supply, its demand and security issues for developed and emerging economies. *Renewable and Sustainable Energy Reviews,* 11(7),1388-1413.

AZAPAGIC, A., (1999) Life cycle assessment and its application to process selection, design and optimisation. *Chemical Engineering Journal,* 73(1)**,** 1-21.

AZAPAGIC, A., (2004) Developing a framework for sustainable development indicators for the mining and minerals industry. *Journal of Cleaner Production,* 12(6)**,** 639-662.

AZAPAGIC, A., & CLIFT, R., (1999) The application of life cycle assessment to process optimization. *Computers and Chemical Engineering Journal,* 23(10), 1507-1526.

AZAPAGIC, A., EMSLEY, A. & KHAMERTON, I. (2003) *Polymers, the environment and sustainable development*, Chichester, John Wiley & Sons.

AZAPAGIC, A., & PERDAN, S,. (Eds.) (2011) *Sustainable development in practice: Case studies for engineers and scientist,* UK, John Wiley & Sons.

AZAPAGIC, A., PERDAN, S., & CLIFT, R,. (2004) *Sustainable development in practice-Case studies for engineers and scientists,* West Sussex, U.K, John Wiley & Sons.

BALAT, M., BALAT, H., & OZ, C., (2008) Progress in bioethanol processing. *Progress in Energy and Combustion Science,* 34(5)**,** 551-573.

BALAT, M., & BALAT, H., (2008) A critical review of bio-diesel as a vehicular fuel. *Energy Conversion and Management,* 49(10)**,** 2727-2741.

BALLESTEROS, I., OLIVA, J. M., NEGRO, M. J., MANZANARES, P. & BALLESTEROS, M., (2002) Enzymic hydrolysis of steam exploded herbaceous agricultural waste (Brassica carinata) at different particule sizes. *Process Biochemistry*, 38(2), 187-192.

BALS, B., WEDDING, C., BALAN, V., SENDICH, E. & DALE, B. (2011) Evaluating the impact of ammonia fiber expansion (AFEX) pretreatment conditions on the cost of ethanol production. *Bioresources Technology,* 102(2)**,** 1277-1283.

BAUMANN, H., & TILLMAN, A. M., (2004) The Hitch Hikers's guide to LCA, Luud Sweden, Studentlitteratur.

BEHRENDT, F., NEUBAUER, Y., OEVERMANN, M., WILMES, B., & ZOBEL, N., (2008) Direct liquefaction of biomass. *Chemical Engineering & Technology,* 31(5)**,** 667-677.

BINBING, H., WALTER, C., CANILHA, L., DA SILVA, S. S., ALMEIDA E SILVA, J. B., MCMILLAN, J. D., & WICKRAMASINGHE, S. R., (2006) Adsorptive membranes vs. resins for acetic acid removal from biomass hydrolysates. *Desalination,* 234(1-3)**,** 144-151.

BLACK, M., & MILLER, R., (2006) Platform chemicals from crops. *Journal of Chemical Technology & Biotechnology,* 81(11) 1725-1728.

BOATENG, A. A., DAUGAARD, D. E., GOLDBERG, N. M., & HICKS, K.B., (2007) Bench-scale fluidized-bed pyrolysis of switchgrass for bio-oil production. *Industrial & Engineering Chemistry Research,* 46(7)**,** 1891-1897.

BOYLE, H., EZEKIEL, U. H., HEROLD, I., LABASTIDA, R. R., & RYBCZYNSKA, A., (2010) Next generation ethanol and bio chemicals:what's in it for Europe.

BOZBAS, K., (2008) Biodiesel as an alternative motor fuel: Production and policies in the European Union. *Renewable and Sustainable Energy Reviews,* 12(2)**,** 542-552.

BOZELL, J. J., (2008) Feedstocks for the future - Biorefinery production of chemicals from renewable carbon. *CLEAN-Soil Air Water,* 36(8)**,** 641-647.

BRITISH SUGAR (2010) http://www.britishsugar.co.uk/Bioethanol.aspx, accessed 30 June 2012

BREHMER, B., BALS, B., SANDERS, J., & DALE, B., (2008) Improving the corn-ethanol industry: Studying protein separation techniques to obtain higher value-added product options for distillers grains. *Biotechnol Bioeng* 101(1), 49-61.

BRYAN, P., (2011) Turning Waste Into Fuel: How the INEOS Biorefinery Is Changing the Clean Energy Game. (http://energy.gov/articles/turning-waste-fuel-how-ineos-biorefinery-changing-clean-energy-game), Assesed 12th May 2011.

BRIDGWATER, A. V., (2003) Renewable fuels and chemicals by thermal processing of biomass. *Chemical Engineering Journal,* 91(2), 87-102.

BRIDGWATER, A. V., (2004) Biomass Fast Pyrolysis. *Thermal Science,* 8(2)**,** 21-49.

BSI (2011) Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. PAS 2050:2011

CARPENTIERI, M., CORTI, A.,& LOMBARDI, L., (2005). Life cycle assessment of an integrated biomass gasification combined cycle IBGCQ with CO2 removal. *Energy Conversion and Management*, 46(11),1790-1808.

CCALC (2011) Carbon calculation over the life cycle of industrial activities. UK.

CDRPC (2007) Department of labour. Producer Price Index for chemicals.

CHANDEL, A. M., CHAN, E S., RUDRAVARAM, R., LAKSHMI NARASU, M., VENKATESWAR RAO, L. & RAVINDRA, P., (2007) Economics and environmental impact of bioethanol production technologies: an appraisal. *Biotechnology and Molecular Biology Review,* 2(1)**,** 014-032.

CHARLTON, A., ELIAS, R., FISH, S., FOWLER, P., & GALLAGHER, J., (2009) The biorefining opportunities in Wales: Understanding the scope for building a sustainable, biorenewable economy using plant biomass. *Chemical Engineering Research and Design,* 87(9)**,** 1147-1161.

CHANGKOOK, R., SHARIFI, V.N., SWITHENBANK, J., (2007) Waste pyrolysis and generation of storable char. *International Journal of Energy Research,* 31(2)**,** 177-191.

CHERUBINI, F., (2010) The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Conversion and Management,* 51(7)**,** 1412-1421.

CHERUBINI, F., & JUNGMEIER, G., (2010) LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass. *Int J Life Cycle Assess*, 15(1) 53-66

CHERUBINI, F., & ULGIATI, S., (2009) Crop residues as raw materials for biorefinery systems - A LCA case study. *Applied Energy,* 87(1)**,** 47-57.

CHESTER, L., (2009) Conceptualising energy security and making explicit its polysemic nature. *Energy Policy,* 38(2)**,** 887-895.

CHRISTEN, E. W., SHEPHEARD, M. L., MEYER, W. S., JAYAWARDANE, N. S., & FAIRWEATHER, H., (2006) Triple bottom line reporting to promote sustainability of irrigation in Australia. *Irrigation and Drainage Systems,* 20(4)**,** 329-343.

CHUM, H. L., & OVEREND, R. P. (2001) Biomass and renewable fuels. *Fuel Processing Technology,* 71(1)**,** 187-195.

CLARK, J. H., & DESWARTE, F., E.ds (2008) *Introduction to Chemicals from biomass.* United Kingdom, Wiley & Sons.

CHRISTENSEN, C.H., RASS-HANSEN, J., MARSDEN, C.C., TAARNING, E., & EGEBLAD, K., (2008) The renewable chemicals industry.*ChemSusChem* 1(4), 283-289.

COPELAND, J., & TURLEY, D., (2008) National and regional supply/demand balance for agricultural straw in Great Britain. York.

COSKATA (2011) Coskata Supported Biorefinery Selected To Receive $250 Million Loan Guarantee From USDA. (http://www.businesswire.com/news/home/20110120006425/en/Coskata-Supported-Biorefinery-Selected-Receive-250-Million), Assesed 25th June 2011.

DATAR, R. P., SHENKMAN , R. M., CATENI, B. G., HUHNKE, R. L., & LEWIS, R. S., (2004) Fermentation of biomass-generated producer gas to ethanol.*Biotechnology and Bioengineering*, 86(5), 587-594

DEBDOUBI, A., EL AMARTI, A., COLACIO, E., BLESA, M. J., & HAJJAJ, L. H., (2006) The effect of heating rate on yields and compositions of oil products from esparto pyrolysis. *International Journal of Energy Research,* 30(15)**,** 1243-1250.

DE VRIJE, T., DE HAAS, G. G., TAN, G. B., KEIJSERS, E. R. P., & CLAASSEN, P. A. M., (2002) Pretreatment of miscanthus for hydrogen production by Thermotoga elfii. *International Journal of Hydrogen Energy,* 27(11)**,** 1381-1390.

DECC (2010a) Biomass prices in the heat and electricity sectors in the UK : For the department of energy and climate change

DECC (2010b) Digest of united kingdom energy statistics London.

DECC (2011) Quaterly Energy Prices, A National Statistics Publication (http://www.decc.gov.uk/assets/decc/11/stats/publications/qep/3906-qep-dec11.pdf), accessed December 2011

DEFRA & DTI (2007) Creating value from renewable resources. *Response to 2 year progress report on strategy for non-food crops and uses.* UK.

DEMIRBAS, A., (2001) Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion and Management,* 42(11)**,** 1357-1378.

DEMIRBAS, A., (2005) Bioethanol from cellulosic materials: A renewable motor fuel

from biomass. *Energy Sources,* 27(4)**,** 327-337.
DEMIRBAS, A., (2007) Progress and recent trends in biofuels. *Progress in Energy and Combustion Science,* 33(1)**,** 1-18.
DEMIRBAS, A., (2008) Co-firing coal and municipal solid waste. *Energy Sources Part A-Recovery, Utilization, and Environmental Effects*, 30(4)**,** 361-369.
DEMIRBAS, A., (2000) Mechanisms of liquefaction and pyrolysis reactions of biomass. *Energy Conversion and Management,* 41(6)**,** 633-646.
DEMIRBAS, A., (2004) Current technologies for the thermo-conversion of biomass into fuels and chemicals. *Energy Sources,* 26(8)**,** 715-730.
DEMIRBAS, A., (2005a) Pyrolysis of ground beech wood in irregular heating rate conditions. *Journal of Analytical and Applied Pyrolysis,* 73(1)**,** 39-43.
DEMIRBAS, A., (2005b) Thermochemical conversion of biomass to liquid products in the aqueous medium. *Energy Sources,* 27(13)**,** 1235-1243.
DEMIRBAS, A., (2008) Conversion of corn stover to chemicals and fuels. *Energy Sources Part a-Recovery Utilization and Environmental Effects,* 30(9)**,** 788-796.
DENNIS, R. A., & COLFER, C. J P., (2006) Impacts of land use and fire on the loss and degradation of lowland forest in 1983-2000 in East Kutai District, East Kalimantan, Indonesia. *Singapore Journal of Tropical Geography,* 27(1), 30-48
DEVERELL, R., MCDONNELL, K., WARD, S., & DEVLIN, G., (2009) An economic assessment of potential ethanol production pathways in Ireland. *Energy Policy*, 37,(10) 3993-4002.
DIEN, B. S., NICHOLS, N. N., & BOTHAST, R. J., (2002) Fermentation of sugar mixtures using Escherichia coli catabolite repression mutants engineered for production of L -lactic acid. *Journal of Industrial Microbiology & Biotechnology,* 29(5)**,** 221-227.
DODDS, R. D., & GROSS, R. A., (2007) Chemicals from biomass. *Science.*318(5854),1250-1251.
DOE (2007) DOE Selects Six Cellulosic Ethanol Plants for Up to $385 Million in Federal Funding US. (https://inlportal.inl.gov/portal/server.pt?open=514&objID=1555&mode=2&featurestory=DA_85842) accessed May 2010
DOMAC, J., RICHARDS, K., & RISOVIC, S., (2005) Socio-economic drivers in implementing bioenergy projects. *Biomass and Bioenergy,* 28(2)**,** 97-106.
DONES, R., C., B., BOLLIGER, R., BURGER, B., FAIST EMMENENGGER, M., FRISCHKNECHT, R., HECK, T., JUNGBLUTH, N., RODER A. & TUCHSCHMID, M. (2004) Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. Dubendorf, Pauk Scherrer Institut Villigen, swiss centre for life cycle inventories.
DRISSEN, R. E. T., MAAS, R. H. W., TRAMPER, J., & BEEFTINK, H. H., (2009) Modeling ethanol production from cellulose: separate hydrolysis and fermentation versus simultaneous saccharification and fermentation. *Biocatalysis and Biotransformation*, 27(1)**,** 27-35.
DUNNETT, A.J., ADJIMAN, C.S., SHAH, N., (2008) A spatially explicit whole-system model of the lignocellulosic bioethanol supply chain: an assessment of decentralised processing potential. *Biotechnology for Biofuels*, 1(13),
DWIVEDI, P., & ALAVALAPATI, J. R. R., (2009) Stakeholders perceptions on forest biomass-based bioenergy development in the southern US. *Energy Policy,* 37(5)**,** 1999-2007.
ECOINVENT (2007) Ecoinvent database. 4.3 ed. Switzerland, Swiss Centre for Life Cycle Inventories.

EDWARDS, J. F., & NICHOLAS, F., (2002) The state of health and safety in the UK construction industry with a focus on a plant operators. *Structural Survey,* 20(2)**,** 78-87.

EGGEMAN, T., & ELANDER, R. T., (2005) Process and economic analysis of pretreatment technologies. *Bioresource Technology,* 96(18)**,** 2019-2025.

EISENTRAUT, A. (2010) Sustainable production of second -generation biofuels. Potential and perspectives in major economies and developing countries. International Energy Agency

ELGHALI, L., CLIFT, R., SINCLAIR, P., PANOUTSOU, C., & BAUEN, A., (2007) Developing a sustainability framework for the assessment of bioenergy systems. *Energy Policy,* 35(12)**,** 6075-6083.

ERDEI, B., FRANKÓ, B., GALBE, M., & ZACCHI, G., (2012) Separate hydrolysis and fermentation for improved xylose utilization in integrated ethanol production from wheat meal and wheat straw. *Biotechnology for Biofuel* 5(12)1-12.

EU (2001) Towards a European strategy for the security of energy supply. Brussels.

FERNANDO, S., ADHIKARI, S., CHANDRAPAL, C., & MURALI, N., (2006) Biorefineries: Current status, challenges, and future direction. *Energy and Fuels,* 20(4)**,** 1727-1737.

FOTEINIS, S., KOULOUMPIS, V., & TSOUTSOS, T., (2011) Life cycle analysis for bioethanol production from sugar beet crops in Greece. *Energy Policy,* 39(9)**,** 4834-4841.

FRANZLUEBBERS, A. J., (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage Research,* 66(2)**,** 197-205.

FREDERICK JR, W. J., LIEN, S. J., COURCHENE, C. E., DEMARTINI, N. A., RAGAUSKAS, A. J. & IISA, K,. (2008a) Co-production of ethanol and cellulose fiber from Southern Pine: A technical and economic assessment. *Biomass and Bioenergy,* 32(12)**,** 1293-1302.

FREDERICK JR, W. J., LIEN, S. J., COURCHENE, C. E., DEMARTINI, N. A., RAGAUSKAS, A. J. & IISA, K. (2008b) Production of ethanol from carbohydrates from loblolly pine: A technical and economic assessment. *Bioresource Technology,* 99(11)**,** 5051-5057.

GALLAGHER, E., (2008) The Gallagher Review of the indirect effects of biofuels production.

GBEP (2007)-Global Bio-energy Partnership. A review of the current state of bioenergy development in G8 + 5 countries. GBEP Secretariat, Food and Agriculture Organisation of the United Nations (FAO); Rome

GEMIS (2004) Global emission model for integrated systems (GEMIS) Version 4.5. Germany.

GNANSOUNOU, E., & DAURIAT, A., (2010) Techno-economic analysis of lignocellulosic ethanol: A review. *Bioresource Technology,* 101(13)**,** 4980-4991.

GOLD, S., & SEURING, S., (2010) Supply chain and logistics issues of bio-energy production. *Journal of Cleaner Production,* 19(1), 32-42.

GONZALEZ, R., TREASURE, T., PHILLIPS, R., JAMEEL, H. & SALONI, D., (2011) Economic of cellulosic ethanol production:green liquor pretreatment for softwood and hardwood, greenfield and repurpose scenarios. *Bioresources,* 6(3)**,** 2551-2567.

GONZÁLEZ-GARCÍA, S., HOSPIDO, A., AGNEMO, R., SVENSSON, P., SELLING, E., MOREIRA, T., & FEIJOO,G., (2011) Environmental life cycle assessment of swedish dissolving pulp mill integrated biorefinery. *Journal of Industrial Ecology* 4(15) 568-583.

GRAHAM, R. L., (2007) Forecasting the magnitude of sustainable biofeedstock supplies: the challenges and the rewards.*Biofuel, Bioproducts and Biorefining* 1(4), 255-263

GARCIA-PEREZ, M., WANG, X. S., SHEN, J., RHODES, M. J., TIAN, F., LEE, W. J., WU, H. & LI, C. Z. (2007) Fast Pyrolysis of Oil Mallee Woody Biomass: Effect of Temperature on the Yield and Quality of Pyrolysis Products. *Industrial & Engineering Chemistry Research,* 47(6)**,** 1846-1854.

GRAY, K. A., (2007) Cellulosic ethanol - state of the technology. *International Sugar Journal*, 109**,**(1299), 145-146.

GRI (2011) Global reporting initiative. United Kingdom.

GROOM, M. J., GRAY, E. M., & TOWNSEND, P. A., (2008) Biofuels and biodiversity: Principles for creating better policies for biofuel production. *Conservation Biology,* 22(3)**,** 602-609.

GUERMOUD, N., OUADJNIA, F., ABDELMALEK, F., TALEB, F., & ADDOU, A., (2009) Municipal solid waste in Mostaganem city (Western Algeria). *Waste Management,* 29(2)**,** 896-902.

GUINEE, J. B., GORREE, M., HEIJUNGS, R., HUPPES, G., KLEIJN, R., VAN OERS, L., WEGENER S.A., UDO DE HAES, H. A., BRUIJN, J. & DUIN, V. R. (2001) Life Cycle Assessment: an operational guide to the ISO standards. . IN KLUWER ACADEMIC PUBLISHERS, D. (Ed.) The Netherlands. Centre for Environmental Science,University of Leiden.

HAHN-HAGERDAL, B., GALBE, M., GORWA-GRAUSLUND, M. F., LIDEN, G., & ZACCHI, G., (2006) Bio-ethanol - the fuel of tomorrow from the residues of today. *Trends in Biotechnology,* 24(12)**,** 549-556.

HAMELINCK, C. N., HOOIJDONK, G., & FAAIJ, A. P. C., (2005) Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. *Biomass & Bioenergy,* 28(4)**,** 384-410.

HAMELINCK, C. N., & FAAIJ, A. P. C., (2006) Outlook for advanced biofuels. *Energy Policy,* 34(17)**,** 3268-3283.

HENDRIKS, A. T. W. M., & ZEEMAN, G., (2009) Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresource Technology,* 100(1)**,** 10-18.

HENSEN, I. E., (2005) An assessment of changes in biomass carbon stocks in tree crops and forests in Malaysia. *Journal of Tropical Forest Science* 17(2)**,** 279-296.

HENSTRA, A. M., SIPMA, J., RINZEMA, A., & STAMS, A. J. M., (2007) Microbiology of synthesis gas fermentation for biofuel production. *Current Opinion in Biotechnology,* 18(3)**,** 200-206.

HESS, P., JOHNSTON, M., BROWN-STEINER, B., HOLLOWAY, T., DE ANDRADE, J. B. & ARTAXO, P., (2008) Air quality issues sssociated with biofuel production and use. in Howarth, R. W. & Bringezu, S. (Eds.).

HSE, (1998) Safe use of work equipment. Provision and Use of Work Equipment Regulations. *Approved Code of Practice and guidance.*

HSE, (2010) The Health and Safety Executive Statistics 2009/10. UK.

HSE, (2011a) About health and safety in agriculture. UK.(http://www.hse.gov.uk/agriculture/hsagriculture.htm), accessed 30th August 2012

HSE, (2011b) Manufacturing: Work related injuries and ill health

HUANG, H.-J., RAMASWAMY, S., TSCHIRNER, U. W., & RAMARAO, B. V., (2008) A review of separation technologies in current and future biorefineries. *Separation and Purification Technology,* 62(11)**,** 1-21.

HUANG, H. J., RAMASWAMY, S., AL-DAJANI, W., TSCHIRNER, U., &

CAIRNCROSS, R. A., (2009) Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis. *Biomass and Bioenergy*, 33(2)**,** 234-246.
HUBER, G. W., IBORRA, S., & CORMA, A., (2006) Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering. *ChemInform,* 37(52)**,** 4044-4098.
HUSTON, M. A., & MARLAND, G., (2003) Carbon management and biodiversity. *Journal of Environmental Management*, 67(1)**,** 77-86.
ICHEME (2002) The Sustainability Metrics, IChemE. *Sustainable Development Progress Metrics recommended for use in the Process Industries.* london.
ICIS (2012) ICIS Pricing oxo-Alcohols (http://www.icispricing.com/il_shared/Samples/SubPage153.asp), accessed January 2012
ICIS (2012) ICIS Pricing Isopropanol (http://www.icispricing.com/il_shared/Samples/SubPage148.asp), accessed January 2012
ICIS (2012) ICIS Pricing Acetic acid (http://www.icispricing.com/il_shared/Samples/SubPage167.asp), accessed January 2012
ICIS (2012) ICIS Pricing (Ethanolhttp://www.icispricing.com/il_shared/Samples/SubPage173.asp), accessed January 2012
INEOS (2010) INEOS Bio awarded £7.3 m grant form One North East and the Department for Energy and Climate change for construction of Europe's first advanced bioethanol from waste using the INEOS Bio Energy Process Technology, www.ineos.com/new_item.php?id_press=270, accessed August 2012
IOGEN, (2004) Iogen's Cellulosic Ethanol Demonstration Plant. Canada.
ISO, (2006a) Environmental Management — Life cycle assessment — Principles and Framework.
ISO, (2006b) Environmental management-Life cycle assessment, requirement and guidelines.
KADAM, K. L., WOOLEY, R. J., ADEN, A., NGUYEN, Q. A., YANCEY, M. A. & FERRARO, F. M., (2000) Softwood Forest Thinnings as a Biomass Source for Ethanol Production: A Feasibility Study for California. *Biotechnology Progress.* 16(6)**,** 947-957.
KALOGO, Y., HABIBI, S., MACLEAN, H. L., & JOSHI, S. V., (2007) Environmental implications of municipal solid waste-derived ethanol. *Environ. Sci. Technol.*, 41(1)**,** 35-41.
KAMM, B., GRUBER, P. R., & KAMM, M., (Eds.) (2006) *Biorefineries-Industrial Process and Products*, Wiley-VCH.
KAMM, B., & KAMM, M., (2004) Principles of biorefineries. *Applied microbiology and biotechnology*, 64(2)**,** 137-145.
KATAHIRA, S., MIZUIKE, A., FUKUDA, H., & KONDO, A., (2006) Ethanol fermentation from lignocellulosic hydrolysate by a recombinant xylose- and cellooligosaccharide-assimilating yeast strain. *Applied Microbiology and Biotechnology*, 72(6)**,** 1136-1143.
KATHIRVALE, S., MUHD YUNUS, M. N., SOPIAN, K., & SAMSUDDIN, A. H., (2004) Energy potential from municipal solid waste in Malaysia. *Renewable Energy*, 29(4)**,** 559-567.
KAYLEN, M., VAN DYNE, D. L., CHOI, Y. S., & BLASE, M., (2000) Economic

feasibility of producing ethanol from lignocellulosic feedstocks. *Bioresource Technology,* 72(1)**,** 19-32.

KAZI, F. K., FORTMAN, J. A., ANEX, R. P., HSU, D. D., ADEN, A., DUTTA, A., & KOTHANDARAMAN, G., (2010) Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. *Fuel,* 89(1), 20-28.

KEMPPAINEN, A. J., & SHONNARD, D. R., (2005) Comparative life-cycle assessments for biomass-to-ethanol production from different regional feedstocks. *Biotechnology Progress,* 21(4)**,** 1075-1084.

KERSTETTER, J. D., & LYONS, J. K., (2001) Wheat straw for ethanol production in Washington: A resource, technical and economic assessment. Washington State University.

KESHWANI, D. R., & CHENG, J. J., (2009) Switchgrass for bioethanol and other value-added applications: A review. *Bioresource Technology,* 100(4)**,** 1515-1523.

KIM, S., & DALE, B. E., (2008) Life cycle assessment of fuel ethanol derived from corn grain via dry milling. *Bioresource Technology,* 99(12)**,** 5250-5260.

KLEIN-MARCUSCHAMER, D., SIMMONS, B. A., & BLANCH, H. W., (2010) Techno-economic analysis of a lignocellulosic ethanol biorefinery with ionic liquid pre-treatment. *Biofuels, Bioproducts and Biorefining,* 5(5)**,** 562-569.

KROTSCHECK, C., KONIG, F., & OBERNBERGER, I., (2000) Ecological assessment of integrated bioenergy systems using the Sustainable Process Index. *Biomass and Bioenergy,* 18(4)**,** 341-368.

KRUYT, B., VAN VUUREN, D. P., DE VRIES, H. J. M., & GROENENBERG, H., (2009) Indicators for energy security. *Energy Policy,* 37(6)**,** 2166-2181.

KULKARNI, M. G., & DALAI, A. K., (2006) Waste cooking oil-an economical source for biodiesel: A review. *Industrial & Engineering Chemistry Research,* 45(9)**,** 2901-2913.

KUMAR, A., CAMERON, J. B., & FLYNN, P. C., (2005) Pipeline transport, and simultaneous saccharification of corn stover. *Bioresource Technology,* 96(7)**,** 819-829.

KUMAR, P., BARRETT, D. M., DELWICHE, M. J., STROEVE, P., (2009) Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. *Ind. Eng. Chem,* 48(8) 3713-3729.

LABUSCHAGNE, C., BRENT, A. C., & VAN ERCK, R. P. G., (2005) Assessing the sustainability performances of industries. *Journal of Cleaner Production,* 13(4)**,** 373-385.

LAL, R., (2006a) Crop residues as soil amendments and feedstock for bioethanol production. *Waste Management.* 28(4), 747-758.

LAL, R., (2006b) Soil and environmental implications of using crop residues as biofuel feedstock. *International Sugar Journal,* 108 (1287)**,** 161-167.

LARSON, E. D., (2008) Biofuel production technologies: *status, prospects and implications for trade and development.* Newyork and Geneva.

LASER, M., JIN, H., JAYAWARDHANA, K., DALE, B. E., & LYND, L. R., (2009a) Projected mature technology scenarios for conversion of cellulosic biomass to ethanol with coproduction thermochemical fuels, power, and/or animal feed protein. *Biofuels, Bioproducts and Biorefining,* 3(2)**,** 231-246.

LASER, M., JIN, H., JAYAWARDHANA, K., & LYND, L. R., (2009b) Coproduction of ethanol and power from switchgrass. *Biofuels, Bioproducts, Biorefining* 3(2)**,** 195-218.

LASER, M., LARSON, E., DALE, B., WANG, M., GREENE, N., & LYND, L. R., (2009c) Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios. *Biofuels, Bioproducts & Biorefining,* 3(2)**,** 247-270.

LEE, K. H., KANG, B. S., PARK, Y. K., & KIM, J. S., (2005) Influence of reaction temperature, pretreatment, and a char removal system on the production of bio-oil from rice straw by fast pyrolysis, using a fluidized bed. *Energy & Fuels*, 19(5)**,** 2179-2184.

LENS, P., WESTERMANN, P., HABERBAUER, M., & MORENO, A., (Eds.) (2005) Biofuels for fuel Cells: renewable energy from biomass fermentation. London Seattle.

LEWANDOWSKI, I., SCURLOCK, J. M. O., LINDVALL, E., & CHRISTOU, M., (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass and Bioenergy,* 25(4)**,** 335-361.

LI, L. I. N., & ZHANG, H., (2005) Production and characterization of pyrolysis oil from herbaceous biomass (Achnatherum Splendens). *Energy Sources,* 27(4)**,** 319-326.

LI, A., ANTIZAR-LADISLAO, B., & KHRAISHEH, M., (2007) Bioconversion of municipal solid waste to glucose for bio-ethanol production. *Bioprocess Biosystems Engineering,* 30(3)**,** 189-196.

LIN, Y., & TANAKA, S., (2006) Ethanol fermentation from biomass resources: current state and prospects. *Applied Microbiology and Biotechnology,* 69(6)**,** 627-642.

LINDEGAARD, K., (2012) Why we need energy crops in the south west. UK.

LU, Y., & MOSIER, N. S., (2008) Current technologies for fuel ethanol production from lignocellulosic plant biomass. *Genetic Improvement of Bioenergy Crops***,** 103(6),161-182.

LU, Y., WU, X., & GUO, J., (2009) Characteristics of municipal solid waste and sewage sludge co-composting. *Waste Management*, 29(3)**,** 1152-1157.

LUO, L., VAN DER VOET, E., & HUPPES, G., (2010) Biorefining of lignocellulosic feedstock - Technical, economic and environmental considerations. *Bioresource Technology,* 101(13)**,** 5023-5032.

LUQUE, R., HERRERO-DAVILA, L., CAMPELO, J. M., CLARK, J. H., HIDALGO, J.M., LUNA, D., MARINAS, J.M., & ROMERO, A. A., (2008) Biofuels: a technological perspective. *Energy Environmental Science,* 1**,** 542-564.

MACLEAN, H., & SPATARI, S., (2009) The contributions of enzymes and process chemcials to the life cycle of ethanol. *Environmental Research Letters,* 4(1).

MARCUS, C. R., (2005) Economic assessment of municipal waste management systems--case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). *Journal of Cleaner Production,* 13(3)**,** 253-263.

MCKENDRY, P., (2002) Energy production from biomass (part 2): conversion technologies. *Bioresource technology,* 1(83), 47-54.

MIKKILÄ, M., HEINIMÖ, J., PANAPANAAN, V., LINNANEN, L., & FAAIJ, A., (2009) Evaluation of sustainability schemes for international bioenergy flows. *International Journal of Energy Sector Management,* 3(4)**,** 359-382.

MITCHELL, C. P., STEVENS, E. A., & WATTERS, M. P., (1999) Short-rotation forestry - operations, productivity and costs based on experience gained in the UK. *Forest Ecology and Management,* 121(1/2)**,** 123-136.

MOHAN, D., PITTMAN, C. U., & STEELE, P. H., (2006) Pyrolysis of wood/biomass for bio-oil: A Critical Review. *Energy & Fuels,* 20(3)**,** 848-889.

MU, D., SEAGER, T., RAO, P. S., & ZHAO, F., (2010) Comparative life cycle assessment of lignocellulosic ethanol production: biochemical versus thermochemical conversion. *Environmental Management,* 46(4), 565-578.

NNFCC (2007) Lignocellulosic Ethanol Plant in the UK Feasibility Study. IN Black and Veatch UK.
NNFCC, (2012) UK jobs in the bio-energy sectors by 2020
NNFCC, (2012) NNFCC Renewable Chemicals Fact sheet: Lactic acid (http://www.nnfcc.co.uk/publications/nnfcc-renewable-chemicals-factsheet-lactic-acid), accessed January 2012
NURUL ISLAM, M., NURUL ISLAM, M., RAFIQUL ALAM BEG, M., & ROFIQUL ISLAM, M., (2005) Pyrolytic oil from fixed bed pyrolysis of municipal solid waste and its characterization. *Renewable Energy,* 30(3)**,** 413-420.
NREL, (2011a) Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol; *dilute-acid pretreatment and enzymatic hydrolysis of corn stover*. National Renewable Energy Laboratory Golden, Colorado.
NREL, (2011b) Process design and economics for conversion of lignocellulosic biomass to ethanol: *thermochemical pathway by indirect gasification and mixed alcohol.* National Renewable Energy Laboratory Golden, Colorado.
OASMAA, A., & KUOPPALA, E., (2003) Fast Pyrolysis of Forestry Residue.3. Storage stability of liquid fuel. *Energy & Fuels,* 17(4)**,** 1075-1084.
OASMAA, A., KUOPPALA, E., & SOLANTAUSTA, Y., (2003) Fast Pyrolysis of Forestry Residue. 2. Physicochemical Composition of Product Liquid. *Energy & Fuels* 17(2)**,** 433-443.
OGIER, J. C., BALLERINI, D., LEYGUE, J. P., RIGAL, L., & POURQUIE, J., (1999) Ethanol production from lignocellulosic biomass. *Oil & Gas Science and Technology-Revue De L Institut Francais Du Petrole,* 54(1)**,** 67-94.
ÖHGREN, K., BURA, R., SADDLER, J., & ZACCHI, G., (2007) Effect of hemicellulose and lignin removal on enzymatic hydrolysis of steam pretreated corn stover. *Bioresource Technology,* 98(13)**,** 2503-2510.
OLOFSSON, K., BERTILSSON, M., & LIDEN, G., (2008) A short review on SSF - An interesting process option for ethanol production from lignocellulosic feedstocks. *Biotechnology for Biofuels,* 1(1), 1-7.
PAN, X., & SANO, Y., (2005) Fractionation of wheat straw by atmospheric acetic acid process. *Bioresource Technology,* 96(11)**,** 1256-1263.
PANG, X. Y., & YOU, T. T., (2008) Preparation of biodiesel through transesterification of animal oil and alcohol under the catalysis of SO4 / TiO2. *Journal of Chemistry,* 6(1)**,** 189-195.
PARRISH, D. J., & FIKE, J. H., (2005) The biology and agronomy of switchgrass for biofuels. *Critical Reviews in Plant Sciences,* 24(5/6)**,** 423-459.
PARIKKA, M., (2004) Global biomass fuel resources. *Biomass and Bioenergy,* 27(6)**,** 613-620.
PASTER, M., PELLEGRINO, J. L., & CAROLE, T. M., (2003) Industrial Bioproducts: Today and Tomorrow. US.
PAYÁ, J., MONZÓ, J., BORRACHERO, M. V., DÍAZ-PINZÓN, L., & ORDÓÑEZ, L. M., (2002) Sugar-cane bagasse ash (SCBA): studies on its properties for reusing in concrete production. *Journal of Chemical Technology & Biotechnology,* 77(3)**,** 321-325.
PE, (2007) Life cycle assessment software (GaBI) version 4. PE International, Germany.
PEREZ-VERDIN, G., GREBNER, D. L., SUN, C., MUNN, I. A., SCHULTZ, E. B., & MATNEY, T. G., (2009) Woody biomass availability for bioethanol conversion in Mississippi. *Biomass and Bioenergy,* 33(3)**,** 492-503.
PERLACK, R. D., & TURHOLLOW, A. F., (2003) Feedstock cost analysis of corn

stover residues for further processing. *Energy*, 28(14)**,** 1395-1403.

PERLACK, R.D., WRIGHT, L.L., TURHULLOW, A.F., GRAHAM, R.L (2005) Biomass as feddstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annal supply (http://www.ornl.gov/~webworks/cppr/y2001/rpt/123021.pdf).

PETERS, M. S., TIMMERHAUS, K. D., & WEST, R. E., (2003) Plant design and economic for chemical engineers, Colorado, McGraw-Hill.

PHILLIPS, S., ADEN, A., JECHURA, J., & DAYTON, D., (2007) Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass. United States.

PIEMONTE, V., (2011) Wood residue as a raw material for biorefinery systems: LCA case study on bioethanol and electricity production. *Journal of polymers and the environment*, 20(2), 299-304.

PICCOLO, C., & BEZZO, F., (2009) A techno-economic comparison between two technologies for bioethanol production from lignocellulose. *Biomass and Bioenergy,* 33(3)**,** 478-491.

PIMENTEL, D., & PATZEK, T. W., (2005) Ethanol production using corn, switchgrass, and Wood; biodiesel production using soybean and sunflower. *Natural Resource Research,* 14(1), 65-76.

PROCESS ENGINEERING, 2001-2007. UK and international plant cost indices. Volumes 82 Issue 10 to Volume 88 Issue 6.

QIN, X., MOHAN, T., EL-HALWAGI, M., CORNFORTH, G., & MCCARL, B. A., (2006) Switchgrass as an alternate feedstock for power generation: An integrated environmental, energy and economic life-cycle assessment. *Clean Technologies and Environmental Policy,* 8(4)**,** 233-249.

QURESHI, N., & EZEJI, T. C., (2008) Butanol, 'a superior biofuel' production from agricultural residues (renewable biomass): recent progress in technology. *Biofuel, Bioproducts and Biorefining*, 2(4), 319-330.

RAVINDRANATH, N.H., MANUVIE, R., FARGIONE, J., CANADELL, J.G., BERNDES, G., WOODS, J, WATSON, H., SATHAYE, J., (2009) Greenhouse gas implications of land use and Land conversion to biofuel crops. In: Biofuels: Environmental consequences and interactions with changing land use. Howarth, R.W, Bringezu, S. (eds), Scientific Committee on Problems of the Environment (SCOPE), Island Press, New York. Online access: http://cip.cornell.edu/biofuels

ROES, A. L., & PATEL, M. K., (2007) Life cycle risks for human health: A comparison of petroleum versus bio-based production of five bulk organic chemicals. *Risk Analysis*, 27(5)**,** 1311-1321.

RFA, (2012) The renewable Fuel standard, timeline of successful policy, biotechnology industryorganisation *www.bio.org/sites/default/files/TimelineRenewableFuelStandard.pdf* Accessed August 2012

SADDLER, J., & MABEE, W., (2007) Choosing biorefining platforms for the commercialisation of the biomass-to-ethanol process. *Biomass & Bioenergy,* 31(4)**,** I-V.

SAHA, B. C., & COTTA, M. A., (2007) Enzymatic hydrolysis and fermentation of lime pretreated wheat straw to ethanol. *Journal of Chemical Technology and Biotechnlogy*, 82(10), 913-919.

SAMMONS JR, N. E., YUAN, W., EDEN, M. R., AKSOY, B., & CULLINAN, H. T., (2008) A systematic framework for biorefinery production optimization. *Computer Aided Chemical Engineering.* 25, 1077-1082.

SAMMONS, N., EDEN, M., YUAN, W., CULLINAN, H., & AKSOY, B., (2007) A flexible framework for optimal biorefinery product allocation. *American Institute of Chemical Engineers* 26(4)**,** 349-354.

SCHELLA, C., RILEYB, C., & PETERSENC, G. R., (2008) Pathways for development of a biorenewables industry. *Bioresource Technology*, 99(12), 5160-5164.

SCHULTEA, P. A., & CHUN, H., (2009) Climate Change and Occupational Safety and Health: Establishing a Preliminary Framework. *Journal of Occupational and Environmental Hygiene,* 6(9)**,** 542-554.

SCHWIETZKE, S., LADISCH, M., RUSSO, L., KWANT, K., MAKINEN, T., KAVALOV, B., MANIATIS, K. & ZWART, R. (2006) Gaps in the research of 2nd Generation Transportation Biofuels. *Analysis and identification of gaps in the research of second generation liquid transportation biofuels.* United States,

SEARCHINGER, T., HEIMLICH, R., HOUGHTON, R. A., DONG, F., ELOBEID, A., FABIOSA, J., TOKGOZ, S., HAYES, D., & YU, T. H., (2008) Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, 319(5687), 1238-1240.

SENDICH, M., LASER, M., KIM, S., ALIZADEH, H., LAUREANO-PEREZ, L., DALE, B. E., & LYND, L. R., (2008) Recent process improvement for the ammonia fiber expansion (AFEX) process and resulting reductions in minimum ethanol selling price. *Bioresource Technology*, 99(17)**,** 8429-8435.

SHEAFFERA, C. C., MARTINB, N. P., LAMB, J. F. S., CUOMOD, G. R., JEWETTA, J. G., & QUERING, S. R., (2000) Leaf and Stem Properties of Alfalfa Entries. *Agronomy Journal*, 92(4)**,** 733-739.

SIMS, R., TAYLOR, M., SADDLER, J., & MABEE, W., (2008) From 1st to 2nd Generation Biofuel Technologies. IN OECD/IEA (Ed.) *An overview of current industry and RD&D activities.*

SPATARI, S., ZHANG, Y., & MACLEAN, H. L., (2005) Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. *Environmental Science and Technology,* 39(24)**,** 9750-9758.

Al-Zuhair, S., (2007) Production of biodiesel: possibilities and challenges. *Biofuel, Bioproducts and Biorefining*, 1(1), 57-66.

SUN, Y., & CHENG, J., (2002) Hydrolysis of lignocellulosic materials for ethanol production: a review. *Bioresource Technology,* 83(1)**,** 1-11.

SWATLOSKI, R. P., SPEAR, S. K., HOLBREY, J. D., & ROGERS, R. D., (2002) Dissolution of cellose with ionic liquids. *Journal of American Chemical society,* 124(18)**,** 4974-4975.

TAHERZADEH, M. J., & KARIMI, K., (2008) Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: A review. *International Journal of Molecular Sciences,* 9(9)**,** 1621-1651.

TAHERZADEH, J. & KARIMI, K.,(2007 Enzyme based hydrolysis processes for ethanol from lignocellulosic materials: A review. *Bio Resources* 2(4) 707-738.

TALLY, S., (2002) Making biofuel from corn stover. *BioCycle,* 43(11)**,** 62-62.

TAYLOR, G., (2008) Biofuels and the biorefinery concept. *Energy Policy,* 36(12)**,** 4406-4409.

TROSCHINETZ, A. M., & MIHELCIC, J. R., (2009) Sustainable recycling of municipal solid waste in developing countries. *Waste Management,* 29(2)**,** 915-923.

TUCKER, M. P., KIM, K. H., NEWMAN, M. M., & NGUYEN, Q. A., (2003) Effects of temperature and moisture on dilute-acid steam explosion pretreatment of corn stover and cellulase enzyme digestibility. *Applied Biochemistry and Biotechnology,* 105**,** 165-177.

TURNER, M. B., SPEAR, S. K., HOLBREY, J. D., & ROGERS, R. D., (2004) Production of Bioactive cellulose films reconstituted from ionic liquids. *Biomacromolecules,* 5(4)**,** 1379-1384.

UN, (2007) Indicators of sustainable development: guidelines and methodologies. In development

UNION, E., (2004) Agriculture in the European Union, statistical and economic information.

VADAS, P. A., BARNETT, K. H., & UNDERANDER, D. J., (2008) Economics and Energy of Ethanol Production from Alfalfa, Corn, and Switchgrass in the Upper Midwest, USA. *BioEnergy Research,* 1**,** 44-55.

VAN DEN OEVER, M. J. A., ELBERSEN, H. W., KEIJSERS, E. R. P., GOSSELINK, R. J. A., & DE KLERK-ENGELS, B., (2003) Switchgrass (Panicum virgatum L.) as a reinforcing fibre in polypropylene composites. *Journal of Materials Science,* 38(18)**,** 3697-3707.

VASSILEV, S. V., BAXTER, D., ANDERSEN, L. K., & VASSILEVA, C. G., (2010) An overview of the chemical composition of biomass. *Fuel,* 89(5)**,** 913-933.

VELEVA, V., HART, M., GREINER, T., & CRUMBLEY.C., (2003) Indicators for measuring environmental sustainability: A case study of the pharmaceutical industry. *Benchmarking: An International Journal,* 10(2)**,** 107-119.

VENEDAAL, R., JORGENSEN, U., & FOSTERS, C. A., (1997) European energy crops: A synthesis. *Biomass and Bioenergy,* 13(3)**,** 147-185.

VILLEGAS, J. D., & GNANSOUNOU, E., (2008) Techno-economic and environmental evaluation of lignocellulosic biochemical refineries: need for a modular platform for integrated assessment (MPIA). *Journal of Scientific & Industrial Research,* 67**,** 927-940.

VINK, E. T. H., RABAGO, K. R., GLASSNER, D. A., & GRUBER, P. R., (2003) Applications of life cycle assessment to NatureWorks (TM) polylactide (PLA) production. *Polymer Degradation and Stability,* 80**,** 403-419.

WERPY, T., & PETERSEN, G., (2004) Top Value Added Chemicals from Biomass, National Renewable Energy. & Labouratory, Pacific Northwest National Labouratory. (Eds.) *Volume 1- Results of Screeing for Potential Candidates from sugars and synthesis gas.* United States.

WERNER F., ALTHAUS, H.J., KUNNIGER, T., RICHTER, K., & JUNGBLUTH, N., (2007) Life cycle Inventories of Wood as Fuel and Construction Material. Final report ecoinvent 2000 No 9. EMPA Dubendorf, Swiss Centre for Life Cycle Inventories, Dubendorf, CH.

WILLAMS, A., (2010) Ethanol company looks to build in Iowa in 2011. *The Messenger.*

WINGREN, A., GALBE, M., & ZACCHI, G., (2003) Techno-Economic evaluation of producing ethanol from softwood: Comparison of SSF and SHF and identification of bottlenecks. *Biotechnol.Prog* 19(4)1109-1117

WOOLEY, R., RUTH, M., SHEEHAN, J. & IBSEN, K. (1999) Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios. IN NREL (Ed.) Colorado.

WRIGHT, M. W., & BROWN, R. C., (2007) Comparative economics of biorefineries based on the biochemical and thermochemical platforms. *Biofuels, Bioproducts and Biorefining,* 1(1), 49-56

WU, M., WU, Y., & WANG, M., (2006) Energy and emission benefits of alternative transportation liquid fuels derived from switchgrass: A fuel life cycle assessment. *Biotechnology Progress,* 22(4)**,** 1012-1024.

WYMAN, C. E., (2003) Potential synergies and challenges in refining cellulosic biomass to fuels, chemicals, and power. *Biotechnology Progress*, 19(2)**,** 254-262.

YAMAN, S., (2004) Pyrolysis of biomass to produce fuels and chemical feedstocks. *Energy Conversion and Management*, 45(5)**,** 651-671.

YORGUN, S., SENSÖZ, S., & KOÇKAR, Ö. M., (2001) Characterization of the pyrolysis oil produced in the slow pyrolysis of sunflower-extracted bagasse. *Biomass and Bioenergy,* 20(2)**,** 141-148.

YUAN, J. S., TILLER, K. H., AL-AHMAD, H., STEWART, N. R., & STEWART, C. N., (2008) Plants to power: bioenergy to fuel the future. *Trends in Plant Science*, 13(8)**,** 421-429.

ZHANG, Y. H. P., (2008) Reviving the carbohydrate economy via multi-product lignocellulose biorefineries. *Journal of Industrial Microbiology & Biotechnology,* 35(5)**,** 367-375.

ZHI F, G., CHAN, A. W., & MINNS, D. E., (2003) Life cycle assessment of bio-ethanol derived from cellulose. *The International Journal of Life Cycle assessment* 8(3)**,** 137-141.

ZHU, B. N., GIKAS, P., ZHANG, R. H., LORD, J., JENKINS, B., & LI, X. J., (2009) Characteristics and biogas production potential of municipal solid wastes pretreated with a rotary drum reactor. *Bioresource Technology,* 100(3)**,** 1122-1129.

APPENDIX 1: METHODOLOGY FOR ESTIMATING THE ECONOMIC INDICATORS

In this study, the life cycle cost is the sum of the capital cost and the manufacturing cost of the plant for the 30 years of operation. The total capital investment (TCI) is the sum of the total installed equipment cost (TIE), direct and indirect cost. Direct cost include purchased equipment with installation, instrumentation and control, piping and electrical systems, construction costs, process and auxiliary building, service facilities such as utilities and distribution, investment costs for land acquisition (Kaylen et al. 2000). The indirect cost is cost not directly associated with the day to day running of the plant. These are engineering and supervision and inspection cost, legal expenses, construction expenses, contractor's fee and any contingency cost. These can be obtained from the materials and energy balance and process conditions derived from the process simulation. This information along side the material of construction is used to get a capital cost estimate.

The manufacturing costs (MC) are variable cost, fixed cost and plant overhead cost. The variable cost is expenses that are directly proportional to the process operation. They are incurred as when the plant operates. They include raw materials, utilities, plant maintenance; operating supplies and royalties (Deverell et al. 2009). The fixed costs are incurred independent of the process operation for example, taxes, and insurance. The plant overhead cost is similar to the fixed cost and is also called the production overhead cost. It is also referred to as indirect labour and cost, such as quality assurance and medical and life insurance (Peters et al. 2003). The revenue from the products is estimated from the quantities produced and multiplied by the unit cost of the product.

The economic profitability of the plant is estimated using the NPV (Net Present Value) and the IRR (Internal Rate of Return) and the Payback Period (PBP). The NPV is used in discounted cash flow (DCF) analysis. The NPV is the difference between the sum of discounted cash inflows and out flows while considering the value of money today to the present value of money in future (Peters et al. 2003); see equation 2.1 for the formula. NPV analysis involves the use of a discount rate to evaluate the time value of money. The discount rate is the minimum expected rate of investment. For projects such as this, 10% has been assumed to be the appropriate discount rate. If the total NPV is positive, then the project can be accepted and taken as a good investment.

$$NPV = \sum_{k=1}^{N} \frac{F_K}{(1+i)^k} - TCI \qquad 2.1$$

where *N* is the plant life, assumed to be 30 years, *i* is the discount rate, 10% and F_k is the net cash flow after tax at the *kth* year equal to

$$F_k = R - MC - T - D \qquad 2.2$$

where R is the revenues from product sales, T and D are the taxes and depreciation.

The deprecation method used is the straight line method. Depreciation is the income tax payable in the years in which it is charged (Peters, et al. 2003, p 310). In the straight line depreciation method, it is assumed that the property decreases linearly with the recovery time period. The amount depreciated each year is depicted in equation 2.3

$$d = \frac{TCI}{n} \quad 2.3$$

where *d* is the annual depreciation, *TCI* is the capital investment and *n* is the length of the straight line recovery period. The recovery period of 9.5 years is assumed for chemical plants and therefore used in this study (Peters et al. 2003).

The IRR is defined as the value of the discount rate at which the total NPV is equal zero and it is calculated by iterating the value of *i*. It is used to compare profitability of more than one investment. It is classified as a measure of efficiency and yield of an investment. It is a way of comparing the profitability of more than one investment with similar capital cost. The higher the IRR, the more desirable it is to invest in such project. The pay back period is the time in years, taken to recover the project cost (breakeven point).

APPENDIX 2: CALCULATION OF PRODUCT OUTPUTS FOR DIFFERENT FEEDSTOCKS

NB: The equations quoted below refer to Table 4.2 and 4.3

Example calculations for wheat straw: Ethanol production

Working calculations of C5 sugars hydrolysis
Calculate arabinan conversion to arabinose =0.00235x0.75=0.0176 units of sugar
Calculate galactan conversion to galactose = 0.0075x0.75 = 0.0056 units of sugar
Calculate mannan conversion to mannose = 0.0031x0.75 = 0.0023 units of sugar
Calculate xylan conversion to xylose = 0.192x0.85 = 0.1632 units of sugar
Total convertible hemicellulose sugars = 0.189 units of sugars

Fermentation of these hemicellulose sugars to ethanol using Z mobilis
Calculate xylose conversion to ethanol using eqn. (12):
2 moles xylose to 5 moles ethanol
RMM xylose = 150 kg/kmol
Ethanol converted = 0.082 units of ethanol

Saccharification of cellulose to glucose using enzymes
Calculate glucose conversion = 0.32x0.9 = 0.31 units of glucose
Fermentation of glucose to ethanol using eqn. (7)

1 mole glucose to 2 moles ethanol
RMM glucose =180 kg/kmol
RMM ethanol = 46 kg/kmol
Ethanol converted =0.146 unit of ethanol
Add ethanol results from the conversions =0.082 + 0.146 = 0.228 units of ethanol
For total feedstock quantities = 0.228x112,968= 25,756 kg of ethanol
Assume 7% sugar loss = **24 tonnes of ethanol**

Example calculations for wheat straw: Acetic acid production
Acetate component of the feedstock = 0.0224x1= 0.022 units of acetic acid
From eqn 10:
1 mole of glucose to 2 moles of acetic acid
RMM acetic acid = 60.05 kg/kmol
Conversion efficiency = 1.5%
Acetic acid = 0.003 units of acetic acid
From eqn 16:
2 moles of xylose to 5 moles of acetic acid
Conversion efficiency = 1.4%
Acetic acid = 0.003 units of acetic acid
Total = 0.028 units of acetic acid
Total feedstock = 0.02816x112,968= **3,181 kg of acetic acid**

Example calculations for wheat straw: Lactic acid production
From eqn 11:
1 mole of glucose to 2 moles of lactic acid
RMM lactic acid = 90.08 kg/kmol

Conversion efficiency = 0.2%
lactic acid = 6.23×10^{-4} units of lactic acid
From eqn 17:
2 moles of xylose to5 moles of lactic acid
Conversion efficiency = 1.4%
Lactic acid = 2.65×10^{-3} units of lactic acid
Total = 0.003 units of lactic acid
Total feedstock = 3.27×10^{-3}x112,968= **369 kg of lactic aci**d

Example calculations for poplar: Ethanol production

Working calculations of C5 sugars hydrolysis
Calculate arabinan conversion to arabinose =0.0079x0.75=0.0059 units of sugar
Calculate galactan conversion to galactose = 0.0024x0.75 = 0.0018 units of sugar
Calculate mannan conversion to mannose = 0.0393x0.75 = 0.0294 units of sugar
Calculate xylan conversion to xylose = 0.1905x0.85 = 0.161 units of sugar
Total convertible hemicellulose sugars = 0.199 units of sugars

Fermentation of these hemicellulose sugars to ethanol using Z mobilis
Calculate xylose conversion to ethanol using eqn. (12):
2 moles xylose to 5 moles ethanol
RMM xylose = 150 kg/kmol
Ethanol converted = 0.0865 units of ethanol

Saccharification of cellulose to glucose using enzymes
Calculate glucose conversion = 0.42x0.9 = 0.378 units of glucose
Fermentation of glucose to ethanol using eqn. (7)
1 mole glucose to 2 moles ethanol
RMM glucose =180 kg/kmol
RMM ethanol = 46 kg/kmol
Ethanol converted =0.181 unit of ethanol
Add ethanol results from the conversions =0.181+ 0.0865 = 0.267 units of ethanol
For total feedstock quantities = 0.267x97000= 25,947 kg of ethanol
Assume 7% sugar loss = **24131 kg of ethanol**

Example calculations for poplar: Acetic acid production
Acetate component of the feedstock = 0.046x1= 0.046 units of acetic acid
From eqn 10:
1 mole of glucose to 2 moles of acetic acid
RMM acetic acid = 60.05 kg/kmol
Conversion efficiency = 1.5%
Acetic acid = 0.004 units of acetic acid
From eqn 16:
2 moles of xylose to 5 moles of acetic acid
Conversion efficiency = 1.4%
Acetic acid = 0.004 units of acetic acid
Total = 0.053 units of acetic acid
Total feedstock = 0.053x97000= **5141 kg of acetic acid**

Example calculations for poplar: Lactic acid production
From eqn 11:
1 mole of glucose to 2 moles of lactic acid
RMM lactic acid = 90.08 kg/kmol
Conversion efficiency = 0.2%
lactic acid = $7.69x10^{-4}$ units of lactic acid
From eqn 17:
2 moles of xylose to5 moles of lactic acid
Conversion efficiency = 1.4%
Lactic acid = $2.79x10^{-3}$ units of lactic acid
Total = $3.56x10^{-3}$ units of lactic acid
Total feedstock = $3.56x10^{-3}$ x97000 **=345 kg of lactic aci**d

Example calculations for miscanthus: Ethanol production

Working calculations of C5 sugars hydrolysis
Calculate arabinan conversion to arabinose =0.018x0.75=0.014 units of sugar
Calculate galactan conversion to galactose = 0.004x0.75 = 0.003 units of sugar
Calculate mannan conversion to mannose = 0.031x0.75 = 0.023 units of sugar
Calculate xylan conversion to xylose = 0.19x0.85 = 0.161 units of sugar
Total convertible hemicellulose sugars = 0.201 units of sugars

Fermentation of these hemicellulose sugars to ethanol using Z mobilis
Calculate xylose conversion to ethanol using eqn. (12):
2 moles xylose to 5 moles ethanol
RMM xylose = 150 kg/kmol
Ethanol converted = 0.0874 units of ethanol

Saccharification of cellulose to glucose using enzymes
Calculate glucose conversion = 0.38x0.9 = 0.342 units of glucose
Fermentation of glucose to ethanol using eqn. (7)
1 mole glucose to 2 moles ethanol
RMM glucose =180 kg/kmol
RMM ethanol = 46 kg/kmol
Ethanol converted =0.162 unit of ethanol
Add ethanol results from the conversions =0.162+ 0.0874 = 0.249 units of ethanol
For total feedstock quantities = 0.249x104000= 25935 kg of ethanol
Assume 7% sugar loss = **24092 kg of ethanol**

Example calculations for miscanthus: Acetic acid production
Acetate component of the feedstock = 0.018x1= 0.018 units of acetic acid
From eqn 10:
1 mole of glucose to 2 moles of acetic acid
RMM acetic acid = 60.05 kg/kmol
Conversion efficiency = 1.5%
Acetic acid = 0.003 units of acetic acid
From eqn 16:
2 moles of xylose to 5 moles of acetic acid
Conversion efficiency = 1.4%

Acetic acid = 0.003 units of acetic acid
Total =0.018+0.003+ 0.003 = 0.024 units of acetic acid
Total feedstock = 0.0243x104000= **2523 kg of acetic acid**

Example calculations for miscanthus: Lactic acid production
From eqn 11:
1 mole of glucose to 2 moles of lactic acid
RMM lactic acid = 90.08 kg/kmol
Conversion efficiency = 0.2%
lactic acid = 6.88×10^{-4} units of lactic acid
From eqn 17:
2 moles of xylose to5 moles of lactic acid
Conversion efficiency = 1.4%
Lactic acid = 2.82×10^{-3} units of lactic acid
Total = 3.51×10^{-3} units of lactic acid
Total feedstock = 3.51×10^{-3} x104000 **=364 kg of lactic aci**d

Example calculations for forest residue: Ethanol production

Working calculations of C5 sugars hydrolysis
Calculate arabinan conversion to arabinose =0.0148x0.75=0.011 units of sugar
Calculate galactan conversion to galactose = 0.0203x0.75 = 0.015 units of sugar
Calculate mannan conversion to mannose = 0.0086x0.75 = 0.0645 units of sugar
Calculate xylan conversion to xylose = 0.092x0.85 = 0.078 units of sugar
Total convertible hemicellulose sugars = 0.170 units of sugars

Fermentation of these hemicellulose sugars to ethanol using Z mobilis
Calculate xylose conversion to ethanol using eqn. (12):
2 moles xylose to 5 moles ethanol
RMM xylose = 150 kg/kmol
Ethanol converted = 0.0737 units of ethanol

Saccharification of cellulose to glucose using enzymes
Calculate glucose conversion = 0.44x0.9 = 0.396 units of glucose
Fermentation of glucose to ethanol using eqn. (7)
1 mole glucose to 2 moles ethanol
RMM glucose =180 kg/kmol
RMM ethanol = 46 kg/kmol
Ethanol converted =0.186 unit of ethanol
Add ethanol results from the conversions =0.186+0.073 = 0.259 units of ethanol
For total feedstock quantities = 0.259x99000= 25641 kg of ethanol
Assume 7% sugar loss = **23846 kg of ethanol**

Example calculations for forest residue: Acetic acid production
Acetate component of the feedstock = 0.028x1= 0.028 units of acetic acid
From eqn 10:
1 mole of glucose to 2 moles of acetic acid
RMM acetic acid = 60.05 kg/kmol
Conversion efficiency = 1.5%

Acetic acid = 0.004 units of acetic acid
From eqn 16:
2 moles of xylose to 5 moles of acetic acid
Conversion efficiency = 1.4%
Acetic acid = 0.002 units of acetic acid
Total =0.028+0.004+ 0.002 = 0.034 units of acetic acid
Total feedstock = 0.034x99000= **3390 kg of acetic acid**

Example calculations for forest residue: Lactic acid production
From eqn 11:
1 mole of glucose to 2 moles of lactic acid
RMM lactic acid = 90.08 kg/kmol
Conversion efficiency = 0.2%
lactic acid = 7.94×10^{-4} units of lactic acid
From eqn 17:
2 moles of xylose to5 moles of lactic acid
Conversion efficiency = 1.4%
Lactic acid = 2.38×10^{-3} units of lactic acid
Total = 3.17×10^{-3} units of lactic acid
Total feedstock = 3.17×10^{-3}x99000 **=314 kg of lactic aci**d

APPENDIX 3: RESULTS FOR THE BIO-CHEMICAL CASE STUDY

This appendix presents the environmental (LCA) and economic assessment results for the bio-chemical case study in the following order:

1. Total annual environmental impacts
2. Environmental impacts with system expansion
3. Environmental impacts with economic allocation
4. Comparisons of environmental impacts of bio-chemical with fossil-based refineries
5. Comparisons of environmental impacts of ethanol from 2nd with 1st generation feedstocks
6. Comparisons of environmental impacts of bio-ethanol with petrol
7. Results of the economic assessment.

1. Total annual environmental impacts for the bio-chemical system

Abiotic Depletion Potential (ADP) [t Sb-Eq.]					
		Wheat straw	**Poplar**	**Miscanthus**	**Forest residue**
Stage					
Feedstock	Wheat straw	255.00	0	0	0.00
	Poplar	0.00	96.00	0	0.00
	Miscanthus	0	0	102	0.00
	Forest residues	0	0	0	65.30
Pre-treatment and conditioning	Lime	38.19	32.78	35.15	33.47
	Sulphuric acid	28.99	24.89	26.69	25.41
Saccharification and fermentation	DAP	38.72	33.64	35.66	34.02
	DDGS	84.78	72.82	78.08	74.36
	Waste	5.72	4.9	5.2	5.02
	Transport	30.2	27.5	29.6	27.4
Total		**481.6**	**292.5**	**312.3**	**264.9**

Table 3.1a ADP results per year

	Acidification Potential (AP) [t SO_2 Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	580.00	0	0	0
	Poplar	0.00	190.90	0	0
	Miscanthus	0	0	204	0
	Forest residue	0	0	0	64.8
Pretreatment and Conditioning	Lime	15.11	12.90	13.91	13.25
	Sulphuric acid	410.90	352.90	378.4	360.27
Saccharification and fermentation	DAP	15.48	13.40	14.26	13.6
	DDGS	25.17	21.62	23.19	22.08
Others	Boiler	239.00	225.00	232	219

	Waste	3.17	3.02	3.24	3.08
	Transport	33.30	28.60	30.68	29.20
Total		**1322.13**	**848.34**	**899.68**	**725.28**

Table 3.2a AP results per year

	Eutrophication Potential (EP) [t PO_4-Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	803.00	0	0	0
	Poplar	0.00	53.27		0
	Miscanthus	0	0	57.12	0
	Forest residue	0	0	0	11.92
Pretreatment and Conditioning	Lime	1.85	1.58	1.7	1.62
	Sulphuric acid	5.19	4.40	4.78	4.55
Saccharification and fermentation	DAP	2.63	2.20	2.42	2.31
	DDGS	3.70	3.18	3.41	3.25
Others	Boiler	10.00	10.00	12	9
	Waste	0.64	0.68	0.66	0.63
	Transport	6.18	5.30	5.69	5.40
Total		**833.19**	**80.61**	**87.78**	**38.68**

Table 3.3a EP results per year

	Freshwater Aquatic Ecotoxicity Potential (FAETP) [t DCB Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	9,450.00	0	0	0
	Poplar	0	756.00	0	0
	Miscanthus	0	0	811	0
	Forest residue	0	0	0	957
Pretreatment and Conditioning	Lime	46.90	40.34	43.25	41.18
	Sulphuric acid	880.60	756.00	810.85	772
Saccharification and fermentation	DAP	391.40	340.00	360.49	343
	CSL	283.00	218.60	261.14	248
	Waste	14.00	13.00	14.57	13.87
	Transport	0.14	0.11	0.13	0.12
Total		**11066.04**	**2125.72**	**2301.43**	**2375.17**

Table 3.4a FAETP results per year

	Global Warming Potential (GWP) [t CO_2-Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	81,039.00	0	0	0
	Poplar	0.00	30,703.00	0	0
	Miscanthus	0	0	32919	0
	Forest residue	0	0	0	9558
Pretreatment and Conditioning	Lime	16,664	14,308	15,339	14,604
	Sulphuric acid	4,196.00	3,604.00	3863	3678
Saccharification and fermentation	DAP	4,399.00	3,823.00	4051	3865
	CSL	11,253.00	9,666.00	10365	9869
	Enzymes	18,556.00	18,794.00	18789	18717
Others					
	Waste	473.00	406.00	435	414.00
	Transport	4,427.00	3,801.00	4076	3,880.00
Total	**Total**	**141,007.00**	**85,105.15**	**89,837.00**	**64,585.00**

Table 3.5a GWP results per year

	Human Toxicity Potential (HTP) [t DCB Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	90,844.00	0	0	0
	Poplar	0.00	4,017.00	0	0
	Miscanthus	0	0	4307	0
	Forest residue	0	0	0	1857
Pretreatment and Conditioning	Lime	193.00	166.00	178	169.84
	Sulphuric acid	4,233.00	3,636.00	3898	3711
Saccharification and fermentation	DAP	2,241.00	1,948.00	2064	1,969.00
	DDGS	887.00	762.00	817	778.00
Others	Boiler	115.00	110.02	120	104
	Waste	43.28	41.00	44	42.06
	Transport	150.00	129.00	138.82	132.00
Total	**Total**	**98,706.28**	**10,809.02**	**11,566.82**	**8,762.90**

Table 3.6a HTP results per year

	Marine Aquatic Ecotoxicity Potential. (MAETP) [t DCB-Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	13,775,256	0	0	0
	Poplar	0	2,580,391	0	0
	Miscanthus	0	0	2,766,604	0
	Forest residue	0	0	0	340,0540
Pretreatment and Conditioning	Lime	217,142	186,443	199,884	171880
	Sulphuric acid	2,229,244	1,914,674	2,052,505	1,760,000
Saccharification and fermentation	DAP	1,409,694	1225014	1298329	1,238,601
	CSL	2,777,499	2,385,865	2,558,386	2,199,000
	Waste	48,775	41,882	44,905	38,614
	Transport	481,000	171,000	182,000	166,000
Total	**Total**	**20,938,610**	**8,505,269**	**9,102,613**	**8,974,635**

Table 3.7a MAETP results per year

	Ozone depletion Potential (ODP) [kg R-11-Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	3.811	0.000	0.000	0.000
	Poplar	0.000	1.648	0.000	0.000
	Miscanthus	0.000	0.000	1.767	0.000
	Forest residue	0.000	0.000	0.000	0.944
Pretreatment and Conditioning	Lime	1.158	0.994	1.066	1.015
	Sulphuric acid	0.395	0.339	0.364	0.346
Saccharification and fermentation	DAP	0.606	0.520	0.558	0.532
	DDGS	1.130	0.970	1.041	0.991
	Waste	0.150	0.122	0.131	0.124
	Transport	0.96	0.67	0.723	0.664
Total	Total	7.250	4.594	4.927	3.953

Table 3.8a ODP results per year

Photochemical. Ozone Creation Potential (POCP) [t Ethene-Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	28.30	11.15	0	0
	Poplar	0.00	0.00	0	0
	Miscanthus	0	0	12	0
	Forest residue	0	0	0	30
Pretreatment and Conditioning	Lime	5.24	4.50	4.83	4.1
	Sulphuric acid	20.75	17.82	19.11	16.40
Saccharification and fermentation	DAP	1.52	1.32	1.40	1.20
	DDGS	2.52	2.17	2.32	1.90
Others	Boiler	13.00	12.40	12.60	10.05
	Waste	0.52	0.49	0.53	0.500
	Transport	2.30	2.24	2.41	2.29
Total	**Total**	**74.15**	**52.08**	**55.19**	**66.44**

Table 3.9a POCP results per year

	Terrestrial exotoxicity Potential (TETP) [DCB Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	48,977.00		0.00	0.00
	Poplar	0.00	114.67	0.00	0.00
	Miscanthus	0.00	0.00	122.90	0.00
	Forest residue	0.00	0.00		74.24
Pretreatment and Conditioning	Lime	5.94	5.10	5.47	5.21
	Sulphuric acid	107.20	91.92	98.53	93.81
Saccharification and fermentation	DAP	65.42	56.85	60.25	57.48
	CSL	16.90	14.59	15.65	14.90
	Waste	1.34	1.14	1.23	1.17
	Transport	5.08	2.24	2.40	2.40
Total	**Total**	**49,178.88**	**286.51**	**306.43**	**249.21**

Table 3.10a TETP results per year

	Land use [m2yr]]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	1.40E+08			
	Poplar		7.79E+08		
	Miscanthus			8.39E+08	
	Forest residue				3.79E+08
Pretreatment and Conditioning	Lime	1.81E+04	1.55E+04	1.67E+04	1.43E+04
	Sulphuric acid	3.25E+05	2.79E+05	2.99E+05	2.50E+05
Saccharification and fermentation	DAP	1.18E+05	1.02E+05	1.08E+05	9.34E+04
	CSL	3.91E+05	3.35E+05	3.59E+05	3.09E+05
	Waste	1.06E+05	9.13E+04	9.78E+04	8.41E+04
Total	**Total**	**1.41E+08**	**7.8E+8**	**8.4E+08**	**3.80E+08**

Table 3.11a Land use result per year

Total environmental impacts (per year)				
	Wheat straw	**Poplar**	**Miscanthus**	**Forest residue**
ADP [t Sb-Eq.]	451	265	284	238
AP [t SO_2-Eq.]	1,324	849	788	506
EP [t PO_4-Eq.]	834	81	98	30
FAETP [t DCB-Eq.]	11,069	2,151	2,302	2,377
GWP [t CO_2-Eq.]	141,010	85,108	89,841	64,590
HTP [t DCB-Eq.]	98,716	10,811	11,653	8,661
MAETP [t DCB-Eq.]	20,938,610	8,505,269	9,102,613	8,974,635
ODP [kg R11-Eq.]	7.250	4.594	4.927	3.953
POCP [t Ethene-Eq.]	75	52	55	64
TETP [t DCB-Eq.]	49,174	284	304	247
Land use [m^2 yr]	1.41E+08	7.8E+8	8.4E+08	3.80E+08

Table 3.12a Total LCA results per year

2. Environmental impacts for the bio-chemical system with system expansion per litre of ethanol

Abiotic Depletion Potential (ADP) [g Sb-Eq./l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	1.038	0.000	0.000	0.000
	Poplar	0.000	0.360	0.000	0.000
	Miscanthus	0.000	0.000	0.419	0.000
	Forest residue	0.000	0.000	0.000	0.290
Pretreatment and Conditioning	Lime	0.157	0.098	0.152	0.138
Saccharification and fermentation	Sulphuric acid	0.119	0.074	0.115	0.011
	DAP	0.160	0.100	0.154	0.140
	DDGS	0.350	0.219	0.330	0.300
	Waste	0.020	0.015	0.016	0.015
Avoided burden	Transport	0.086	0.082	0.087	0.082
	Lactic acid	-0.142	-0.088	-0.135	-0.011
	Electricity	-3.150	-2.300	-2.600	-2.580
	Acetic acid	-2.200	-3.400	-1.790	-2.300
Total	**Total**	**-3.562**	**-4.840**	**-3.252**	**-3.916**

Table 3.13a ADP results with system expansion

Acidification Potential (AP) [g SO_2 Eq./l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	2.365	0.000	0.000	0.000
	Poplar	0.000	0.720	0.000	0.000
	Miscanthus	0.000	0.000	0.830	0.000
	Forest residue	0.000	0.000	0.000	0.290
Pretreatment and Conditioning	Lime	0.640	0.053	0.057	0.054
	Sulphuric acid	1.690	1.400	1.560	1.480
Saccharification and fermentation	DAP	0.064	0.054	0.062	0.050
	DDGS	0.100	0.090	0.096	0.091
Others	Boiler	0.976	0.630	0.698	0.668
	Waste	0.011	0.013	0.010	0.011
	Transport	0.104	0.099	0.105	0.099
Avoided burden	Lactic acid	-0.186	-0.160	-0.179	-0.147
	Electricity	-2.900	-2.300	-2.550	-2.510
	Acetic acid	-0.440	-0.680	-0.350	-0.450
Total	**Total**	**2.424**	**-0.081**	**0.338**	**-0.365**

Table 3.14a AP results with system expansion

Eutrophication Potential (EP) [g PO_4 Eq./ l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	3.09	0.00	0.00	0
	Poplar	0.00	0.20	0.00	0
	Miscanthus	0	0	0.23	0
	Forest residue	0.0000	0.0000	0.0000	0.0540
Pretreatment and Conditioning	Lime	0.0076	0.0047	0.0051	0.0067
	Sulphuric acid	0.0214	0.0133	0.0143	0.0189
Saccharification and fermentation	DAP	0.0108	0.0068	0.0079	0.0096
	DDGS	0.0152	0.0096	0.0111	0.0136
Others	Boiler	0.0439	0.0672	0.0016	0.0302
	Waste	0.0021	0.0018	0.0020	0.0019
	Transport	0.0212	0.0200	0.0215	0.0201
Avoided burden	Lactic acid	-0.0349	-0.0297	-0.0321	-0.0262
	Electricity	-0.140	-0.110	-0.127	-0.125
	Acetic acid	-0.150	-0.230	-0.122	-0.157
Total	**Total**	**2.89**	**-0.04**	**0.01**	**-0.15**

Table 3.15a EP results with system expansion

Fresh Aquatic Ecotoxicity Potential (FAETP) (g DCB Eq./ l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat Straw	38.70	0.00	0.00	0.00
	Poplar	0.00	2.87	0.00	0.00
	Miscanthus	0	0	3.30	0.00
	Forest residue	0	0	0.00	3.99
Pretreatment and Conditioning	Lime	0.19	0.12	0.13	0.17
	Sulphuric acid	3.63	2.26	3.50	3.19
Saccharification and fermentation	DAP	1.60	1.01	1.50	1.40
	DDGS	1.17	0.73	0.11	0.15
	Waste	0.05	0.04	0.04	0.06
	Transport	0.10	0.10	0.10	0.10
Avoided burden	Lactic acid	-4.40	-3.70	-4.00	-3.30
	Electricity	-0.83	-0.63	-0.69	-0.68
	Acetic acid	-7.30	-11.00	-5.86	-7.50
Total	**Total**	**32.91**	**-8.20**	**-1.87**	**-2.42**

Table 3.16a FAETP results with system expansion

Global Warming Potential (GWP) [g CO2 Eq./ l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	331.00	0	0.00	0
	Poplar	0.00	116	0.00	0
	Miscanthus	0	0	134.00	
	Forest residue	0	0	0.00	42.42
Pretreatment and Conditioning	Lime	68.80	42.68	66.30	60.30
	Sulphuric acid	17.78	10.75	16.70	15.21
Saccharification and Fermentation	DAP	18.30	11.39	17.50	15.90
	DDGS	46.70	29.11	44.90	40.80
	Enzymes	61.05	61.45	61.50	59.42
	Waste	1.60	1.21	1.30	1.70
	Transport	14.38	12.99	14.56	13.63
Avoided burden	Lactic acid	-24.00	-22	-24.02	-19.00
	Electricity	-553.00	-458	-465.50	-423.00
	Acetic acid	-126.00	-206.95	-105.00	-135.00
Total	**Total**	**-143.38**	**-401.37**	**-237.76**	**-327.61**

Table 3.17a GWP results with system expansion

Human toxicity Potential (HTP) (g DCB Eq./ l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	370.	0.000	0.000	0.000
	Poplar	0.000	15.2	0.000	0.000
	Miscanthus	0.000	0.000	17.5	0.000
	Forest residue	0.000	0.000		7.77
Pretreatment and Conditioning	Lime	0.800	0.496	0.770	0.700
	Sulphuric acid	17.400	15.000	16.800	15.340
Saccharification and fermentation	DAP	9.200	5.804	8.940	8.140
	DDGS	3.600	2.296	3.540	3.210
Others	Boiler	0.476	0.644	0.341	0.327
	Waste	0.144	0.123	0.170	0.170
	Transport	0.854	0.809	0.868	0.812
Avoided burden	Lactic acid	-9.600	-8.066	-8.900	-7.340
	Electricity	-38.00	-29.000	-32.15	-31.60
	Acetic acid	-35.30	-54.00	-28.00	-36.023
Total	**Total**	**319.574**	**-50.694**	**-20.121**	**-38.494**

Table 3.18a HTP results with system expansion

Marine Aquatic Ecotoxicity Potential (MAETP) (g DCB Eq./l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	56,105	0	0	0
	Poplar	0	9,791	0	0
	Miscanthus	0	0	11,268	
	Forest residue	0	0	0	14,158
Pretreatment and Conditioning	Lime	896	772	865	787
	Sulphuric acid	9,204	7,918	8,819	8,080
Saccharification and fermentation	DAP	5,832	4,999	5,627	5,122
	DDGS	11,487	9,868	11,086	10,074
	Waste	179	125	179	177
	Transport	503	479	513	480
Avoided burden	Lactic acid	-16,632	-14,513	-16,000	-13,209
	Electricity	-25,922	-15,980	-22,639	-22,312
	Acetic acid	-31,253	-50,619	-25,978	-33,359
Total		**10,399**	**-47,161**	**-26,259**	**-30,002**

Table 3.19a MAETP results with system expansion

	Ozone layer depletion Potential (ODP) [g R-11 Eq./ l ethanol]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat Straw	1.52E-05	0.00E+00	0.00E+00	0.00E+00
	Poplar	0.00E+00	8.38E-06	0.00E+00	0.00E+00
	Miscanthus	0	0	7.19E-06	0.00E+00
	Forest residue	0	0		4.30E-06
Pretreatment and Conditioning	Lime	4.77E-06	4.33E-06	4.61E-06	4.05E-06
	Sulphuric acid	1.62E-06	1.47E-06	1.57E-06	1.44E-06
Saccharification and fermentation	DAP	2.56E-06	2.51E-06	2.47E-06	2.24E-06
	DDGS	4.69E-06	4.20E-06	4.50E-06	4.09E-06
	Waste	4.25E-07	5.69E-07	3.90E-07	3.74E-07
	Transport	2.02E-06	0.00E+00	2.06E-06	1.93E-06
Avoided burden	Lactic acid	-3.35E-06	-4.23E-06	8.36E-08	8.36E-08
	Electricity	-8.14E-05	-6.18E-05	-4.40E-06	-3.66E-06
	Acetic acid	-1.66E-06	-9.60E-05	-6.70E-05	-6.90E-05
Total	**Total**	**-5.51E-05**	**-1.41E-04**	**-4.85E-05**	**-5.42E-05**

Table 3.20a ODP results with system expansion

Photochemical Ozone Creation Potential (POCP) (g Ethene Eq./ l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat Straw	0.115	0.000	0.000	0.000
	Poplar		0.057	0.000	0.000
	Miscanthus		0.000	0.048	0.000
	Forest residue				0.142
Pretreatment and Conditioning	Lime	0.022	0.020	0.014	0.020
	Sulphuric acid	0.085	0.078	0.057	0.075
Saccharification and fermentation	DAP	0.006	0.006	0.005	0.006
	DDGS	0.010	0.009	0.008	0.009
Others	Boiler	0.054	0.025	0.039	0.037
	Waste	0.002	0.000	0.002	0.002
	Transport	0.011	0.010	0.011	0.010
Avoided burden	Lactic acid	-0.012	-0.011	-0.011	-0.010
	Electricity	-0.170	-0.130	-0.145	-0.121
	Acetic acid	-0.171	-0.280	-0.136	-0.175
Total	**Total**	**-0.048**	**-0.216**	**-0.110**	**-0.005**

Table 3.21a POCP results with system expansion

	Terrestrial Ecotoxicity Potential (TETP) (g DCB Eq./ l ethanol)				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	199.000	0.000	0.000	0.000
	Poplar	0.000	0.430	0.000	0.000
	Miscanthus	0.000	0.000	0.500	0.000
	Forest residue	0.000	0.000	0.000	0.282
Pretreatment and Conditioning	Lime	0.024	0.015	0.024	0.022
Saccharification and fermentation	Sulphuric acid	0.440	0.274	0.400	0.380
	DAP	0.270	0.169	0.260	0.237
	DDGS	0.070	0.044	0.060	0.062
	Waste	0.004	0.003	0.004	0.005
	Transport	0.012	0.011	0.012	0.011
Avoided burden	Lactic acid	-0.270	-0.164	-0.250	-0.207
	Electricity	-0.390	-0.300	-0.330	-0.327
	Acetic acid	-0.860	-1.340	-0.680	-0.884
Total		**198.300**	**-0.857**	**-0.001**	**-0.420**

Table 3.22a TETP results with system expansion

Land use (m2yr/ l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	1.47			
	Poplar		3.17		
	Miscanthus			3.42	
	Forest residue				1.73
Pretreatment and Conditioning	Lime	1.19E-05	9.70E-06	6.80E-05	6.56E-05
	Sulphuric acid	4.49E-05	3.68E-05	1.24E-03	1.17E-03
Saccharification and fermentation	DAP	2.50E-05	2.05E-05	4.48E-04	2.20E-05
	DDGS	4.44E-03	3.64E-03	1.49E-03	3.89E-03
	Waste	9.92E-05	1.02E-04	4.03E-04	1.02E-04
Avoided burden	Lactic acid	-8.61E-04	-7.17E-04	-7.91E-04	-6.84E-04
	Acetic acid	-2.45E-03	-3.80E-03	-1.95E-03	-2.62E-03
Total	**Total**	**1.47**	**3.17**	**3.43**	**1.73**

Table 3.23a Land useresults with system expansion

Impacts (g/l ethanol)	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
ADP [Sb-eq.]	-3.500	-4.840	-3.252	-3.916
AP [SO_2-eq.]	3.000	-0.081	0.343	-0.365
EP [PO_4-eq.]	2.889	-0.042	0.046	-0.152
FAETP [DCB-eq.]	32.909	-6.480	-1.867	-2.423
GWP [CO_2-eq.]	-143.388	-401.37	-237.764	-327.61
HTP [DCB-eq.]	319.574	-50.694	-20.121	-38.494
MAETP [DCB-eq.]	10,399	-47,161	-26,259	-30,002
ODP [R11-eq.]	-5.51E-5	-1.41E-4	-4.85E-5	-5.42E-5
POCP [Ethene-eq.]	-0.048	-0.216	-0.110	-0.005
TETP [DCB-eq.]	198.300	-0.857	-0.001	-0.420
Land use[m^2 yr]	1.47	3.16	3.43	1.73

Table 3.23a Total LCA results with system expansion

		Feedstock	Operations	Co-products credits
ADP [g Sb-eq./litre ethanol]	Wheat straw	103	89	-549
	Poplar	0.36	0.58	-5.78
	Miscanthus	0.419	0.85	-4.52
	Forest residue	0.29	0.68	-4.89
AP [g SO_2-eq./litre ethanol]	Wheat straw	2.3	3.58	-3.52
	Poplar	0.72	2.33	-3.14
	Miscanthus	0.83	2.58	-3.07
	Forest residue	0.291	2.45	-3.1
EP [g PO_4-eq./ litre ethanol]	Wheat straw	3.09	0.122	-0.33
	Poplar	0.21	0.123	-0.37
	Miscanthus	0.232	0.063	-0.281
	Forest residue	0.054	0.1	-0.308
FAETP [g DCB-eq./ litre ethanol]	Wheat straw	38.7	6.7	-6.7
	Poplar	2.8	4.2	-4.2
	Miscanthus	3.3	5.3	-5.3
	Forest residue	3.9	5.07	-5.07
GWP [g CO_2-eq./litre ethanol]	Wheat straw	331	228	-703
	Poplar	116	169	-686
	Miscanthus	134	222	-594
	Forest residue	42.4	206	-577
HTP [g DCB-eq./litre ethanol]	Wheat straw	370	32	-82.9
	Poplar	15	25	-91
	Miscanthus	17.5	31	-69
	Forest residue	7.76	28	-74.9
MAETP [g DCB-eq./litre ethanol]	Wheat straw	56105	28100	-73800
	Poplar	9700	24100	-81100
	Miscanthus	11268	27089	-64617
	Forest residue	14150	24719	-68880
ODP [g R11-eq./litre ethanol]	Wheat straw	1.52E-05	1.28E-05	-8.64E-05
	Poplar	8.30E-06	1.31E-05	-1.62E-04
	Miscanthus	7.19E-06	1.56E-05	-1.17E-04
	Forest residue	4.30E-06	1.41E-05	-1.33E-04
POCP [g Ethene-eq./litre ethanol]	Wheat straw	0.115	0.19	-0.353
	Poplar	0.057	0.147	-0.42
	Miscanthus	0.048	0.135	-0.292
	Forest residue	0.142	0.159	-0.306
TETP [g DCB-eq./litre ethanol]	Wheat straw	199	0.82	-1.52
	Poplar	0.43	0.517	-1.8
	Miscanthus	0.5	0.759	-1.26
	Forest residue	0.282	0.716	-1.42
Land use [m2 yr/litre ethanol]	Wheat straw	1.47	4.63e-3-	3.31E-3
	Poplar	3.17	3.81E-3	-4.52E-3
	Miscanthus	3.42	3.64E-3	-2.74E-3
	Forest residue	1.73	5.25E-3	-3.3E-3

Table 3.24a Total LCA results for feedstock, operations, and co-product credit for bio-chemical case study with system expansion

3. Environmental impacts for the bio-chemical system with economic allocation per litre of ethanol

Products	**Quantity**	**Cost**	**Units**	**Total**	**Allocation factor**
Ethanol (kg/hr)	24,000	808	£/t	19,392.00	0.85
Electricity (MWh)	24	0.069	£/kWh	1,656.00	0.07
Acetic acid (kg/h)	3,181	407	£/t	1,294.67	0.06
Lactic acid (kg/h)	369	1,027	£/t	378.96	0.02

Table 3.25a Allocation ratio for the products from wheat straw

Impacts	**Total (g)**	**Ethanol (g/l)**	**Acetic acid (g/l)**	**Lactic acid (g/l)**	**Electricity (g/l)**
ADP [Sb-eq.]	1.900	1.622	0.108	0.032	0.138
AP [SO_2-eq.]	5.950	5.078	0.339	0.099	0.434
EP [PO_4-eq.]	3.212	2.741	0.183	0.054	0.234
FAETP [DCB-eq]	45.439	38.780	2.589	0.758	3.312
GWP [CO_2-eq.]	559.612	477.607	31.886	9.334	40.786
HTP [DCB-eq.]	402.474	343.495	22.933	6.713	29.333
MAETP [DCB-eq.]	84206	71867	4798	1404	6137
ODP [R11-eq.]	3.13E-05	2.67E-05	1.78E-06	5.22E-07	2.28E-06
POCP [Ethene-eq.]	0.305	0.260	0.017	0.005	0.022
TETP [DCB-eq.]	199.820	170.538	11.386	3.333	14.563
Land use [m2yr]	1.47	1.25	0.08	0.02	0.11

Table 3.26a LCA results after economic allocation for wheat straw feedstock

Products	**Quantity**	**Cost**	**Units**	**Total**	**Allocation factor**
Ethanol (kg/hr)	24,000	808.	£/t	19,392	0.84
Electricity (MWhr)	19	0.069	£/kWh	1,311	0.06
Acetic acid (kg/hr)	5,144	407	£/t	2,094	0.09
Lactic acid (kg/hr)	345	1027	£/t	354	0.02

Table 3.27a Allocation ratio for the products from poplar

Impacts	Total (g)	Ethanol (g/l)	Acetic acid (g/l)	Lactic acid (g/l)	Electricity (g/l)
ADP [Sb-eq.]	0.95	0.79	0.09	0.01	0.05
AP [SO_2-eq.]	3.06	2.56	0.28	0.05	0.17
EP [PO_4-eq.]	0.33	0.27	0.03	0.00	0.02
FAETP [DCB-eq]	7.13	5.97	0.64	0.11	0.40
GWP [CO_2-eq.]	285.57	239.20	25.83	4.37	16.17
HTP [DCB-eq.]	40.37	33.82	3.65	0.62	2.29
MAETP [DCB-eq.]	33951	28438	3070	520	1923
ODP [R11-eq.]	2.15E-05	1.80E-05	1.94E-06	3.28E-07	1.21E-06
POCP [Ethene-eq.]	0.20	0.17	0.02	0.00	0.01
TETP [DCB-eq.]	0.95	0.79	0.09	0.01	0.05
Land use [m2yr]	3.16	2.65	0.18	0.063	0.18

Table 3.28a LCA results after economic allocation for poplar feedstock

Products	Quantity	Cost	Units	Total	Allocation factor
Ethanol (kg/hr)	24,000	808	£/t	19,392	0.87
Electricity (MWhr)	20	0.069	£/kWh	1,380	0.06
Acetic acid (kg/hr)	2,523	407	£/t	1,027	0.05
Lactic acid (kg/hr)	354	1,027	£/t	364	0.02

Table 3.29a Allocation ratio for the products from miscanthus

Impacts	Total (g)	Ethanol (g/l)	Acetic acid (g/l)	Lactic acid (g/l)	Electricity (g/l)
ADP [Sb-eq.]	1.27	1.11	0.06	0.02	0.08
AP [SO_2-eq.]	3.42	2.99	0.16	0.06	0.21
EP [PO_4-eq.]	0.30	0.26	0.01	0.00	0.02
FAETP [DCB-eq]	8.68	7.60	0.40	0.14	0.54
GWP [CO_2-eq.]	356.76	312.16	16.53	5.85	22.21
HTP [DCB-eq.]	48.93	42.81	2.27	0.80	3.05
MAETP [DCB-eq.]	38358	33563	1777	629	2388
ODP [R11-eq.]	2.28E-05	1.99E-05	1.06E-06	3.74E-07	1.42E-06
POCP [Ethene-eq.]	0.18	0.16	0.01	0.00	0.01
TETP [DCB-eq.]	1.26	1.10	0.06	0.02	0.08
Land use [m2yr]	3.43	2.96	0.17	0.06	0.20

Table 4.30a LCA impacts results after economic allocation for miscanthus feedstock

Products	Quantity	Cost	Units	Total	Allocation factor
Ethanol (kg/hr)	24,000	808	£/t	19,392	0.87
Electricity (MWhr)	16	0.069	£/kWh	1,104	0.05
Acetic acid (kg/hr)	3,635	407	£/t	1,479	0.07
Lactic acid (kg/hr)	312	1027	£/t	320	0.01

Table 3.31a Allocation ratio for the products from forest residue

Impacts	Total (g)	Ethanol (g/l)	Acetic acid (g/l)	Lactic acid (g/l)	Electricity (g/l)
ADP [Sb-eq.]	0.98	0.85	0.06	0.01	0.05
AP [SO_2-eq.]	2.74	2.39	0.18	0.04	0.14
EP [PO_4-eq.]	0.15	0.13	0.01	0.00	0.01
FAETP [DCB-eq]	9.06	7.88	0.60	0.13	0.45
GWP [CO_2-eq.]	249.38	216.90	16.55	3.58	12.35
HTP [DCB-eq.]	36.47	31.72	2.42	0.52	1.81
MAETP [DCB-eq.]	38878	33814	2580	559	1925
ODP [R11-eq.]	1.84E-05	1.60E-05	1.22E-06	2.65E-07	9.12E-07
POCP [Ethene-eq.]	0.30	0.26	0.02	0.00	0.01
TETP [DCB-eq.]	1.00	0.87	0.07	0.01	0.05
Land use [m2yr]	1.74	1.51	0.115	0.025	0.09

Table 3.32a LCA impacts results after economic allocation for forest residue feedstock

3. Comparison bio-refinery with refinery using fossil feedstocks

Impacts (t/yr)	Ethanol from ethylene	Power grid mix	Acetic acid from acetaldehyde	Acetic acid from butane	Lactic acid from organic chemicals	Total fossil (min)	Total fossil (max)	Total bio-refinery with wheat straw
ADP [Sb-eq.]	4,033	718	532	522	31	5,304	5,314	451
AP [SO2-eq.]	701	707	226	102	42	1,552	1675	1324
EP [PO4-eq.]	283	35	61	36	8	362	387	834
FAETP [DCB-eq]	7,787	192	21,924	17,08	958	10,646	30,862	11069
GWP [CO2-eq.]	243,747	127,917	66,331	30,945	5,714	408,322	443,709	141010
HTP [DCB-eq.]	34,291	8,916	1,6401	8,173	2,086	53,467	61,694	98,716
MAETP [DCB-eq.]	26,381,257	6,279,350	35,515,396	7,568,976	3,753,801	43,983,385	7,192,9804	20,938,610
ODP [R11-eq.]	0.00701	0.01883	0.00288	0.01364	0.00104	0.04053	0.02977	0.00724
POCP [Ethene-eq.]	393	40	167	40	3	475	603	75
TETP [DCB-eq.]	752	92	391	201	59	1103	1294	49174
Land use [m2yr]	2527	0	63	672	66	3265	2656	1.45E8

Table 3.33a Environmental impacts of fossil-based refinery and bio-refinery using wheat straw

Impacts (t/yr)	Ethanol from ethylene	Power grid mix	Acetic acid from acetaldehyde	Acetic acid from butane	Lactic acid from organic chemicals	Total fossil (min)	Total fossil (max)	Total bio-refinery with poplar
ADP [Sb-eq.]	4,033	568	860	844	29	5,491	5,474	265
AP [SO2-eq.]	701	559	365	165	39	1665	1,465	8,493
EP [PO4-eq.]	283	28	99	58	7	417	376	808
FAETP [DCB-eq]	7,787	152	35,454	2763	896	44,289	11,598	2,151
GWP [CO2-eq.]	24,3747	101,268	107,265	50,041	5,343	457,622	400,398	851
HTP [DCB-eq.]	34,291	7,058	26,523	13,217	1,951	69,823	56517	1081
MAETP [DCB-eq.]	26,381,257	4,971,152	57,432,873	12,239,989	3,509,621	92,294,903	47,102,019	851
ODP [R11-eq.]	0.0070	0.0149	0.0047	0.0221	0.0010	0.0276	0.0450	0.0046
POCP [Ethene-eq.]	393	32	270	64	2	697	491	522
TETP [DCB-eq.]	752	73	633	324	55	1513	1204	284
Land use [m^2yr]	2527	0	75	951	58	2660	3536	7.8E8

Table 3.34a Environmental impacts of fossil-based refinery and bio-refinery using poplar

Impacts (t/yr)	Ethanol from ethylene	Power grid mix	Acetic acid from acetaldehyde	Acetic acid from butane	Lactic acid from organic chemicals	Total fossil (min)	Total fossil (max)	Total bio-refinery with miscanthus
ADP [Sb-eq.]	4,033	568	422	414	30	5,053	5,045	283
AP [SO2-eq.]	701	589	179	81	40	1,509	1,411	787
EP [PO4-eq.]	283	29	49	28	7	369	348	97
FAETP [DCB-eq]	7,787	160	17,389	1,355	919	26,256	10,222	2,302
GWP [CO2-eq.]	243,747	106,597	52,611	24,544	5,481	408,436	380,369	89,840
HTP [DCB-eq.]	34,291	7430	13,009	6,483	2,001	56,731	50,205	11,653
MAETP [DCB-eq.]	26,381,257	5,232,792	2,816,9298	6,003,389	3,600,714	63,384,061	41,218,152	9,103,000
ODP [R11-eq.]	7.01E-03	1.57E-02	2.29E-03	1.08E-02	9.99E-04	2.60E-02	3.45E-02	4.93E-03
POCP [Ethene-eq.]	393	33	133	32	3	561	460	55
TETP [DCB-eq.]	752	77	311	159	56	1,196	1,044	304
Land use [m2 yr]	2527	0	32	462	59	2618	3048	8.4E8

Table 3.35a Environmental impacts of fossil-based refinery and bio-refinery using miscanthus

Impacts (t/yr)	**Ethanol from ethylene**	**Power grid mix**	**Acetic acid from acetaldehyde**	**Acetic acid from butane**	**Lactic acid from organic chemicals**	**Total fossil (min)**	**Total fossil (max)**	**Total bio-refinery with forest residue**
ADP [Sb-eq.]	4,033	479	608	596	27	5,146	5,134	237
AP [SO2-eq.]	701	471	258	117	35	1,466	1,324	506
EP [PO4-eq.]	283	23	70	41	6	383	354	29
FAETP [DCB-eq]	7,787	128	25,053	1,952	810	33,778	10,678	2,377
GWP [CO2-eq.]	243,747	85,278	75,798	35,361	4830	409,652	369,216	64,590
HTP [DCB-eq.]	34,291	5,944	18,742	9,340	1,763	60,740	51,338	8,661
MAETP [DCB-eq.]	26,381,257	4,186,233	40,584,064	8,649,201	3,173,082	74,324,636	42,389,774	8,975,000
ODP [R11-eq.]	7.01E-03	1.26E-02	3.30E-03	1.56E-02	8.80E-04	2.37E-02	3.60E-02	3.95E-03
POCP [Ethene-eq.]	393	27	191	45	2	613	467	64
TETP [DCB-eq.]	752	61	447	229	50	1310	1092	246
Land use [m2 yr]	2527	0	49	626	53	2629	3206	3.79E8

Table 3.36a Environmental impacts of fossil-based refinery and bio-refinery using forest residue

4. **Comparisons of environmental impacts of ethanol from 2nd and 1st generation feedstocks**

Impacts (g/l ethanol)	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**	**Wheat grain**	**Sugar beet**
ADP [Sb-eq.]	-3.500	-4.840	-3.252	-3.916	4.400	17.206
AP [SO_2-eq.]	3.000	-0.081	0.343	-0.365	11.600	5.735
EP [PO_4-eq.]	2.889	-0.042	0.046	-0.152	16.700	0.316
FAETP [DCB-eq]	32.909	-6.480	-1.867	-2.423	141.600	33.971
GWP [CO_2-eq.]	-143.388	-366.379	-237.764	-362.617	1950.000	368.676
HTP [DCB-eq.]	319.574	-50.694	-20.121	-38.494	8900.000	461.765
MAETP [DCB-eq.]	10,399	-47,161	-26,259	-30,002	27,610	123,093
ODP [R11-eq.]	-5.51E-05	-1.41E-04	-4.85E-05	-5.42E-05	7.40E-05	3.38E-04
POCP [Ethene-eq.]	-0.048	-0.216	-0.110	-0.005	0.430	0.263
TETP [DCB-eq.]	198.300	-0.857	-0.001	-0.420	71.000	3.647

Table 3.37a LCA results for ethanol from 1st and 2nd generation feedstocks with system expansion

Impacts (g/l ethanol)	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**	**Wheat grain**	**Sugar beet**
ADP [Sb-eq.]	1.600	0.794	1.114	0.848	4.400	17.000
AP [SO2-eq.]	5.078	2.560	2.990	2.380	11.600	5.700
EP [PO4-eq.]	2.741	0.273	0.258	0.135	16.700	0.310
FAETP [DCB-eq]	3.878	5.970	7.590	7.870	141.600	33.900
GWP [CO2-eq.]	478	239	312	216	1950	368
HTP [DCB-eq.]	343	34	43	32	8900	461
MAETP [DCB-eq.]	71,860	28400	33560	33814	276700	123900
ODP [R11-eq.]	2.67E-05	1.79E-05	1.99E-05	1.60E-05	740	3300
POCP [Ethene-eq.]	0.260	0.171	0.160	0.262	0.430	0.263
TETP [DCB-eq.]	170.538	0.790	1.102	0.860	71.000	3.640

Table 3.38a LCA results for ethanol from 1st and 2nd generation feedstocks with economic allocation

6a Comparison of bio-ethanol with petrol (cradle to gate)

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Wheat grain	Sugar beet	Petrol [low-sulphur]	Petrol [unleaded]
ADP [Sb-eq.]	-0.167	-0.230	-0.155	-0.186	0.210	0.810	0.571	0.571
AP [SO2-eq.]	0.143	-0.004	0.016	-0.017	0.552	0.271	0.169	0.076
EP [PO4-eq.]	0.138	-0.002	0.002	-0.007	0.795	0.015	0.045	0.012
FAETP [DCB-eq]	1.567	-0.309	-0.089	-0.115	6.743	1.614	0.845	0.635
GWP [CO2-eq.]	-6.828	-19.090	-11.322	-17.267	92.857	17.524	16.824	18.165
HTP [DCB-eq.]	15.218	-2.414	-0.958	-1.833	423.810	21.952	4.293	2.606
MAETP [DCB-eq.]	495	-2246	-1250	-1429	13177	5861	4553	2485
ODP [R11-eq.]	-2.62E-06	-6.69E-06	-2.31E-06	-2.58E-06	3.52E-06	1.57E-05	1.13E-05	1.72E-05
POCP [Ethene-eq.]	-2.29E-03	-1.03E-02	-5.22E-03	-2.19E-04	2.05E-02	1.25E-02	2.25E-02	3.43E-02
TETP [DCB-eq.]	9.443	-0.041	0.000	-0.020	3.381	0.173	0.101	0.048

Table 3.39a LCA impacts of ethanol from 2nd generation feedstock using system expansion compared with petrol and 1st generation ethanol (system boundary: from 'cradle to gate')

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Petrol [low-sulphur]	Petrol [unleaded]
ADP [Sb-eq.]	0.077	0.038	0.053	0.040	0.571	0.571
AP [SO2-eq.]	0.242	0.122	0.142	0.114	0.169	0.076
EP [PO4-eq.]	0.131	0.013	0.012	0.006	0.045	0.012
FAETP [DCB-eq]	1.847	0.284	0.362	0.375	0.845	0.635
GWP [CO2-eq.]	22.743	11.391	14.865	10.329	16.824	18.165
HTP [DCB-eq.]	16.357	1.610	2.039	1.510	4.293	2.606
MAETP [DCB-eq.]	3422.228	1354.214	1598.224	1610.196	4553	2485
ODP [R11-eq.]	1.27E-06	8.56E-07	9.50E-07	7.63E-07	1.13E-05	1.72E-05
POCP [Ethene-eq.]	0.012	0.008	0.008	0.012	0.023	0.034
TETP [DCB-eq.]	8.121	0.038	0.052	0.041	0.101	0.048

Table 3.40a LCA impacts of ethanol from 2nd generation feedstock using economic allocations compared with petrol and 1st generation ethanol (system boundary: from ‘cradle to gate’)

6b Comparison of bio-ethanol with petrol (cradle to grave)

Impacts (g/l ethanol)	Wheat straw	Poplar	Miscanthus	Forest residue	Wheat grain	Sugar beet	Petrol [low-sulphur]
ADP [Sb-eq.]	0.477	0.413	0.489	0.457	0.853	1.453	1.225
AP [SO2-eq.]	0.380	0.233	0.253	0.220	0.789	0.508	0.369
EP [PO4-eq.]	0.209	0.070	0.074	0.064	0.867	0.086	0.093
FAETP [DCB-eq]	13.759	11.883	12.103	12.076	18.934	13.806	2.033
GWP [CO2-eq.]	92.936	80.674	88.442	82.497	192.621	117.288	118.136
HTP [DCB-eq.]	30.045	12.413	13.869	12.994	438.636	36.779	16.785
MAETP [DCB-eq.]	6596.598	3855.847	4851.151	4672.914	19278.265	11963.027	9337.481
ODP [R11-eq.]	9.417E-06	5.347E-06	9.731E-06	9.463E-06	1.557E-05	2.776E-05	2.535E-05
POCP [Ethene-eq.]	0.059	0.051	0.056	0.061	0.082	0.074	0.087
TETP [DCB-eq.]	14.723	5.239	5.280	5.260	8.661	5.453	0.325

Table 3.41a LCA impacts of ethanol from 2nd generation feedstock using system expansion compared with petrol (15% vol ethanol and 85% petrol)and 1st generation ethanol (system boundary: from ‘cradle to grave’)

Impacts	Wheat straw	Poplar	Miscanthus	Forest residue	Wheat grain	Sugar beet	Petrol [low-sulphur]
ADP [Sb-eq.]	0.417	0.417	0.493	0.461	0.857	0.648	1.225
AP [SO2-eq.]	0.368	0.221	0.242	0.208	0.778	0.225	0.369
EP [PO4-eq.]	0.198	0.058	0.062	0.053	0.855	0.060	0.093
FAETP [DCB-eq]	5.661	3.786	4.005	3.979	10.837	4.094	2.033
GWP [CO2-eq.]	93.174	80.912	88.680	82.735	192.860	100.002	118.136
HTP [DCB-eq.]	28.591	10.959	12.415	11.540	437.183	13.373	16.785
MAETP [DCB-eq.]	5974.469	3233.718	4229.022	4050.785	18656.135	5479.469	9337.481
ODP [R11-eq.]	9.59E-06	5.52E-06	9.90E-06	9.63E-06	1.57E-05	1.22E-05	2.54E-05
POCP [Ethene-eq.]	0.059	0.051	0.056	0.061	0.081	0.061	0.087
TETP [DCB-eq.]	10.997	1.513	1.554	1.534	4.935	1.554	0.325

Table 3.42a LCA impacts of ethanol from 2nd generation feedstock using system expansion compared with petrol (4% vol of ethanol and 96% vol petrol)and 1st generation ethanol (system boundary: from 'cradle to grave')

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Petrol [low-sulphur]
ADP [Sb-eq.]	0.721	0.681	0.697	0.684	1.225
AP [SO2-eq.]	0.479	0.359	0.379	0.351	0.369
EP [PO4-eq.]	0.202	0.085	0.084	0.078	0.093
FAETP [DCB-eq]	14.038	12.476	12.553	12.567	2.033
GWP [CO2-eq.]	122.507	111.155	114.629	110.093	118.136
HTP [DCB-eq.]	31.184	16.437	16.865	16.337	16.785
MAETP [DCB-eq.]	9523.826	7455.812	7699.822	7711.794	9337.481
ODP [R11-eq.]	1.331E-05	1.290E-05	1.299E-05	1.280E-05	2.535E-05
POCP [Ethene-eq.]	0.074	0.070	0.069	0.074	0.087
TETP [DCB-eq.]	13.401	5.318	5.332	5.321	0.325

Table 3.43a LCA impacts of ethanol from 2nd generation feedstock using economic allocation compared with petrol (15% vol of ethanol and 85% vol of petrol)and 1st generation ethanol (system boundary: from 'cradle to grave')

Impacts (g/MJ)	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**	**Petrol [low-sulphur]**
ADP [Sb-eq.]	0.725	0.686	0.701	0.688	1.225
AP [SO2-eq.]	0.467	0.347	0.368	0.339	0.369
EP [PO4-eq.]	0.191	0.073	0.072	0.066	0.093
FAETP [DCB-eq]	5.941	4.379	4.456	4.469	2.033
GWP [CO2-eq.]	122.746	111.393	114.867	110.331	118.136
HTP [DCB-eq.]	29.730	14.984	15.412	14.884	16.785
MAETP [DCB-eq.]	8901.697	6833.683	7077.693	7089.665	9337.481
ODP [R11-eq.]	1.35E-05	1.31E-05	1.32E-05	1.30E-05	2.54E-05
POCP [Ethene-eq.]	0.073	0.069	0.069	0.073	0.087
TETP [DCB-eq.]	9.675	1.592	1.606	1.595	0.325

Table 3.44a LCA impacts of ethanol from 2nd generation feedstock using economic allocation compared with petrol (4% vol of ethanol and 85% vol of petrol)and 1st generation ethanol (system boundary: from ‘cradle to grave’)

7 Results of the economic assessment for the bio-chemical system

£M	Wheat straw	Poplar	Miscanthus	Forest residue
Total installed equipment cost (TIE)	187	163	174	165
Ware house	1.8	1.8	1.9	1.9
Site development	4	4	4	4
Engineering and supervision	15	13	13.9	13.2
Legal expenses	3.7	3.3	3.5	3.3
Construction and contractors fee	28.1	24.5	26.1	24.8
Project contingency	18.7	16.3	17.4	16.5
Working capital	38.8	33.9	36.1	34.3
Total capital investment (TCI)	297	259	276	262
Variable cost				
Raw materials & energy	50.08	64.09	69.62	41.3
Fixed cost				
Maintenance	20.8	18.2	19.4	18.3
Operating labour	27.4	27.7	26.7	26.6
Laboratory cost	4.1	4.2	4	4
Operating supplies	3.1	2.7	2.9	2.8
Supervision	2.7	2.8	2.7	2.7
Local taxes	5.9	5.2	5.5	5.2
Insurance	3.0	2.6	2.8	2.6
Royalties	5.5	5.5	5.3	5.3
LCC (£M)	3970	4240	4440	3520

Table 3.45a Capital and operating cost for the bio-chemical refinery

	Wheat straw	**Poplar**	**Miscanthus**	**Forest residue**
Year	Cummulativeannual discounted cash flow (£M)	Cummulative annual discounted cash flow (£M)	Cummulative annual discounted cash flow (£M)	Cummulative annual discounted cash flow (£M)
0	0	0	0	0
1	-54	-47	-50	-48
2	-128	-112	-119	-113
3	-239	-209	-223	-211
4	-204	-179	-198	-173
5	-173	-151	-176	-138
6	-144	-126	-155	-106
7	-117	-103	-137	-77
8	-93	-83	-120	-51
9	-72	-64	-105	-27
10	-52	-47	-91	-5
11	-34	-31	-78	15
12	-18	-17	-66	33
13	-3	-4	-56	49
14	11	7	-46	64
15	23	18	-38	77
16	34	28	-30	90
17	44	36	-23	101
18	53	44	-16	111
19	62	52	-10	120
20	69	58	-5	129
21	76	64	0	136
22	83	70	4	143
23	88	75	8	149
24	94	79	12	155
25	98	83	15	160
26	103	87	19	165
27	106	90	21	169
28	110	93	24	173
29	113	96	26	177
30	116	99	28	180

Table 3.46a NPV estimations for the bio-chemical refinery

APPENDIX 4: RESULTS FOR THE THERMO-CHEMICAL CASE STUDY

This appendix presents the environmental (LCA) and economic assessment results for the thermo-chemical case study in the following order:

1 Total annual environmental impacts
2 Environmental impacts with system expansion
3 Environmental impacts with economic allocation
4 Comparisons of environmental impacts of thermo-chemical with fossil-based refineries
5 Comparisons of environmental impacts of ethanol from 2nd with 1st generation feedstocks
6 Comparisons of environmental impacts of bio-ethanol with petrol
7 Results of the economic assessment.

1. Total annual environmental impacts for the bio-chemical system

Abiotic Depletion Potential (ADP) [t Sb-Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	239.00	0	**0.00**	**0**
	Poplar		124		
	Miscanthus			131.32	
Feedstock	Forest residue				67.70
	Feed handling		0		
Gasification	Gasification	0.75	0.95	0.57	0.90
Gas clean up	Gas clean up	3.90	2.30	2.1	2.30
	Transport	31.30	28.00	30.00	28.20
Total		**274.95**	**155.25**	**163.99**	**99.10**

Table 4.1a ADP results per year

Acidification Potential (AP) [t SO2 Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	546.00		0.00	0
	Poplar		218		
	Miscanthus			232.90	
Feedstock	Forest residue				66.90
	Feed handling	1,878	1,242	1,490	1,218
Gasification	Gasification	0.56	0.55	0.357	0.54
Gas clean up	Gas clean up	3.46	2.02	2.2	2.00
	Transport	42.46	41.10	43.70	40.20
Total		**2470.48**	**1503.67**	**1769.16**	**1327.64**

Table 4.2a AP results per year

	Eutrophication Potential (EP) [t PO4-Eq.]				
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	755.00			
	Poplar		47.00		
	Miscanthus			50.9	
Feedstock	Forest residue				12.49
	Feed handling	217	144	173.5	141.1
Gasification	Gasification	0.21	0.12	0.123	0.12
Gas clean up	Gas clean up	0.49	0.29	0.317	0.29
	Transport	9.60	8.25	8.70	8.07
Total		**980.30**	**199.66**	**233.54**	**162.07**

Table 4.3a EP results per year

Freshwater Aquatic Ecotoxicity Potential (FAETP) [t DCB Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	8,888.00			
	Poplar		921.00		
	Miscanthus			981	
Feedstock	Forest residue				915
	Feed handling				
Gasification	Gasification	86.00	15.00	45	15.20
Gas clean up	Gas clean up	129.00	73.00	82	72.70
	Transport	38	34.00	36.00	27
Total		**9130.00**	**1043.00**	**1144.00**	**1036.27**

Table 4.4a FAETP results per year

Global Warming Potential (GWP) [t CO2 Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	76,636			
	Poplar		24,821		
	Miscanthus			26,440	
Feedstock	Forest residue				9,742
	Feed handling				
Gasification	Gasification	224	170	163	168
Gas clean up	Gas clean up	497	293	332	288
	Transport	5,035	4,506	4,800	4,408
Total		**82,392**	**29,790**	**31,735**	**14,606**

Table 4.5a GWP results per year

Human Toxicity Potential (HTP) (t DCB Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	85,443			
	Poplar		4,520		
	Miscanthus			4,815	1,779
Feedstock	Forest residue				
	Feed handling	2,074	1,376	1,655	1,346
Gasification	Gasification	20	9	12	9
Gas clean up	Gas clean up	695	415	457	411
	Transport	301	274	292	270
Total		**88,483**	**6,594**	**7,231**	**3,815**

Table 4.6a HTP results per year

Marine eco toxicity Potential (MAETP) [t DCB Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	12,956,199.			
	Poplar		3,647,746.02		
	Miscanthus			3,885,640.84	
Feedstock	Forest residue				3,242,364.17
	Feed handling				
Gasification	Gasification	61,484.	14,128.	33,312.	33,291.
Gas clean up	Gas clean up	1,107,416	933,730	965,682	929,895.
	Transport	199,913	169,243	180,280	165,574
Total		**14,245,013.35**	**4,764,847.43**	**5,064,916.28**	**4,341,126.27**

Table 4.7a MAETP results per year

Ozone Depletion Potential (ODP) [t DCB Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	3.58E-03			
	Poplar		2.00E-03		
	Miscanthus			2.15E-03	
Feedstock	Forest residue				1.00E-03
	Feed handling				
Gasification	Gasification	7.04E-06	6.28E-06	6.49E-06	1.98E-05
Gas clean up	Gas clean up	3.86E-05	2.80E-04	3.06E-05	2.85E-05
	Transport	9.67E-04	6.70E-04	7.23E-04	6.64E-04
Total		**4.59E-03**	**2.96E-03**	**2.91E-03**	**1.72E-03**

Table 4.8a ODP results per year

Photochemical Ozone Depletion Potential (POCP) [Ethene Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	26.616			
	Poplar		13.74		
	Miscanthus			14.6	
Feedstock	Forest residue				32.70
	Feed handling	80.7	53.4	64.3	52.30
Gasification	Gasification	0.08	0.06	0.047	0.016
Gas clean up	Gas clean up	0.31	0.18	0.203	0.184
	Transport	4.34	3.56	3.80	3.400
Total		112.05	70.94	82.95	88.601

Table 4.9a POCP results per year

Terrestrial ecotoxicity Potential (TETP) [DCB Eq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	46,065.57			
	Poplar		123.00		
	Miscanthus			131	
Feedstock	Forest residue				64.7
	Feed handling				
Gasification	Gasification	0.59	0.23	0.352	0.23
Gas clean up	Gas clean up	18.72	10.68	11.7	10.50
	Transport	4.71	3.88	4.10	3.80
Total		46088.00	137.79	147.15	79.23

Table 4.10a TETP results per year

Land use [m^2 yr]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	1.36E+08			
	Poplar	0.00E+00	7.7E+08		
	Miscanthus	0.00E+00		8.2E+08	
Feedstock	Forest residue	0.00E+00			3.62E+08
Gasification	Gasification	8.01E+03	7.74E+03	7.86E+03	7.56E+03
Gas clean up	Gas clean up	7.11E+03	6.08E+03	6.79E+03	5.54E+03
Total		**1.36E+08**	**7.7E+08**	**8.2E+08**	**3.62E+08**

Table 4.11a Land use results per year

Total environmental impacts per year				
Impacts (t/yr)	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
ADP [Sb-eq]	276	156	164	99
AP [SO2-eq.]	2,471	1,505	1,769	1,328
EP [PO4-eq]	981	200	233	162
FAETP [DCB-eq]	9,133	1,045	1,146	1,037
GWP [CO2-eq]	82,447	29,792	31,737	14,609
HTP [DCB-eq.]	88,483	6,596	7,232	3,815
MAETP [DCB-eq.]	14,245,015	4,764,849	5,064,917	4,351,939
ODP [R11-Equiv.]	4.6E-03	2.7E-03	2.9E-03	1.7E-03
POCP[Ethene-eq.]	112	71	83	89
TETP [DCB-eq.]	46,088	138	148	79
Land use [m^2 yr0	$1.36x10^8$	$7.7 x10^8$	$8.2 x10^8$	$3.62 x10^8$

Table 4.12a Total LCA results per year

2. Environmental impacts for the thermo-chemical system with system expansion per litre of ethanol

Abiotic Depletion Potential (ADP) [g Sb-Eq./l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	0.959			
	Poplar		0.270		
	Miscanthus			0.374	
	Forest residue				0.266
	Feed handling				
Gasification	Gasification	0.008	0.003	0.008	0.007
Gas clean up	Gas clean up	0.014	0.014	0.014	0.009
	Transport	0.125	0.126	0.114	0.129
Avoided burden	Propanol	-4.491	-4.443	-4.395	-4.473
	Butanol	-0.529	-0.526	-0.517	-0.527
Total	**Total**	**-3.914**	**-4.556**	**-4.402**	**-4.588**

Table 4.13a ADP results with system expansion

Acidification Potential (AP) [g SO_2 Eq./l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	2.184			
	Poplar		0.520		
	Miscanthus			0.744	
	Forest residue				0.269
	Feed handling	7.500	4.890	6.100	4.900
Gasification	Gasification	0.005	0.002	0.005	0.005
Gas clean up	Gas clean up	0.011	0.011	0.011	0.008
	Transport	0.170	0.180	0.162	0.183
Avoided burden	Propanol	-1.426	-1.420	-1.396	-1.420
	Butanol	-0.084	-0.083	-0.082	-0.083
Total	**Total**	**8.360**	**4.099**	**5.545**	**3.861**

Table 4.14a AP results with system expansion

Eutrophication Potential (EP) [g PO_4 Eq./ l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	3.021			
	Poplar		0.103		
	Miscanthus			0.208	
	Forest residue				0.050
	Feed handling	0.860	0.560	0.700	0.560
Gasification	Gasification	0.001	0.000	0.001	0.001
Gas clean up	Gas clean up	0.002	0.002	0.002	0.001
	Transport	0.032	0.036	0.032	0.037
Avoided burden	Propanol	-0.263	-0.262	-0.258	-0.262
	Butanol	-0.009	-0.009	-0.009	-0.009
Total	**Total**	**3.643**	**0.430**	**0.676**	**0.379**

Table 4.15a EP results with system expansion

Fresh Aquatic Ecotoxicity Potential (FAETP) (g DCB Eq./ l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	35.541			
	Poplar		2.010		
	Miscanthus			2.951	
	Forest residue				3.680
	Feed handling				
Gasification	Gasification	0.331	0.060	0.183	0.329
Gas clean up	Gas clean up	0.455	0.448	0.457	0.293
	Transport	0.108	0.149	0.134	0.156
Avoided burden	Propanol	-21.317	-21.230	-20.860	-21.231
	Butanol	-0.934	-0.929	-0.914	-0.930
Total	**Total**	**14.184**	**-19.493**	**-18.049**	**-17.703**

Table 4.16a FAETP results for thermo-chemical case study with system expansion

Global Warming Potential (GWP) [g CO2 Eq./ l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	305.00			
	Poplar		95.00		
	Miscanthus			120.01	
	Forest residue				39.00
	Feed handling				
Gasification	Gasification	1.78	0.60	1.47	1.64
Gas clean up	Gas clean up	1.88	1.85	1.89	1.16
	Transport	20.14	19.70	17.80	20.25
Avoided burden	Propanol	-401.81	-400.16	-393.18	-400.17
	Butanol	-23.92	-23.80	-23.41	-23.82
Total	**Total**	**-96.93**	**-306.81**	**-275.42**	**-361.95**

Table 4.17a GWP results with system expansion

Human toxicity Potential (HTP) (g DCB Eq./ l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	328.00			
	Poplar		9.80		
	Miscanthus			15.66	
	Forest residue				7.15
	Feed handling	8.20	5.40	3.2	5.40
Gasification	Gasification	0.097	0.035	0.071	0.082
Gas clean up	Gas clean up	2.397	2.361	2.411	1.653
	Transport	1.004	1.202	1.087	1.242
Avoided burden	Propanol	-88.520	-88.157	-86.620	-88.160
	Butanol	-4.842	-4.817	-4.738	-4.822
Total	**Total**	**246.33**	**-74.17**	**-72.12**	**-77.45**

Table 4.18a HTP results with system expansion

Marine Aquatic Ecotoxicity Potential (MAETP) (g DCB Eq./l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	51,808.2			
	Poplar		7,965.0		
	Miscanthus			10,064.7	
Feedstock	Forest residue				13,046.0
	Feed handling				
Gasification	Gasification		54.7	145.1	233.7
Gas clean up	Gas clean up	4,301.1	4,237.1	4,327.8	3,741.9
	Transport	479.5	739.6	668.9	233.7
Avoided burden	Propanol	-125,794.4	-125,278.4	-123,095.0	-125,283.5
	Butanol	-4,814.5	-4,790.2	-4,711.6	-4,794.2
Total	**Total**	**-73,776**	**-11,7072**	**-11,2600**	**-11,2822**

Table 4.19a MAETP results with system expansion

Ozone layer depletion Potential (ODP) [g R-11 Eq./ l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
	Wheat straw	1.43E-05			
	Poplar		8.80E-06		
	Miscanthus			6.43E-06	
Feedstock	Forest residue				4.36E-06
	Feed handling				
Gasification	Gasification	2.93E-08	2.46E-08	2.68E-08	7.54E-09
Gas clean up	Gas clean up	1.48E-07	1.46E-07	1.49E-07	1.15E-07
	Transport	3.87E-06	2.97E-06	2.68E-06	3.05E-06
Avoided burden	Propanol	-3.88E-05	-3.87E-05	-3.80E-05	-3.87E-05
	Butanol	-7.27E-07	-7.23E-07	-7.11E-07	-7.24E-07
Total	**Total**	**-2.12E-05**	**-2.75E-05**	**-2.94E-05**	**-3.19E-05**

Table 4.20a ODP results with system expansion

Photochemical. Ozone Potential (POCP) [g EtheneEq.]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	0.106			
	Poplar		0.030		
	Miscanthus			0.043	
	Forest residue				0.131
	Feed handling	0.320	0.210	0.260	0.210
Gasification	Gasification	0.001	0.000	0.001	0.001
Gas clean up	Gas clean up	0.001	0.001	0.001	0.001
	Transport	0.017	0.016	0.014	0.016
Avoided burden	Propanol	-1.474	-1.468	-1.442	-1.468
	Butanol	-0.034	-0.034	-0.033	-0.034
Total	**Total**	**-1.062**	**-1.245**	**-1.156**	**-1.143**

Table 4.21a POCP results with system expansion

Terrestrial Ecotoxicity Potential (TETP) (g DCB Eq./ l ethanol)					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	184.203			
	Poplar		0.269		
	Miscanthus			0.447	
	Forest residue				0.261
	Feed handling				
Gasification	Gasification	0.003	0.001	0.002	0.002
Gas clean up	Gas clean up	0.062	0.061	0.063	0.042
	Transport	0.012	0.017	0.015	0.018
Avoided burden	Propanol	-2.270	-2.260	-2.221	-2.260
	Butanol	-0.115	-0.114	-0.112	-0.114
Total	**Total**	**181.896**	**-2.026**	**-1.806**	**-2.051**

Table 4.22a TETP results with system expansion

Land use [m² yr/ l ethanol]					
Stage		**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Feedstock	Wheat straw	1.350E+00			
	Poplar		6.086E-04		
	Miscanthus			8.080E-04	
	Forest residue				1.530E+00
Gasification	Gasification	0.00005	0.00002	0.00002	0.00004
Gas clean up	Gas clean up	0.00021	0.00022	0.00024	0.00025
	Transport	0.00000	0.00000	0.00000	0.00000
Avoided burden	Propanol	-0.00711	-0.00712	-0.00711	-0.00712
	Butanol	-0.00031	-0.00031	-0.00031	-0.00031
Total	**Total**	**1.34285**	**3.02**	**3.27**	**1.52287**

Table 4.23a Land use results with system expansion

Impacts (g/l ethanol)	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
ADP [SB-eq.]	-3.914	-4.556	-4.402	-4.588
AP [SO2-eq.]	8.360	4.099	5.546	3.862
EP [PO4-eq.]	3.643	0.430	0.677	0.379
FAETP [DCB-eq]	14.184	-19.493	-18.048	-17.703
GWP [CO2-eq.]	-96.932	-306.813	-275.412	-361.853
HTP [DCB-eq.]	246.335	-77.000	-65.420	-77.455
MAETP [DCB-eq.]	-73,775.693	-117,072.271	-112,600.042	-112,289.022
ODP [R11-eq.]	-2.13E-5	-2.01E-5	-2.97E-5	-3.15E-5
POCP [Ethene-eq.]	-1.062	-1.245	-1.156	-1.143
TETP [DCB-eq.]	181.896	-2.026	-1.806	-2.051
Land use [m² yr]	1.34	3.02	3.27	1.522

Table 4.24a Total LCA results with system expansion

		Feedstock	Operations	Co-products credit
ADP [g Sb-eq./litre ethanol]	Wheat straw	0.95	0.149	-5.01
	Poplar	0.27	0.017	-4.99
	Miscanthus	0.37	0.0217	-4.8
	Forest residue	0.266	0.0158	-4.99
AP [g SO_2-eq./litre ethanol]	Wheat straw	2.18	5.01	-1.5
	Poplar	0.52	2.89	-1.48
	Miscanthus	0.74	3.078	-1.38
	Forest residue	0.27	2.89	-1.48
EP [g PO_4-eq./ litre ethanol]	Wheat straw	3.02	0.66	-0.27
	Poplar	0.103	0.35	-0.27
	Miscanthus	0.2	0.45	-0.26
	Forest residue	0.05	0.359	-0.27
FAETP [g DCB-eq./ litre ethanol]	Wheat straw	35	0.89	-21.93
	Poplar	2	0.656	-22.12
	Miscanthus	2.9	0.7	-21.7
	Forest residue	3.68	0.77	-21.6
GWP [g CO_2-eq./litre ethanol]	Wheat straw	305	23	-423
	Poplar	95	22	-423
	Miscanthus	120	23	-423
	Forest residue	39	23	-423
HTP [g DCB-eq./litre ethanol]	Wheat straw	328	9.29	-92.8
	Poplar	9.8	6.59	-92.81
	Miscanthus	15	10.92	-90.6
	Forest residue	7.15	9.16	-92.8
MAETP [g DCB-eq./litre ethanol]	Wheat straw	51808	5024	-130608
	Poplar	7900	5030	-130068
	Miscanthus	10000	5330	-130340
	Forest residue	13046	4741	-130077
ODP [g R11-eq./litre ethanol]	Wheat straw	1.43E-05	3.90E-06	-3.95E-05
	Poplar	7.88E-06	1.10E-05	-3.90E-05
	Miscanthus	6.42E-06	3.26E-06	-3.94E-05
	Forest residue	4.36E-06	3.17E-06	-3.90E-05
POCP [g Ethene-eq./litre ethanol]	Wheat straw	0.106	0.249	-1.18
	Poplar	0.03	0.13	-1.4
	Miscanthus	0.043	0.21	-1.5
	Forest residue	0.163	0.288	-1.49
TETP [g DCB-eq./litre ethanol]	Wheat straw	184	0.0773	-2.37
	Poplar	0.27	0.078	-2.37
	Miscanthus	0.447	0.083	-2.37
	Forest residue	0.26	0.062	-2.3
Land use [m2 yr/litre ethanol]	Wheat straw	1.35	0.00026	-0.00742
	Poplar	3.03	0.00024	-0.00743
	Miscanthus	3.27	0.00026	-0.00742
	Forest residue	1.53	0.00029	-0.00743

Table 4.25a Total LCA results for feedstock, operations and co-product credit for thermo-chemical case study with system expansion

3 Environmental impacts for the thermo-chemical system with economic allocation per litre of ethanol

Products	Quantity	Cost (£/t)	Total	Allocation factor
Ethanol (kg/hr)	24,568	808.00	19,850	0.808
Butanol (kg/hr)	401	1323	530	0.002
Propanol (kg/hr)	3,199	1,345	4,302	0.17
Total			24684	

Table 4.26a Allocation ratio for the products from wheat straw

Impacts	Total (g)	Ethanol (g/l)	Butanol (g/l)	Propanol (g/l)
ADP [Sb-eq.]	1.090	0.877	0.023	0.190
AP [SO2-eq.]	36.515	29.365	0.785	6.365
EP [PO4-eq.]	8.722	7.014	0.187	1.520
FAETP [DCB-eq]	36.435	29.301	0.783	6.351
GWP [CO2-eq.]	328.288	264.009	7.056	57.223
HTP [DCB-eq.]	397.807	319.916	8.550	69.341
MAETP [DCB-eq.]	56826	45699	1221	9905
ODP [R11-eq.]	1.84E-05	1.48E-05	3.95E-07	3.20E-06
POCP [Ethene-eq.]	1.520	1.222	0.033	0.265
TETP [DCB-eq.]	184.280	148.198	3.961	32.122
Land use [m2 yr]	1.35	1.086	0.029	0.235

Table 4.27a LCA impacts results after economic allocation for wheat straw feedstock

Products	Quantity	Cost (£/t)	Total	Allocation factor
Ethanol (kg/hr)	24,973	808	20,178	0.805
Butanol (kg/hr)	405	1,323	535	0.002
Propanol (kg/hr)	3,234	1,345	4,349	0.17
Total			25,063	

Table 4.28a Allocation ratio for the products from poplar

Impacts	Total (g)	Ethanol (g/l)	Butanol (g/l)	Propanol (g/l)
ADP [Sb-eq.]	0.400	0.322	0.009	0.070
AP [SO2-eq.]	3.385	2.725	0.072	0.587
EP [PO4-eq.]	0.456	0.367	0.010	0.079
FAETP [DCB-eq]	2.667	2.147	0.057	0.463
GWP [CO2-eq.]	117.145	94.310	2.504	20.330
HTP [DCB-eq.]	16.402	13.205	0.351	2.847
MAETP [DCB-eq.]	12996	10463	277	2255
ODP [R11-eq.]	1.19E-05	9.61E-06	2.55E-07	2.07E-06
POCP [Ethene-eq.]	0.164	0.132	0.003	0.028
TETP [DCB-eq.]	0.348	0.280	0.007	0.060
Land use [m2 yr]	3.03	2.43	0.065	0.53

Table 4.29a LCA impacts results after economic allocation for poplar feedstock

Products	Quantity	Cost (£/t)	Total	Allocation factor
Ethanol (kg/hr)	24,568	808.00	19,850	0.808
Butanol (kg/hr)	390	1,323	515	0.002
Propanol (kg/hr)	3,111	1,345	4,184	0.17
Total			24,551	

Table 4.30a Allocation ration for the products from miscanthus

Impact (g/hr)	Total (g)	Ethanol (g/l)	Butanol (g/l)	Propanol (g/l)
ADP [Sb-eq.]	0.528	0.427	0.011	0.090
AP [SO2-eq.]	12.541	10.141	0.264	2.138
EP [PO4-eq.]	2.006	1.622	0.042	0.342
FAETP [DCB-eq]	3.759	3.039	0.079	0.641
GWP [CO2-eq.]	143.949	116.390	3.025	24.533
HTP [DCB-eq.]	35.884	29.014	0.754	6.116
MAETP [DCB-eq.]	15396	12449	323	2624
ODP [R11-eq.]	9.70E-06	7.84E-06	2.04E-07	1.65E-06
POCP [Ethene-eq.]	0.541	0.438	0.011	0.092
TETP [DCB-eq.]	0.530	0.429	0.011	0.090
Land use [m^2 yr]	3.27	2.63	0.069	0.559

Table 4.31a LCA impacts results after economic allocation for miscanthus feedstock

Products	Quantity	Cost (£/t)	Total	Allocation factor
Ethanol (kg/hr)	24,418	808.00	19,729	0.808
Butanol (kg/hr)	396	1,323	523	0.002
Propanol (kg/hr)	3,166	1,345	4,258	0.17
Total			24,511	

Table 4.32a Allocation ratio for the products from forest residue

Impacts (g/hr)	Total (g)	Ethanol (g/l)	Butanol (g/l)	Propanol (g/l)
ADP [Sb-eq.]	0.483	0.389	0.010	0.084
AP [SO2-eq.]	6.045	4.866	0.129	1.050
EP [PO4-eq.]	0.740	0.596	0.016	0.129
FAETP [DCB-eq]	5.335	4.295	0.114	0.927
GWP [CO2-eq.]	101.051	81.336	2.160	17.555
HTP [DCB-eq.]	17.928	14.431	0.383	3.115
MAETP [DCB-eq.]	20879.949	16806.354	446.280	3627.315
ODP [R11-eq.]	8.165E-06	6.572E-06	1.745E-07	1.418E-06
POCP [Ethene-eq.]	0.417	0.336	0.009	0.072
TETP [DCB-eq.]	0.385	0.310	0.008	0.067
Land use [m^2yr]	1.53	1.23	0.032	0.265

Table 4.33a LCA impacts results after economic allocation for forest residue feedstock

4. Comparisons of thermo refinery with refinery using fossil feedstocks

Impacts (t/yr)	Ethanol from ethylene	Butanol from propylene	Propanol from propene	Total fossil	Total thermo-refinery with wheat straw
ADP [Sb-eq.]	4,128	132	1,106	5,366	276
AP [SO2-eq.]	718	21	357	1,095	2,471
EP [PO4-eq.]	290	2	66	358	981
FAETP [DCB-eq]	7971	234	5,331	13,536	9,133
GWP [CO2-eq.]	249,515	5,982	100,483	355,980	82,447
HTP [DCB-eq.]	35,103	1,211	22,137	58,450	88,483
MAETP [DCB-eq.]	27,005,614	1,204,010	31,458,374	59,667,998	14,245,015
ODP [R11-eq.]	7.2E-03	1.8E-04	9.7E-03	1.7E-02	4.63E-3
POCP [Ethene-eq.]	402	9	369	779	112
TETP [DCB-eq.]	770	29	568	1,366	46,088
Land use [m^2 yr]	2,580	77	1.7	2659	1.36E8

Table 4.34a Environmental impacts of fossil-based refinery and bio-refinery using wheat straw

Impacts (t/yr)	Ethanol from ethylene	Butanol from propylene	Propanol from propene	Total fossil	Total thermo-refinery with poplar
ADP [Sb-eq.]	4,184	133	1,106	5,424	142
AP [SO2-eq.]	727	21	357	1,105	1,341
EP [PO4-eq.]	294	2	66	362	188
FAETP [DCB-eq]	8,079	236	5,333	13,648	2,397
GWP [CO2-eq.]	252,887	6,041	100,514	359,443	28,086
HTP [DCB-eq.]	35,577	1,223	22,144	58,944	14,959
MAETP [DCB-eq.]	27,370,555	1,215,945	31,468,208	60,054,708	5,258,188
ODP [R11-eq.]	7.3.E-03	1.8.E-04	9.7.E-03	1.7.E-02	2.5.E-03
POCP [Ethene-eq.]	408	9	369	785	64
TETP [DCB-eq.]	780	29	568	1,377	450
Land use[m^2 yr]	2,623	78	1,775	4,476	$7.7x10^8$

Table 4.35a Environmental impacts of fossil-based refinery and bio-refinery using poplar

Impacts (t/yr)	Ethanol from ethylene	Butanol from propylene	Propanol from propene	Total fossil	Total thermo-refinery with miscanthus
ADP [Sb-eq.]	4,117	129	972	5,217	164
AP [SO2-eq.]	716	20	313	1,049	1,769
EP [PO4-eq.]	289	2	58	349	233
FAETP [DCB-eq]	7,949	227	4,684	12,860	1,146
GWP [CO2-eq.]	248,825	5,817	88,282	342,923	31,737
HTP [DCB-eq.]	35,005	1,177	19,449	55,632	7,232
MAETP [DCB-eq.]	26,930,867	1,170,758	27,638,646	55,740,271	5,064,917
ODP [R11-eq.]	7.2E-03	1.8E-04	8.5E-03	1.6E-02	2.9E-03
POCP [Ethene-eq.]	401	8	324	733	83
TETP [DCB-eq.]	767	28	499	1,294	148
Land use[m^2 yr]	2,580	75	1,559	4,215	$8.2x10^8$

Table 4.36a Environmental impacts of fossil-based refinery and bio-refinery using miscanthus

Impacts (t/yr)	Ethanol from ethylene	Butanol from propylene	Propanol from propene	Total fossil	Total thermo-refinery with forest residue
ADP [Sb-eq.]	4,103	131	970	5,204	99
AP [SO2-eq.]	713	21	313	1,047	1,328
EP [PO4-eq.]	288	2	58	348	162
FAETP [DCB-eq]	7,923	231	4,676	12,829	1,037
GWP [CO2-eq.]	247,991	5,906	88,133	342,030	14,609
HTP [DCB-eq.]	34,888	1,195	19,416	55,500	3,815
MAETP [DCB-eq.]	26,840,633	1,188,684	27,592,168	55,621,484	4,351,939
ODP [R11-eq.]	7.1E-03	1.8E-04	8.5E-03	1.6E-02	1.7E-03
POCP [Ethene-eq.]	400	8	323	731	89
TETP [DCB-eq.]	765	28	498	1,291	79
Land use[m^2 yr]	2,572	76	1,557	4,205	$3.62x10^8$

Table 4.37a Environmental impacts of fossil-based refinery and bio-refinery using forest residue

5. **Comparisons of environmental impacts of ethanol from 2nd and 1st generation feedstocks**

Impacts (g/l ethanol)	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**	**Wheat grain**	**Sugar beet**
ADP [Sb-eq.]	-3.914	-4.556	-4.402	-4.588	4.400	17.000
AP [SO2-eq.]	8.360	4.099	5.546	3.862	11.600	5.700
EP [PO4-eq.]	3.643	0.430	0.677	0.379	16.700	0.310
FAETP [DCB-eq]	14.180	-19.493	-18.481	-17.703	1416.000	339.000
GWP [CO2-eq.]	-96.932	-306.813	-275.412	-361.853	1950.000	368.000
HTP [DCB-eq.]	246.335	-77.000	-65.420	-77.455	8900.000	461.000
MAETP [DCB-eq.]	-73775.693	-117072.271	-112600.042	-112289.022	276710.000	123090.000
ODP [R11-eq.]	-2.119E-05	-2.748E-05	-2.9433E-05	-3.1875E-05	0.000074	0.00033
POCP [Ethene-eq.]	-1.062	-1.245	-1.156	-1.143	0.430	0.263
TETP [DCB-eq.]	181.896	-2.026	-1.806	-2.051	71.000	3.640

Table 4.38a LCA results for ethanol from 1st and 2nd generation feedstocks with system expansion

Impacts (g/l ethanol)	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**	**Wheat grain**	**Sugar beet**
ADP [Sb-eq]	0.8898	0.3327	0.4125	0.3315	4.400	17.000
AP [SO2-eq.]	7.9364	4.5100	5.6781	4.3181	11.600	5.700
EP [PO4-eq]	3.1482	0.5643	0.7624	0.5228	16.700	0.310
FAETP [DCB-eq]	29.2969	2.1465	3.0122	3.5878	1416.000	339.000
GWP [CO2-eq]	264.3761	94.2959	114.1352	50.0096	1950.000	368.000
HTP [DCB-eq.]	273.1424	15.1307	20.9696	12.4953	8900.000	461.000
MAETP [DCB-eq.]	45698	10461	12293	14316	276710.000	123090.000
ODP [R11-Equiv.]	1.4776E-05	9.6053E-06	7.5089E-06	6.06403E-06	0.000074	0.00033
POCP[Ethene-eq.]	0.3581	0.2067	0.2579	0.2883	0.430	0.263
TETP [DCB-eq.]	148.1757	0.2802	0.4261	0.2603	71.000	3.640

Table 4.39a LCA results for ethanol from 1st and 2nd generation feedstocks with economic allocation

6a. Comparison of the bio-ethanol with petrol (cradle to gate)

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Wheat grain	Sugar beet	Petrol (low-sulphur)	Petrol (unleaded)
ADP [Sb-eq.]	-0.186	-0.217	-0.210	-0.218	0.210	0.810	0.571	0.571
AP [SO2-eq.]	0.398	0.195	0.264	0.184	0.552	0.271	0.169	0.076
EP [PO4-eq.]	0.173	0.020	0.032	0.018	0.795	0.015	0.045	0.012
FAETP [DCB-eq]	0.675	-0.928	-0.859	-0.843	67.429	16.143	0.845	0.635
GWP [CO2-eq.]	-4.616	-14.610	-13.115	-17.231	92.857	17.524	16.824	18.165
HTP [DCB-eq.]	11.730	-3.667	-3.115	-3.688	423.000	21.952	4.293	2.606
MAETP [DCB-eq.]	-3513	-5575	-5362	-5347	13176	5857	4553	2485
ODP [R11-eq.]	-1.01E-06	-1.31E-06	-1.40E-06	-1.52E-06	3.52E-06	1.59E-05	1.13E-05	1.72E-05
POCP [Ethene-eq.]	-0.051	-0.059	-0.055	-0.054	0.020	0.013	0.023	0.034
TETP [DCB-eq.]	8.662	-0.096	-0.086	-0.098	3.381	0.171	0.101	0.048

Table 4.40a LCA impacts of ethanol from 2nd generation feedstock using system expansion compared with petrol and 1st generation ethanol (system boundary: from 'cradle to gate')

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Petrol (low-sulphur)	Petrol (unleaded)
ADP [Sb-eq]	0.042	0.016	0.020	0.016	0.571	0.571
AP [SO2-eq.]	0.378	0.215	0.270	0.206	0.169	0.076
EP [PO4-eq]	0.150	0.027	0.036	0.025	0.045	0.012
FAETP [DCB-eq]	1.395	0.102	0.143	0.171	0.845	0.635
GWP [CO2-eq]	12.589	4.490	5.435	2.381	16.824	18.165
HTP [DCB-eq.]	13.007	0.721	0.999	0.595	4.293	2.606
MAETP [DCB-eq.]	2176	498	585	682	4553	2485
ODP [R11-Equiv.]	7.04E-07	4.57E-07	3.58E-07	2.89E-07	1.13E-05	1.72E-05
POCP[Ethene-eq.]	0.017	0.010	0.012	0.014	0.023	0.034
TETP [DCB-eq.]	7.056	0.013	0.020	0.012	0.101	0.048

Table 4.41a LCA impacts of ethanol from 2nd generation feedstock using economic allocations compared with petrol and 1st generation ethanol (system boundary: from 'cradle to gate')

6b Comparison of bio-ethanol with petrol (cradle to grave)

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Wheat grain	Sugar beet	Petrol (low-sulphur)
ADP [Sb-eq.]	0.457	0.427	0.434	0.425	0.853	1.453	1.225
AP [SO2-eq.]	0.635	0.432	0.501	0.421	0.789	0.508	0.369
EP [PO4-eq.]	0.245	0.092	0.104	0.090	0.867	0.086	0.093
FAETP [DCB-eq]	12.867	11.263	11.332	11.349	79.620	28.334	2.033
GWP [CO2-eq.]	95.148	85.154	86.649	82.533	192.621	117.288	118.136
HTP [DCB-eq.]	26.557	11.160	11.712	11.138	437.827	36.779	16.785
MAETP [DCB-eq.]	2588.470	526.728	739.691	754.502	19277.789	11958.741	9337.481
ODP [R11-eq.]	1.10E-05	1.07E-05	1.06E-05	1.05E-05	1.56E-05	2.79E-05	2.54E-05
POCP [Ethene-eq.]	0.011	0.002	0.006	0.007	0.082	0.074	0.087
TETP [DCB-eq.]	13.941	5.183	5.194	5.182	8.661	5.451	0.325

Table 4.42a LCA impacts of ethanol from 2nd generation feedstock using system expansion compared with petrol (15% vol of petrol and 85% vol of ethanol)and 1st generation ethanol (system boundary: from 'cradle to grave')

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Wheat grain	Sugar beet	Petrol (low-sulphur)
ADP [Sb-eq.]	0.461	0.431	0.438	0.429	0.857	1.457	1.225
AP [SO2-eq.]	0.623	0.420	0.489	0.409	0.778	0.497	0.369
EP [PO4-eq.]	0.234	0.081	0.092	0.078	0.855	0.075	0.093
FAETP [DCB-eq]	4.770	3.166	3.235	3.251	71.523	20.237	2.033
GWP [CO2-eq.]	95.387	85.392	86.888	82.771	192.860	117.526	118.136
HTP [DCB-eq.]	25.104	9.707	10.258	9.685	436.373	35.326	16.785
MAETP [DCB-eq.]	1966.341	-95.401	117.562	132.373	18655.659	11336.612	9337.481
ODP [R11-eq.]	1.12E-05	1.09E-05	1.08E-05	1.07E-05	1.57E-05	2.81E-05	2.54E-05
POCP [Ethene-eq.]	0.010	0.002	0.006	0.007	0.081	0.074	0.087
TETP [DCB-eq.]	10.216	1.457	1.468	1.456	4.935	1.725	0.325

Table 4.43a LCA impacts of ethanol from 2nd generation feedstock using system expansion compared with petrol (4% vol of ethanol and 96% vol of petrol)and 1st generation ethanol (system boundary: from 'cradle to grave')

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Petrol (low-sulphur)
ADP [Sb-eq.]	0.686	0.659	0.663	0.659	1.225
AP [SO2-eq.]	0.615	0.452	0.507	0.443	0.369
EP [PO4-eq.]	0.222	0.099	0.108	0.097	0.093
FAETP [DCB-eq]	13.587	12.294	12.335	12.362	2.033
GWP [CO2-eq.]	112.353	104.254	105.199	102.146	118.136
HTP [DCB-eq.]	27.834	15.547	15.825	15.422	16.785
MAETP [DCB-eq.]	8277.707	6599.763	6687.000	6783.314	9337.481
ODP [R11-eq.]	1.27E-05	1.25E-05	1.24E-05	1.23E-05	2.54E-05
POCP [Ethene-eq.]	0.079	0.071	0.074	0.075	0.087
TETP [DCB-eq.]	12.336	5.293	5.300	5.292	0.325

Table 4.44a LCA impacts of ethanol from 2nd generation feedstock using economic allocation compared with petrol (15% vol of ethanol and 85% vol of ethanol and 1st generation ethanol (system boundary: from ‘cradle to grave’)

Impacts (g/MJ)	Wheat straw	Poplar	Miscanthus	Forest residue	Petrol (low-sulphur)
ADP [Sb-eq.]	0.690	0.664	0.667	0.664	1.225
AP [SO2-eq.]	0.603	0.440	0.496	0.431	0.369
EP [PO4-eq.]	0.210	0.087	0.096	0.085	0.093
FAETP [DCB-eq]	5.489	4.196	4.238	4.265	2.033
GWP [CO2-eq.]	112.592	104.493	105.437	102.384	118.136
HTP [DCB-eq.]	26.380	14.094	14.372	13.968	16.785
MAETP [DCB-eq.]	7655.577	5977.634	6064.871	6161.185	9337.481
ODP [R11-eq.]	1.29E-05	1.27E-05	1.26E-05	1.25E-05	2.54E-05
POCP [Ethene-eq.]	0.078	0.071	0.073	0.075	0.087
TETP [DCB-eq.]	8.610	1.567	1.574	1.566	0.325

Table 4.45a LCA impacts of ethanol from 2nd generation feedstock using economic allocation compared with petrol (4% vol of ethanol and 96% vol of petrol)and 1st generation ethanol (system boundary: from ‘cradle to grave’)

7. Results of the economic assessment for the thermo-chemical system

£M	**Wheat straw**	**Poplar**	**Miscanthus**	**Forest residue**
Total installed equipment cost(TIE)	161	145	154	142
Site development	4.32	4.3	4.3	4.3
Engineering and supervision	12.8	11.6	12.3	11.4
Legal expenses	3.2	2.9	3.1	2.8
Construction and contractors fee	24.15	21.8	23.1	21.3
Project contingency	16.1	14.5	15.4	14.2
Working capital	33	30	31.8	29.4
Total capital investment (TCI)	254	230		
Variable cost				
Raw materials & energy	38.23	55.7	59.51	32.1
Fixed cost				
Maintenance	17.8	16.1	17.1	15.8
Operating Labour	29.8	30.2	29.6	29.6
Laboratory Cost	4.5	4.5	4.4	4.4
Operating supplies	2.7	2.4	2.6	2.4
Supervision	3	3	3	3
Local taxes	5.1	4.6	4.9	4.5
Insurance	2.5	2.3	2.4	2.3
Royalties	6	6	5.9	5.9
LCC (£M)	3530	3970	4120	3220

Table 4.46a Capital and operating cost for the thermo-chemical case study

Year	Cummulative annual discounted cash flow (£M)	Cummulative annual discounted cash flow (£M)	Cummulative annual discounted cash flow (£M)	Cummulative annual discounted cash flow (£M)
	Wheat straw	Poplar	Miscanthus	Forest residue
0	0.0	0.0	0.0	0.0
1	-46.3	-41.8	-44.4	-41.0
2	-109.6	-98.9	-104.9	-96.9
3	-205.3	-185.3	-196.5	-181.5
4	-157.3	-143.8	-159.5	-130.2
5	-113.7	-106.1	-125.8	-83.6
6	-74.0	-71.8	-95.1	-41.2
7	-38.0	-40.6	-67.3	-2.6
8	-5.2	-12.3	-41.9	32.4
9	24.6	13.5	-18.9	64.3
10	51.7	36.9	2.0	93.2
11	76.4	58.2	21.0	119.6
12	98.8	77.6	38.3	143.5
13	119.1	95.2	54.1	165.2
14	137.6	111.2	68.4	185.0
15	154.4	125.7	81.4	203.0
16	169.7	138.9	93.2	219.4
17	183.6	150.9	103.9	234.2
18	196.3	161.9	113.7	247.7
19	207.8	171.8	122.6	260.0
20	218.2	180.8	130.6	271.2
21	227.7	189.0	138.0	281.3
22	236.3	196.5	144.6	290.6
23	244.2	203.3	150.7	298.9
24	251.3	209.4	156.2	306.6
25	257.8	215.1	161.2	313.5
26	263.7	220.1	165.8	319.8
27	269.1	224.8	169.9	325.5
28	273.9	229.0	173.7	330.7
29	278.4	232.8	177.1	335.5
30	282.4	236.3	180.2	339.8

Table 4.47a Thermo -chemical system NPV table