Evaluation of liquid bio-fuels using the Analytic Hierarchy Process
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Abstract

Biomass derived liquid bio-fuels are being promoted as a major feasible fuel alternative in the European Union, in order to reduce Europe's transport dependency on crude oil. In particular, liquid bio-fuels if used in internal combustion engines can substitute a considerable amount of conventional fuels. These bio-fuels include conventional bio-ethanol and bio-diesel, which are derived from agricultural crops as well as second-generation bio-ethanol and synthetic diesel derived from lignocellulosic biomass. There are numerous pathways dealing with the production and use of liquid bio-fuels, depending on biomass feedstock, production technology, by-product usage and final bio-fuel consumption in vehicle power trains. In order to examine this complete chain of bio-fuel production and use, an evaluation study was carried out. This study used data from the *Well to Wheels* analysis *of future automotive fuels and power trains in the European context* (WTW analysis). Bio-fuels are assessed using the Analytic Hierarchy Process, which comprises of a synthesis of evaluation criteria and a sensitivity analysis. The criteria that were analyzed throughout the complete bio-fuel chain are bio-fuel substitution cost over conventional fuels, potential of substitution, total cycle GHG emissions and total cycle energy consumed.

Keywords: Liquid bio-fuel evaluation; Well to Wheels pathways; Analytic Hierarchy Process

1. Introduction

In order to cover its internal energy needs, the European Union (EU) is heavily dependent on energy imports and in particular on oil imports. The consumption of oil products in the EU is strongly connected with the emission of greenhouse gases (GHG), which contribute to global warming. In particular, the European transport

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sector is almost fully dependent on oil-derived products accounting for an estimated 21% of the total GHG emissions of the EU-25 [1]. Thus, diversifying energy sources and technologies in a sustainable way, which also secures energy supply for transport comprises a vital policy objective of the EU. Amongst transport modes, road transport is the largest energy consumer and GHG emitter, with increasing capacity [2]. Hence, the introduction of cleaner alternative fuels in road transport, whose raw materials and production patterns differ from those of conventional oil-based fuels, is a crucial factor for meeting this goal [3].

Bio-fuels favour against fossil fuels because they derive from renewable energy resources such as biomass. Furthermore, they provide potential income prospects for the agricultural sector. Although their cost is still more expensive than fossil fuels, due to policy measures, their production is growing rapidly. The European Union is supporting bio-fuels with the objective of creating a sustainable transport sector. Their production in rural areas is expected to diversify income and enhance employment while their use will reduce GHG emissions [1].

In particular, liquid bio-fuels are compatible with current infrastructure and vehicle technology and offer the highest potential for fast bio-fuel introduction on a large scale. They are preferably used in low-percentage blends with conventional fuels, because they do not require any modification in the present vehicle power trains. Liquid bio-fuels can be produced in a variety of ways and can be classified in terms of conventional and advanced bio-fuels. Conventional bio-fuels include bio-ethanol and bio-diesel produced from traditional agricultural crops by established technologies, while advanced bio-fuels include second-generation bio-ethanol and synthetic diesel (syn-diesel) produced from lignocellulosic biomass by developing technologies.

The goal of this study is to evaluate the utilization of conventional and advanced liquid bio-fuels in the European transport sector for 2010 and beyond, using the Analytic Hierarchy Process [4]. The evaluation refers to the complete chain of bio-fuel production and use, from the primary energy resources till the vehicle exhaust emissions, described as Well to Wheels chain, and is based on data taken from the WTW analysis [5]. The criteria that were analyzed through the complete bio-fuel chain include bio-fuel production cost, bio-fuel yield, total cycle GHG emissions and total cycle energy consumed.

2. Description of the Well to Wheels Analysis

The Well to Wheels (WTW) analysis of future automotive fuels and power trains in the European context, carried jointly by EUCAR, CONCAWE and JRC/IES, estimates the implications of replacing conventional fossil fuels used for transport with alternative fuels at the 2010-2020 horizon [5]. The present paper uses the data of the WTW analysis for biomass derived liquid bio-fuels that can be used in internal combustion engines and appear relevant for the foreseeable future. The data include an overall assessment of the energy required together with the GHG emitted per unit distance covered, an estimate of the macro-economic costs associated with each bio-fuel pathway and an analysis of the potential of bio-fuel production per biomass feedstock.

In the WTW analysis, low-percentage blends of 5% pure bio-fuels with conventional fuels are considered. It is also assumed that pure bio-fuels are produced in the EU-25 by local biomass feedstock, while conventional fuels are imported from the Middle East. Bio-fuels are consumed in 2010+ conventional combustion engines, i.e. in a Gasoline PISI (Port Injection Spark Ignition) or in a Diesel DICI (Direct Injection Compression Ignition). The performance of the 2010+ power train is derived by establishing an improvement over the 2002 power train level. An open source vehicle simulation tool called ADVISOR, which was developed by the US-based National Renewable Energy Laboratory (NREL), was used and adapted to the New European Driving Cycle (NEDC) in order to evaluate the vehicle power trains in a common basis. All vehicle simulations were based on a common model vehicle, representing a typical European compact size 5-seat Sedan.

The cost estimates of the analysis are derived from a scenario, which assumes substitution of conventional fuels with liquid bio-fuels to a level corresponding to 5% of the transport needs (distance driven) covered by private cars in Europe in 2015. In particular, the scenario assumes substitution of 200 PJ of gasoline and 145 PJ of diesel per annum according to the vehicle population fleet. These costs are additional to those of the reference scenario, in which the demand is covered by conventional fuels and power trains (gasoline and diesel). Bio-fuel costs are affected by crude oil prices and the analysis considered two separate cost scenarios for crude oil prices of 25 and 50 €/bbl. In this study, the crude oil price is considered to be 50€/bbl, because this price seems more realistic, at present. Although some of the data used in the WTW analysis are hypothetical, including assumptions of technical improvements and cost estimates, they are used in a consistent calculation basis and thus considered trustworthy.

3. Description of alternative bio-fuel pathways

The alternative routes for bio-fuel production, distribution and use, which are described by the Well to Wheels chain, are called Well to Wheels pathways. These pathways can be described in terms of successive processes required to produce, distribute and consume the final bio-fuel in vehicle power trains. These processes include cultivation, harvesting and conditioning of biomass feedstock, transportation to the processing plant, bio-fuel production, transportation to reservoirs, blending with conventional fuels, transportation to filling stations and final disposition and use in vehicle power trains. Bio-fuel pathways are classified in four main categories, according to the pure bio-fuel produced in the processing plants i.e. bio-ethanol, bio-diesel, second-generation bio-ethanol or syn-diesel.

The production of bio-fuels follows various routes, while their distribution and use follow the same routes as per gasoline and diesel. Bio-ethanol is blended with gasoline and consumed in gasoline vehicles while bio-diesel as well as syn-diesel is blended with fossil diesel and consumed in diesel vehicles. Their transportation from processing plants to reservoirs and filling stations is carried out with road tankers. Hence, instead of representing the bio-fuel pathways from the primary energy resource till the final use in the vehicle power train, their description will be restricted from the primary energy resource till the pure bio-fuel production.

3.1. Conventional bio-ethanol pathways

Bio-ethanol from sugar beet
Sugar beet is cultivated on high quality farmland and then harvested and stored. Then, the sugar beet (with 76.5% water content) is transported by tracks to the processing plant, which is a conventional fermentation plant. The main steps in the basic processes of the plant are cleaning, slicing, sieving out the pulp by-product, syrup pasteurisation, fermentation, distillation and final bio-ethanol purification. Heat is supplied by a natural gas burner. Process by-products, consisting of sugar beet pulp and slop, are dried (to a 9% water content) using natural gas. These can be used as animal feed (**pulp to fodder**) or as fuel, replacing heating needs of the process covered by natural gas (**pulp to heat**) [6].

Bio-ethanol from wheat
Soft wheat is farmed giving the highest-yield cereal crop, but it also takes the highest inputs. Apart from wheat grain production, straw is also produced which, depending on the circumstances, can be left in the field and ploughed back or used either for various agricultural purposes or as a source of energy. After harvesting, drying and storage, wheat grain (with 13% moisture content) is transported by tracks to the processing plant. There, bio-ethanol is produced from wheat grain via the conventional hydrolysis and fermentation process, which consists in wheat grain milling, hydrolysis, fermentation, distillation and dehydration. A residue is produced from the fermentation process, known as DDGS (Distillers' Dark Grain with Solubles). This protein-rich by-product is conventionally used as animal feed (**DDGS as animal feed**), with a high nutritional value, but can also be used as a source of energy co-fired with lignite in thermal power plants (**DDGS as fuel**) [7].

The energy demand of bio-ethanol processing consists mainly of heat at low temperature and electricity. This energy can be provided by a variety of schemes, such as:

- **A Conventional natural gas fired boiler,** which provides heat**,** while electricity is imported from the grid.

- **Combined cycle gas turbines** where natural gas fired gas turbines with a Heat Recovery Steam Generator (HRSG) provide both heat and power. The HRSG system includes supplementary firing as more heat than electricity is needed for the process. In the process, heat is required as low-pressure steam, thus a backpressure turbine generator is also installed after the HRSG. The surplus electricity produced is exported to the grid leading to GHG credits. The plant size and operation is planned to cover the heat requirements for bio-ethanol production.

- **A Lignite CHP boiler** where high-pressure steam is produced in a lignite boiler. As in the previous scheme, the plant size and operation is planned to cover the heat requirements for bio-ethanol manufacture. A backpressure turbine generator provides both heat as low-pressure steam and electricity for the process. The surplus electricity produced is exported to the grid.

- **A Straw CHP boiler** where straw can be removed without harming the soil and used to fuel the bio-ethanol production process. This pathway can only be applied to concentrated wheat-producing areas of Northern Europe excluding the Netherlands and Denmark. This scheme is similar to the previous one but straw is used instead of lignite.

3.2. Second generation bio-ethanol pathways

Bio-ethanol from wheat straw

Wheat straw can be used as feedstock in a SSCF-type process (Simultaneous Saccharification and Co-Fermentation) that turns cellulose into sugars and then into bio-ethanol. In principle, all cellulose biomass materials can be used. In this pathway, wheat straw is collected from the farmland and transported by tracks to the process plant. The main steps in the basic process are the pre-treatment of feedstock, the enzymatic hydrolysis (conversion of cellulose to glucose), the separation of lignin, bio-ethanol fermentation (conversion of sugar to bio-ethanol) and distillation. The separated lignin is used in a CHP plant [8].

Bio-ethanol from wood

Wood feedstock can be derived from short-rotation forestry farmed on agricultural land (**farmed wood**) or from forest residues (**waste wood**). Farmed wood includes poplar and willow, which are generally the best-yielding species in Central and Northern Europe and eucalyptus in Southern Europe. Typically, willow shoots are harvested every 3 years while poplar trunks are after 8-15 years. After harvesting, wood is transported to the processing plant where it is chipped and stored. At present, since there is no commercial wood to bio-ethanol plants operating, this pathway is based on a SSCF process. This process includes grinding of wood chips, which are then steamed and hydrolysed in dilute sulphuric acid. Then, the product is neutralised and a part of the product goes to enzyme production process under aerobic bacteria with the aid of additional nutrients. Afterwards, the bacteria-rich product joins the rest in the main fermentor, where it passes through a simultaneous saccharification (enzymatic breakdown of cellulose) and fermentation of the different sugars released. After several days, most of the cellulose and xylose is converted into bio-ethanol. The slops (including lignin) and the biogas from the anaerobic digestion are burned in a fluidised bed combustor to raise steam for process heating, while surplus steam goes to a turbine to produce electricity [9].

3.3. Conventional bio-diesel pathways

Bio-diesel from rapeseed

Rape gives the highest oil yield in Northern Europe. However, its crop yield is much lower than this of cereals. Thus, it is usually grown as a low-input break crop, to rest the soil between more profitable cereal crops. After harvesting, rapeseed is transported by tracks to the processing plant. In the oil mill, the rapeseed is crushed and oil is extracted by steam and n-hexane. The by-product is rapeseed cake, a high-protein animal feed. Oil purification follows, where acidity is neutralized. The next process step is a transesterification reaction i.e. the reaction of an alcohol with organic acids. In particular, methanol or bio-ethanol (produced from wheat) react with the fatty acids of the vegetable oil and produce fatty acid methyl or ethyl ester (**FAME/FAEE**) and glycerine. The raw glycerine (containing 80% pure glycerine) could be refined and sold as a distilled pharmaceutical-quality synthetic glycerol (**glycerine as chemical**). Glycerine can also be used as animal feed, replacing wheat (**glycerine as animal feed**). The final process before distribution is bio-diesel (FAME/FAEE) cleaning. Heat is provided by a conventional natural gas fired boiler**,** while electricity is imported from the grid [10].

Bio-diesel from sunflower

Sunflower, as rape, is grown as a low-input break crop, to rest the soil between more profitable cereal crops and is more suited for Southern Europe. This pathway is exactly the same as the one for rapeseed. Transesterification reaction takes place only with methanol and FAME is produced. The only difference from the rapeseed process is that the sunflower process has a slightly higher pressing yield and the sunflower cake by-product has lower protein content.

3.4. Syn-diesel pathways

Syn-diesel from wood

The biomass feedstock for the syn-diesel wood pathway is the same as the one used for bio-ethanol from wood (**farmed and waste wood**). The conversion of biomass into liquid fuel is based on the Fischer-Tropsch (FT) process. Biomass is treated and dried before entering the circulating fluidized bed gasifier. The produced syngas (CO, H_2) from the pyrolysis goes into gas cleaning, where CO_2 is removed by an amine process before the remaining syngas enters a fixed-bed Fischer-Tropsch reactor. There, CO and H_2 react to produce alkanes on the surface of the catalyst. The conditions of the reactor are specially adjusted to maximize the production of liquid fuels and especially kerosene and syn-diesel. The efficiency of the process, the yield and the product mix are all depended on the performance of the FT catalyst, which determines the chain growth probability (CGP). Assuming an average CGP of 0.85, the overall product mix of the process turns out to be 68% syn-diesel and kerosene and 32% naphtha [11].

Syn-diesel from waste wood via Black Liquor

The production of syn-diesel via black liquor, which is the residue of the paper pulp manufacture process, involves the separation of wood cellulose from lignin. The usual process of the paper pulp industry involves burning of black liquor in a recovery boiler. A new process that can be applied in the same industry, replaces the recovery boiler with a gasifier in order to produce syn-diesel. Particularly, instead of burning black liquor in a recovery boiler, this can be burnt in a gasifier in order to produce syn-gas, which is then transformed into liquid fuels via the FT process. The gasifier is oxygen-blown, so that an air separation unit is needed. As the recovery boiler is used to provide process heat for the pulp mill, its replacement by the gasifier needs to be compensated by another energy source to provide the process heat. The lower-cost source is waste wood, which can be transported using the same infrastructure as the stem-wood, feedstock of the paper pulp manufacture process. Thus, the additional heat needed can be supplied by waste wood burnt in a "hog fuel" boiler, which is already present to burn the bark and other residues. The net result of the modification of the paper pulp process is the transformation of waste wood into synthetic fuels. In order to maximize kerosene/diesel production, the other products must be recycled. Thus, naphtha is added to the hog boiler to produce electricity. The efficiency of kerosene/diesel reaches 55% while 1.83 MJ of biomass are needed to produce 1 MJ kerosene/diesel [12,13].

The description of the bio-fuel pathway codes, taken from the WTW analysis, is presented in Table 1.

Table 1 Description of the bio-fuel pathway codes

Conventional bio-ethanol pathways	
SBET1	Bio-ethanol from sugar beet, pulp to fodder
SBET3	Bio-ethanol from sugar beet, pulp to heat
WTET1a	Bio-ethanol from wheat, DDGS as animal feed, conventional natural gas boiler
WTET2a	Bio-ethanol from wheat, DDGS as animal feed, natural gas turbine for CHP
WTET3a	Bio-ethanol from wheat, DDGS as animal feed, lignite for CHP
WTET4a	Bio-ethanol from wheat, DDGS as animal feed, straw for CHP
WTET1b	Bio-ethanol from wheat, DDGS as fuel, conventional natural gas boiler
WTET2b	Bio-ethanol from wheat, DDGS as fuel, natural gas CC turbine for CHP
WTET3b	Bio-ethanol from wheat, DDGS as fuel, lignite for CHP
WTET4b	Bio-ethanol from wheat, DDGS as fuel, straw for CHP
Second generation bio-ethanol pathways	
STET1	Bio-ethanol from wheat straw
WFET1	Bio-ethanol from farmed wood
WWET1	Bio-ethanol from waste wood
Conventional bio-diesel pathways	
ROFA1	Rapeseed Methyl Ester (RME), glycerine used as chemical
ROFE1	Rapeseed Ethyl Ester (REE), glycerine used as chemical
SOFA1	Sunflower seed Methyl Ester (SME), glycerine used as chemical
ROFA2	Rapeseed Methyl Ester (RME), glycerine used as animal feed
ROFE2	Rapeseed Ethyl Ester (REE), glycerine used as animal feed
SOFA2	Sunflower seed Methyl Ester (SME), glycerine used as animal feed
Syn-diesel pathways	
WFSD1	Synthetic diesel from farmed wood
WWSD1	Synthetic diesel from waste wood
BLSD1	Synthetic diesel from waste wood via black liquor

4. Hierarchy structure using the Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a powerful and flexible multi-criteria decision making tool dealing with complex decision problems that allows consideration of both qualitative and quantitative [4]. It reduces complex decisions to a series of pairwise comparisons and then synthesizes results. Developed in the 1970’s by Dr. Thomas Saaty, a professor at the Wharton School of Business, AHP is considered to be the most highly regarded and widely used decision-making theory. The methodology used in the AHP is based on structuring a simple decision hierarchy problem, which involves a goal, evaluation criteria and alternatives of choice. Then, simple pair wise comparison judgments are made throughout each level of the hierarchy to arrive at overall priorities for the alternatives. This is achieved by comparing elements with respect to their parent element. Finally, AHP synthesizes all judgments into a unified whole in which alternatives are clearly classified from best to worst.

In order to evaluate liquid bio-fuels for the European transport sector for 2010 and beyond, evaluation criteria have to be specified. Although the evaluation is conducted between liquid bio-fuels, a key element for their comparison is the conventional fuel they substitute. The evaluation of bio-fuel pathways is a difficult and complicated approach dealing with economic, technical and environmental aspects. These include cost of substitution, subsidies, taxes, by-products disposal, farm income (in case of arable crops), substitution potential, GHG emissions and total energy used. The quantification of some of these factors per bio-fuel pathway is not feasible though, because of location dependence of production plants or lack of data. Hence, the evaluation will be based on cost of substitution, substitution potential, total cycle GHG emissions and total cycle energy consumed. Analytically, the evaluation criteria are:

- **The Economic Criterion** contains the incremental cost of fuel substitution (€/GJ). It represents the cost needed (in €) in order to substitute 1 GJ of conventional fossil fuel with 1 GJ of pure bio-fuel.

- **The Environmental Criterion** contains the total cycle GHG emissions (in $g_{CO2\ equiv}$/100km). It represents the total grams of CO_2 equivalent emitted throughout the fuel cycle, from the primary energy resource till the process of delivering 100 km of vehicle motion with the NEDC cycle. It describes the greenhouse gas emissions of the pathway.

- **The Resource Criterion** contains the total cycle energy consumed (MJ/km). It represents the total primary energy used (in MJ) throughout the fuel cycle, from the primary energy resource till the process of delivering 1 km of vehicle motion with the NEDC cycle. It includes both fossil and renewable energy sources and represents the energy efficiency of the pathway.

- **The Potential Criterion** contains the substitution potential (PJ/a). It represents the energy content (in PJ) of pure bio-fuel that can annually be produced in the EU-25 by domestic biomass feedstock in order to substitute conventional fuels.

The basic elements of evaluation are determined (i.e. goal, criteria and alternatives) and the evaluation is represented in a hierarchy tree, as shown in Figure 1. The next step for the evaluation consists in the determination of the value of each alternative with respect to each criterion.

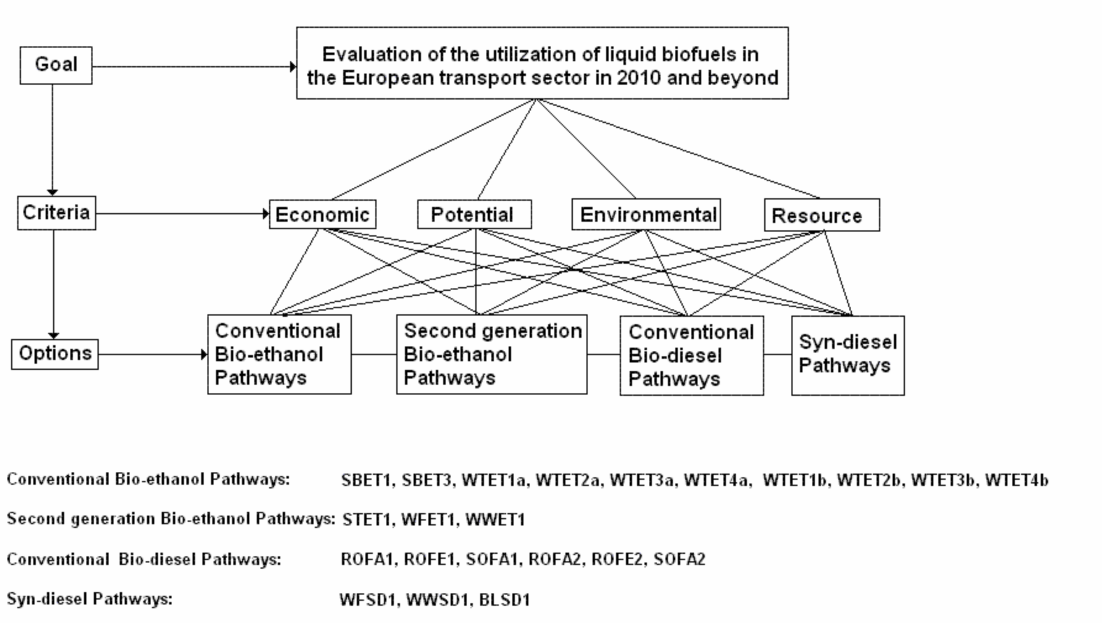

Figure 1: The hierarchy tree for the evaluation of liquid bio-fuels

5. Evaluation of bio-fuel pathways per criterion

The data presented below which are based on the WTW analysis include cost estimates, GHG emissions, energy requirements and potential of bio-fuel production. In order to compare the substitution of fossil fuels with the continuation of their use, a comparison between conventional and bio-fuel costs and their GHG emissions is provided. With the exception of the substitution potential, which is based on a combination of data collected and assumptions made, the other data are taken from the WTW analysis.

5.1. Economic criterion

The Economic criterion contains the additional cost needed to substitute a conventional fossil fuel with a bio-fuel. The additional cost is the production cost of the bio-fuel minus the cost of fossil fuel, which is saved. Thus, the cost of substitution shows the price difference that one has to pay in order to substitute fossil fuels with bio-fuels. The bio-fuel cost is highly depended on the biomass feedstock cost as well as on the cost of by-products. Table 2 shows the costs of biomass resources delivered to processing plants and the costs of by-products. These costs were based on the projections of food commodity prices for 2012 by FAPRI [14], commercial prices of lignocellulosic sources and calculations made by the WTW analysis [5].

The cost of substitution is evaluated as additional to the fossil fuel cost. Although fossil fuel prices are not used in the evaluation, the cost of fossil fuels and bio-fuels are compared. With a crude oil price at 50 €/bbl, the price of fossil fuels is considered to be at 11,9 €/GJ for both gasoline and diesel. Thus, the bio-fuel cost derives by adding the fossil fuel cost with the additional cost of substitution, as shown in Figure 2. In Figure 2, the dark colour represents the fossil fuel cost while the light colour represents the additional cost of substitution. This is also shown in Table 5.

Table 2 Cost of biomass resources

Biomass feedstock	€/t
Wheat grain	100
Sugar beet	26
Rapeseed	248
Sunflower seed	278
Wheat straw	37
Waste wood	53
Farmed wood	81
By-products substitutes	
Animal feed substitute	105
Glycerine substitute	218

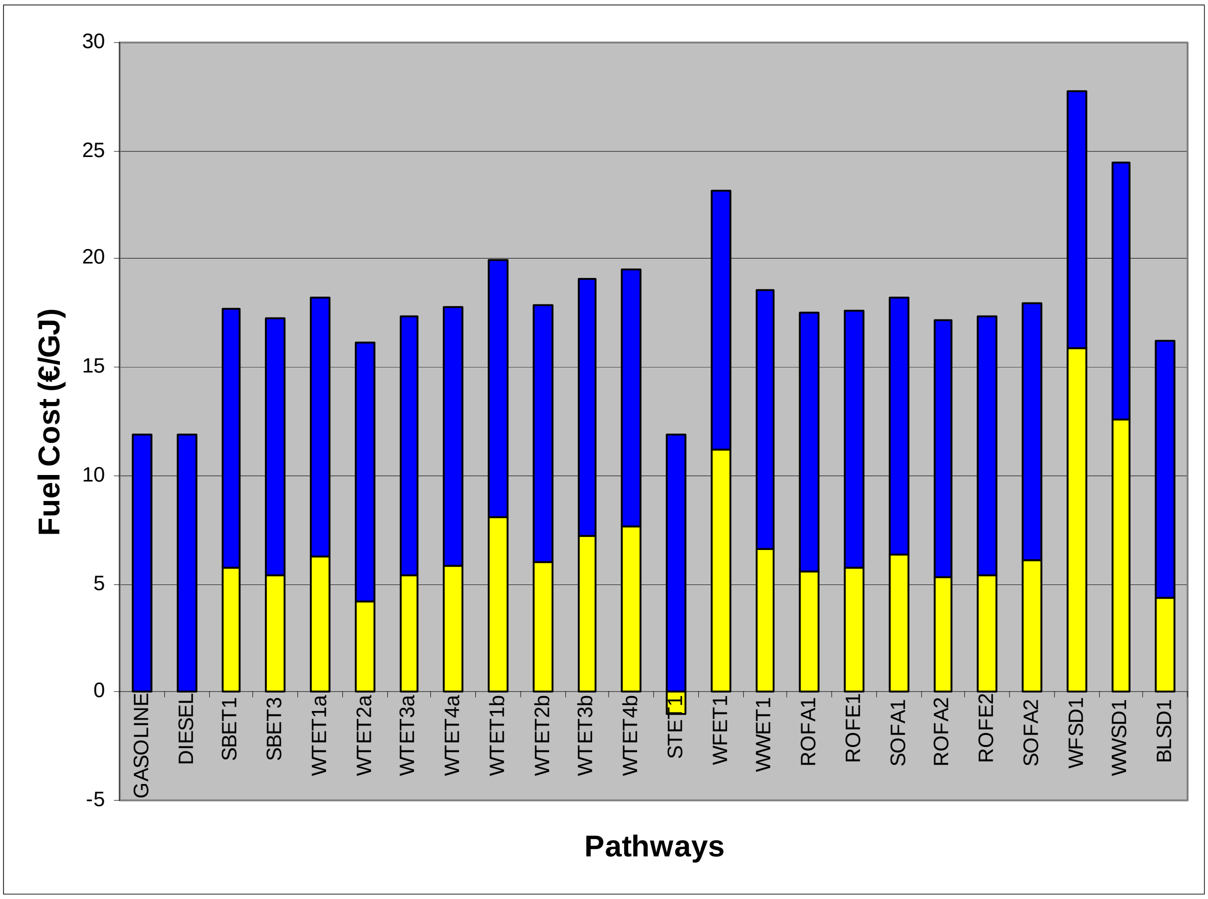

Figure 2: Evaluation of conventional and bio-fuel pathways with respect to fuel cost

A negative substitution cost means that the bio-fuel cost is lower than the fossil fuel cost. As shown in Figure 2, the only bio-fuel pathway that has a negative additional cost and can compete conventional fuels is the bio-ethanol from wheat straw pathway (STET1). This means that the production cost of this bio-fuel is lower than the fossil fuel cost that it will substitute. The next most economic pathways include the bio-ethanol from wheat pathway (WTET2a: process heat and power produced from natural gas turbine, DDGS used as animal feed) and the syn-diesel via black liquor pathway (BLSD1). On the other hand, the most expensive pathways include syn-diesel produced from farmed (WFSD1) and waste wood (WWSD1), followed by bio-ethanol from farmed wood (WFET1).

5.2. Environmental criterion

The Environmental criterion is defined as the total cycle GHG emissions per km driven through the NEDC cycle. The GHG emissions per bio-fuel pathway include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The CO_2 equivalent of the above emitters is presented in Table 3 according to the conversion coefficients recommended by the third assessment report of the Inter-governmental Panel for Climate Change (IPCC) [15].

Table 3 CO_2 equivalent conversion coefficients

Greenhouse Gas	$t_{CO2\ equiv}/t$
CO_2	1
CH_4	23
N_2O	296

The total CO_2 equivalent emitted throughout the fuel cycle for both conventional fuel and bio-fuel pathways are shown in Figure 3. It should be mentioned that the emission data per bio-fuel pathway (also shown in Table 5) comprise of average values, as there is a variation of nitrous oxide emissions from agriculture in the EU-25. It is remarkable that syn-diesel pathways (WFSD1, WWSD1, BLSD1) have the lowest GHG emissions, resulting in high GHG savings compared to fossil fuels. On the contrary, bio-ethanol from wheat (WTET3a, WTET3b) pathways (which consist in process heat produced from lignite-fired combined heat and power scheme) produce the same GHG emissions or more than gasoline per km driven through the NEDC cycle.

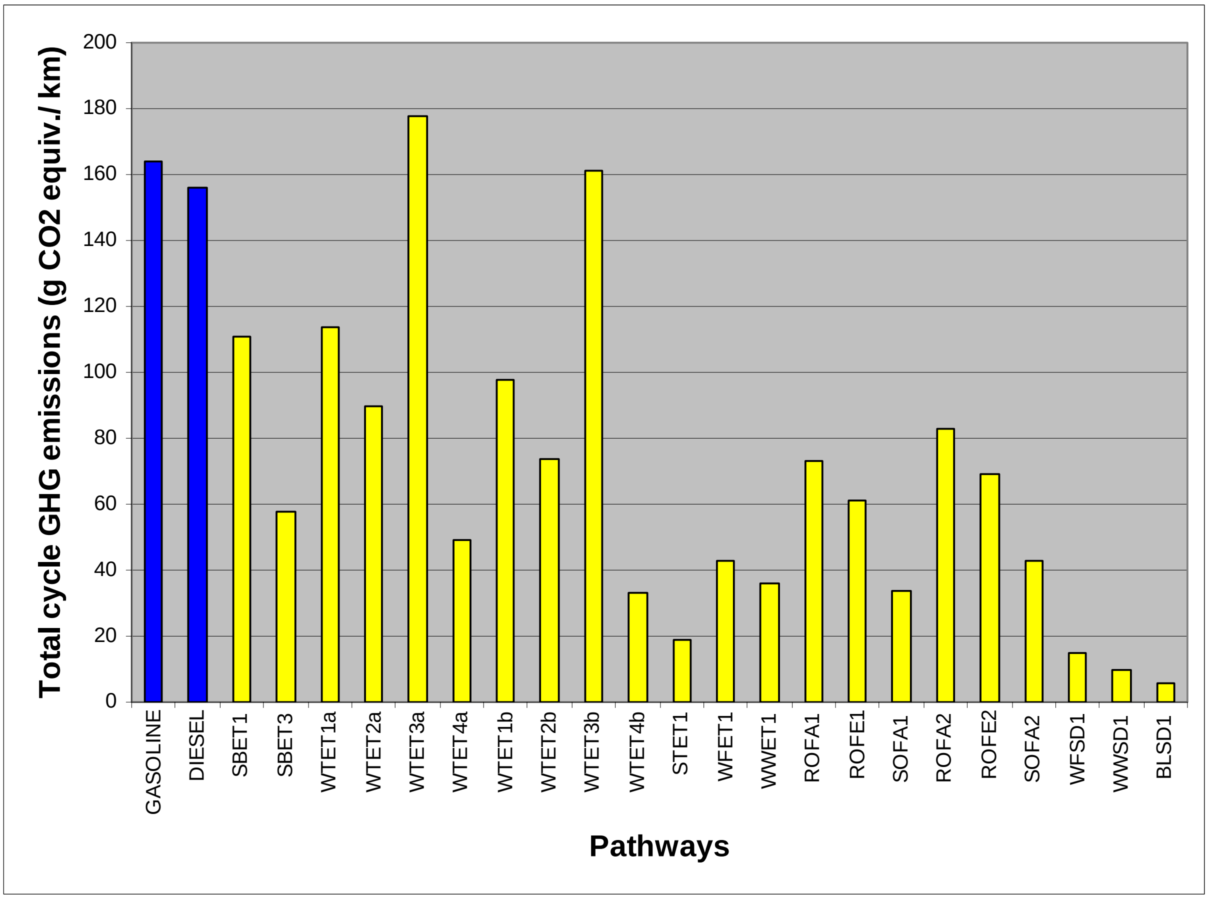

Figure 3: Evaluation of conventional and bio-fuel pathways with respect to total cycle CO_2 equivalent emissions.

5.3. Resource criterion

The Resource criterion is defined as the total cycle energy used (MJ) in order to deliver 1 km of vehicle motion with the NEDC cycle. It includes the energy content of fossil fuels as well as non-fossil resources, which were used throughout the fuel cycle. These resources include biomass feedstock, fertilizers and pesticides. The evaluation of the total energy used per bio-fuel pathway is given in Figure 4. Bio-diesel from sunflower (SOFA1, SOFA2) and syn-diesel via black liquor (BLSD1) comprise the most energy efficient pathways. On the opposite side, bio-ethanol from farmed (WFET1) and waste wood (WWET1) are the most energy intensive pathways.

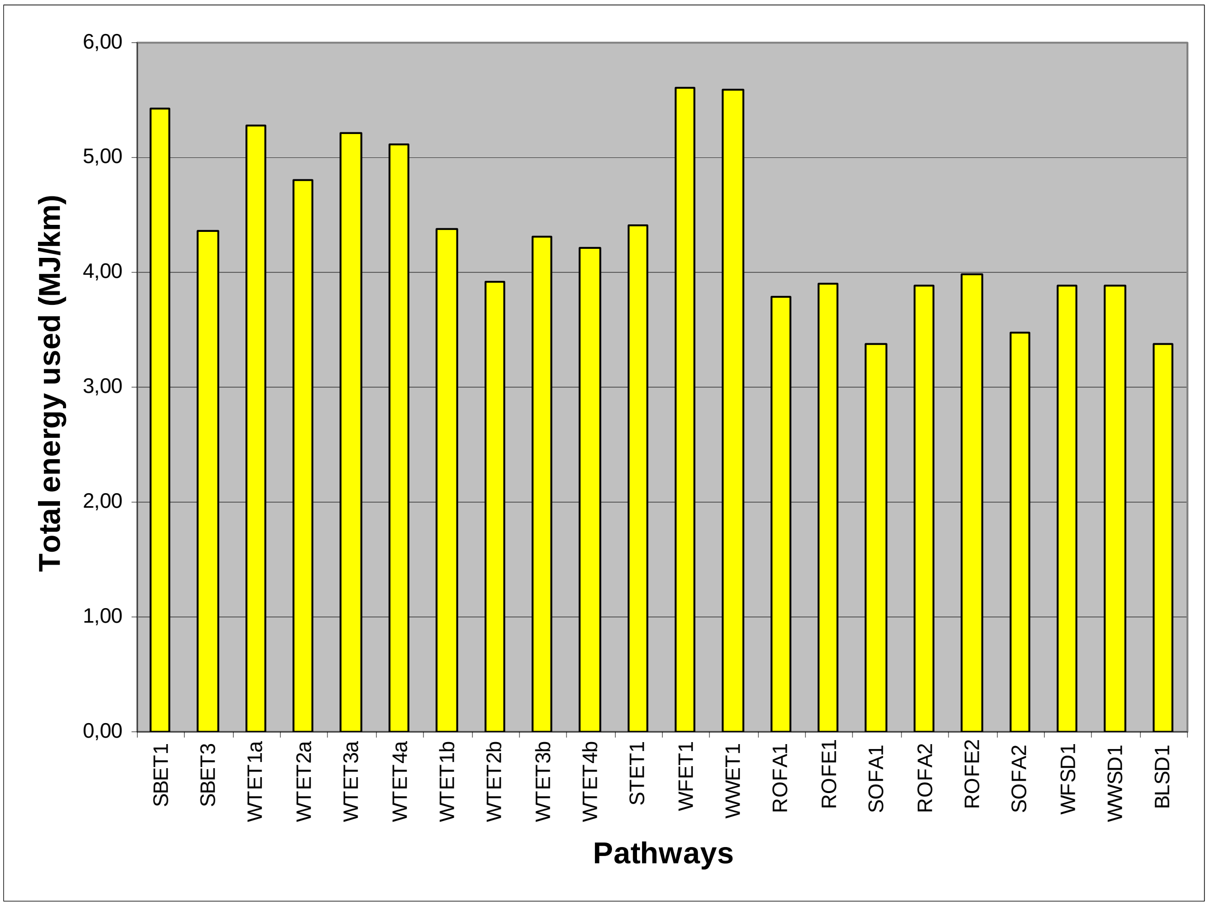

Figure 4: Evaluation of bio-fuel pathways with respect to total energy used.

5.4. Resource criterion

The potential of substitution of conventional fossil fuels with bio-fuels in the EU-25 depends on the potential of utilization of EU domestic sources for bio-fuel production. The potential supply of these sources is a strong function of their cost, which has to be competitive. Furthermore, the utilization of arable crops (i.e. wheat, sugar beet, rapeseed and sunflower) for conventional bio-fuel production has to compete food crops as well as lower-cost imported crops, which can be used for bio-fuel production. Likewise, utilization of lignocellulosic biomass sources (i.e. wheat straw, farmed and waste wood) for advanced bio-fuel production has to compete with the usage of these sources for combined heat and power production. The evaluation of both conventional and advanced bio-fuel pathways with respect to substitution potential is shown in Figure 5. The potential for conventional and advanced bio-fuel production is analytically presented in the sections, which follow.

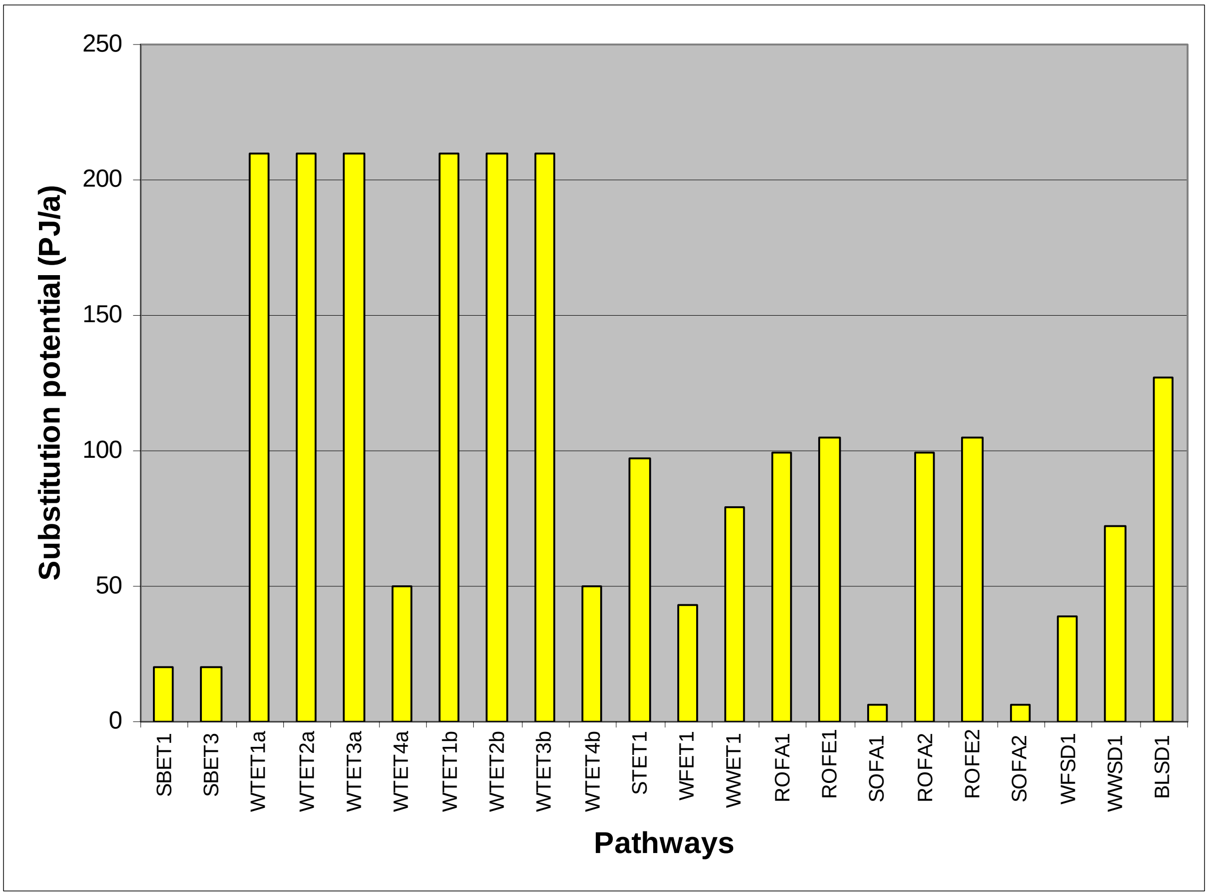

Figure 5: Evaluation of conventional and advanced bio-fuel pathways with respect to substitution potential.

5.4.1. Conventional bio-fuels potential

The supply/coverage of bio-diesel replacing fossil diesel and of bio-ethanol replacing gasoline was assumed to be the same, accounting for 5.75% each. This assumption was made by the WTW analysis because the bio-fuels directive target of 5.75% replacement of road fuels by 2010 [16] does not specify how this should be split between gasoline and diesel.

At first, the availability of arable land in the EU-25 is determined. Considering land as the primary resource leads to difficulties because of the large variations in land quality and therefore potential yields. Instead the WTW analysis used cereal production as a proxy for yield postulating a constant ratio between the yield of cereal and the yield of other crops. The measure of agricultural capacity defined as Mt Average Cereals Equivalent (ACE) describes the potential of soft wheat production (in Mt) if it substitutes an alternative crop grown in the same land. For instance, 1Mt of rapeseed has an average cereals equivalent of 1.58 Mt ACE, which means that in the same land where we produce 1 Mt rapeseed, we can produce 1.58 Mt of soft wheat. Table 4 presents the conversion coefficients per arable crop. It should be mentioned that 1 Mt of feed wheat has an average cereals equivalent (ACE) of 1.135 Mt, because the new varieties of feed wheat now coming into use show a 13.5% better yield than the weighted average of the present mix of wheat types.

Table 4 Average soft wheat cereals equivalence per arable crop

Arable crops	Mt ACE/Mt crop
Sugar beet	8.66
Feed wheat	1.135
Rapeseed	1.58
Sunflower	1.47

The agricultural potential of bio-fuel production derived from the WTW analysis, takes into consideration the agricultural market projections of DG-AGRI for 2012 [17] together with the implications of the reform of the EU sugar policy. According to DG-AGRI the arable area of the EC-25 would remain practically unchanged from the 2005 level i.e. an area of 58 Mha. The agricultural capacity, which can be used to increase the present bio-fuel production without disturbing food production for internal EU consumption includes:

1. Diversion of the baseline cereal exports, which are projected to be 14.9 Mt ACE.
2. Land use release by the reform of the EU sugar policy, assumed to be 9.3 Mt ACE
3. Additional production of arable crops by liberation of compulsory set-aside land equivalent to 16 Mt ACE.

The potential of growing biomass sources in the EU apart from the cost, is also dependent on the production compatibility according to climatic conditions, existing trade agreements of the EU for various crops and policy measures. These factors should be taken into consideration in combination with WTW projections of availability of biomass sources. This potential of bio-fuel production per biomass feedstock is described below:

Bio-ethanol from sugar beet

Baring in mind the reform of the EU sugar policy [18], sugar beet potential for bio-ethanol production is restricted. This potential is determined by the “C sugar”, which is sugar produced in excess of the food-quota. It cannot be sold for food in the EU but can be sold for bio-ethanol production. The sugar reform proposal allows up to 1 Mt of “C sugar” production (equivalent to 8 Mt sugar beet), which can annually produce 16 PJ of bio-ethanol. Adding about 4 PJ of bio-ethanol produced at present leads to a total potential of 20 PJ/a of bio-ethanol production from sugar beet.

Bio-ethanol from wheat

At present, bio-ethanol production from wheat is about 8 PJ/a. In order to achieve a 5.75% coverage of gasoline replacement (adding bio-ethanol from sugar beet), its potential should be 202 PJ/a, requiring 22.4 Mt ACE. Thus, the total bio-ethanol potential is 210 PJ/a. This potential is less if wheat straw is used to fuel the production plant in a combined heat and power scheme, since wheat straw can be collected from certain fields without harming the soil. If straw is used for CHP (WTET4a, WTET4b) it is assumed that the bio-ethanol production potential would be 50 PJ/a.

Bio-diesel from rapeseed and sunflower seed

At present, bio-diesel production in the EU-25 is entirely based on rapeseed. In particular, 5.6 Mt/a of rapeseed are used with methanol (RME) to produce 78 PJ/a of bio-diesel. If the same amount of rapeseed was used to produce bio-diesel with bio-ethanol (REE) the annual production would be 83 PJ/a. Although an extra demand of 31 Mt/a oilseeds are needed to reach the 5.75% bio-diesel target, the increase in EU oilseeds supply would be 1,9 Mt/a, according to WTW analysis. This is because of the large expansion of bio-diesel production would increase world oilseed prices significantly. The fact that Europe is climatically better suited to cereals production than oilseeds makes it better to import oilseeds to cover the rest of the bio-diesel production. The remaining of the agricultural capacity could be used for cereal exports (that is why the EU already imports almost half of its present oilseed requirements and exports cereals). Assuming an 80/20-land use ratio between rapeseed and sunflower seed, which will require 3 Mt ACE, would lead to the production of 21 PJ/a bio-diesel from RME or 22 PJ/a from REE and 6 PJ/a from sunflower. Thus, the total bio-diesel potential is 99 PJ/a from RME, 105 PJ/a from REE and 6 PJ/a from sunflower (SME).

5.4.2. Advanced bio-fuels potential

Advanced bio-fuels are produced from biomass sources including wheat straw, farmed wood and waste wood. Their processing plants are complex and capital intensive and should be large in order to gain from economies of scale. By contrast, the usage of these sources in biomass boilers or small-scale CHP plants is easy, economic and produces less GHG emissions, making them more competitive from bio-fuel production. It should also be mentioned that wheat straw and waste wood are dispersed sources, thus their availability for bio-fuel production will be restricted to areas where they can logistically be brought to large processing plants.

Bio-ethanol from wheat straw

Taking into account a GIS-based study on the availability of straw in the EU for feeding power stations [19], WTW analysis estimates that 15,9 Mt straw would be logistically available to large processing plants to produce 97 PJ/a bio-ethanol.

Bio-ethanol and syn-diesel from farmed wood

According to the current European Common Agricultural Policy (CAP), voluntary set-aside land cannot be used to grow arable bio-fuel crops, but can be used for wood farming. Thus, it is assumed that short rotation forestry (SRF) is produced on voluntary set aside land equivalent to 6.9 Mt ACE. As the voluntary set-aside land would give low yield wheat production, it is assumed that the yield ratio between SRF and wheat is 1Mt ACE. The bio-fuel potential, if all farmed wood is used for bio-ethanol or syn-diesel production, would be 43 PJ/a and 39 PJ/a respectively.

Syn-diesel from waste wood via black liquor

The WTW analysis used data from a study of black liquor gasification [13] to estimate that 325 PJ of forest residuals could be economically used to fully exploit the possibilities of black liquor gasification in the EU-25 by 2012. Taking into account logistic limitations, about 238 PJ of these sources could realistically be exploited to produce transport fuels. This leads to a production potential of 127 PJ/a syn-diesel.

Bio-ethanol and syn-diesel from waste wood

The WTW analysis used data from a study estimating energy wood potential in Europe [20] to calculate the maximum technical availability of forest residuals and roundwood for bio-fuel production. Subtracting the 325 PJ available at pulp mills for processing by the black-liquor gasification route, 683 PJ are left for other uses. Assuming that at most 1/3 of the supply could be logistically available to large processing plants, leads to a potential of 230 PJ waste wood. The bio-fuel production of this potential would be 79 PJ/a for bio-ethanol and 72 PJ/a for syn-diesel production.

5.5. Evaluation of pathways with respect to criteria

The evaluation of the bio-fuel pathways per criterion, which was discussed above, are presented in Table 5. The final step needed in order to apply the Analytic Hierarchy Process is to determine the weight factor of each criterion with respect to the goal.

Table 5 Contribution of bio-fuel pathways per criterion

	Substitution cost (€/GJ)	Substitution Potential (PJ/a)	GHG emissions (g CO2 equiv./km)	Total Energy used (MJ/km)
Conventional bio-ethanol pathways				
SBET1	5.78	20	111	5.43
SBET3	5.41	20	58	4.36
WTET1a	6.28	210	114	5.28
WTET2a	4.21	210	90	4.81
WTET3a	5.42	210	178	5.21
WTET4a	5.86	50	49	5.11
WTET1b	8.06	210	98	4.38
WTET2b	5.99	210	74	3.91
WTET3b	7.20	210	161	4.31
WTET4b	7.64	50	33	4.21
Second generation bio-ethanol pathways				
STET1	-1.03	97	19	4.41
WFET1	11.23	43	43	5.60
WWET1	6.64	79	36	5.59
Bio-diesel pathways				
ROFA1	5.61	99	73	3.79
ROFE1	5.70	105	61	3.90
SOFA1	6.34	6	34	3.38
ROFA2	5.31	99	83	3.88
ROFE2	5.43	105	69	3.98
SOFA2	6.05	6	43	3.48
Syn-diesel pathways				
WFSD1	15.85	39	15	3.88
WWSD1	12.58	72	10	3.88
BLSD1	4.34	127	6	3.38

6. Evaluation of criteria weights

The evaluation of criteria weights is based on a subjective pairwise comparison of the criteria in a standard 1-9 AHP measurement scale [4]. This scale defines the intensity of importance of one criterion upon another, as shown in Table 6.

Table 6 Standard 1-9 AHP measurement scale

Intensity of Importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance

Bio-fuel evaluation prioritises the criteria in a scale according to their importance. It is considered that priority is given to minimise performances against all criteria, that is to cost (economic criterion), substitution potential by domestic sources (potential criterion), GHG emissions reduction (environmental criterion) and finally energy used for bio-fuel production (resource criterion). The pairwise comparison of these criteria with respect to goal is presented in Table 7. This table shows that the economic criterion has a moderate, strong and very strong importance upon the potential, environmental and resource criterion respectively. Furthermore, the potential criterion favours moderately upon the environmental criterion and strongly upon the resource criterion. Finally, the environmental criterion has a moderate importance upon the resource criterion.

Table 7 Pair wise comparison of criteria with respect to goal

Criteria	Economic	Potential	Environmental	Resource
Economic	1	3	5	7
Potential	1/3	1	3	5
Environmental	1/5	1/3	1	3
Resource	1/7	1/5	1/3	1

According to Table 7, the criteria weights are those presented in Figure 6. The economic indicator is ranked first, having the highest weighting factor (56.5%) followed by the potential (26.2%), the environmental (11.8%) and the resource indicator (5.5%).

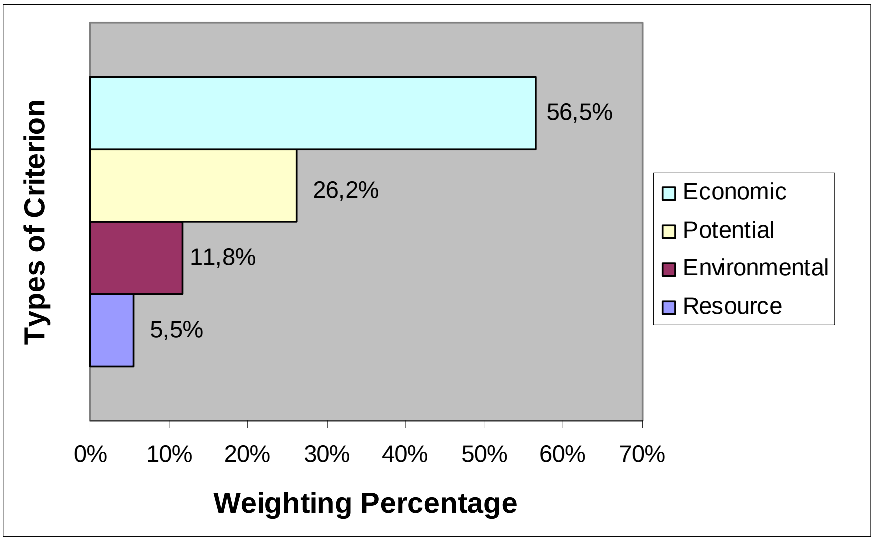

Figure 6: Criteria weights with respect to goal

7. Results

The normalised scores of the alternative pathways with respect to each criterion, are presented in Figure 7 to Figure 10 in decreasing order.

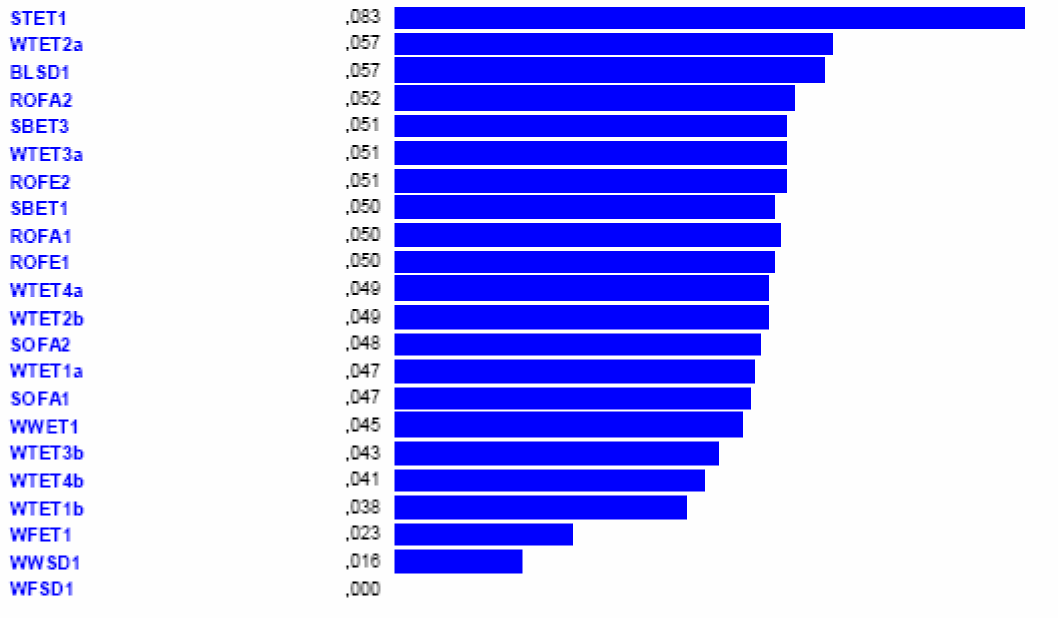

Figure 7: Normalised sorted evaluation of bio-fuel pathways with respect to the economic indicator.

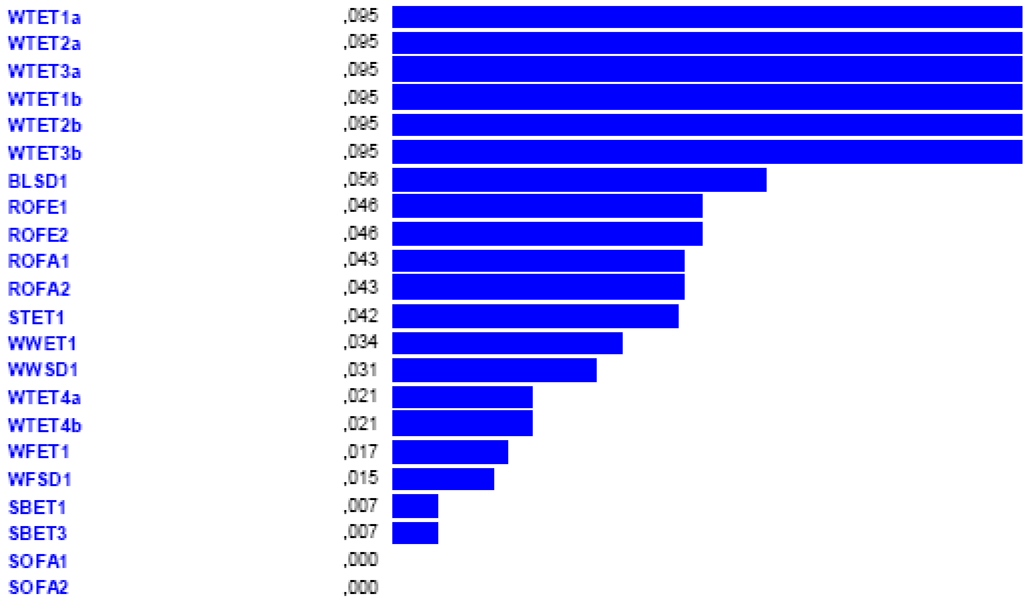

Figure 8: Normalised sorted evaluation of bio-fuel pathways with respect to the potential indicator.

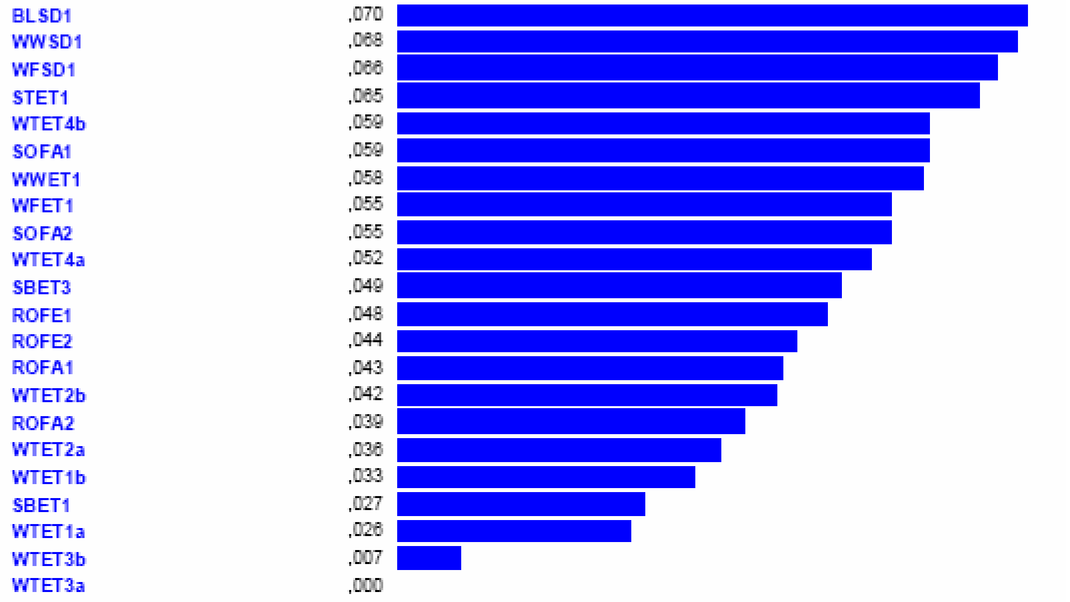

Figure 9: Normalised sorted evaluation of bio-fuel pathways with respect to the environmental indicator.

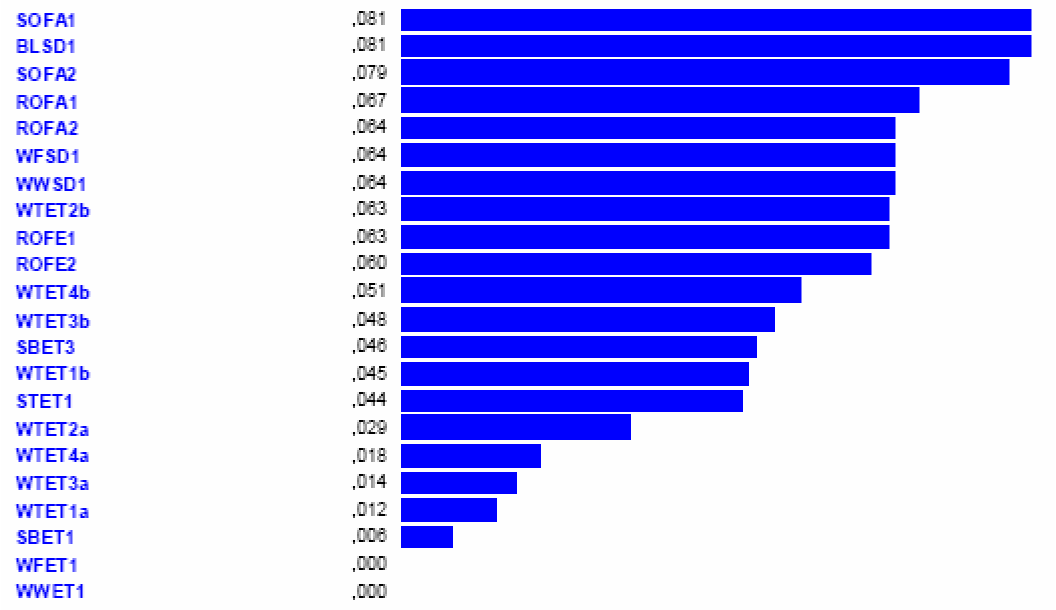

Figure 10: Normalised sorted evaluation of bio-fuel pathways with respect to the resource indicator.

The synthesis of normalised evaluations and criteria weights using AHP, result to the overall score and ranking of bio-fuel pathways presented in Figure 11. The bio-fuel pathways are ranked from the best (with the highest priority) to the worst. The best bio-fuel pathways are for bio-ethanol produced from wheat straw (STET1), followed by bio-ethanol from wheat with process heat and power produced from natural gas turbines (WTET2a, WTET2b) and the syn-diesel via black liquor (BLSD1).

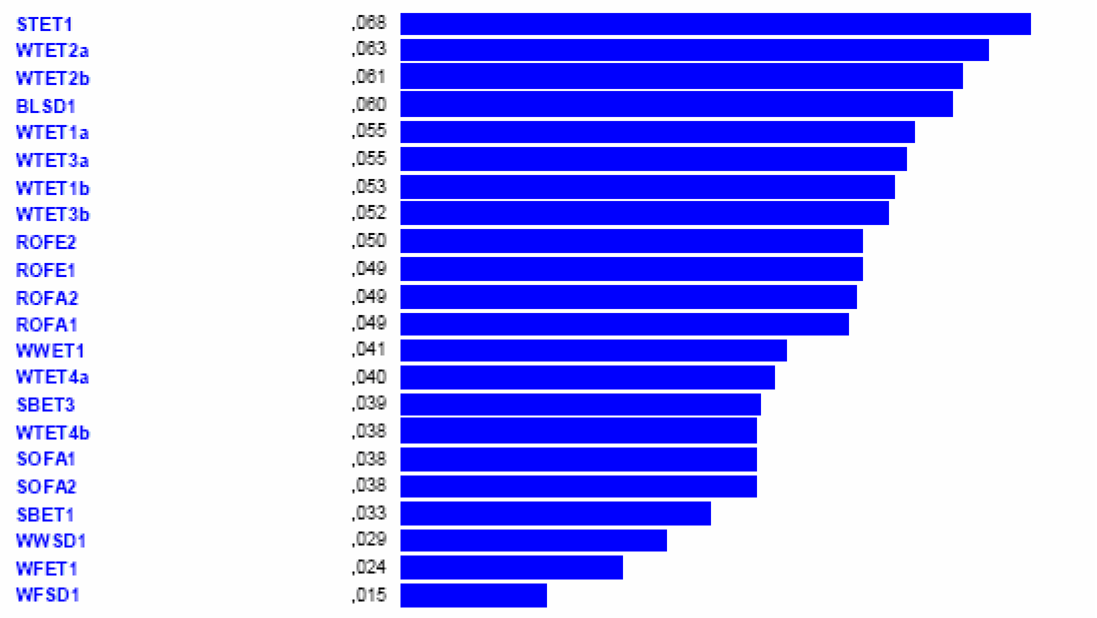

Figure 11: Overall sorted evaluation of bio-fuel pathways

The second most competitive group of pathways include bio-ethanol produced from wheat with process heat covered by a conventional natural gas boiler (WTET1a, WTET1b) or by a lignite-fired combined heat and power scheme (WTET3a, WTET3b). The third most competitive group includes bio-diesel produced from rapeseed (ROFE2, ROFE1, ROFA2, ROFA1). The fourth group includes bio-ethanol produced from waste wood (WWET1), bio-ethanol produced from wheat with wheat straw used for CHP (WTET4a, WTET4b), bio-ethanol from sugar beet (SBET3, SBET1) and bio-diesel from sunflower (SOFA1, SOFA2). At the bottom of the scale, the less competitive pathways include syn-diesel produced from farmed (WFSD1) and waste wood (WWSD1) and bio-ethanol produced from farmed wood (WFET1).

8. Sensitivity Analysis

Sensitivity analysis is used to examine the effect on the model results by changing the weight factors of the different criteria. Figure 12 presents the effect on bio-fuel priorities by changing the weight factors of the criteria. The first column of the Figure presents the base subjective evaluation of the weight factors together with the alternative performances ranked from the best priority of the bio-fuel pathways to the worst. The other four columns present four different cases that were examined and their results. In each case there is one prioritized criterion with a weight factor of 60.1% while the other criteria have an equal weight factor of 13.3%. The results of every case are shown below the weight factors and can be compared with the results of the original subjective evaluation.

Thus, if priority is given to the economic indicator, as shown in the second column of Figure 12, there will be a slight difference in the ranking order. Bio-ethanol produced from the wheat straw pathway (STET1) will remain in the first place, as it has the highest weight factor with respect to the economic indicator. The bio-ethanol from wheat pathways with process heat and power produced from natural gas turbines (WTET2a, WTET2b) will be surpassed by the syn-diesel via black liquor pathway (BLSD1), which will occupy the second place. The priorities of bio-ethanol from wheat (WTET) pathways (excluding WTET4a, WTET4b where straw is used to fuel the bio-ethanol production process) will fall significantly because they are ranked between the last places of the economic indicator. Furthermore, the priorities of bio-diesel from sunflower pathways (SOFA1, SOFA2) will have a significant increase. This is due to the fact that these pathways have the lowest weight factors in the potential indicator and as the priority of this indicator is decreased, the overall weight factors of these pathways are increased. The priorities of the other pathways will almost remain the same.

If priority is given to the potential indicator, as shown in the third column of Figure 12, there will be a major increase in the ranking of the bio-ethanol from wheat pathways (WTET), with the exception of the pathways where straw is used to fuel the bio-ethanol production process (WTET4a, WTET4b), because these pathways have the highest substitution potential. Thus, increasing the weight factor of the potential indicator will place the bio-ethanol produced from wheat pathways in the first six places. The syn-diesel via black liquor pathway (BLSD1) will follow in the seventh rank followed by the bio-ethanol from wheat straw pathway (STET1). The ranking of the bio-ethanol from sugar beet pathways (SBET1, SBET3) and the bio-diesel from sunflower pathways (SOFA1, SOFA2) will fall significantly as they have a low substitution potential. Also, the other syn-diesel pathways (WWSD1, WFSD1) will rank higher while the second-generation bio-ethanol from wheat pathways (WWET1, WFET1) ranking will be lower. In addition, bio-diesel from rapeseed pathways (ROFA, ROFE) ranking will drop slightly.

If priority is given to the environmental indicator, as shown in the fourth column of Figure 12, the ranking of the bio-ethanol from wheat pathways will fall significantly as they carry the last places in the evaluation with respect to the environmental indicator. Exception of these pathways comprise the pathways where straw is used to fuel the bio-ethanol production process (WTET4a, WTET4b), whose rankings will rise. Bio-diesel from rapeseed pathways (ROFA, ROFE) will drop slightly while bio-diesel from sunflower (SOFA1, SOFA2) will rise substantially. As for the sugar beet pathways, if pulp is used for animal fodder (SBET1) then its ranking will drop slightly, while if pulp is used as fuel to produce process heat, then its ranking will rise moderately. As for the advanced bio-fuels, the syn-diesel from black liquor pathway (BLSD1) and the bio-ethanol from waste wood (WWET1) will rise slightly and the bio-ethanol from straw pathway (STET1) will drop slightly. The other advanced bio-fuel pathways will have a remarkable rise in their ranking, because their overall evaluations with respect to the environmental indicator are amongst the first places. Thus, if the weight factor of the environmental criterion reaches 60.1 % the syn-diesel via black liquor pathway (BLSD1) will surpass the bio-ethanol from straw pathway (STET1), taking the first place and the other advanced bio-fuel pathways will be competitive with the conventional ones.

Finally, if priority is given to the resource indicator, that is if it has a 60.1% weight as shown in the fifth column of Figure 12, there would also be noticeable changes in the ranking order. This occurs because the bio-ethanol pathways are energy intensive, while the bio-diesel and the syn-diesel pathways are more energy efficient. The rankings of all the bio-ethanol pathways will sharply drop, apart from those where the by-products are used to fuel the process, which will drop slightly. Only two of the bio-ethanol from wheat pathways show a rise in their rank: the pathway where process heat and power are produced from natural gas turbines and the DDGS are used as fuel (WTET2b) which will slightly rise; and the pathway where straw is used to fuel the bio-ethanol production process and the DDGS are used as fuel (WTET4b), which will rise significantly. The reason of this rise in their ratings has to do with the low performance of this pathway with respect to the economic and the potential indicator. As for the bio-diesel from rapeseed pathways, they will slightly rise while the bio-diesel from sunflower pathways would grow substantially. Also, the syn-diesel pathways would sensibly rise. Hence, the syn-diesel via black liquor pathway (BLSD1) takes the first place, followed by the bio-ethanol from wheat pathway with process heat and power produced from natural gas turbines, DDGS used as fuel (WTET2b) and the bio-diesel from sunflower pathway with glycerine used as animal feed (SOFA2).

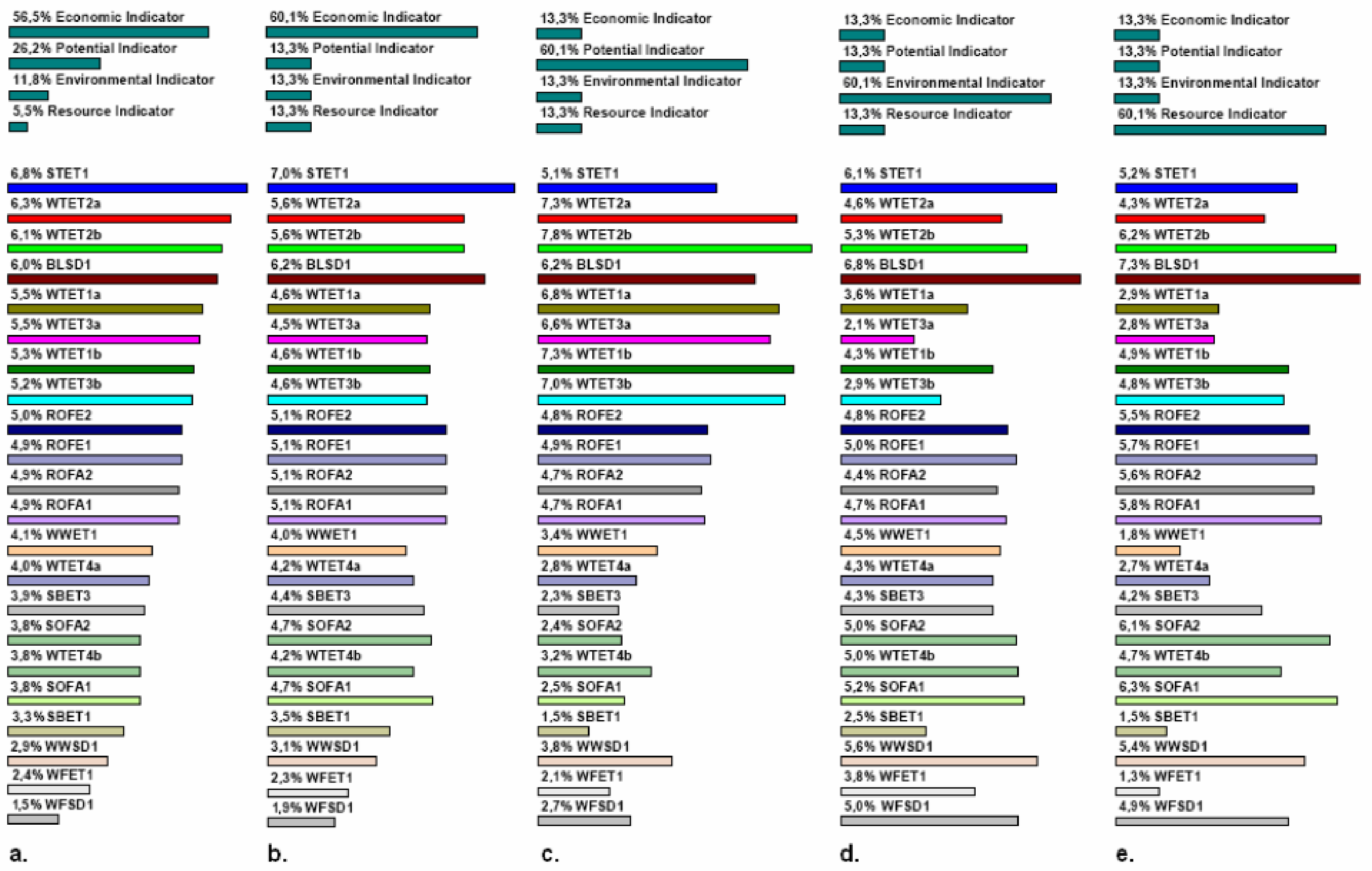

Figure 12: Effects on bio-fuel rankings by changing the weight factors of the criteria. a: Base subjective evaluation, b: Evaluation with priority given to the economic indicator, c: Evaluation with priority given to the potential indicator, d: evaluation with priority given to the environmental indicator, e: Evaluation with priority given to the resource indicator.

The analysis shows that three pathways remain in the first places of the ranking, no matter which criterion has the highest priority. These consist of the syn-diesel via black liquor pathway (BLSD1), the bio-ethanol from wheat pathway with process heat and power produced from natural gas turbines, DDGS used as fuel (WTET2b) and the bio-ethanol produced from wheat straw pathway (STET1). Although the last pathway has a lower rank with respect to the potential and resource indicators, it is the most economic one and should be taken into account. The reason is that the limiting factor for bio-fuels used today is their high cost compared to fossil fuels. In conclusion, the above pathways comprise of the best choices for the production of bio-fuels, as they tend to carry significant order amongst the different rankings of the evaluation criteria.

9. Conclusions

This study evaluated bio-fuel pathways, which can be used to substitute conventional fuels in the European transport sector for 2010 and beyond. The best bio-fuel pathways using EU domestic sources include bio-ethanol produced from wheat straw, syn-diesel produced from waste wood via black liquor and bio-ethanol produced from wheat with process heat supplied from a natural gas fired gas turbine with a combined heat and power scheme. It should be mentioned that in real life, the development of the most attractive bio-fuel pathways, will result due to the cost competitiveness of the primary biomass resources delivered to the processing plants, which shows the importance of the economic criterion in the evaluation.

Among conventional bio-fuel pathways, bio-ethanol produced from wheat has advantages over the other pathways because Europe favours the production of cereals rather than oilseeds. At present, bio-diesel production from rapeseed presents a significant increase, although it is restricted by the interaction between the EU oilseed production and the oilseed price. Bio-ethanol production from sugar beet is also restricted by the reform of the European sugar policy. Finally, bio-diesel from sunflower carries a low place in the rank, as sunflower is more competitive for food use.

As for the advanced bio-fuel pathways, they have the lowest GHG emissions, but most of them are not cost competitive. Thus, apart from bio-ethanol produced from wheat straw and syn-diesel produced from waste wood via black liquor, the other pathways comprise the less competitive choices according to current European policy priorities and these are ranked in the last places of the evaluation. Hence, it is better to use wood feedstock in combined heat and power plants until it can competitively be used for bio-fuel production.

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