Biofuels and their Environmental Performance

Today, the development of biofuel pathways is closely associated with targets for the reduction of greenhouse gas (GHG) emissions in the transport sector. Well-to-wheel assessments indicate that the use of these automotive fuels of vegetable origin yield definite benefits in terms of GHG emissions and fossil energy consumption compared to petroleum-based automotive fuels.

In recent years, there has been a strong revival of interest in biofuels, mainly due to their potential for reducing oil consumption and GHG emissions in the transport sector. Assessments of biofuel performance that bear on these two criteria are therefore critical: public authorities rely on them in designing and implementing systems to support the development of the pathways concerned. Today, most of the relevant existing or planned regulatory texts concentrate on minimizing GHS emissions (in line with the Kyoto Protocol at global scale and the "Plan Climat" in France). They all compare biofuels with petroleum-based automotive fuels (gasoline and diesel) to evaluate the potential of biofuels for reducing GHG emissions in the transport sector. Let us recall that the transport sector currently generates about 14% of GHG emissions worldwide (about 5.9 billion $C0_2$ eq–tons/year) with a growth rate of about 2% a year that is particularly hard to curb.

Controversy over the non-renewable energy (NRE) and greenhouse gas balance results of biofuel pathways

Assessments may differ but the conclusion remains the same

Controversy over GHG and NRE balance results is fueled by the fact that dozens have been published and they usually come up with different findings. The scope of study is always the same: they aim to make a complete consumption and emissions inventory for a given biofuel pathway taking into account each step of its life cycle. For automotive fuels, this is called a "well to wheel" assessment. Sometimes, the differences between these studies are very substantial and can change pathways rankings for environmental performance. This being said, the results of these studies, seen from the qualitative standpoint, all seem to indicate that the use of biofuels enables a significant reduction in terms of GHG emissions and NRE consumption compared to conventional petroleum-based automotive fuels. In other words, biofuels induce definite benefits with respect to these two criteria, but it is still difficult to quantify these benefits with precision.

Why assessments of biofuel pathways differ

There are several reasons why findings vary, among them differences in methodology and the uncertainties associated with specific types of data.

As far as methodology is concerned, two elements have a major influence on results. The first is the scope of the study: scoping involves identifying the particular steps whose emissions and energy consumption will be inventoried. All of these studies tend to work from the same assumptions and explain them in the same way, so this is not what gives rise to differences in findings. On the other hand, the choice of method used to account for co-processing in a pathway is often responsible for differences. When biofuels are produced, several very different coproducts are generated in large quantities (two tons of coproduct per ton of biofuel, on average). For instance, the production of biodiesel from rapeseed oil using VOME (Vegetable Oil Methyl Esters) technology also yields straw, rapeseed press cake (animal feed) and glycerin. Although a few studies ignore coproducts and allocate all emissions and energy consumption to the biofuel, most of them take coproducts into consideration. This means deciding how to break down emissions and consumption between the various products. One way is to allocate impacts (in this case, GHG emissions and NRE consumption) to different products on a prorata basis depending on their mass, energy content or economic value. The "avoided impacts" method is also used. It involves assigning all impacts to the biofuel and subtracting from this value a "credit" corresponding to the impacts that would have been generated in producing the same quantity of coproduct with the conventional production route. For instance, let's take the glycerin coproduced during VOME synthesis. If we assume that this product replaces the glycerin produced by the chemicals industry, then the balance of the latter is used to calculate the credit to be allocated to the biodiesel. Today, the allocation of impacts is a burning issue in Europe and the United States. Although the method of prorata impact allocation based on mass seems to be the easiest to implement, a consensus seems to be emerging in favor of the "avoided impacts" method, which seems to represent the reality of the pathways more accurately, taking into account the nature of coproduct valorization.

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Furthermore, the value computed for GHG emissions and NRE consumption savings gains also depends on the data used, especially that concerning nitrogen protoxide emissions (N_2O) at the biomass culture step. Their influence is especially great because this gas is nearly 300 times more harmful in terms of the "greenhouse effect" impact than CO_2. Since these emissions depend on the amounts of fertilizer used, weather conditions, soil quality and so forth, it is difficult to make a precise evaluation.

Methodology

Life cycle analysis (LCA) is used to make well-to-wheel analysis for automotive fuel pathways. This is the only environmental assessment method covered by international standards (ISO 14040 to 43). All of the basic interrelated steps involved in the production of a product are analyzed, i.e. each stage in the life of the product, from obtaining raw materials to end-of-life (recycling, incineration or landfilling). This global approach is imperative to avoid transferring pollution from one stage to another: if one stage is analyzed and optimized separately from the others, impacts could be shifted to another stage, whose impacts would thus increase.

The first step of LCA is goal definition, i.e. selecting the categories of impacts to be examined. Generally, a biofuel study will focus on the impacts on the greenhouse effect and the depletion of natural non-renewable resources (e.g. fossil fuels).

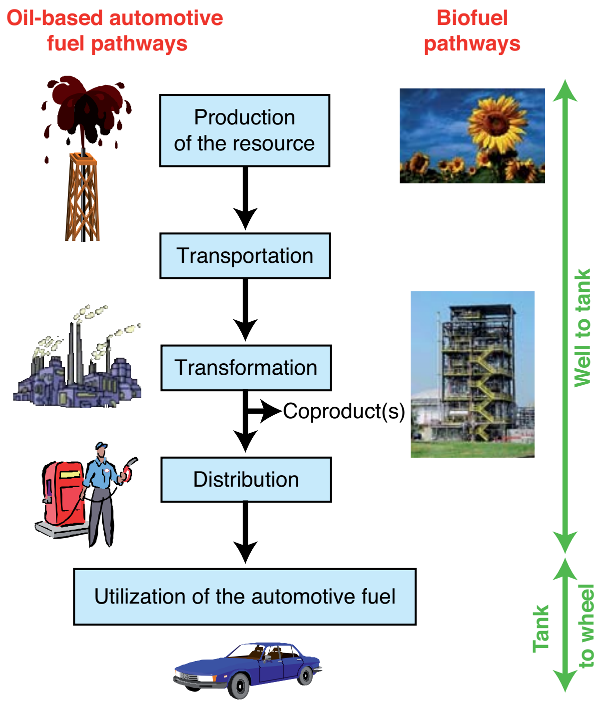
The next step consists of scoping the study. First, system boundaries are established by listing the life cycle steps that will be included or not. For an automotive fuel, a well-to-wheel life cycle analysis has two parts: the well/field-to-tank part and the tank-to-wheel part. The following stages are included:

- **Production of the resource:** For petroleum-based automotive fuels, this refers to extraction/production. For biofuels, it means biomass cultivation, harvest and collection.
- **Transportation:** During this stage, the resource is shipped from the place of production to the place where it will be transformed into automotive fuel products. Many modes of transportation are used: road, rail, waterway, maritime, pipeline or combined transport systems.
- **Transformation:** Conversion of the resource to an automotive fuel: crude refined into conventional products or vegetable materials into liquid products for biofuels. In the latter instance, the transformation requires special processes and generates large quantities of coproducts.
- **Distribution:** The motor fuel products are shipped to service stations for distribution at the pump.
- **Use of the automotive fuel:** The fuel is burned in the engine of the vehicle.

The stages involved in the supply of raw materials (especially fertilizer production), the supply of energy (e.g. electricity production and transmission, natural gas production and transportation) and waste processing are also included as activities necessary to the production of automotive fuel.

Scoping also involves defining geographical and time factors, which determine the choice of data concerning production modes and technologies. This parameter has a major impact on environmental performance. Let's take GHG emissions, for instance. The consumption of one kWh of electricity in France is not at all equivalent to consuming one kWh of electricity in Europe at a given time (2010). In France, electricity of nuclear origin covers more than 75% of consumption and this pathway generates extremely low GHG emissions. The bulk of average European consumption is covered by thermal power plants, the GHG balance is therefore much higher: something like 450 g CO_2eq/kWh versus 100 g CO_2eq/kWh in France. As we can see, the findings of any environmental analysis are representative of a particular context. This point partly explains the differences between biofuel pathway assessments: they use different basic data. By way of an illustration, the technical route taken by ethanol from corn in the United States is different than for ethanol from sugar cane in Brazil or ethanol from sugar beet in Europe. For ethanol,

Fig. 1 Life cycle of an automotive fuel



environmental performance results vary greatly by region. Moreover, today's practices will no longer be in use tomorrow. In the case of the European ethanol production pathways, the GHG balance could be substantially improved by using renewable combustibles (e.g. straw or wood) instead of fossil fuels for the distillation of alcohol.

Using the LCA methodology, inputs (consumption of raw materials, energy, etc.) and outputs (products; discharges to air, water and soil; waste) are compiled and quantified for step of the life cycle. The possible environmental impacts of these inputs and outputs are calculated for the impact categories selected. To establish the GHG emissions balance, three different gases are taken into account: carbon dioxide (CO_2) of fossil origin[1], methane (CH_4) and nitrogen protoxide (N_2O). The total balance is expressed in grams of CO_2 equivalent (gCO_2eq) using conversion factors[2] that translate the effect of each of these GHGs compared to CO_2.

The results are then expressed in terms of the functional unit, the basis used to compare all equivalent systems. When comparing automotive fuels, all results are expressed "per kilometer driven by the same vehicle", based on the standardized European drive cycle or NEDC[3]. Then the results are expressed in gCO_2eq/km (GHG emissions) and in MJ/km (NRE consumption).

Well-to-wheel balance results

Tables 1 and 2 shows the results of two reference studies that are often cited and compared:

- A 2002 study by PricewaterhouseCoopers on behalf of France's agency for the environment and energy management (ADEME) and the department of energy and mineral resources (DIREM).
- A European study carried out in 2004 (updated May 2006) by the Joint Research Council of the European Commission, CONCAWE (a European association set by oil companies to study environmental issues) and EUCAR (which coordinates R&D for the European automotive industry trade association).

These two studies present findings that diverge significantly. Their differences are due to the choice of different allocation methods. The former study uses the prorata method based on mass, the latter uses the avoided impacts method.

These results call for several comments. First of all, generally speaking, biofuels do lead to a significant reduction in GHG emissions compared to petroleum-based automotive fuels, ranging from 30 to 94% when used pure. As far as GHG emissions are concerned, the biggest benefits are obtained during the transformation of lignocellulosic materials via second-generation technologies. When wood or straw is the raw material, part is often used to supply utilities (heat, electricity) for the process, which gives rise to substantial emissions savings. This explains why, for ethanol production pathways, the best results are obtained using sugar cane; the bagasse (fibrous residue left over from sugar cane processing) is used to generate the heat needed for the distillation stage. In addition, the method used for the JRC/EUCAR/CONCAWE study is less favorable, because the benefits computed for a given pathway are generally lower.

The energy balance results presented in Table 2 indicate several things. First, the production of a biofuel consumes non-negligible amounts of fossil energy, so that the final benefits compared to the "petroleum-based automotive fuels" solution will never be 100%. Depending on the assumptions that are made and the pathways considered, these gains can range from 22% to more than 90%. The breadth of this range shows that the subject of energy consumption reduction yielded by the use of biofuels must be approached with caution. One notes once again that the gains obtained for the JRC/EUCAR/CONCAWE study are generally lower. Like for GHG emissions, the biggest NRE consumption reduction is yielded by second-generation pathways using lignocellulosic materials and sugar cane for ethanol production.

Overall, the two studies converge on VOMEs and diverge on ethanol. Both show that the biodiesel pathway is more favorable in terms of fossil energy consumption and GHG emissions than the ethanol from wheat or from sugar beet technologies. On the other hand, while the ADEME/DIREM study indicates that the use of ethanol yields reduction of about 60% for GHG emissions and NRE consumption alike, the JRC/EUCAR/CONCAWE study arrives at a much less favorable result: reductions of about 30% for GHG emissions and only 20% for fossil energy consumption.

The ADEME/DIREM study is alone in evaluating pathways used to produce pure vegetable oils. It cites benefits of about 80% compared to conventional diesel for both of the usual indicators. These reductions are about 10% higher than those obtained for biodiesel. But when the avoided impact method is implemented instead of the mass-based prorata method,

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(1) The CO_2 given off by the combustion of biomass is not included in GHG balance assessments. It is considered that this CO_2 was captured previously by biomass during the plant growth stage: the balance is therefore nil. For biofuels that are used pure, it holds therefore that there are no fossil CO_2 emissions (the GHG balance is zero for the utilization stage).

(2) These conversion factors are known as the Global Warming Potential (GWP). This coefficient is equal to 1 for CO_2, 23 for CH_4 and 296 for N_2O.

(3) New European Drive Cycle: A cycle representative of average driving conditions in Europe (driving speeds, average distances traveled and start-up phases, for both city and highway driving).

Table 1
GHG balance results for biofuels compared to the reference petroleum-based automotive fuel

	GHG emissions					
	Results of the ADEME/DIREM study (December 2002)			Results of the JRC/EUCAR/CONCAWE study (May 2006)		
	gCO_2éq/MJ	Reference gCO_2éq/MJ	**Gains versus reference oil-based automotive fuel**	gCO_2éq/km	Reference (gCO_2éq/km)	**Gains versus reference oil-based automotive fuel**
Ethanol, from wheat	34.4	85.9	**60%**	114	164	**30%**
Ethanol, from sugar beet	33.6	85.9	**61%**	111	164	**32%**
Ethanol, from lignocellulosic material	not given	–	**–**	36	164	**78%**
Ethanol, from sugar cane	not given	–	**–**	19	164	**88%**
Biodiesel, rapeseed	23.7	79.3	**70%**	73	156	**53%**
Biodiesel, sunflower	20.1	79.3	**75%**	34	156	**78%**
Pure rapeseed vegetable oil	17.8	79.3	**78%**	not given	–	**–**
Pure sunflower vegetable oil	13.2	79.3	**83%**	not given	–	**–**
BTL (from forest and farm waste)	not given	–	**–**	10	156	**94%**

Table 2
NRE balance results for biofuels compared to the reference petroleum-based automotive fuel

	Consumption of non-renewable energy (NRE)					
	Results of the ADEME/DIREM study (December 2002)			Results of the JRC/EUCAR/CONCAWE study (May 2006)		
	MJ_{ex}/MJ	Reference MJ_{ex}/MJ	**Gains versus reference oil-based automotive fuel**	MJ_{ex}/km	Reference (MJ_{ex}/km)	**Gains versus reference oil-based automotive fuel**
Ethanol, from wheat	0.489	1.15	**57%**	1.68	2.16	**22%**
Ethanol, from sugar beet	0.488	1.15	**58%**	1.65	2.16	**24%**
Ethanol, from lignocellulosic material	not given	–	**–**	0.51	2.16	**76%**
Ethanol, from sugar cane	not given	–	**–**	0.2	2.16	**91%**
Biodiesel, rapeseed	0.334	1.09	**69%**	0.73	2.05	**64%**
Biodiesel, sunflower	0.316	1.09	**71%**	0.54	2.05	**74%**
Pure rapeseed vegetable oil	0.214	1.09	**80%**	not given	–	**–**
Pure sunflower vegetable oil	0.183	1.09	**83%**	not given	–	**–**
BTL (from forest and farm waste)	not given	–	**–**	0.12	2.05	**94%**

one obtains slightly better values for biodiesel assuming equivalent basic data (consumption and emissions at each stage are identical to those in the ADEME/DIREM study). This reverses the rankings for both indicators in favor of the biodiesel, due to the fact that the credit allocated to the biodiesel to account for the coproduction of glycerin (replacing glycerin manufactured in the chemical industry) more than compensates for the GHG emissions and NRE consumption associated with additional stages (semi-refining and esterification) that consume little energy.

Although large GHG emissions and NRE consumption reductions are obtained by using neat biofuels, as mentioned previously, the latter are generally incorporated into automotive fuels at fairly low contents (5 to 10% or 20-25% at most in Brazil). In Europe, existing regulations limit the maximum bio-content to 5% (volume) for automotive fuels to be used in current gasoline engines. This measure goes counter to the 2010 biofuel incorporation target of 5.75% (energy) announced for Europe. On the other hand, larger ETBE contents of up to 15% are authorized and planned. But when computing the reductions obtained by one automotive fuel containing 5% ethanol (E5 in France) and by another containing 10% ETBE (ETBE10), one gets the same result, with an overall benefit of about 2% (cf. Table 3).

E85 (85% volume of ethanol in gasoline) yields much larger benefits: between 18 and 45% for NRE consumption and between 24 and 48% for GHG emissions, depending on the data source (balance results for ethanol and gasoline pathways taken from the ADEME/DIREM study, or from the JRC/EUCAR/CONCAWE study). The fact remains that ethanol blends penetrate the market a lot faster than E85 automotive fuel because they are compatible with existing infrastructure, whereas the implementation of E85 means that distributors need new pumps and consumers need to buy flex-fuel vehicles (FFVs) that cost slightly more than the equivalent conventional models (about €200-300 more per vehicle). It would take about 600,000 FFVs running solely on E85 to replace 5% of French gasoline consumption with E85. This would represent a reduction of something like 2% in terms of GHG emissions, equivalent to those obtained by bringing the E5 or ETBE10 automotive fuels in general use. Furthermore, this reduction would only be effective if users were systematically to choose ethanol over gasoline. This is not going to happen. First, drivers may not be able to find the right pumps when they need to fill up their tank. Second, E85 is at a competitive disadvantage compared to gasoline: it has a lower energy content, which obliges the motorist to consume about 30-40% more fuel. In Brazil, FFV owners choose between low-ethanol and E100 automotive fuels based on the price at the pump. The deployment of E85 could achieve a comparable reduction (2%) in terms of GHG emissions, but this would be more difficult and take longer (new infrastructure, conversion of the automobile fleet, etc.) than blending ethanol with gasoline to obtain an automotive fuel for standard distribution (E5 or ETBE10 automotive fuels). In France, given the length of time needed to deploy E85 and get consumers to acquire FFVs, this solution will not have much impact before 2008, the target date by which France had hoped to achieve a 5.75% biofuel content in motor fuels. This pathway will not be in a position to play a significant role before 2010.

Table 3

GHG and NRE balance results for biofuels used in blends compared to the reference petroleum-based automotive fuel

		2005 70% sugar beet and 30% wheat*		**2010** 30% sugar beet and 70% wheat**	
		Gain compared to the 2005 reference gasoline		**Gain compared to the 2010 reference gasoline**	
		For NRE consumption	For GHG emissions	For NRE consumption	For GHG emissions
E5	ADEME	**1.9%**	**2.0%**	**1.9%**	**2.0%**
	EUCAR	**1.2%**	**1.4%**	**0.8%**	**1.0%**
E85	ADEME	**45%**	**48%**	**45%**	**48%**
	EUCAR	**28%**	**34%**	**18%**	**24%**
ETBE 10	ADEME	**1.3%**	**1.6%**	**1.3%**	**1.6%**
	EUCAR	**1.7%**	**2.9%**	**0.5%**	**1.8%**

* **Ethanol mix representative of French output in 2005.**

** **Ethanol mix representative of French output in 2010.**

Relying as it does on individual consumer behavior, this alternative also presents more risks than blending ethanol with gasoline for standard distribution. At the time of writing, the business environment is less ethanol-friendly than in the first half of 2006. The price per barrel of crude has hit its lowest level in over a year (about USD55/bbl) and world cereals prices have risen sharply since September 2006. Used widely in the United States (corn) and increasingly in Europe (wheat), this raw material represents the biggest cost component in the production of ethanol. Any attempt to draw conclusions from these trends, which can be isolated occurrences and vary greatly even over short periods, must be approached with caution.

Finally, the systems used to distribute low-ethanol gasoline blends and virtually neat ethanol, respectively, are not necessarily in direct competition. In countries that have pushed biofuel development (Brazil, United States, Sweden), these systems co-exist and are perceived as complementary.

Balance results for tailpipe emissions

For the other pollutants considered to impact the environment (air quality) and health, the balance is only computed for the fuel utilization stage (combustion in the engine), because the amounts emitted at exhaust are much higher than the estimated total for all steps of automotive fuel production. These polluting emissions are regulated by European standards containing upper limits that are regularly lowered. Values are set for a given type of vehicle (defined by weight) and a specified automotive fuel (diesel or gasoline). Effective since January 2005, the Euro 4 standard limits the following for passenger cars:

- **For cars running on gasoline:** carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxide (NOx) emissions;
- **For diesel cars:** CO+HC and NOx emissions as well as particulates.

Table 4 shows the emissions reductions obtained using a biofuel compared to the equivalent petroleum-based automotive fuel. These values were calculated on the basis of tailpipe emissions measurements made at IFP for a Euro 4 vehicle running alternatively on a biofuel and the reference fuel (gasoline or diesel).

Table 4

Balance results for regulated polluting tailpipe emissions given off by biofuels compared to the reference petroleum-based automotive fuel

	Gains for regulated polluting tailpipe emissions compared to the reference petroleum-based automotive fuel (measured on Euro 4 vehicles)			
	For HC	**For NOx**	**For particulates**	**For CO**
E85	**not given**	**61%**	**–**	**50%**
EMC50	**11%**		**53%**	**7.3%**
BtL	**78%**	**– 7%**	**39%**	**95%**

Source: IFP.

Almost all of these benefits are positive, indicating that the use of biofuels induces a reduction in local polluting emissions.

Tailpipe emissions for E85 were measured on a flex-fuel vehicle belonging to a fleet deployed by a French local authority (Conseil Général de la Marne) as part of a one-year experiment, with ADEME and IFP supplying the scientific expertise. These tests showed that the use of E85 yields a substantial decrease in CO and NOx emissions as well as certain unregulated pollutants such as benzene and 1.3-butadiene (molecules classified as toxic by the U.S. Environmental Protection Agency). The only increase noted was for the emissions of acetaldehyde. This unregulated pollutant, which results from partial oxidation of ethanol, is also classified as toxic by the EPA. Optimizing the post-treatment system and the strategies for its implementation could substantially limit this increase. The values found for regulated emissions are lower than the Euro 4 ceilings. In fact, they are even lower than the ceilings expected to figure in the Euro 5 standard, which should be issued in the near future and take effect in 2008.

The results obtained for EMC50 (a fifty-fifty VOME-diesel blend) indicate a reductions in particulate emissions compared to diesel. The "HC+NOx" emissions value exceeds the Euro 4 threshold, but is still lower than the reference diesel fuel. Since this type of automotive fuel is not a high priority for development, no attempts at optimization have been made. In other words, it should be possible to bring this type of vehicle into Euro 4 compliance by working on this type of blend for that specific purpose.

The BTL syndiesel enables significant reductions in polluting emissions. This is especially true for CO and HC emissions (respective reductions of 95% and 78% compared to the reference diesel). The NOx emissions show a slight increase (negative gain) but all of the emissions are well under the upper limits set by the Euro 4 standard. General use of this automotive fuel in diesel vehicles equipped with particulate filters (the vehicles used for measurements were not so equipped) would induce a reduction in these emissions even greater than those already mentioned (gains of 39% and 53%). In addition, the development of this technology would augment flexibility. Today, it is necessary to seek a trade-off between particulates and NOx emissions, which are linked. A considerable reduction in particulates would lead to greater flexibility with respect to NOx emissions.

Conclusion and outlook

It has been amply demonstrated that the use of biofuels to replace conventional automotive fuels can lead to reductions in terms of GHG emissions and NRE consumption. This is one of the prime arguments in favor of large-scale implementation: when used pure, they can induce GHG emissions gains that can exceed 90% for the most efficient pathways (ethanol from sugar cane or second-generation biodiesel). The NRE consumption gains are on the same order of magnitude.

Under present circumstances, biofuels are most often used in blends at relatively low contents, therefore the total benefit with regard to the greenhouse effect can seem small. Given a conventional automotive fuel with a 5-10% biofuel content, the emissions benefit is lower than 5%. This may seem low at first glance. However, it must be stressed that these are obtainable gains in a sector where growth is very difficult to control and few solutions offering the same benefit are available in the relatively short term. Biofuels may not be THE solution to the problem of GHG emissions in the transport sector, but it is one component of the solution that, taken in combination with others (changes in motor technologies, behaviors, etc.), can help make a good start.

In conclusion, the LCA method used for well-to-wheel assessments can be applied to other impacts studied much more infrequently (e.g. acidification, eutrophication, the depletion of natural resources or the thinning of atmospheric ozone). Certain studies now underway are attempting to broaden the assessment of biofuel pathways in particular and that of alternative transport pathways in general to include all or some of these other impacts. A project has been undertaken by IFP in partnership with INRA, AFOCEL, the CEA, Total, Air Liquide and Renault to develop a multi-criteria analysis methodology based on LCA principles, applicable to pathways for the production of energy from biomass. This method takes technical, economic, social and environmental criteria into account[4]. Its assessment of the environmental performance of these pathways should cover not only GHG emissions and NRE consumption but also the impact that large-scale development of these pathways could have on natural resources, especially water.

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