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A prospective study of second-generation biofuels: an analysis of their economic and environmental efficiency

- Biofuels are currently the primary substitutes for fossil fuels. As the first generation of biofuels, made from food crops, have come under heavy fire in recent years, attention has turned towards second-generation biofuels, mainly biodiesel and bioethanol, which are made from various kinds of plant matter (e.g. whole plants, lignin or perennial grasses, agricultural and forestry residue). As these are not expected to become workable before 2015-2020, few studies have estimated future production costs and the environmental impacts of the production processes.

- Using technical data from 2009, this paper assesses the potential economic efficiency of three manufacturing technologies for second-generation biodiesel in the fight against the greenhouse effect. It also estimates production costs for the three technologies and as well as related costs for reducing greenhouse gases (known as abatement costs).

- The study shows that projected environmental balances for second-generation procedures are distinctly better than their predecessors in terms of impact on the greenhouse effect and other environmental impacts. However, their production costs, which have been calculated for various scenarios of raw material prices, are markedly higher that those of the first generation. Consequently, the cost per ton of CO2 saved is high. Second-generation technologies would thus require large-scale public subsidies until at least 2020.

- Nevertheless, there is a great deal of uncertainty concerning many parameters, and the possible (and potentially significant) gains from lower costs due to technological advances have not been assessed in this study. Public support for research will play a critical role in helping the EU transport sector reach its target of 10% renewable energy by 2020. Such support would encourage full development of the various alternative pathways, so that public monies are not too heavily committed to a single technology.

MINISTÈRE DE L'ÉCONOMIE
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1. Limitations in the first generation of biofuels have raised expectations as to the second

In April 2009, as part of the effort to check global warming, EU Member States adopted a Directive on the promotion of the use of energy from renewable sources (2009/28/EC). Among its various measures, the Directive stipulates that, by 2020, 10% of the energy consumed in transport must be from renewable sources.

Currently, the main substitutes for fossil fuels are first-generation biofuels, which are made from the storage organs of food plants. There are two major processes for first-generation fuels: the bioethanol process (produced primarily in France using beets and wheat) and the colza-based biodiesel process.

First-generation biofuels have been sharply criticised for three reasons. First, **support for first-generation biofuels draws heavily on State resources**. Tax relief granted to biofuels is high given its uncertain employment outcomes. Moreover, the expediency of simultaneously maintaining two delicately-interconnected economic instruments (tax relief and mandatory incorporation under TGAP[1] requirements) raises legitimate concerns. Most importantly, **the environmental balance in terms of emission reductions compared to fossil fuel equivalents during the entire life cycle of biofuels is very uncertain and the subject of disagreements, depending on the applied methodology.** According to a recent ADEME study (2010)[2], the balance is positive for all types of biofuels consumed in France. However, the results vary widely when emissions caused by land-use change are taken into account. And yet, these emissions have not been included in the balances due to the current lack of consensus on plausible scenarios[3]. Finally, the issue of food and energy crop substitution entails direct competition between the two options for land use, **with the development of biofuel production potentially jeopardizing the foodstuff market**.

Consequently, hopes have shifted toward second-generation biofuels, which are produced from the full range of plant matter (such as whole plants, whether woody or herbaceous, and agricultural and forest residue). The main expected gains from second-generation biofuels include improved environmental balances, higher yield per hectare, and resources that do not compete with food crops. These would be particularly advantageous pathways for deployment in developing countries. As the pathways are not expected to become workable before 2015-2020, few studies have provided estimates of future production costs and the environmental impacts of the various processes.

2. Second-generation technologies use complex, varied processes and should harness new biomass feedstock

There are two major production processes for second-generation biofuels.

The biochemical process for bioethanol: this process encompasses the same main stages as its predecessor: enzymatic hydrolysis of the raw materials, followed by ethanolic fermentation of the sugars thus released, and distillation to recover the bioethanol. The difference stems from the type of raw material used, which requires an adjustment of the hydrolysis and fermentation stages. Various uses for the lignin by-product are being studied (burning it as fuel is currently the most widespread option). Another possible process with greater value added would be to use the lignin as a raw material for plant chemistry (e.g. manufacture of glues, resins), thus replacing the usual raw fossil materials.

The thermochemical process for various types of fuels, depending on the selected synthesis stage. These include synthetic diesel, kerosene, dimethylether (DME), methanol and ethanol. This study focuses on the production of synthetic diesel, currently the priority research avenue. Unlike the biochemical process, there are no similarities between the first- and second-generation thermochemical processes, and the properties of the resulting diesel also differ. Its higher cetane content, absence of sulphur and low aromatic

(1) The 2005 Finance Act created a general tax on polluting activities (TGAP). Distributors are exempt from the said tax if they incorporate a given amount of biofuels. If distributors have not purchased the amount of biofuels required for tax exemption, they may buy an incorporation certificate from another distributor who has incorporated the requisite amount. Consequently, fuel distributors are ready to pay higher prices for biofuels to comply with the mandatory incorporation target and not pay any penalties. This is comes down to subsidising biofuel manufacturers.

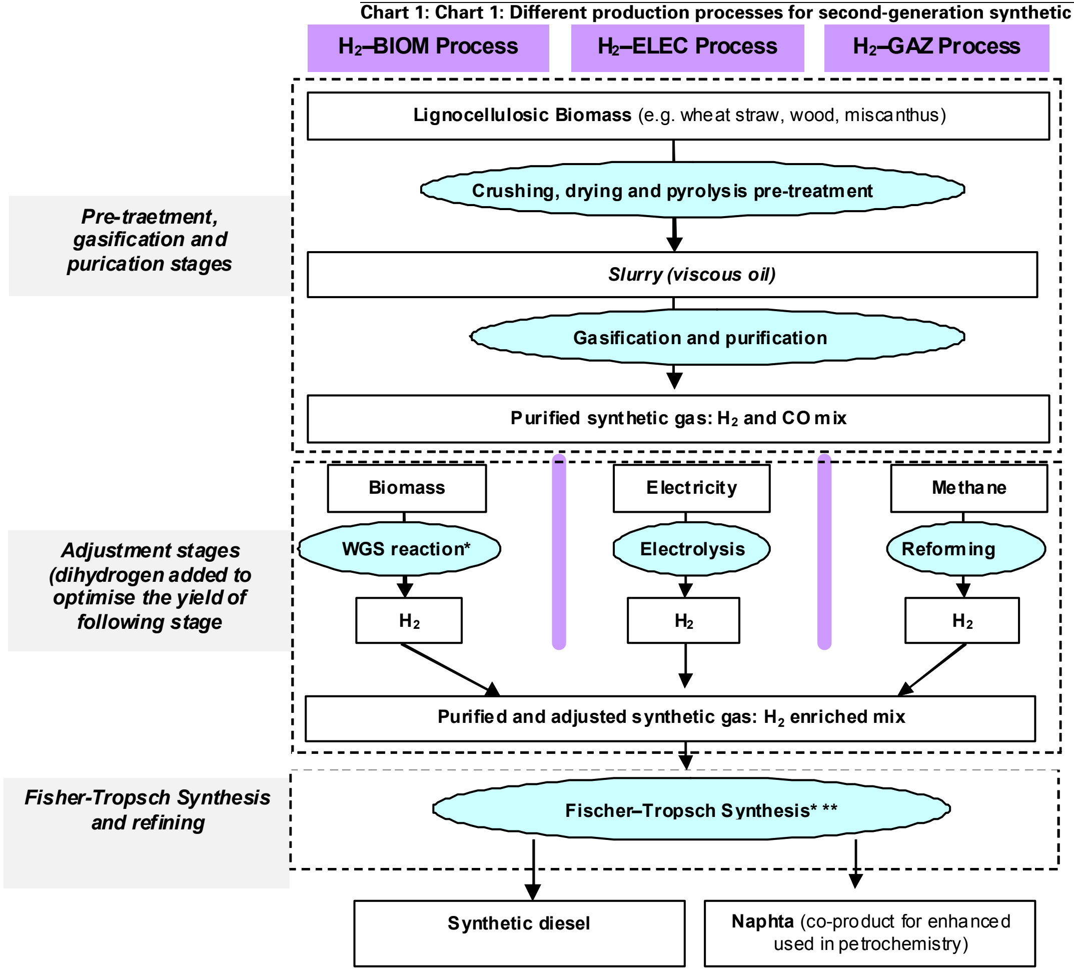
(2) ADEME (2010) Life Cycle Assessments Applied to First-generation Biofuels used in France.

(3) The balances may be negative when land with high carbon content is converted and used to grow agricultural crops for biofuels. ADEME has scheduled two studies that will take account of the impact of land-use changes on the environmental balances of biofuel pathways.

compound content mean a higher quality biodiesel (improved combustion and fewer GHG emissions) than first-generation biodiesel and fossil diesel. The thermochemical pathway has two stages: biomass gasification followed by fuel synthesis from the resulting gas. Depending on the selected synthesis method, different gaseous (dimethylether, methanol or ethanol) or liquid (diesel and kerosene) fuels may be produced.

According to the CEA (France's Alternative Energies and Atomic Energy Commission) (Dupont, 2008), **the most promising pathway is producing synthetic diesel with the Biomass to Liquids (BtL) route**, which we study in this paper. Three processes in particular, which use different energy sources to produce dihydrogen (H_2) are analysed. The first is an autothermal process we call **'H_2-BIOM'** (dihydrogen ex-biomass), the technology that is the furthest along the path to maturity. Two allothermal routes (more energy-consuming and costlier in terms of investment, but with higher mass yield) are then examined, **'H_2-ELEC'** (the additional dihydrogen comes from water electrolysis[4]) and **'H_2-GAS'** (the dihydrogen comes from methane reforming[5]). The latter technology is not being considered because it is highly pollutant. However, it has been retained for the study to serve as benchmark and because it is the cheapest technology of the three. The stages of the three processes analysed in our study can be found in chart 1.

Chart 1: Chart 1: Different production processes for second-generation synthetic diesel



(4) Electrolysis of water: $2H_2O \rightarrow 2H_2 + O_2$.

(5) Methane reforming: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$.

The type of biomass has a critical impact on process yield whichever process (biochemical or thermochemical) is used (Ballerini, 2006). For instance, several research projects are now addressing the identification of the species that are the most appropriate for each process. Today's growing demand for biomass (and the ensuing competing uses for biomass) raises the issue of how much biomass will be available for producing second-generation biofuels.

Different categories of resources may be used to produce biofuels: **industrial waste** (e.g. residue from logging, co-products from the agro-foodstuffs industry), **agricultural residue** (cereal straw) and **forestry residue** (forest and non-forest residue) and **energy crops solely for** producing biofuels requiring low inputs and providing high biomass yield (e.g. sorghum, alfalfa, miscanthus, short-rotation coppice poplar and eucalyptus). The option of using agricultural and forestry residues, industrial waste and energy crops grown on fallow land (marginal land with poor soil) as feedstock is being addressed to ease pressure on the land for food crops. The available amounts and required supply chain logistics (e.g. concentrated or disseminated resource, seasonal or year-long crops) are extremely variable depending on biomass type. On the other hand, the resources are more or less suitable for the two (biochemical and thermochemical) production pathways due to the diversified chemical composition of the feedstock.

3. Synthetic diesel production costs, where investment costs and biomass purchase expenditures are predominant, are much higher than fossil diesel production costs

Synthetic diesel production technologies are not mature and mass production is not feasible before 2020. **However, future production costs for second-generation biofuels may be assessed using simulation calculations based on technical data from pilot projects**. Comparing estimates with production costs for fossil fuels make it possible to assess biofuel competitiveness. Production costs for the three above-mentioned thermochemical processes have been estimated.

Biofuel output, investment costs and operating costs must be estimated beforehand to calculate an average updated cost for each process. Operating costs are the annual overhead expenditures that would be spent by each plant. They include raw material and operational costs. The technical data for the three 'fictitious plants' result from CEA[6] simulation calculations for the processes. As the data is based on current knowledge and considering technological advances, the data will have changed by the time the processes are marketed. The technical data supplied by CEA are summarised in Table 1.

Table 1: Projected technical data for the three relevant production processes

Process	H_2–BIOM	H_2–ELEC	H_2–GAS
Plant capacity	100 tonnes of dry biomass per hour		
Economic life cycle	20 years		
Yearly operating time	8,000 hours		
Investment cost (million €)	650	800	800
Biomass consumption: - GJ per GJ of diesel-naphta mix	1.64	1.13	1.13
Power consumption: - kWh per GJ of diesel-naphta mix	30.6	183,3	19.4
Gas consumption: - kWh per kWh of diesel-naphta mix	100	75	191.6
Diesel-naphta mix production (Gigajoule/yr)	$8.43{,}10^6$	$12.3{,}10^6$	$12.3{,}10^6$

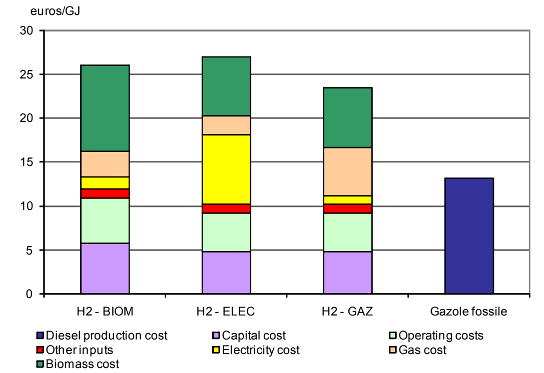
Source: (Seiler, Hohwiller et al, 2009)

(6) CEA Grenoble published the data for the 8th World Congress of Chemical Engineering (Montreal, 23-27 August 2009), Seiler J.M. & Hohwiller C., "Technical and economical evaluation of sustained carbon biomass to liquid fuel processes".

The final mix should be a hydrocarbon mix (70% synthetic diesel and 30% naphtha). Investment costs do not take account of land purchase, building and plant dismantling expenditures. On the other hand, the residual value of the investment is assumed to be nought. Calculating production costs requires making assumptions about raw material purchase prices in 2020. Two scenarios were considered. A 'central scenario' is based on €55 per oil barrel and €5.5 per GJ of biomass. A 'favourable scenario' is based on low biomass prices (€3 per GJ) and high oil prices (€85 per barrel).

Chart 2 compares the cost of one gigajoule (GJ) of fossil diesel with the cost of one GJ of synthetic diesel manufactured by each of the three processes, in the 'central scenario'.

Chart 2: Breakdown of production costs for one gigajoule of synthetic diesel for each of the processes, compared with the price of fossil diesel, in the 'central scenario'

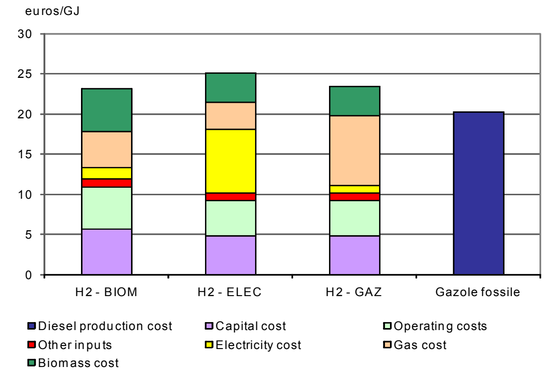


Source: DGTrésor.

Chart 2 shows that capital cost (economic depreciation) is a high budget item (roughly 20%), and virtually the same for the different production pathways. The energy source used to produce the additional hydrogen is the largest expenditure for each process. Biomass purchases account for high expenditures, regardless of the process, even if they are appreciably higher for the H_2-BIOM process. The bottom line is that **the decisive factors for synthetic diesel production costs are investment and biomass expenditures for all the processes**, the cost of electricity for the H_2-ELEC process and the cost of gas for the H_2-GAS process. Importantly, **production costs for the three relevant processes are nearly twice as high as fossil diesel costs**.

If we take a very favourable scenario for viable biofuel production (see chart 3), viz. high oils prices (€85 per barrel), we can see that the three production processes for synthetic diesel are not always profitable, but that additional costs are much lower. Nevertheless, a situation where such high oil prices coexisted with such low biomass costs is highly unlikely. A sharp rise of oil prices would probably increase the demand for biomass, which would then become a resource much in demand. Its market price could then be expected to soar.

Chart 3: Breakdown of production costs for a gigajoule of product, in the 'favourable scenario'



Source: DGTrésor.

In these conditions, **substantial public support is requisite to compensate for additional production costs if second-generation biofuels are to become a reality**. Public support would be warranted, among other things, by potential environmental benefits, viz. lower CO_2 due to the replacement of fossil fuels by biofuels. Abatement costs (i.e. the ratio of additional production costs over CO_2 emissions savings) for the different technologies must be estimated to assess the economic relevance of support to second-generation biofuels.

4. Steep abatement costs for synthetic diesel using current technologies

Life Cycle Assessment (LCA) is the most common method for assessing the environmental impacts[7] of a product (or service). The method has been standardised by the International Organisation for Standardisation. Currently, there is no LCA for second-generation biofuels based on the observation of an extant industrial production plant, as the technologies are not mature. On the other hand, several 'prospective' LCAs have been done using the data from pilot facilities. Specifically, there are two reference studies: the Well-to-Wheels study (JRC, 2007)[8] and the RENEW[9] (Renewable Fuels for Advanced Powertrains, 2006) study. The results of both studies are summarised in Table 2, thus making it possible to calculate emission reductions compared to the replaced fossil fuel.[10]

Table 2: Impact on GHG of the different biofuel production pathways (expressed in gCO_2eq^a emitted per megajoule of produced biofuel)

Source study	Biomass	Final Product	GHG Emissions (gCO2eq/MJ)
Thermochemical Pathway			
Autothermal			
RENEW (2006)	SRC willow	Synthetic diesel	29.6
JRC (2007)	SRC poplar	Synthetic diesel	6.9
JRC (2007)	Forestry residue	Synthetic diesel	4.8
Allothermal			
RENEW(2006)	SRC willow	Synthetic diesel (ELEC)	18.3
Construted data[b]	SRC willow	Synthetic diesel (GAS)	46.9
Biochimical pathway			
JRC (2007)	Poplar SRC	Bioethanol	22.0
JRC (2007)	Forestry residue	Bioethanol	19.0
JRC (2007)	Wheat straw	Bioethanol	8.7

a. Equivalent gram of CO_2 - This unit provides an equivalence in terms of GHG output, between different GHG and carbon dioxide (CO_2).

b. Neither study examines a process similar to H_2-GAS. However, the process is much like H2-ELEC, the only difference is the energy source used for synthesising the additional dihydrogen. So, GHG emissions from manufacturing, supplying and using the gas enabling the synthesis of the H_2 required for producing one GJ of synthetic diesel in the H_2-GAS process are added to the emissions released by the H_2-ELEC process.

NB: SRC = short-rotation coppice

Comparing the RENEW and JRC evaluations of the two similar processes highlights the major uncertainties about emission measurements. For instance, if synthetic diesel manufactured from the auto-thermal process using SRC (willow or poplar) replaces fossil diesel, emissions are 65% lower according to the RENEW study, and 92% lower according to the JRC study. The difference can be explained by methodological choices as well as major uncertainties about second-generation processes.

Thus, the abatement cost for one ton of CO2 savings may be obtained by calculating the ratio of additional production costs for synthetic diesel (compared to fossil diesel) found in Chart 2 over the emission savings found in Table 2. Table 3 illustrates abatement cost estimates for each of the relevant technologies.

(7) Here we only consider GHG emissions even if the approach may be simplistic. The impact on biodiversity or on water quality may actually prevail and warrant the choice of pathways where the carbon balance is not quite as good.

(8) See http://ies.jrc.ec.europa.eu/WTW.html

(9) See http://www.renew-fuel.com

(10) For emissions from fossil fuel production and use, we use the reference value found in the Renewable Energies Directive (2009/28/CE), i.e. 83.8 gCO_2eq/MJ.

Table 3: Abatement costs per technology

Processes	H_2– BIOM	H_2–ELEC	H_2– GAS
Additional production cost (€/GJ)	13 [7-24]	14 [8-25]	10 [6-20]
Emission savings (gCO_2eq/MJ)	54.2[a] / 76.9[b]	65.5	36.9
Abatement cost[c] (€/tCO_2eq)	239 [137-435] / 168 [97-307]	212 [122-380]	279 [169-537]

a. Source: RENEW, 2006.
b. Source: JRC, 2006.
c. Abatement cost = additional production cost / emission savings.
NB: lthe above calculations were done in 2010. They do not take account of the recent results of the 'HyFrance3' project on the development of hydrogen markets for the H_2-ELEC pathway. The results seem to point to higher production costs than those found in the previous table for the H_2-ELEC pathway.

Therefore, abatement cost estimates per ton of CO2 are higher than €100 per tCO2eq for all three processes. As the cost of one ton of CO2 savings has been calculated as the ratio of a difference of expenditures over a difference of emissions, it is very sensitive to the slightest variation of each of the terms, leading to extremely changeable results. Strong uncertainty weighs on numerous parameters, as can be seen in the range of the results in the table. Sensitivity tests of certain key parameters were applied to reach the said results: biomass prices, oil prices, electricity prices and the selected discount rate[11].

5. Given the lack of maturity of current second-generation technologies and European targets for 2020, support to research on these processes is critical.

Projected environmental balances for second-generation processes are clearly more favourable than those of their predecessors (save for bioethanol made from Brazilian sugarcane). In the case of energy crops, *a priori* production yield per area unit of biofuel would also be higher than first-generation yield, meaning the optimisation of energy crop areas. If the biofuel production method harnesses residual biomass feedstock (forestry, agricultural and industrial residues) or energy crops on fallow land, the impact of second-generation pathways would be much more favourable than first-generation routes in terms of competition with food crops. The type of feedstock that will be used will depend on the changing demand for alternative uses (e.g. energy, plant chemistry) now undergoing development, when second-generation technologies are fully mature.

However, **production costs for second-generation pathways are still very high, meaning very high costs per ton of CO2 savings**. Accordingly, strong uncertainties about abatement cost estimates and the fact that one technology does not clearly stand out as substantially reducing GHG emissions for the transport sector mean that **support to research is a critical prerequisite so as to promote the optimisation of all the different pathways. Importantly, inordinate amounts of public resources should not be committed to a single technology and long-term production costs must be lowered**.

The 10% renewable energies target for the transport sector by 2020 set by the European Union makes it mandatory to develop alternatives to fossil fuels, whether the technologies are or are not efficient compared to the tutelary value of carbon. Therefore, comparing biofuel production technologies of both generations with alternative technologies (electric vehicles) will be needed to determine which technologies will be available at the lowest cost by 2020, and will perhaps help us reach the target.

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(11) In the selected scenarios biomass prices range from €3 to €8 per GJ, oil prices from €30 to €85 per barrel, electricity prices from €45 to €84 per MWh and discount rates from 4 to 8%.

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