Bioenergy – I: *From Concept to Commercial Processes*
March 5-10, 2006, Tomar, Portugal

A comparative assessment of rapeseed oil and biodiesel (RME) to replace petroleum diesel use in transportation

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Acknowledgments:
Stelios Rozakis, INRA, France & Agricultural University of Athens, Gree

Structure

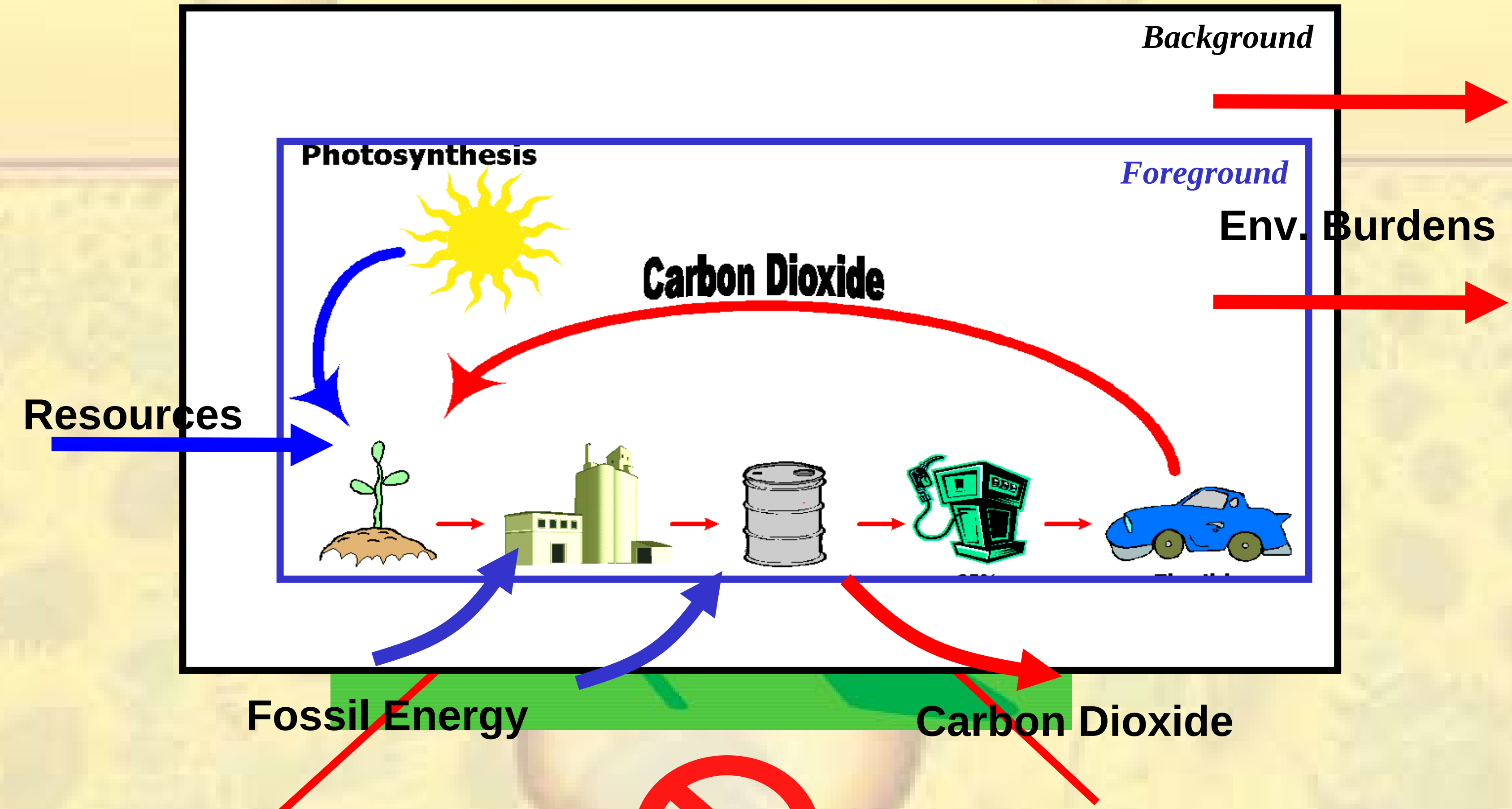
- **Motivation and background**
  - **Biofuels & Life Cycle thinking...** relevance for decision-supporting

- **Methodology**
  - Environmental Life Cycle assessment & Life Cycle Energy Analysis
  - Energy efficiency... Renewability... GHG emissions
  - Multifunctionality and Allocation

- **Case Study: Biodiesel Chain in France**
  - RO and RME life cycle modeling
  - Flowchart, energy inventory, co(by)-products allocation
  - Rapeseed oil *vs* RME (Biodiesel). Comparison with fossil diesel

- **Preliminary Results and Conclusions**
  - Energy efficiency and renewability.
  - Allocation methods: implications…
  - Avoided GHG emissions and Fossil Energy Savings

Biofuel Life Cycle



- Possible reduction of CO_2 emissions
- Possible Energy Savings (reduction of fossil fuel resources)
- Intensive use of soils, Intensive use of fertilizers and pesticides:
  - Possible Eutrofication and Acidification

Eco-certification for biofuels?

WWF asks for mandatory eco-certification for biofuels
08 February 2006:

"It is imperative that the EU establishes a legally binding certification system for both imported and domestic biofuels," said Elizabeth Guttenstein, Head of European Agriculture and Rural Development at WWF. "The certification system must be based on enhancing the ***potential of biofuels to cut GHG emissions****, while avoiding the wider environmental impacts of biofuel production.* ***This will help to protect the environment in developing countries and contribute to CO2 emissions reductions in the EU in a sustainable way****."*

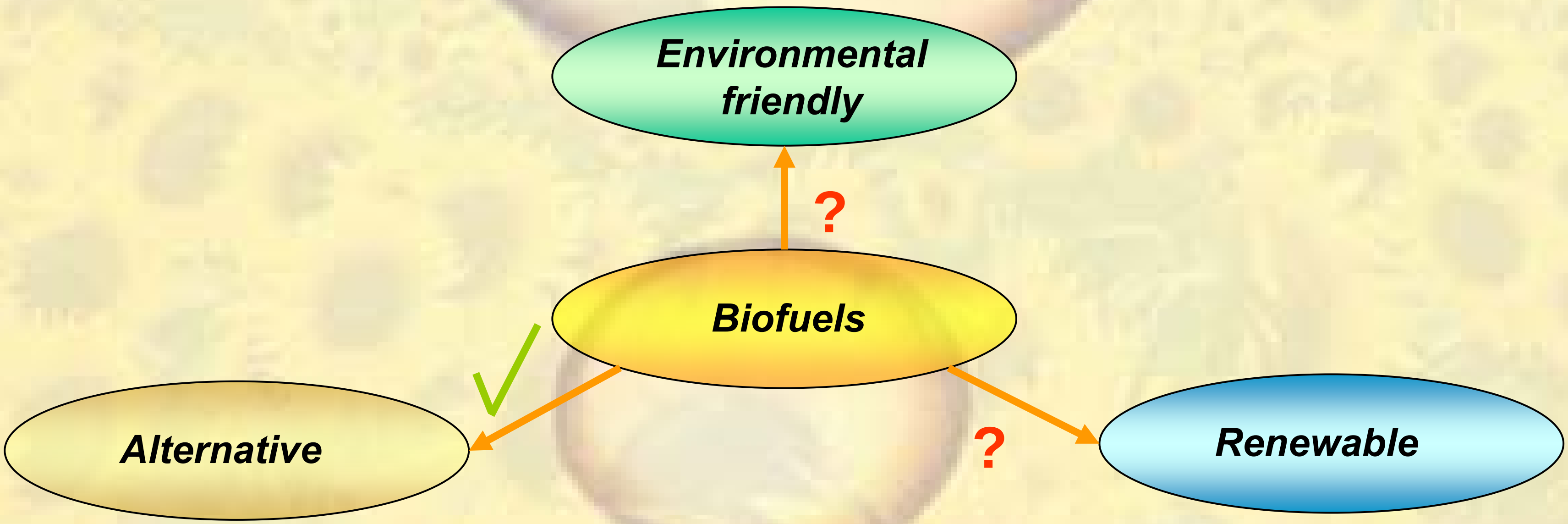
"The current practice of automatically classifying all biofuels as 'renewable' regardless of how they are produced is counter-productive," commented Dr Stephan Singer, Head of WWF's European Climate & Energy Policy Unit. "If the EU is to meet its Kyoto and renewable targets, ***it must promote those biofuels which offer the greatest greenhouse gas savings****, such as sustainably produced forest and wood products."*

Motivation

The ...

Need of Life Cycle decision-support tools assessing (integrating?!) Energy, Environmental and Economic analysis (or optimization!)

Environmental Life Cycle Assessment (LCA)



Life Cycle Energy Analysis (LCEA)

But how efficient in energy, environmental and economic terms ?

Life Cycle Methodology

***Biofuel Life Cycle Assessment*: To demonstrate that biofuel has a positive energy balance, saves GHG emissions and to quantify how much biofuel is renewable, a life cycle approach must be employed**

- It includes setting the system boundaries, designing the flow diagrams, collecting the data for each of these processes, performing allocation steps for multifunctional processes.
- Its main result is an inventory table, in which the material and energy flows are compiled and quantified

Goals

- Identify opportunities for improvement and optimization
- To have an holist view, enabling the integration of energy, environment and economic aspects through the entire life cycle
- **Comparison with fossil fuels and comparison of different biofuel schemes: Calculate fossil energy savings, GHG emissions avoided and analyze the *renewability* of biofuels.**

Energy Eficiency Indicators and Renewability

In the energy analysis literature several indicators are used (lack of consensus)

A novel Renewability indicator[1]

- Fossil E

Energy Renewability Efficiency, ***ERE***

- Net energy value: ***NEV* =** $E_{out} - E_{fóssil,in}$

$$ERE = (E_{out} - E_{fóssil,in}) / E_{out}$$

$0\% < ERE < 100\%$ → **Renewable**

$ERE < 0\%$ → **Non renewable**

ments, $E_{req} = E_{fóssil,in} / E_{out}$

(primary fossil energy input per delivered biofuel energy output)

- E_{out} – Fuel energy content (FEC) per unit of mass (LHV)
- $E_{fóssil,in}$ – Total accumulated inputs of fossil energy (in primary energy terms) needed to produce one unit of mass of biofuel

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[1] Malça J and Freire F. (2006) *Renewability and life-cycle energy efficiency of bioethanol and bio-ethyl tertiary butyl ether (bioETBE): assessing the implications of allocation*. **Energy the International Journal** (forthcoming)

Calculation of GHG emissions and abatement costs

- **GHG emissions** **(direct + indirect) for the bioethanol life cycle**

  i) **The total amount of each GHG (CO_2, CH_4, N_2O, …) is calculated by using suitable coefficients and combustion emission factors**

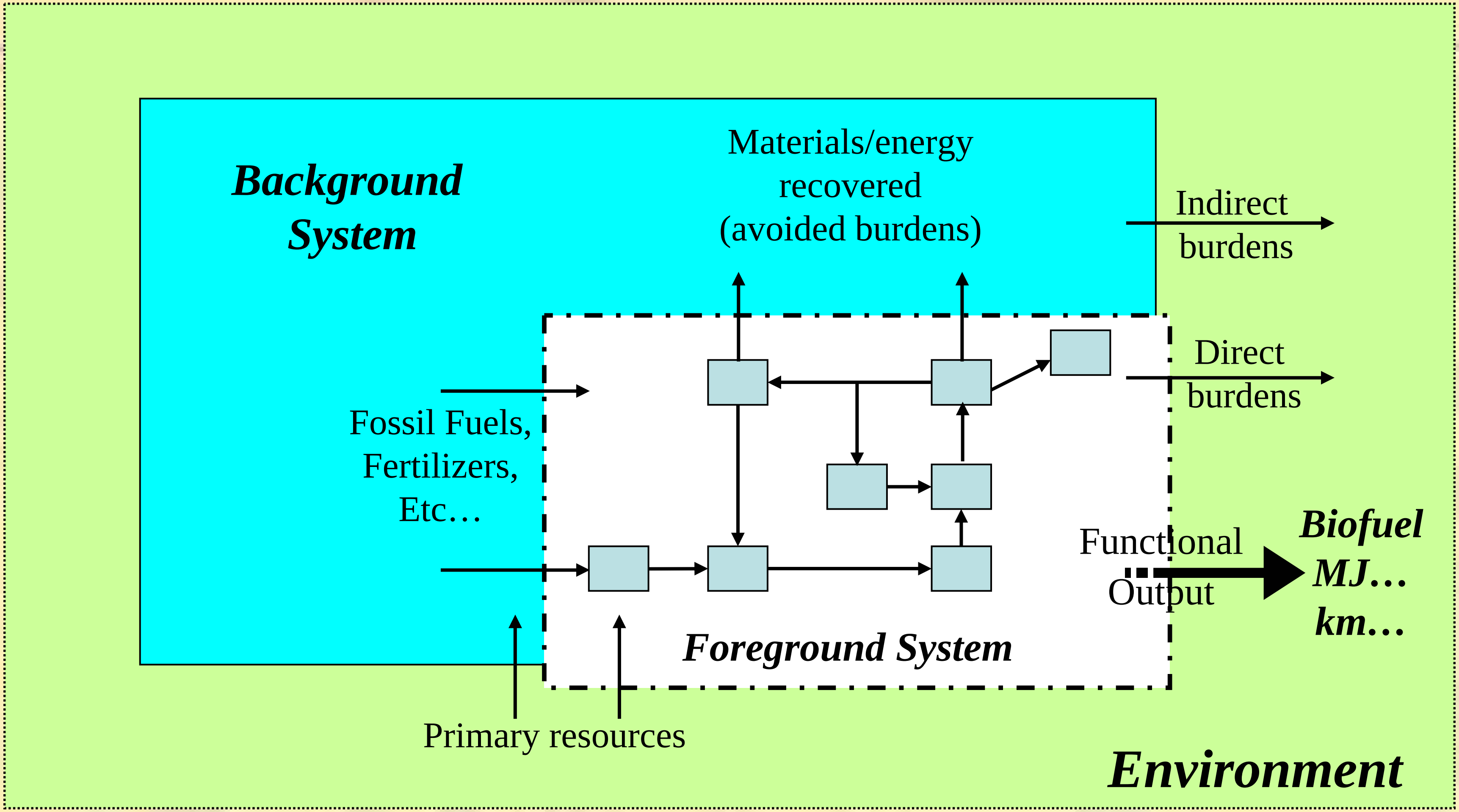
  ii) **Individual GHG emissions are aggregated in an indicator of Global Warming Potential (GWP), obtained by multiplying individual emissions by their corresponding impact factors**
  (CO2=1, CH4=23 and N2O=296; 100 year time horizon)

- **Economic aspects**

Biofuel production costs

→ **Calculation of GHG abatement costs [€/kg CO_2eq]**

Foreground and Background Systems



Multifunctionality and Allocation

Biofuel production generates several co(by)-products…

- **Multifunctionality: How should the resource consumption and emissions be distributed over the various co(by)-products?**

- **An appropriate procedure is required to partition the relevant inputs and outputs to the functional unit under study**

- **The international standards on LCA (ISO 14041) state that**

i) **allocation should be avoided where possible by sub-division or system boundary expansion**

ii) **allocation should be undertaken based on causal relationships of the co-products (output weight, energy content, economic value, replacement value)**

Rapeseed Oil (RO) and RME (biodiesel)

Life Cycle Modeling: Goal and scope

Functional unit: 1MJ of fuel energy delivered to road transport vehicles

Adequate basis for comparison of the function provided by different (bio)fuels

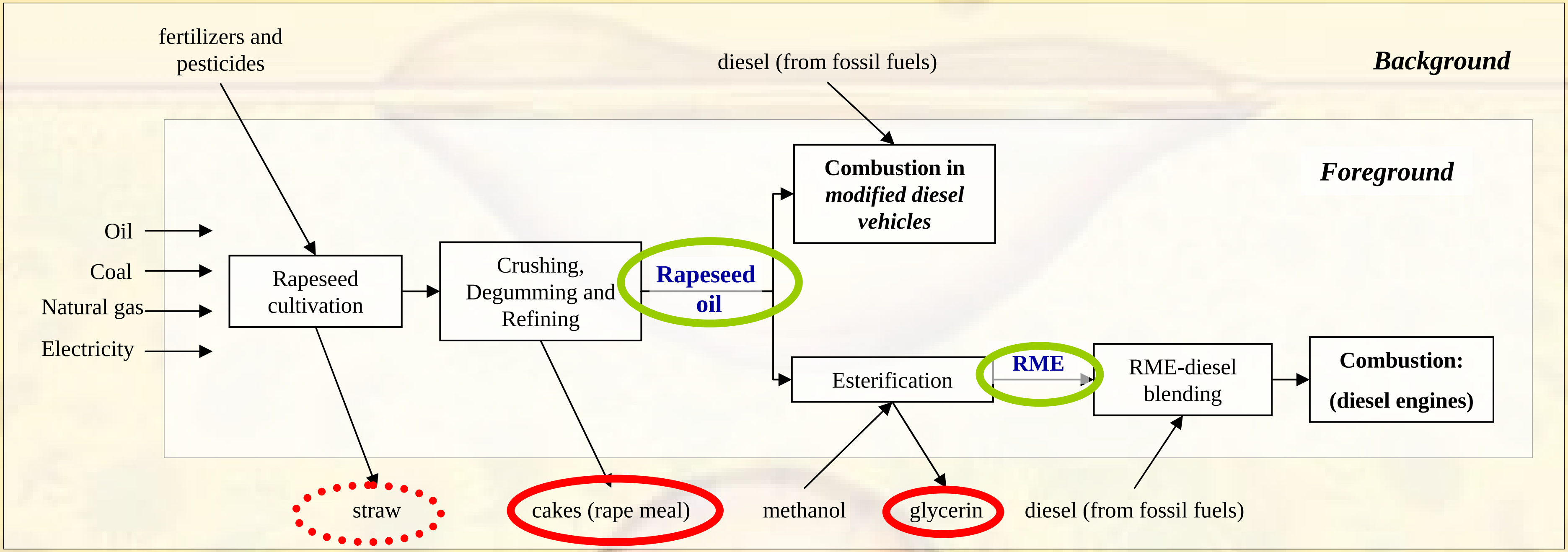
Well-to-Tank analysis

- **Primary focus of the study: Establishing energy and GHG balances for the RO and RME chains in France**

- **Comparison with petroleum diesel**

- **Calculate avoided GHG emissions and energy savings for RO and RME replacing petroleum diesel use, per unit of energy, …**

RO and RME Modeling
Life Cycle production chain



Legend

- *Main products*
- *Co-(by-)products*

RO and RME Modeling
Main Assumptions

- A reference system consisting of set-aside agricultural land was considered

- Biomass yields, fertilizer application rates, road and rail transportation models apply to the French case study

- Energy embodied in the materials used to construct biofuel plants, transportation equipment and farm machinery ("capital energy") was not considered

- GWP was calculated for CO_2, CH_4 and N_2O; other GHG are not taken into account (negligible emissions)

Main Inventory Results

Agricultural and industrial data for the annual production of **1 tonne of RME**

	Cultivation	Oil extraction	Esterification
Land [ha]	–0.787	—	—
N fertilizer [kg]	–157.5	—	—
P_2O_5 fertilizer [kg]	–47.2	—	—
K_2O fertilizer [kg]	–94.5	—	—
Straw [t]	3.47	—	—
Oilseed rape [t]	2.61	-2.61	—
Rapeseed cake [t]	—	1.59	—
→ Rapeseed oil [t]	—	1.02	-1.02
Methanol [t]	—	—	-0.1
Glycerin [t]	—	—	0.1
→ **RME [t]**	—	—	**1**

Coefs. conversao en. primária		
	Natural Gas	1,1
	Oil	1,2
	Coal	1,06
	Electricity	3,04

IPCC GWP coeffs: (100 years)		
	CO_2	1
	CH_4	23
	N_2O	296

Epelly 1993, p.42. Nas outras folhas p/ esta cadeia, ainda não tinha incluído um reference system.

	Quantity	Imput Prim Energy MJ/ha	No allocation, per hectar — Output CO_2 kg/ha	CH_4 kg/ha	N_2O kg/ha	Total GHG kg/ha
Cultivation						
N fertilizer [kg/ha]	211,5	10976,85	554,13	2,92E+00	2,50E-02	6,29E+02
P2O5 fertilizer [kg/ha]	34	663	40,80	8,09E-02	7,99E-03	4,50E+01
K2O fertilizer [kg/ha]	33,5	305,185	17,82	4,96E-02	2,18E-03	1,96E+01
Pesticides [kg/ha]	5	387,5	11,50	2,62E-02	1,92E-03	1,27E+01
Diesel fuel [l/ha]	115	4542,5	334,65	1,76E-02	4,66E-03	3,36E+02
Reference system [l/ha]	-22,8	-900,6	-66,35	-3,49E-03	-9,23E-04	-6,67E+01
Wheat Transp (road)						
Diesel fuel [l]	5,03	198,6	15,79	2,89E-03	7,44E-03	1,81E+01
Starch Plant + Distillery						
Natural gas [kg/ha]	787,5	39849,6	1952,63	4,06E+00	3,62E-03	2,05E+03
Electricity [MJ/ha]	4046,5	12301,2	133,25	2,79E-01	1,46E-03	1,40E+02
savings (DDGS credit)						
Ethanol Transp (rail)						
Diesel+Electricity [t.km]	426	198,9	2,45	4,00E-04	0,00E+00	2,46E+00
ETHANOL						
Total [/ha]		68522,9	2996,7	7,429	0,053	3183,3
Total [/ton eth]		32170,4	1406,9	3,488	0,025	1494,5
Total [/MJ eth]		**1,200**	0,052	1,30E-04	9,34E-07	0,0558
ERenE [%]		**-20,0**				
ERenE_2 [%]						
ETBE Production						
Isobutene [kg/ton ETBE]	530	113250,0	2,83E+03	1,08E+01	3,75E-04	3082,22
Natural Gas [kg/ ton ETBE]	59	**13523,9**	6,63E+02	1,38E+00	1,23E-03	694,70
Electricity [MJ/ton ETBE]	50,4	694,1	7,52E+00	1,57E-02	8,26E-05	7,90
ETBE+gasoline Transp (road)						
Diesel fuel [l/ha]	27,01	1066,8	8,48E+01	1,55E-02	4,00E-02	97,00
ETBE						
Total [/ha]		197057,6	6584,7	19,67	0,09	7065,1
Total [/ton ETBE]		43500,6	1453,6	4,34	0,0210	1559,6
Total [/MJ ETBE]		**1,205**	0,040	1,20E-04	5,81E-07	0,0432
ERenE [%]		**-20,5**				
ERenE_2 [%]						

Area [ha]	1
Yield [ton{ha]	7,62
Wheat [ton]	7,62
Ethanol [ton]	2,13
Ethanol [l]	2683
DDGS [ton]	2,873
ETBE [ton]	4,53
ETBE [l]	6081

Coefficients	Prim Energy	CO_2	CH_4	N_2O
N fertilizer [kg]	51,9	2,62	1,38E-02	1,18E-04
P2O5 fertilizer [kg]	19,5	1,2	2,38E-03	2,35E-04
K2O Fertilizer [kg]	9,11	0,532	1,48E-03	6,51E-05
Pesticides	77,5	2,3	5,23E-03	3,83E-04
Diesel fuel [l] tractor	39,5	2,91	1,53E-04	4,05E-05
Diesel fuel [l] lorry	39,5	3,14	5,75E-04	1,48E-03
Electricity [MJ]	3,04	0,03293	6,90E-05	3,62E-07
Natural gas [kg]	50,6	0,0539	1,12E-04	1,00E-07
Transport by rail [t.km]	0,467	5,75E-03	9,40E-07	0
Oil [kg]	49,8	8,11E-02	2,30E-05	6,00E-07
Isobutene [kg]	25	1,18E+00	4,51E-03	1,56E-07
Coal [kg]	30,952	2,84E+00	1,07E-02	3,65E-05
soyameal replaced by DDGS	-0,1055	-4,02E+00	-2,90E-02	-4,86E-02

Allocation Procedures

1. Allocation was undertaken based on causal relationships:
   - Output weight
   - Energy content
   - Economic value

2. Replacement value of co-products (each by-product generates energy and emission credits equals to those associated with producing a substitute for that co-product):
   - Glycerin can be used instead of synthetic glycerin or propylene glycol
   - Rapeseed cake can replace soy meal as a high-protein animal feed
   - Glycerin can be used for process heat

3. Results are also calculated without co-product credits

Sensitivity Analysis:

Allocation methods and implications for the results (energy efficiency, renewability and GHG emissions)

Data Used for Allocation

Table 1 – Rapeseed oil (RO) chain

Allocation Procedure	Mass [kg/ kg RO]	Economic (Market value) [€/tonne]	Energy (LHV) [MJ/kg]	Replacement credits of co-products	
				Energy [MJ/kg cakes]	GHG [kg CO_2eq/kg cakes]
Cakes	1.57	100	16.0	2.13	0.184
RO	**1**	158	37.2	–	–

Table 2 – RME (biodiesel) chain

Allocation Procedure		Mass [kg/kg RME]	Economic (Market value) [€/tonne]	Energy (LHV) [MJ/kg]	Replacement credits of co-products	
					Energy [MJ/kg co-product]	GHG [kg CO_2eq/kg co-product]
Cakes		1.59	100	16.0	2.13	0.184
RO		1.015	158	37.2	–	–
	(a)				68.7	4.77
Glycerine	(b)	0.1	457	16.0	13.8	0.71
	(c)				1.9	0.37
RME		**1**	158	37.5	–	–

(a) replacing a typical chemical product (propylene glycol)
(b) for process heat
(c) for animal fodder

Results (1)

Ereq [MJ/MJ]: primary fossil energy input per delivered biofuel energy output

Total GHG emissions (kg Co2 eq/MJ)

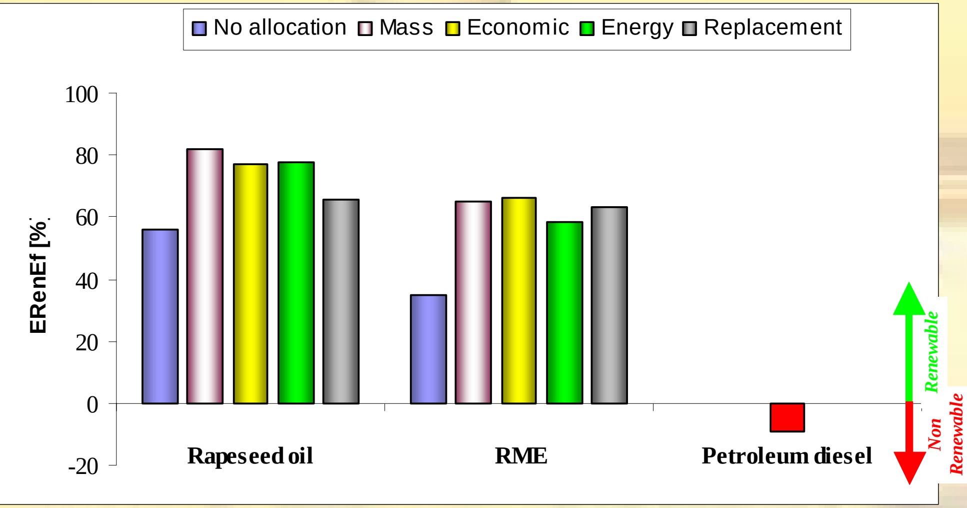
	Prim Energy MJ/MJ RME	[%]	Total GHG kg/MJ RME	[%]
Cultivation	0,3191	49,2	4,51E-02	73,5
Rapeseed Transp (road)	0,0072	1,1	6,59E-04	1,1
Grain's drying	0,0117	1,8	1,33E-04	0,2
Oil extraction	0,0903	13,9	3,23E-03	5,3
Degumming/Refining	0,0114	1,8	5,29E-04	0,9
Esterification	0,2048	31,6	1,14E-02	18,6
RME distribution	0,0040	0,6	2,68E-04	0,4
Total	**0,648**	**100,0**	**0,061**	**100,0**

NB: No allocation (no credits for co(by-)products !)

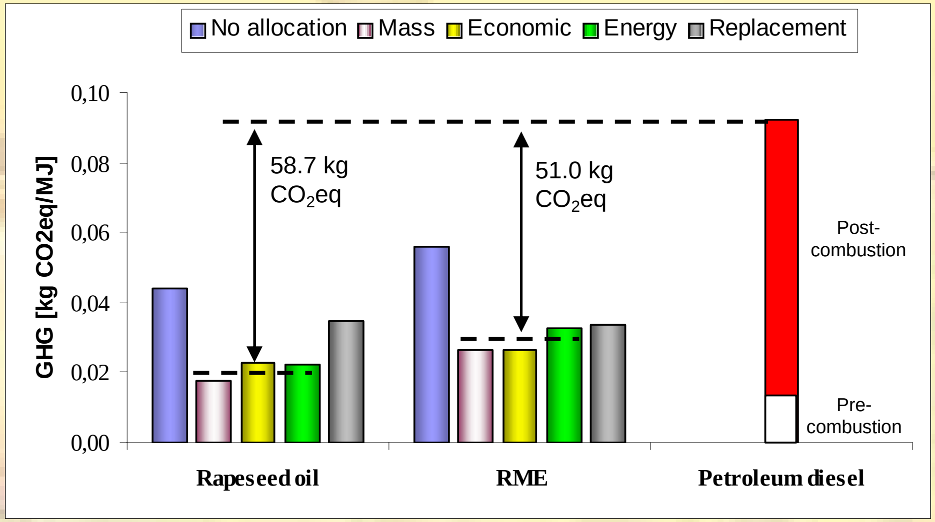
Results (2)

	Prim Energy MJ/MJ RME				Total GHG kg/MJ RME			
	Mass	Market value	Energy	Replacement	Mass	Market value	Energy	Replacement
Cultivation	0,1131	0,1247	0,1522	0,3191	1,60E-02	1,76E-02	2,15E-02	4,51E-02
Rapeseed Transp (road)	0,0026	0,0028	0,0035	0,0072	2,34E-04	2,58E-04	3,14E-04	6,59E-04
Grain's drying	0,0041	0,0046	0,0056	0,0117	4,72E-05	5,21E-05	6,35E-05	1,33E-04
Oil extraction	0,0320	0,0353	0,0431	-0,0067	1,14E-03	1,26E-03	1,54E-03	-6,14E-03
Degumming/Refining	0,0103	0,0088	0,0109	0,0114	4,81E-04	4,10E-04	5,07E-04	5,29E-04
Esterification	0,1862	0,1588	0,1964	0,0216	1,04E-02	8,84E-03	1,09E-02	-1,30E-03
RME distribution	0,0040	0,0040	0,0040	0,0040	2,68E-04	2,68E-04	2,68E-04	2,68E-04
Total	**0,352**	**0,339**	**0,416**	**0,368**	**0,029**	**0,029**	**0,035**	**0,039**

Results (3)



Comparative ERenEf values



Comparative GHG emissions

- Both RO and RME are clearly renewable, even before adding co-product energy credits.
- A maximum ERE value of about 80% (mass allocation) was obtained for RO, meaning that than about 80% of the fuel energy content is indeed renewable energy
- In contrast (and as expected!), petroleum diesel exhibits a negative ERenEf value
- Significant avoided GHG emissions per MJ of delivered energy can be obtained
- RO is more energy and GHG efficient than RME

•co-product credits cannot be ignored → Allocation has influence in the results

GHG and energy savings[1] per ton, GJ and hectare, for RO versus RME replacing petroleum diesel

	Primary energy savings [GJ]			Avoided GHG emissions [ton CO_2eq]		
	per ton	*per GJ*	*per ha*	*per ton*	*per GJ*	*per ha*
RO	32.74	0.88	42.25	2.18	58.7	2.81
RME	27.09	0.72	34.40	1.92	51.2	2.44

[1] averaged values (mass, energy and economic allocation)

Main Conclusions

• Biodiesel (RME) and/or RO production is energy efficient, exhibiting a high degree of renewability, thus, reducing fossil fuel depletion

• Significant net savings in GHG emissions are achieved by replacing petroleum diesel with RO or RME

• Allocation plays a major role, emphasizing the importance of optimum use of co-products

• These conclusions support EU *Directive 2003/96/EC*, on energy taxation and *Directive 2003/30/EC*, on the promotion of the use of biofuels

Some of our work on biofuels...

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