Climate design of
Pure Vegetable Oil Fuels

Mathematical model for the calculation and optimization of
green house gas emission savings through the use of
pure vegetable oil as fuel notably in agricultural equipment
in line with the Fuel Quality Directive 2009/30/EC

Short Version – English

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Executive summary

The use of bio-fuels in agricultural equipment is an option for meeting climate protection requirements which are presently placed on manufacturers of mobile off-road machinery by the European Commission. Pure vegetable oil is an interesting candidate among bio-fuels because the production can be done on the farm itself from the field into the tank. Rape seed oil however, which is predominantly used in Central Europe and which allows for green house gas emissions (GHGE) savings of 57% compared to diesel fuel, just falls short of the minimum GHGE saving of 60% that will be compulsory from 2018 on. A solution are optimized cultivation and production methods for rape seed oil, but notably false flax (Camelina sativa) oil that is produced in mixed cultivation and from which phosphorous, alkali metals and alkaline earth metals have been completely removed. The proof of suitability of such cleaned false flax oil as fuel for advanced internal combustion engines is one of the outstanding results of the 2ndVegOil project.

In this work, a mathematical model is formulated that translates the provisions of the EU Fuel Quality Directive (FQR)[1] into calculation rules for complex production processes. The provisions which are relevant for this work can be found identically in the Renewable Energies Directive (RED)[2]. The developed model is equivalent to the public version 4 of the BioGrace GHG Tool[3]. In contrast to the latter, it is designed to assess process chains with an arbitrary number of steps and by-products at each step in a clear notation. This allows calculating GHGE of the production of pure vegetable oils in mixed cultivation, and notably the influence of small changes of the input parameters on the results, in a stringent and transparent manner. At the same time, the model is open to take into account further process steps and potential further co-products. This opens the possibility for a targeted climate design of pure vegetable oil fuels.

At first this model has been tested and verified on the example of the standard pure rape seed oil production process which is incorporated in the FQD and the BioGrace GHG Tool. Then optimisation possibilities were explored. The decisive phase is the cultivation of the oil seeds. In the case of pure rape seed oil, 82% of all GHGE are produced in the cultivation and only 18% in the subsequent process steps. Compliance with the minimum of 60% GHGE saving can already be achieved when simply the produced rape seed oil substitutes diesel as auxiliary fuel in its own production. For investigating this option the GHGE of the produced rape seed oil are broken down by the following formula:

(1) $$\mathbf{E_B = a + b \cdot I}$$

Here, E_B denotes the GHGE of the rape seed oil, I the specific GHGE that result from the use of diesel fuel in the production of rape seed oil, a the part of E_B that is due to the part of diesel that is going to be substituted by rape seed oil, and b a

[1] (Fuel Quality Directive (FQD), 2009)
[2] (Renewable Energy Directive (RED), 2009)
[3] www.biograce.net

proportionality coefficient. E_B and a are given in units of g $CO_{2\text{-eq}}/MJ_{oil\ in\ the\ tank}$ (the GHGE are referred to the energy content of the biofuel that finally arrives in the tank of the machine where it is used as fuel), I respectively in g $CO_{2\text{-eq}}$ /$MJ_{diesel\ in\ the\ tank}$, and b is a dimensionless quantity. I has the value 87.64 g $CO_{2\text{-eq}}MJ_{diesel\ in\ the\ tank}$ and b is a number smaller than 1, if replacing diesel by rape seed oil makes sense, i.e. if this lowers the GHGE. This condition is equivalent to E_B being smaller than I. Then it follows that b is smaller than 1.

If the produced rape seed oil substitute diesel in a continuous production process of rape seed oil, the GHGE of the latter amount to:

(2) $$\mathbf{E_B = \lim_{n\to\infty}\left[a \cdot \sum_{i=0}^{n-1} b^i + I \cdot b^n\right] = \lim_{n\to\infty}\left[a \cdot \frac{1-b^n}{1-b} + I \cdot b^n\right] = \frac{a}{1-b}}$$

The values of a and b depend on the part of diesel that is substituted by rape seed oil and on the resulting allocation of the GHGE to the constant term a and the variable term b·I.

Table 1 shows the GHGE savings for rape seed oil for different substitution scenarios. In all cases, the threshold of 60% GHGE saving is exceeded. Note that 87.64 g $CO_{2\text{-eq}}$/MJ was used not only as value of the GHGE of diesel as auxiliary fuel, but also as value of the GHGE of diesel as fossil fuel comparator, for which the FQD indicates 83.8 g $CO_{2\text{-eq}}$/MJ (this is an inconsistency of the FQD; see below). However, the threshold of 60% is also reached or exceeded if the latter value is used.

Table 1: GHGE saving of more than 60% through substitution of diesel by rape seed oil in the production process of the latter (here 87.64 g $CO_{2\text{-eq}}$/MJ is used for GHGE of fossil fuel comparator)

Ersatz von Diesel durch Rapsöl bei: / *Substitution of diesel through rape seed oil for:*	a [g $CO_{2\text{-äq}}/MJ_{Öl\_im\_Tank}$] / *a [g $CO_{2\text{-eq}}/MJ_{Oil\_in\_tank}$]*	b / *b*	E_B [g $CO_{2\text{-äq}}/MJ_{Öl\_im\_Tank}$] / *$E_B$ [g $CO_{2\text{-eq}}/MJ_{Oil\_in\_tank}$]*	THGE Einsparung / *GHGE saving*
Keinem Prozessschritt / *No process step*	36,051	0,000	36,051	58,86%
Anbau / *Cultivation*	32,358	0,042	33,782	61,45%
Anbau und Rapssaattransport / *Cultivation and rape seed transport*	31,989	0,046	33,544	61,72%
Anbau und Rapsöltransport / *Cultivation and rape seed oil transport*	32,178	0,044	33,666	61,59%
Anbau und Rapssaat- und -öltransport / *Cultivation and rape seed and rape seed oil transport*	31,809	0,048	33,427	61,86%
Allen Dieselverwendungen / *All diesel usage in standard production process*	31,793	0,049	33,416	61,87%

Finally, the model was applied for calculating the GHGE of false flax oil from mixed cultivation with wheat. The results are shown in Figure 1. The minimum GHGE saving of 60% is clearly exceeded by false flax oil from mixed cultivation with wheat (CS-W curves) for a broad range of mixing ratios.

The key parameter is the heat energy-to-green house gas ratio (HER), i.e. the ratio of the lower heating value of the produced crop to the GHGE that are related to its cultivation. Wheat has a better HER than 36.79 MJ/g $CO_{2\text{-eq}}$ if one uses the same

figures for wheat as the FQD and the BioGrace GHG Tool. According to our calculations, 36.79 MJ/g $CO_{2\text{-eq}}$ is the minimum value that an oil crop must reach in order that the oil passes the threshold of the minimum GHGE saving of 60% - provided the oil seeds are processed in a similar manner than rape seed in the standard rape seed oil production process (see black horizontal curve for a fictitious mixture within which both components have a HER of 36.79 MJ/g $CO_{2\text{-eq}}$). The minimum value of the HER is different if one deviates from the standard production process (e.g. if the oil press yield is different), but the difference is negligeable.

The high HER of wheat compensates the low HER of false flax for a wide range of mixing ratios. If false flax was combined with a crop X with the same HER, the GHGE saving would remain below 60% for all mixing ratios (see CS-X curves).

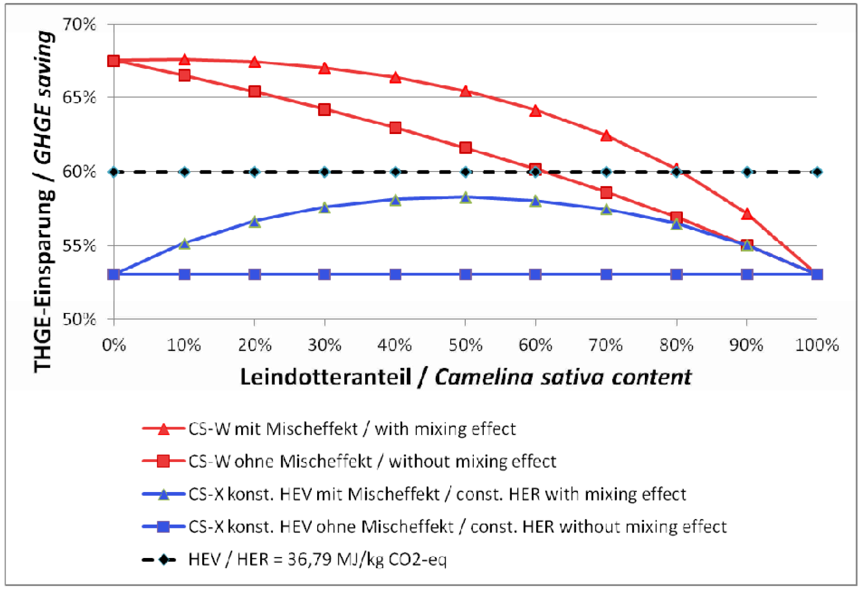

Figure 1: GHGE saving as a function of the false flax content (Camelina sativa, CS) in mixtures with wheat (W) or a fictitious grain crop (X) with equal HER than false flax

Experiments with mixed cultivation have shown that it allows achieving higher yields of the associated crops than one would expect from linear interpolation of the pure culture yields[4,5]. For this reason, the yields were modelled not only linearly, but also with a quadratic interpolation. For that literature values of experiments with mixed

4 Paulsen H M (2007) Mischfruchtanbausysteme mit Ölpflanzen im ökologischen Landbau: 1. Ertragsstruktur des Mischfruchtanbaus von Leguminosen oder Sommerweizen mit Leindotter (Camelina sativa L. Crantz). Landbauforschung Völkenrode 57(1):107-117

5 Gollner, G., et al., Körnerleguminosen in Mischkulturen mit Leindotter (*Camelina sativa*) im Ökologischen Landbau unter pannonischen Standortbedingungen, Journal für Kulturpflanzen, 62 (11). S. 402–408, 2010, ISSN 0027-7479

cultivation were used. The difference between the bent curves in Figure 1 and the straight ones illustrates the thus modelled mixing effect. The higher yields resulting from the latter lead to a gain of several percent GHGE saving!

The method of mixed cultivation thus offers a powerful option for reducing the GHGE of pure vegetable oil fuels through a targeted climate design. The key parameter is the HER and those parameters which describe the higher yield that is due to the mixing effect. With these parameters, suitable mixtures of oil crops with other crops can be selected. For that purpose the following guidelines can be formulated:

1. One of the associated crops should have a higher HER than 36.79 MJ/kg $CO_{2\text{-eq}}$ if the oil press yield in terms of energy content and the GHGE of the subsequent process chain have the same values as for the standard rape seed oil production process that is underlying the FQD. Otherwise a slightly different threshold applies for the HER that then has to be calculated.
2. At first an oil crop should be chosen whose HER is as high as possible.
3. If the oil crop does not reach the threshold for the HER it should be associated with a grain crop whose HER is above the threshold.
4. If 3. applies the mixture of both crops should be adjusted such that its HER is above the threshold. The smaller the HER of the oil crop, and the less the HER of the associated crop exceeds the threshold, the bigger the part of the associated crop must be in the mixture.
5. If the HER of the mixture exceeds the threshold for a broad range of mixing ratios, the mixture should be chosen such that the synergy effects are maximised. Besides optimising the climate balance other targets can be addressed.
6. The produced pure vegetable oil should be used as much as possible as heating and/ or engine fuel in its own production, first and foremost as fuel in agricultural machines for the cultivation of the oil crop, and secondly in CHP which produce heat and power for oil seed drying and pressing. Thirdly its use as heating and/ or engine fuel within the closer region should be considered, for instance in neighbouring agricultural enterprises.

In the course of this work, we noticed the above-mentioned inconsistency in the use of the GHGE reference value for diesel fuel within the FQD and its implementation. The authors pled for correcting this in the forthcoming revised FQD and suggest to use, in the case that a bio-fuel is replacing diesel fuel, 87.64 g $CO_{2\text{-eq}}$/MJ instead of 83.8 g $CO_{2\text{-eq}}$/MJ as value of the GHGE of the fossil fuel comparator, i.e. that value which is also used in the public version 4 of the BioGrace GHG Tool for the GHGE of diesel when diesel is used as auxiliary fuel in a bio-fuel production process. This will slightly increase the calculated GHGE savings of bio-fuels that replace diesel fuel, but all the results that are presented here are valid independently of the suggested correction.

The authors advocate further for a threshold for the consideration of carbon stock changes caused by indirect land use changes for bio-fuels which are produced by an

agricultural enterprise and used for own use or consumed within the closer region. For further specifying this criterion, a limit could be set at 10% of the agricultural area of an area that is used for the production of bio-fuels for own use or for consumption in the closer region.

Further need for research exists notably with regard to the functional relationships of N_2O field emissions, nitrogen fertilisation, soil conditions and climate/ weather. This work has also shown that GHGE calculations with European average values can lead to big differences to actual GHGE under real cultivation and production conditions. Here, further research is needed about the possibilities to conduct more precise regionally differentiated calculations with a reasonable effort.

For assessing with greater reliability differences in GHGE that are due to regional characteristics, and for controlling that conditions are met for the non-consideration of indirect land use changes, the cooperation is recommended with regional marketing initiatives such as UNSER LAND which certify the regional origin of products and similar criteria, very often in relation to sustainability aspects. The use of typical regional values for the GHGE calculations for bio-fuels could be legitimised by a certification of such bio-fuels by accredited certification systems of regional marketing initiatives.

The authors

Dr. Michael Stöhr, born 1964, studied Physics in Bonn, Toulouse and Grenoble and prepared his PhD in experimental semiconductor Physics on silicon at the European High Magnetic Field Facility in Grenoble. From 1992-2000 he worked as scientific officer at WIP, Munich, in the field of renewable energies. Since 2000 he is Director for International and Energy Projects at B.A.U.M. Consult GmbH, Munich. His responsibilities include the technical and administrative lead of European research projects, teaching and strategic consultation about renewable energies, and the development of regional energy concepts. Since 2002, M. Stöhr has been working in several European projects on the development of concepts for the use of pure vegetable oils as fuel. In the 2ndVegOil project, he has been working as external consultant to John Deere in the project coordination and has been responsible, among others, for the project assessment.

Prof. Dr.-Ing. Peter Pickel has studied mechanical Engineering at the Technical University Berlin where he prepared subsequently his PhD about vehicle dynamics simulation of agricultural machines. After having hold two positions in industry in the railway signalling and working machinery sectors, he was appointed professor for agricultural, environmental, and communal technology at the Martin-Luther-University Halle-Wittenberg where he was Dean of the Agricultural Faculty from 2003-2006. Since 2007 he was working as Manager Tractor Applications at John Deere Werke, Mannheim. Since 2010 he is Deputy Director of the John Deere European Technology Innovation Center in Kaiserslautern. The focus of his research and development activities is on decentralised, integrated sustainable energy production and supply concepts for rural areas, including the development of electrification concepts for mobile off-road machinery. Further Prof. Pickel is working in the field of automation and communication technology for agricultural equipment. In the field of sustainable energy supply, he has been coordinating the European research project 2ndVegOil.