Quantifying the Life Cycle Sustainability of Renewable Energy Carriers

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Abstract

For many years the attribute "renewable" was taken as synonym for "sustainable". More and more it became clear, that this is not always appropriate and that large differences exist among various renewable energy carriers. Life Cycle Assessment acc. to ISO 14040 ff helps in this differentiation and in the meanwhile also allows to be one step ahead: LCA has developed from an ex-post method of comparative assessment of products and technologies that are already in the market into a powerful tool for integrated sustainability decision support in parallel to R&D. It helps developers of technologies and products to steer R&D towards more sustainable solutions already from the beginning on. Consequent employment of this approach based upon sound technical understanding in combination with LCA-specific experience is the key. This paper gives an overview over a selection of projects performed in the area of renewable energy carriers by IKP within the past 15 years. IKP's and PE Europe's joined LCI database GaBi is the most comprehensive one and available world-wide. It is based on over 200 person years of studies and also made available externally. Together with the GaBi 4 Software-System it supports decision makers in industry and policy making.

Keywords
Ethanol, crude oil refinery, crop model, electricity mix, sustainability assessment, LCA, technology benchmarking

1. Purpose of the work

The technological improvement of renewable energy carriers and of their conversion and production technologies is to be evaluated quantitatively along their life cycles (Figure 1).
Sustainability optimisation potentials and concrete weak-points are to be shown. Task-specific approaches are to be employed to perform this task in the most effective and efficient way. Technical understanding and experience in such tasks form the know-how-basis to be able to even assess very complex products and systems with affordable manpower at required quality and reliability of the results. Finally, only the integration of environmental, cost and social issues provides a complete sustainability assessment.

2. Approach

Providing decision support already in parallel to development of renewable energy technologies or carriers is the most advanced approach for steering R&D towards the most sustainable solutions. Benchmarking with conventional energy carriers sets the target to be met and quantifies advantages of renewable energies in absolute numbers. Based upon long-years experience in hundreds of studies for industry partners from many different sectors and for public bodies as well as a comprehensive LCI-database, IKP brought this approach into R&D decision support practice. By linking production inventories of emissions and resource consumption with relevant Impact Assessment categories, several hundreds of different emissions are aggregated to few impacts (see Table 1), of which the dominant 3 to 4 are identified thereby providing transparent, but focussed decision support.

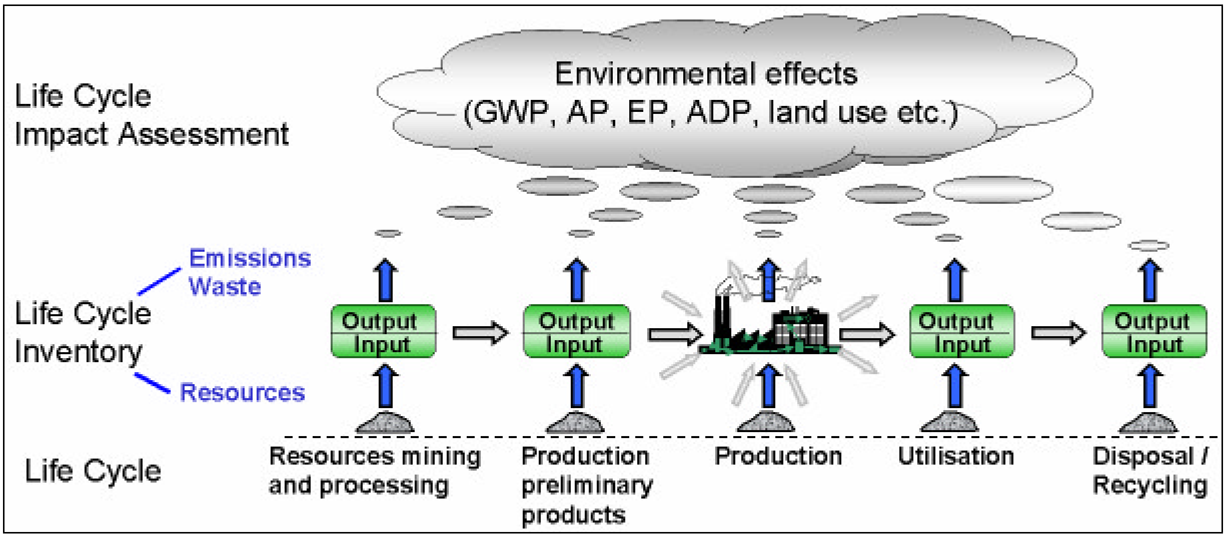

Figure 1: Life Cycle of products and its inventory and impact assessment

Table 3 – Overview of Impact Categories

	Categories, that are widely accepted for decision support in LCA practice
GWP	**G**lobal **W**arming **P**otential [kg CO_2 equiv.], caused by emissions of e.g. CO_2, CH_4 , N_2O, SF_6, FCKWs etc.
ODP	**O**zone **D**epletion **P**otential [kg R11 equiv.], caused by emissions of FCKWs, # etc. (--> stratospheric ozone depletion)
PE	**P**rimary **E**nergy Consumption [MJ], (actually an Inventory Category as well) accounting for use of crude oil, coal, natural gas, uranium ore etc.
ADP	**A**biotic **D**epletion **P**otential [MJ surplus energy], accounting for depletion of fossil fuels as well as mineral resources
AP	**A**cidification **P**otential [kg SO_2 equiv.], caused by emissions of e.g. SO_2, NOx, HCl, NH_3 etc.
EP	**E**utrophication **P**otential [kg PO_4^{3-} equiv.], caused by emissions of e.g. NO_3^-, PO_4^{3-}, COD, NOx etc.
POCP	**P**hotochemical **O**zone **C**reation **P**otential [kg Ethene equiv.], caused by emissions of e.g. hydrocarbons, NOx etc. (--> tropospheric ozone formation)
	Categories, that are under scientific development and should <u>not</u> directly be used for decision support in LCA practice, but as "red flags" for a more detailed look at emission sources, only
HTP	**H**uman **T**oxicity **P**otential [kg Dichlorobenzene equiv.], caused by emissions of e.g. Pb, Cd, Cr, halogenic organic compounds, pesticides etc.
AETP	**A**quatic **E**cotoxicity **P**otential [kg Dichlorobenzene equiv.], caused by emissions of e.g. Pb, Cd, Cr, halogenic organic compounds, pesticides etc.
TETP	**T**erristric **E**cotoxicity **P**otential [kg Dichlorobenzene equiv.], caused by emissions of e.g. Pb, Cd, Cr, halogenic organic compounds, pesticides etc.
Land use	**Land use** [quality m2*a], accounting for land occupation and land transformation and its effects on groundwater formation, filtering, biodiversity, erosion etc.

3. Scientific innovation and relevance

For many years LCA studies were carried out at the end of R&D only, evaluating or comparing already existing products. Extensive background data and efficient tools used with technical understanding and know-how bring LCA to the beginning phase of R&D, where real improvements can be realised (Figure 2).
Scenario-based evaluation of the technical potential of technologies under development - such as many renewable energy systems - helps substantially to assess achievable goals in mid-term to long-term and to show concrete bottle-necks to overcome (Figure 3).

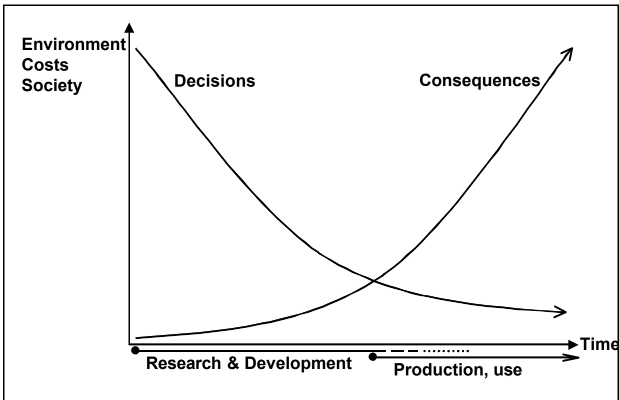

Figure 2: Only early decision support yields maximum effect

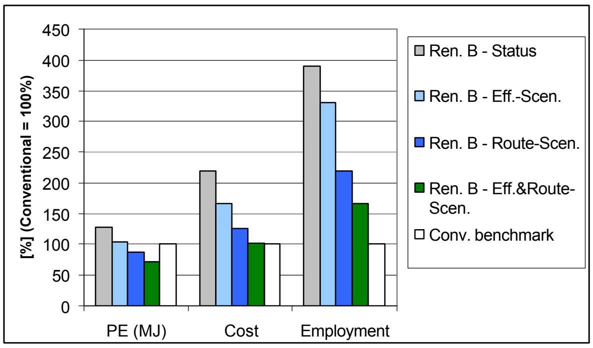

Figure 3: Scenario-based evaluation of technologies supports sustainability-oriented R&D

4. Results

Based upon several completed projects, the various task-specific approaches that were developed and applied are presented:

4.1 Ethanol and plant oils vs crude oil based fuels

Ethanol production (Figure 4) and plant-oil extraction processes are classical processing industry-type processes and require good understanding on material handling, separation technologies, energy management and waster water treatment issues, i.e. process engineering. Refinery products such as gasoline are main benchmarks for ethanol and plant oils; a detailed refinery LCI-model allows to appropriately model all types of refineries as well as the country-specific refinery mix. Figure 5 shows the model as set up in GaBi 4 software. Judging the degree of sustainability of renewables always requires a benchmark, e.g. conventional energy carriers, that perform the same function, here as fuel for automotive engines.

4.2 Agrarian and plantation model

For modeling the cropping phase of renewable resources such as wheat or sugar cane, a comprehensive parameterised cropping model has been developed. It integrates all relevant inputs (fertiliser, agromachinery, pesticides etc.), emissions (NO_3^-, NH_3, N_2O, NOx, particles, CO_2, etc.) and land use for a precise but flexible modelling of all types of energy crops. While large amounts of Nitrogen enter the agrarian system e.g. as fertiliser or by N2-fixation and large amounts leave the system as harvest, it is the relatively small difference, that is emitted. NO_3^- to groundwater as well as NH_3 and N_2O to air are dominant emissions (Figure 6).

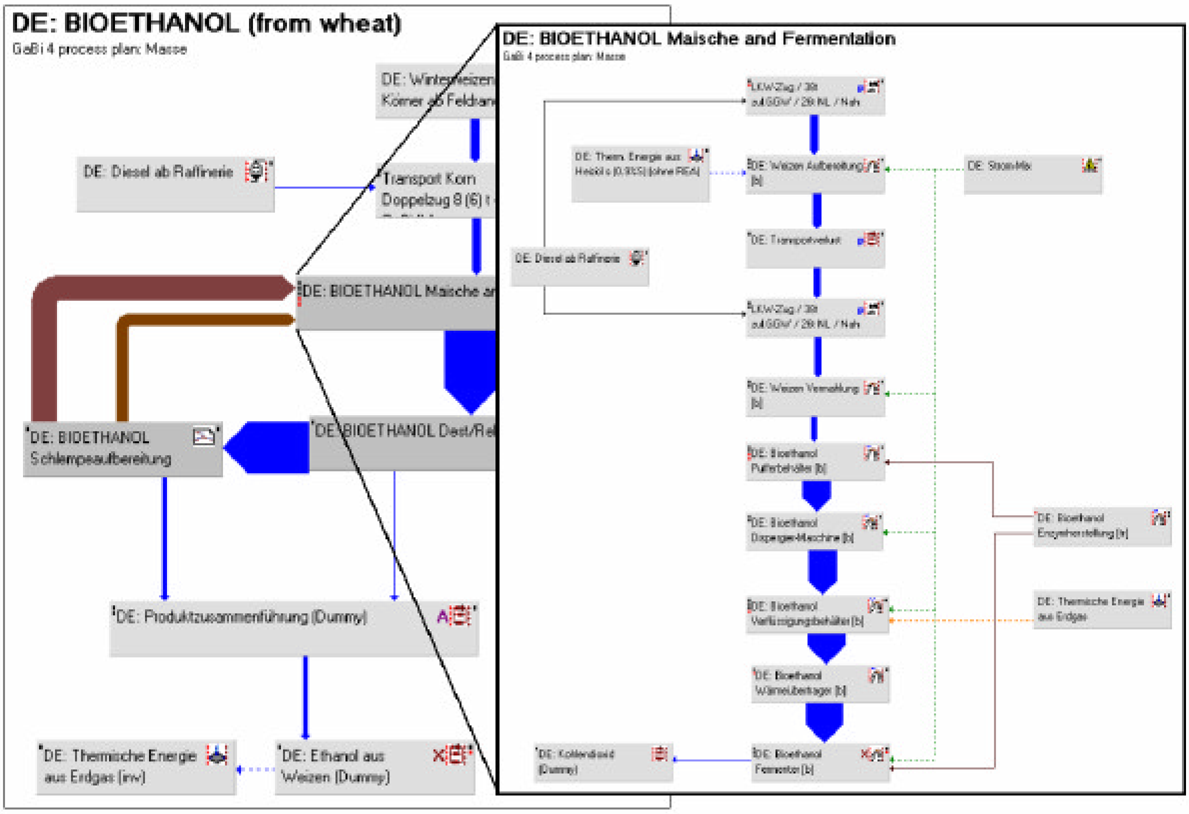

Figure 4: Ethanol from wheat; model extracts

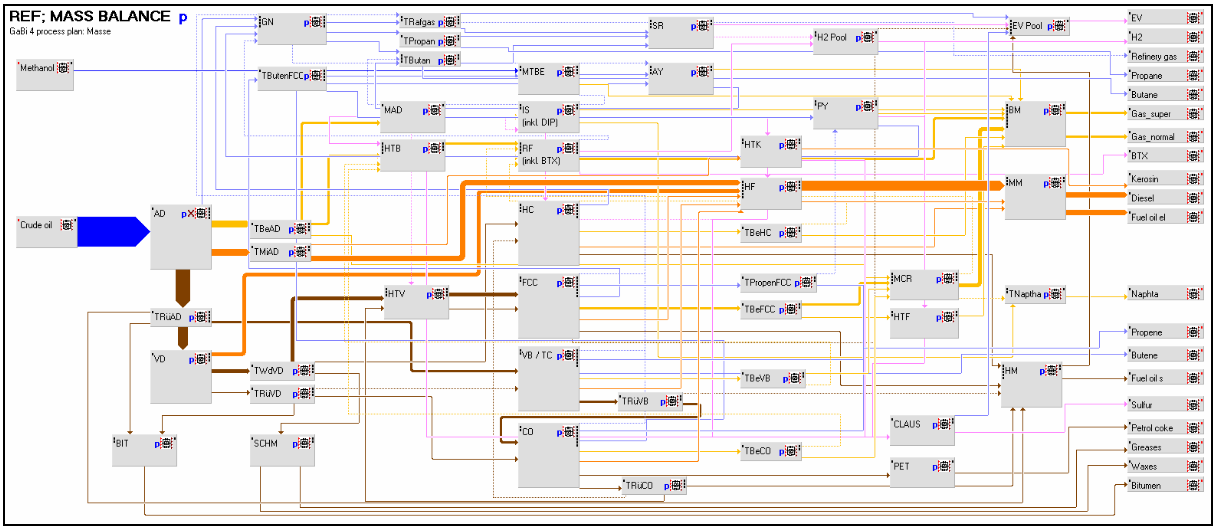

Figure 5: Detailed refinery model with parameterised processes in GaBi 4

Often simple and not cost decisive aspects are main weak-points. By setting up the complete picture, the relevant factors are identified and decision support can be given on how to substantially improve the cropping system.

Figure 7 shows the advanced model developed by one of the authors at IKP. Being a mixed balance-compartment-time step model, it focuses on relevance-dependent factors and combines the required aspects considering the limited data situation in reality.

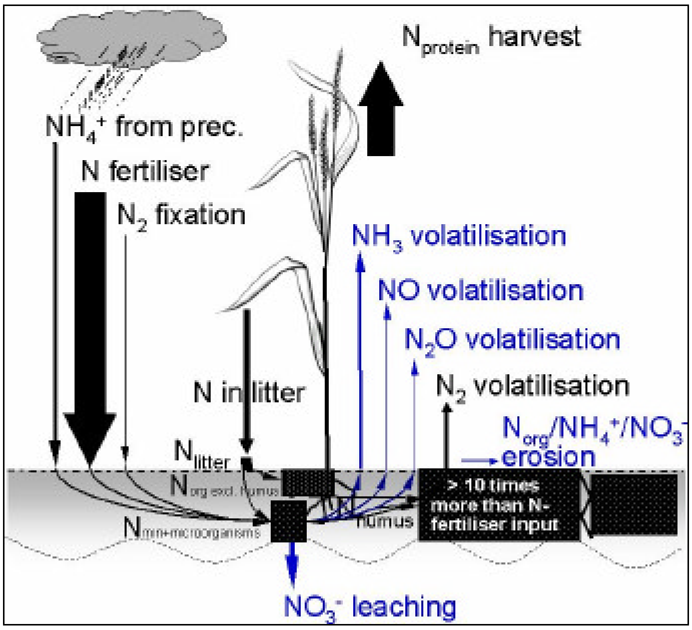

Figure 6: N-emissions are small difference of large inputs and outputs of system, while N-stock changes play a crucial role, too.

It allows for a very flexible depicting of specific management practises, but also of rough modelling - depending on required detail and the data situation. While it requires a good process understanding in use, it allows to achieve stable results with a quite limited data demand.

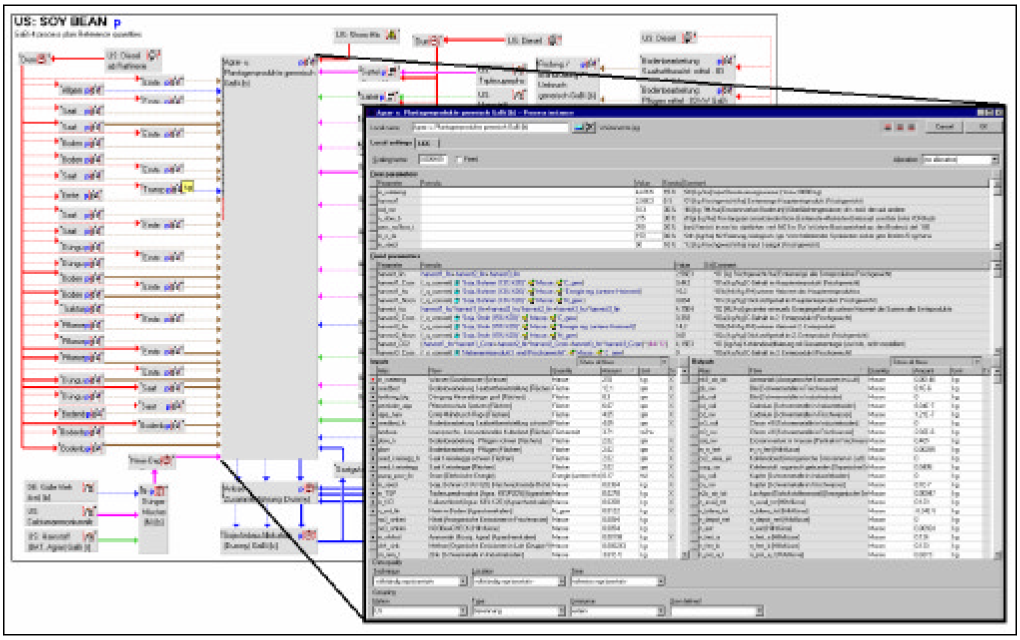

Figure 7: Advanced Agrarian- and plantation model in GaBi used at IKP and PE Europe for modeling of renewable energy (and material) crops production world-wide - LCI data sets are made available externally

4.3 Wind power - environmental performance of on steel, concrete and its benchmark of conventional power production is the key

LCA of wind power has to focus on production and maintenance of the wind power plants; yield data has to consider site options and temporal distribution of the wind as well as possible storage technologies. Consistent background data on materials such as steel, concrete, copper, glass fibre, resins etc. and appropriate benchmark data on conventional power production are most relevant issues. This makes clear, that LCA is a data intensive issue, but also, that once a comprehensive database is set up the single data sets can be used in modelling of complex products and systems in the same way as prefabricated parts are used for quickly setting up a complete house. Among all these "background" data, electricity mixes are the main basis for most LCA studies and are indispensable benchmarks for renewable-based electricity production - energy conversion routes back to the resources of all main contributors to national grid mixes are the pre-requisite. IKP's energy background model and parameterised conversion power plants is shown in Figure 8:

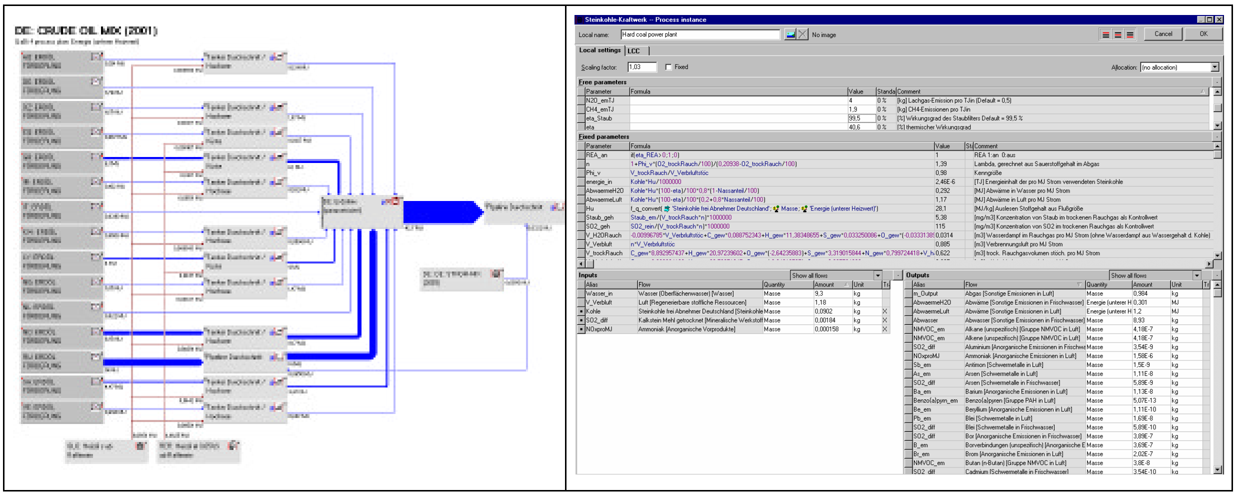

Figure 8: Excerpt of energy carrier mix model - crude-oil mix Germany (left). Advanced power plant model used in energy-carrier depending electricity modeling: e.g. heavy metal-content is linked non-linearly to corresponding emissions depending on dust filter settings (right)

5. Conclusions and Outlook

LCA has developed from an ex-post method of comparative assessment of products and technologies that are already in the market into a powerful tool for integrated sustainability decision support in parallel to R&D. Industry typically prefers tailor-made, parameterised models, which enable them to repeatedly use these by simple parameter setting - reflecting changed yield or other operation settings, material choices and the like. It helps developers of technologies and products to steer R&D towards more sustainable solutions already from the beginning on. Consequent employment of this approach based upon technical understanding and experience is the key. LCA is a tool, that can be used for detailed modelling of complex technical systems, but also for quickly depicting simple production for checking of weak-points. Through consistent modeling of cost effects along the life cycle, consequences of alternatives can be calculated, yielding the Life Cycle Engineering approach.

By inclusion of social aspects, such as seconds of human labour related to a product, accidents etc., the analysis becomes more complete, yielding a thorough Life Cycle Sustainability Assessment. In this regard see also the paper by Barthel et al. in these proceedings.

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