Sustainable Biorefineries

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SUSTAINABLE BIOFUELS

Opportunities and Challenges

As the global demand for energy continues to rise, biofuels hold the promise of providing a renewable alternative to fossil fuels. High oil prices and the threat of negative climate change impacts have sparked a surge in research and business activities. National security concerns and the desire to increase farm incomes have prompted governments around the world to enact policies in favor of biofuels. Developing countries hope to increase access to inexpensive fuel in isolated areas. Biofuels are also seen as an option to reduce air pollution in urban areas. However, the current boom has sparked controversy as well. Opponents accuse biofuels of requiring more energy inputs and causing more greenhouse gas emissions than their fossil counterparts. Many concerns center on possible environmental degradation: erosion, deterioration of soil health, depletion of aquifers, losses in biodiversity. Large scale biofuels production is often regarded as a threat to food production and conservation efforts [Hill et al. - 2006; Worldwatch Institute - 2006].

Sustainability assessments aimed at quantifying the economic, environmental and societal impacts can help to move the often heated debates over biofuels to a more factual level. Science-based methods like life cycle assessment (LCA), a holistic approach to quantify environmental impacts throughout the value chain of a product [ISO 14040 - 2006], have gained acceptance among decision makers.

Biofuels Sustainability in Well-to-Wheels Perspective

To assess the sustainability of (bio)fuels, all stages of the fuel value chain have to be considered (see Figure1): feedstock production and supply, fuel production and distribution, and vehicle operation. An assessment of the entire value chain, i.e. well-to-wheel (WTW), allows a fair comparison of different fuels, whereas a well-to-tank (WTT) or cradle-to-gate (CTG, here: extraction of raw materials from the ground to fuel production) approach is adequate to compare different technologies to make the same fuel.

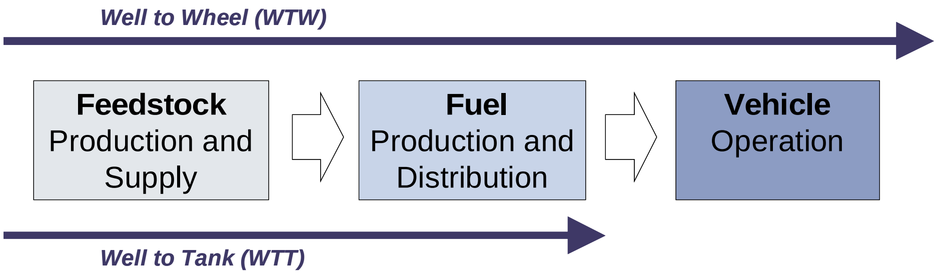

Figure 1: Fuel value chain

CASE STUDY: BIOREFINERY TECHNOLOGY DEVELOPMENT

The Integrated Corn-Based Biorefinery (ICBR)

The DuPont ICBR process will use innovative technology to convert corn grain and stover into fermentable sugars for the parallel production of value-added chemicals and fuel ethanol [US Department of Energy - 2006]. Current R&D efforts in the ICBR program focus on optimized process design for the conversion of lignocellulosic biomass to ethanol. From the beginning, economic evaluation and LCA have been used side by side to guide researchers to the most sustainable process alternative (see Figure 2).

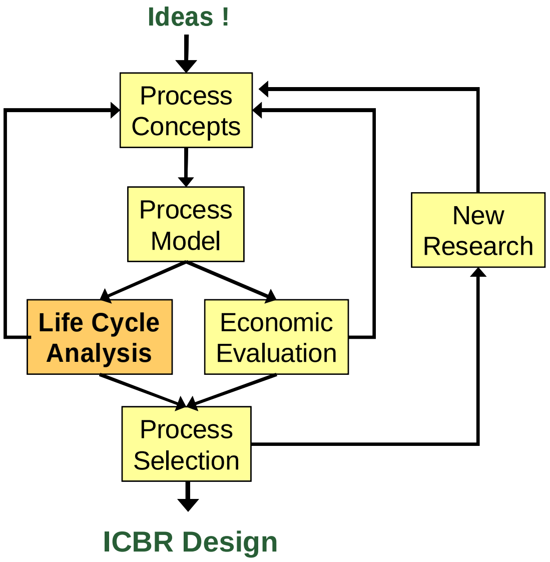

Figure 2: Integration of LCA into process development

In the ICBR program, stakeholder engagement was critical to setting relevant sustainability goals. Stakeholder interests are represented by an external advisory panel of subject matter experts from government agencies, academia, industry and non-governmental organizations (NGOs), who helped to prioritize topics, translate them into quantifiable metrics and formulate specific targets for the environmental performance of the ICBR technology. The panel's independent, critical review of life cycle methodology and results has been invaluable to the ICBR program.

ICBR Life Cycle Analysis

Life cycle assessment sheds light on relative or directional changes in sustainability resulting from ICBR technology choices. The LCA model follows all natural resources extracted from the environment and all material releases to the environment that cross the system boundaries shown as the dotted line in Figure 3. Many of these flows are then aggregated into impact assessments, e.g. fossil energy consumption, which includes petroleum, natural gas, coal and lignite use; or greenhouse gas (GHG) emissions, where gases like anthropogenic CO_2, CH_4 and N_2O are weighted by their global warming potential.

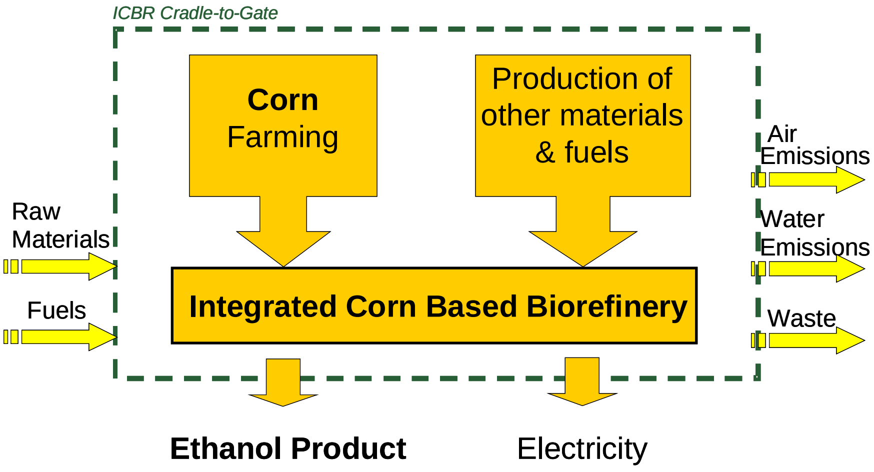

Figure 3: Cradle-to-gate LCA model of the ICBR

A process model of ethanol production from corn stover in an ICBR facility forms the core of the LCA model. The environmental impacts of material and energy inputs to the biorefinery are tracked back to ground, using LCA databases and publicly available information to describe upstream processes. Michigan State University provided a rigorous LCA model of corn farming, including agrochemicals manufacture and the production of fuels used in corn farming [Kim et al. 2007]. Most ICBR designs assume that non-fermentable biomass provides fuel for an on-site cogeneration facility, with the option to sell excess electricity to the local grid. The LCA credit for electricity sales covers the environmental burden of electricity generation all the way back to primary energy sources [Kim and Dale - 2005].

As the ICBR process development progressed, the LCA model was continuously updated. Multiple scenario and sensitivity analyses helped to identify favorable design options and optimized process parameter settings.

Comparison vs. Benchmarks

Eventually, ICBR technology will have to be competitive against other technologies to produce ethanol from corn. The LCA model has also been used to benchmark the environmental performance of the ICBR vs. the incumbent technology, i.e. ethanol from corn grain [Graboski – 2002], and potential alternative routes to produce ethanol from corn stover [Sheehan et al. - 2004]. Publicly available benchmark data were carefully reviewed when the environmental targets for the ICBR were defined. When necessary, critical assumptions and data sources were aligned to ensure a fair comparison.

Results for cradle-to-gate fossil energy consumption, a metric commonly used to address the energy balance of biofuels are shown in Figure 4. In all three scenarios, the CTG fossil energy footprint to produce a gallon of bioethanol is well below the lower heat value of the fuel, i.e. the energy ultimately delivered to a vehicle. The ICBR compares favorably against both benchmarks.

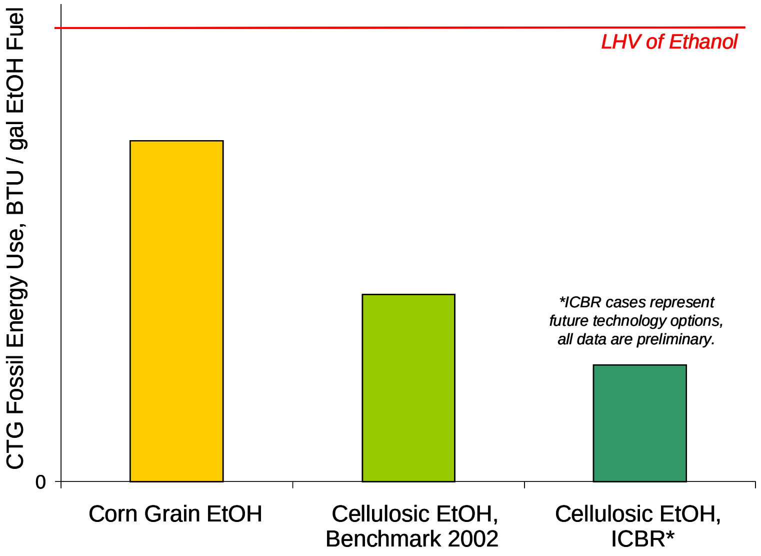

Figure 4: Cradle-to-gate fossil energy use of selected biofuels

Greenhouse gas emissions have emerged as a priority metric in policy making. To benchmark biofuels against the incumbent fossil fuel, differences in the energy content of the fuels need to be considered. Figure 5 shows well-to-wheel greenhouse gas emissions normalized to an equal amount of fuel energy for US gasoline and the three biofuel alternatives discussed above.

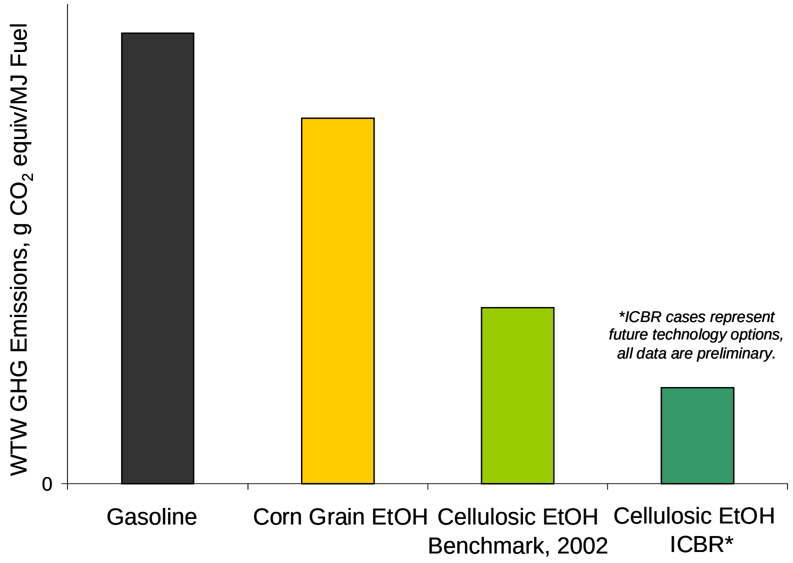

Figure 5: Well-to-wheel greenhouse gas emissions of selected fuels

All three biofuels cause less GHG emissions along the fuel value chain than gasoline. Cellulosic ethanol offers significant advantages in GHG reductions, since corn stover has a smaller GHG footprint than corn grain [Kim et al. - 2007] and provides renewable fuel to the ethanol production facility, whereas conventional dry mills rely on natural gas or coal [Graboski – 2002]. The ICBR ethanol presents the largest GHG reduction potential of all cases shown, thanks to advanced pretreatment and fermentation technologies and optimized process integration. A breakthrough in stover to ethanol technology could pave the way for ethanol from other lignocellulosic feedstocks, such as perennial grasses, agricultural or forestry residues.

ATTRIBUTES OF SUSTAINABLE BIOREFINERIES

Fundamental learnings from the in-depth analysis of a broad spectrum of ICBR technology options can be applied to biorefineries in general:

Feedstock Selection

The cradle-to-refinery gate footprint of the primary biorefinery feedstock is a significant contributor to the overall footprint of a biofuel. Generally, lignocellulosic biomass has a lower environmental burden than food crops. In LCA terms, waste materials from industrial processes or municipal collection would come free of burden if using them in biorefinery processing would result in the avoidance of disposing theses materials. Similarly, the footprint of processing chemicals used at the biorefinery needs to be considered, especially in the pretreatment of cellulosic feedstocks.

Biorefinery Process Efficiency

As a rule of thumb, cost efficient measures to improve process efficiency will have a positive impact on both the economic and the environmental performance of biorefineries. The common engineering goal to maximize product yield usually translates into reductions in feedstock footprint, waste generation and energy consumption. Increasing the effective concentration of solids, intermediates and products in aqueous process streams not only reduces the amount of water taken from the watershed, but also reduces the burden on separation steps. Measures to lower the energy consumption within biorefinery battery limits, e.g. by heat integration or equipment design, have a positive impact on the overall biofuel energy balance, whether they reduce the need to bring supplemental fuel to the biorefinery or enable additional energy exports.

Industrial Ecology of Biorefineries

Typically, the biofuel is not the only material output of a biorefinery. If more outputs find their ways into beneficial uses, then the economic and environmental burdens of the biorefinery operation can be allocated among a wider range of co-products, effectively reducing both the production cost and the cradle-to-gate footprint of the biofuel. For example, lignin and other non-fermentable components of biomass feedstocks need not be disposed as wastes, but can be used as fuels to generate thermal or electrical energy on site or off site. Other potential co-products include animal feed, fertilizer and intermediates for specialty chemicals.

The co-location of biorefineries with other facilities processing agricultural and forestry feedstocks, livestock feedlots or power plants in industrial parks will facilitate the beneficial exchange of material and energy flows to a great extent.

REFLECTIONS:

SUSTAINABILIY IN TECHNOLOGY DEVELOPMENT

In the development of sustainable fuels, materials and services for the future, researchers are challenged to find innovative technical solutions without losing sight of the economic, societal and environmental impacts of their work. The ICBR program demonstrates how the early integration of sustainability analysis into the creative process of technology development enables a holistic approach to research guidance, where economic and environmental metrics are used alongside product performance standards to define and monitor success.

ACKNOWLEDGEMENTS

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