論文の内容の要旨

Life Cycle Assessment of Alternative Fuels Production and Utilisation in Light Passenger Vehicle Fleets in Brazil and India（ブラジルおよびインドにおける自動車用代替燃料の生産と利用に対するライフサイクル評価）

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Abstract

Alternative fuels are commonly indicated as one of the feasible strategies for curbing Greenhouse Gas (GHG) emissions and protecting the security of the energy supply. This is mainly based on the postulate that biomass-based alternative fuels are a renewable source and are carbon neutral, i.e., carbon dioxide released during its combustion in vehicular engines is supposedly absorbed during biomass growth through photosynthesis processes. Nevertheless, critical voices advocate that large-scale conventional biomass-based fuels can actually increase, rather than decrease, life cycle GHG emissions, as energy input and raw material consumption flows can be highly carbon intensive. Additionally, alternative fuel production on a large-scale might have implications for food chain competition and increase pressure on land use.

Life Cycle Assessment (LCA) is a sophisticated tool commonly applied to evaluate alternative fuel production through its entire life cycle on a comparative basis. It accounts for the environmental impacts derived from the alternative fuel production (Well-To-Tank ? WTT) and its utilisation stages in vehicular engines (the Tank-To-Wheel analysis ? TTW). However, numerous studies on alternative fuels life cycle, report a wide range of benefits and pressures on the environment, stressing the fact that they may or may not be competitive vis-a-vis conventional fossil fuels. This is partly due to: differing background assumptions (e.g.: system boundaries, inclusion of by-products, estimation of land use change) and methodological approaches (e.g.: functional units, allocation processes) applied to evaluating alternative fuel life cycles. Another important factor is related to the dependency of alternative fuels on local specificity factors, including farming practices, climatic conditions, feedstock/production technologies, transportation distances, energy auxiliary systems, co-product recovery chains, vehicular engine type, and mobility patterns. These factors heavily constrain the overall environmental performance and energy balance of chains. Therefore, hitherto the most environmentally friendly production pathways and their circumstances are yet to be understood.

In this tangled purview, this study aims at contributing to the field by identifying the most environmentally friendly alternative fuel life cycles and clarifying which local and regional factors most constrain the overall analysis and how to deal with the uncertainty associated with methodological issues in LCA. Understanding these matters will help policy makers to create policies and economic incentives to steer alternative fuel production in pro of

sustainable development.

The research objectives are fourfold: (1) to develop a life cycle model that evaluates the environmental impacts of alternative fuel production and utilisation systems (Well-To-Wheel ? WTW ? analysis), and that forecasts likely improvements in a 2030 timeframe; (2) to identify and optimise the most environmentally friendly production pathways and competitive light passenger vehicular technologies in different regional and time horizon scales and compare them vis-a-vis conventional fuels; (3) to evaluate the influence of LCA methodology in the accuracy of life cycle results and quantify the discrepancy from selecting different allocation procedures, functional units, and system boundaries; and (4) to assess the constraints of locally specific factors in the overall life cycle analysis.

To this end, the LCA methodology has been applied to evaluate two case-studies: a WTT-LCA on sugarcane ethanol production in Brazil and Jatropha curcas L. (hereafter jatropha) biodiesels production in India, as well as TTW-LCA on sugarcane ethanol utilisation in Light Passenger Vehicle (LPV) fleets in Brazil and Japan, and jatropha biodiesels utilisation in LPV fleets in India. Both case studies were compared with a reference system that describes the life cycle of conventional fossil fuels, gasoline and diesel. The inventory analysis was conducted, giving primacy to locally representative data collected during respective field surveys in Brazil and India, as well as regionally and globally applicable data. Whenever allocation methods could not be avoided, two approaches were followed: allocation through products energy content, and system expansion. In the impact assessment interpretation, inventory flows have been aggregated, adopting the midpoint method Impact 2002+. The following impact categories have been chosen: Non-Renewable Energy (NRE) consumption, Global Warming Potential (GWP), Respiratory Inorganic Effects (RIE), and Terrestrial Acidification Potential (TAP).

In order to evaluate sugarcane ethanol production pathways and identify those that lessen energy expenditure, a baseline scenario (reflecting the current trends of production and likely future forecasts) and two alternative scenarios have been designed. Alternative scenarios assess the use of bagasse and straw either to generate cellulosic ethanol, via biochemical processes, or to enhance surplus electricity, through gasification. Additionally, two sub-systems have been proposed to analyse vinasse recovery as an organic fertiliser or to be anaerobically digested to generate biogas and electricity.

Forecasts in a 2030 horizon reveal that ethanol production carriers are competitive with gasoline fuel from the viewpoint of NRE consumption and GHG savings, as gasoline production life cycle scores 1.20$\mathrm{MJ_{xp}.MJ^{-1}}$ and 15.52 $\mathrm{gCO_{2e}.MJ_{fuel}^{-1}}$, whereas ethanol baseline chain scores between -0.10 and 0.18 MJxp.MJ-1 and between -3.70 and 14.02 $\mathrm{gCO_{2e}.MJ_{fuel}^{-1}}$. As against this, in terms of RIE and TAP, the ethanol production baseline scenario displayed higher impacts, than the gasoline life cycle, ranging between 0.029-0.039 $\mathrm{gPM_{2.5e}.MJ_{fuel}^{-1}}$ and 1.17-1.58 $\mathrm{gSO_{2e}.MJ_{fuel}^{-1}}$. Analysis of alternative scenarios suggests that both biochemical and thermochemical routes of recovery of co-products (bagasse and straw) potentially reduce impacts on the environment. The enhanced ethanol route yields lower direct emissions, but it generates less electricity than the enhanced electricity route. Thus, following the allocation approach, biochemical treatment of bagasse and straw is the most competitive option, leading to a 57% reduction in GHG emissions (8.78 $gCO_{2e}.MJ_{fuel}^{-1}$). On the other hand, following a system expansion approach, the enhanced electricity route presents the lowest GWP impact (-9.77/-8.49 $gCO_{2e}.MJ_{fuel}^{-1}$), due to grid electricity avoidance by surplus electricity generation. In terms of RIE and TAP impact categories, the system expansion approach yields higher emissions than allocation methods (0.033-0.034 $gPM_{2.5e}.MJ_{fuel}^{-1}$ and 1.43-1.47 $gSO_{2e}.MJ_{fuel}^{-1}$ for RIE and TAP, respectively), suggesting that grid electricity displacement is not determinant to mitigate these impacts. As for vinasse recovery, both sub-systems show similar impacts, implying that few credits arise from anaerobic digestion treatment of vinasse.

Similarly to ethanol production pathways, Jatropha Methyl Ester (JME) product chains have been evaluated adopting a baseline scenario and three alternative routes. The baseline scenario reflects the generation of JME via Jatropha Crude Oil (JCO) extraction and transesterification, assuming current trends. Alternative routes assess the processing of JCO into hydrogenated oil (HVO) diesel, via hydrogenation processes and the recovery of woody co-products (wooden stem, hull and husk), either via the Fischer-Tropsch (FT) process for generating FT diesel, or through gasification to maximise surplus electricity generation. Additionally, two sub-systems have been proposed to analyse recovery of seedcake as an organic fertiliser or its anaerobic digestion to generate biogas and electricity.

Jatropha fuel systems yield GHG savings if co-products are utilised and system expansion methods are applied in the LCA analysis. Thus, the baseline scenario reveals a potential reduction GWP between -325% and -165%, compared to the reference system (diesel production). With regard to NRE expenditure, all jatropha fuel carriers are more favourable than conventional diesel production. In fact, both the baseline and alternative scenario energy requirements are lower than 1, between -0.73MJ_{xp} and 0.60MJ_{xp} per MJ of fuel reinforcing the fact that jatropha fuels are indeed a renewable fuel. As for RIE and TAP indicators, none of the jatropha fuel carriers is competitive with the diesel production life cycle, yielding additional burdens, ranging between 0.02 and 0.06 $gPM_{2.5e}.MJ^{-1}$, and between 1.62 and 3.70 $gSO_{2e}.MJ^{-1}$. Refining JCO via hydrogenation results in no significant gains to the environment, when compared with the transesterification route. Yet, savings can be gained from enhanced recovery of co-products. Indeed, routes reflecting enhanced recovery of co-products show savings ranging between -522% and 60% of GWP potential and between -64% and 54% of NRE consumption, compared to the reference system. Gains are achieved particularly when assuming a system expansion approach for routes that maximise surplus electricity generation. In fact, grid electricity in India is highly dependent on coal.

The Light Passenger Fleets model examines the environmental impacts associated with the utilisation of alternative fuels in passenger fleets in Brazil, India, and Japan. In Brazil, the model assumes a narrative scenario, following the Business-As-Usual trend of fuels market and mobility patterns, whereas in Japan and India prospective scenarios have been designed to assess the introduction of fuel blends E3, E10, E20, and hypothetically E100 (Japan), B3, B5, B10, and hypothetically B100 (India). Additionally, the introduction of alternative powertrain technology Flexible Fuel vehicles (FFV) has also been considered in Japan (in a percentage of 10 and 30% of new vehicles sales). The automotive fleets' typology and mobility patterns have been projected upon a 2030 timeframe, through employing algorithms based on new vehicle sales and scrapped vehicle curves. Overall, impact categories display a descending curve from 2008 over the simulation period, mainly due to increases in fuel economy and stricter emission control regulations. Results disclose that GWP and NRE indicators fall with an increase of ethanol and biodiesel blends, as these fuels are assumed to be carbon neutral. On the other hand, RIE and TAP show no significant changes with the introduction of alternative fuel blends.

The full life cycle integrated model, in which production and utilisation stages were combined in the WTW analysis, reveals that sugarcane ethanol and jatropha biodiesel carriers introduced in LPV fleets reveal significant savings of GHG emissions and NRE consumption. In Brazil and Japan, in 2030, the introduction of ethanol blended fuels results in saving of up to -3.14 $MJ_{xp}.MJ^{-1}$ and -2.84 $MJ_{xp}.MJ^{-1}$ and -195 $gCO_{2e}.MJ^{-1}$ and -204 $gCO_{2e}.MJ^{-1}$, respectively. Similarly, in India, the introduction of biodiesel blended fuels could yield saving up to -4.12 $MJ_{xp}.MJ^{-1}$ and -299 $gCO_{2e}.MJ^{-1}$. As for RIE and TAP, overall WTW emissions from alternative fuels are higher than conventional fuels, in a range of 113%-226% $PM_{2.5e}$ and 184%-271% SO_{2e}. Although alternative fuel TTW emissions are slightly lower, they are offset by the higher emissions in the WTT phase. Nevertheless, it is important to underline that in terms of urban air quality, substitution of alternative fuels for conventional ones brings advantages, since emissions from the utilisation stage are less than those of conventional fuels. This emphasises the relevance of system boundaries in the overall LCA results.

With regard to the influence of LCA methodology on the accuracy of overall results, this study concludes that allocation procedures and functional unit selection are major sources of discrepancy in the assessment of alternative fuels. The influence of allocation methods on results depends on production pathways and system expansion selection. The allocation approach benefits carriers that promote production of liquid fuels rather than electricity carriers. On the other hand, system expansion suggests lower impacts to systems in which displaced systems are highly impactful. Given the influence of external systems in the alternative fuel carriers, this study suggests the necessity for defining a new LCA framework to evaluate multifunctional bioenergy systems. Functional units are also revealed to have a strong influence on the overall conclusion. In Brazil, when applying product-based functional units, benefits are given to the scenarios that prioritise enhanced electricity production; whereas, feedstock-based functional unit show more benefits to enhanced liquid fuel scenarios. This suggests that functional unit parameter needs to be carefully selected, depending on the LCA goals and application.