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Assessing butanol from integrated forest biorefinery: A combined techno-economic and life cycle approach

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HIGHLIGHTS

- Butanol production from pre-hydrolysate in a Kraft pulp mill is assessed.
- Energy efficiency is critical to ensure competitiveness among alternative fuels.
- Butanol can penetrate the transportation sector under climate policy scenarios.
- The butanol carbon footprint is not yet competitive with that of comparable fuels.
- The life cycle and techno-economic approach proposed is broadly applicable.

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ABSTRACT

The life cycle assessment (LCA) methodology is increasingly used to ensure environmental sustainability of emerging biofuels. However, LCA studies are usually not performed at the process design stage, when it would be more efficient to identify and control environmental aspects. Moreover, the long-term economic profitability of biofuels depends on future energy and climate policies, which are usually not considered in techno-economic feasibility studies. This paper combines the LCA method and a TIMES energy system model, to offer a simultaneous assessment of potential environmental impacts and market penetration under different energy and climate policy scenarios of emerging energy pathways. This combined approach is applied to butanol produced from pre-hydrolysate in a Canadian Kraft dissolving pulp mill. Indeed, the integration of biorefinery processes into existing pulp and paper mills has been identified as a promising avenue to maintain mills activities. It could increase and diversify revenues, keep the forestry-based communities alive, and potentially mitigate climate change by replacing fossil-based fuels or products. Results show that (1) the energy efficiency of the butanol production process is a critical aspect to consider in future design and implementation steps in order to make butanol a competitive fuel among all other alternative fuels, (2) with a 50% internal heat recovery, butanol has a role to play in the transportation sector under climate policy scenarios, and may have a lower carbon footprint than gasoline as estimated by a 2010 US EPA study, and (3) higher supply costs for feedstock might undermine the competitiveness of butanol on the medium term (2030), but probably not on the long-term (2050). This combination of assessment methods is replicable to analyze any types of emerging energy pathways in Canada and in other countries, and to help designing more sustainable forest biorefinery processes in other countries with important forest sector.

1. Introduction

Biofuels are often claimed to be better alternatives than their fossil-based counterparts in terms of environmental impacts, climate change, and non-renewable resource depletion. Several jurisdictions, such as the United States and the European Union, have

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implemented renewable fuel policies to increase energy security and mitigate climate change [1,2]. However, recent literature has shown that biofuels may also lead to economic, environmental and social issues which should be carefully taken into account to improve their sustainability. For instance, biofuel production may have adverse effects on biodiversity and ecosystem services [3–5], or on climate change if land-use change emissions are substantial [6]. Issues with climate change and resource depletion may also arise if supply chains and transformation processes require large amounts of fossil fuel [7].

The life cycle assessment (LCA) method, supported by the ISO 14040/44 standards [8,9], is the preferred approach to assess biofuels potential environmental impacts while considering the entire supply chain, and to quantify the potential reduction of greenhouse gas (GHG) emissions compared to substituted fossil-based fuels. Indeed, the LCA method is a life cycle-based and multi-impacts approach. It can therefore identify shifting of potential impacts toward other life cycle stages or other environmental issues that could be missed if only a portion of the value chain (e.g. biofuel combustion) or one single impact indicator (e.g. GHG emissions) was considered. For these reasons, LCA has often been used in recent literature to assess the environmental sustainability of biofuels [10] and to guide policies such as the Renewable Fuel Standard in the United States [11].

Several factors affect biofuels competitiveness, and associated uncertainties create challenges for potential investors [12]. For example, economic profitability of biofuels highly depends on the availability of low-cost feedstock, and on the energy prices that usually account for a substantial part of operating costs for biofuel production. Biofuels competitiveness also depends on fossil fuel prices, as increasing prices stimulate the market for alternative fuels and vice versa [13]. Moreover, future market penetration of biofuels will be affected by future policies such as renewable fuel regulations, carbon taxes or cap-and-trade systems. These factors are not all taken into account in traditional techno-economic calculations performed during the process design, which usually only include capital cost analysis, as well as revenue and operation costs estimation [14]. Moreover, the evolution of the energy sector should be analyzed on a long-term horizon to improve decision-making, given the long-lived nature of the capital stock to which energy production and consumption is tied.

A prospective approach is especially needed to evaluate emerging technologies such as advanced biofuels because technological innovations and political environment play a determining role [15]. Environmental challenges add yet another layer of complexity when assessing sustainability and viability of emerging biofuels. The complexity of these interrelated dimensions suggests the use of a holistic approach that would combine several methodologies such as energy system modeling and life cycle assessment. Today, decision makers are lacking this type of approach that would improve their understanding of how the energy system would react to the widespread deployment of new energy pathways. Indeed, consequences of such structural changes are traditionally assessed by analyzing technological, environmental and socio-economic aspects using separate approaches in separate studies.

There is a growing interest for combining techno-economic models with LCA to generate prospective scenarios and identify potential indirect impacts of policies or widespread deployment of new energy pathways. However, the combination of such approaches is still in its infancy [16]. For instance, Eriksson and colleagues have used scenarios coming from a dynamic optimization model of electricity and district heat production in Nordic countries (NELSON model) to identify marginal technologies for electricity production to be used in an LCA study [17]. These authors have identified several limitations regarding the suitability of these scenarios for their study, but they have shown that the use of a bottom-up energy system model can be effectively used in LCA. Other studies have discussed the importance of using energy system models to identify marginal technologies for electricity production in LCA [18,19]. As another example, Earles has combined LCA with the US Forest Products Module, an existing partial equilibrium model, to look at potential environmental and economic impacts of emerging forest bioenergy pathways [20]. However, this model is specific to the US forest sector and does not consider the rest of the energy system. Choi and colleagues have combined LCA with a techno-economic model of the energy system (US MRM under the MARKAL framework) to look at potential environmental impacts associated with electricity generation in the US under different policy scenarios [15]. The US MRM model provided prospective electricity mixes that were then combined with life cycle inventory data for different energy generation technologies.

Menten and colleagues have proposed to integrate LCA GHG emissions data to the French MIRET model (under the TIMES framework) to look at the impact of the introduction of the BTL technology ("biomass-to-liquid", i.e. synthetic biodiesel). [21]. TIMES (The Integrated MARKAL-EFOM System) is a bottom-up model representing the entire energy system of a country or region over a long-term horizon. This typically includes extraction, transformation, distribution, end-uses, and trade of various energy forms. Each step of the energy value chain is described by specific technologies represented with their techno-economic characteristics (e.g., cost and efficiency). TIMES also computes GHG emissions from fuel combustion and processes. Emission reduction is brought about in particular by technology and fuel substitutions. TIMES is cast as a dynamic linear programming model. Under the assumption that energy markets are under perfect competition, a single optimization, which searches to meet the exogenously defined demand for energy services at minimum cost, simulates energy market equilibrium. From this perspective, it computes a perfect foresight partial-equilibrium for energy goods, obtained through the optimization of energy uses, while respecting (in some cases) specific policy constraints such as GHG emission reduction targets [22].

The work performed by Menten and colleagues [21] presents a first attempt to use a TIMES model in combination with LCA. The TIMES model was used to determine changes in the French energy system caused by the introduction of BTL fuel, as well as associated GHG emissions. In this paper, we combine (1) the life cycle assessment (LCA) method and (2) a TIMES model (NATEM-Canada) to offer a simultaneous comprehensive assessment of potential environmental impacts and market penetration of energy pathways. We then apply this combined approach to the assessment of butanol produced from pre-hydrolysate in a Canadian Kraft dissolving pulp mill, a biofuel from a process that is still at the design stage.

In recent years, the Canadian forest sector has undergone a substantial decline, as also observed in other developed countries with important forest sector [23]. In response to this decline, the forest sector is currently experiencing major transformation through the development of new products and processes [24]. The current climate change context is also driving this transformation since forest products are often seen as preferable alternatives to non-renewable materials, chemicals, and energy sources. Therefore, an increasing number of policies and programs aim to promote the use of forestry- and agricultural-based biomass to replace fossil fuels [25].

The integration of biorefinery processes into existing pulp and paper mills, to convert lignocellulosic biomass into a broad spectrum of products, has been identified as a promising avenue to maintain mills activities in Canada but also in other countries such as the United States, Brazil, Finland and Sweden [26]. These products could increase and diversify revenues, and keep the forestry-

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