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Commercial feasibility of an integrated closed-loop ethanol-feedlot-biodigester system based on triticale feedstock in Canadian Prairies

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ABSTRACT

This paper presents techno-economic assessment of a closed-loop integrated system combining ethanol plant, feedlot, and biodigester in the Canadian Prairies. Triticale is the primary feedstock for ethanol production. Wet distiller's grains (WDG) and thin stillage from the ethanol plant is used as feed for feedlot beef cattle. Feedlot manure is used to produce methane via anaerobic digestion (AD), for subsequent conversion to electricity and heat through a combined heat and power generation facility. Three scenarios and two system scales were investigated. Total investment in the integrated system was $38–54 (small scale) and $132–237 million (large scale). The results showed that only one scenario in a large scale case has potential to generate profit; in this case, only the feedlot generated positive net present value (*NPV*) due to savings in feed cost of feeding WDG. Both the ethanol plant and biodigester generated negative returns under the integrated system. Co-locating a feedlot with an ethanol plant enhances ethanol plant profitability along with generation of extra revenue from feedlot operations. Compared to the non-integrated feedlot, the integrated feedlot saves $71.51 in feed cost per cow when cattle are fed 25% WDG. Electricity and heat from the biodigester could only supply 7–20% and 46–71% of the demand of the ethanol plant respectively. Sensitivity analysis tested key factors affecting the profitability of the subsystems. The ethanol plant generates profit under higher ethanol prices. However, *NPV* for all biodigesters is negative, even under favourable changes in investment and electricity prices. The study also showed that incorporating straw into ethanol fermentation and biogas production was not economically profitable in comparison with single triticale grain fermentation and manure digestion. Overall results suggest need for more policy support to improve economics of anaerobic digesters under current conditions, in the context of clean technology strategies.

1. Introduction

Globally, agriculture accounts for 30–35% of total greenhouse gas (GHG) emissions [1]. Within this sector, livestock has come under increased scrutiny because it accounts for 80% of emissions from agriculture [2]. Livestock's most significant impact comes from enteric methane (CH_4) from anaerobic microbial fermentation in the gastrointestinal tract of ruminants. It is estimated that ruminant livestock produces 33% of global CH_4 emissions [3]. The focus on CH_4 is based on the fact that its global warming potential is 28–36 times that of carbon dioxide (CO_2), implying that one kg of CH_4 emission is equivalent to 24 kg of CO_2 emission in terms of impact on climate change [4]. These concerns have galvanized concerted international cooperation to mitigate emissions from this sector, as demonstrated by the recent Paris Climate Agreement in which countries have established targets for reducing GHG emissions from livestock [5].

In this connection, Canada's clean technology strategy in support of these global efforts includes the development of clean energy pathways for reducing GHG emissions from Canada's livestock sector, in particular, the beef cattle industry which accounts for approximately 43% of Canada's total GHG emissions from agriculture [6]. In particular, the Canadian Prairie provinces of Saskatchewan and Alberta (with 12 million head of cattle) account for over 60% of the cattle economy [7], thus making the two provinces the largest contributors to GHG emissions from the beef sector. Feedlots emit CH_4 and nitrous oxide (N_2O) from livestock activity, animal manure, and organic wastes typified by concentration and high stocking density [8]. Enteric CH_4 production accounts for 46% of the emissions, while the combination of CH_4 and

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N_2O from manure management contributes 27%.

In this regard, on-farm anaerobic digestion (AD) is considered as an environmentally sustainable strategy for managing manure and mitigating these emissions from intensified livestock production operations [9].

Life cycle assessment has shown that biogas produced via AD in Alberta beef feedlot operations reduced GHG emissions by 90% (880 kg CO_2.eq) per MWh electricity compared to grid-average electricity [10]. On-farm AD systems have also averted direct emission of 45,000 t of CH_4, equivalent to 944,000 t of CO_2 [11]. A study by Poeschl et al. [12] reported that each kWh of electricity generated via biogas resulted in CO_2 emission reduction of 414 g in comparison with fossil fuels. Morris et al. [13] reported a 50% reduction in GHG emissions from installing anaerobic digesters on five Massachusetts farms. Besides GHG emission mitigation, on-farm anaerobic biogas production has co-benefits such as reducing odor, pathogens, and water contamination by digestion of manure, recovering thermal energy from combined heat and power generator, increasing crop nutrient value and reducing weed seed germination by application of stable, pathogen-free digestates [14,15]. Taken together, these co-products can enhance and stabilize farm income by integrating renewable energy generation and various feedlot farm operations [11,14]. In this context, AD has generally been conceptualized as an integral component of a closed-loop system involving co-location with bioethanol, feedlot cattle production, and biogas production from manure.

The concept of an integrated system is not totally new. Its hypothetical mass flow through the system has been estimated to be more efficient [16]. Hallberg and Schlesinger also claimed patents on integrated processes for corn ethanol production and bio-gas production from cattle manure based on 25,000 head of feedlot cattle [17,18]. Another potential of integrating AD into the ethanol facility is adding ethanol co-products wet distiller's grains (WDG) into biogas production, which has been practised at both lab and pilot scale [19–21]. Mixing 25% WDG and 75% manure could achieve a CH_4 concentration of 49% in biogas while 100% manure could achieve a 59% CH_4 concentration [21]. Although the technical advantages of such closed-loop systems are well recognized, there is a dearth of information on the technoeconomic and financial viability of such systems in Canada, let alone the Canadian prairies which dominate feedlot beef cattle production. Available studies on the financial feasibility of AD system have presented different results depending on geographic location and AD system. Most studies on anaerobic digesters in US dairy farms found such systems financially unfeasible without any government supports, resulting in a negative net present value [11,22–24]. The adoption of AD has also been constrained by requirements for grant funding to reduce capital investment uncertainty [25] or significant coproduct sales to justify a CH_4 digester [26]. On the other hand, some studies in Canada (specifically looking at dairy farms in the province of Ontario) reported financial feasibility under certain conditions [15,27–29]. For instance, according to White et al. [15] biogas production via AD and its subsequent use in the generation of electricity on larger farms in Ontario is currently economically attractive due to the Ontario Feed-In Tariff (FIT) program which provides incentivized rates for the production of electricity from biogas. The researchers however note that while larger farms can take advantage of the FIT program (higher rates for electricity), there are significantly more small-sized farms for which individually designed and engineered AD systems would be prohibitively expensive. Overall, there has been limited adoption of ADs in Ontario in spite of the FIT program [27,28].

Very few studies have examined the economic feasibility of integrated closed-loop systems. DeVuyst et al. [30] evaluated the economic feasibility of a 20,000-head feedlot with an appropriately sized anaerobic digester co-located with an existing corn ethanol plant. The researchers reported a negative net present value (*NPV*), noting that project revenues could not support additional investment in confined feedlot and AD digester, even with co-product sales. Canada has companies such as Pound-Maker, a fully integrated 26,000-head feedlot and 14 million litre ethanol plant; and Highmark Renewables and Highland Feeders Ltd. which integrate feedlot and AD systems. However, to the best of our knowledge, there are no industries in North America currently operating integrated ethanol-feedlot-biodigester systems. In 2007, E3 Biofuels (Mead, NE, USA) launched the world's first closed-loop 94.6 million L ethanol plant. The $80 million plant was co-located with 30,000 head of cattle, and a biodigester system [30,31]. However, the plant never achieved commercial viability, leading to bankruptcy in less than one year [31].

The objective of this study is to investigate the commercial feasibility of an integrated ethanol-feedlot-biodigester system. Triticale is incorporated as a primary feedstock into the ethanol subsystem of the integrated closed-loop. Overall, this study aims to provide ex ante information for enabling investors, farmers, policymakers, and public to evaluate costs and returns of such systems, including parameters for enabling clean technology policies.

2. Methodology

2.1. Rationale for anaerobic digestion and closed-loop system

2.1.1. Anaerobic digestion

Anaerobic digestion has been used to treat municipal sewage sludge and solid waste, agricultural and forestry industrial waste, livestock waste, agricultural residues, and energy crops [32–36]. Anaerobic digestion involves the decomposition of manure (or organic matter in general) by the application of a consortium of microorganisms composed of hydrolytic and fermentative bacteria in the absence of oxygen [37]. This results in the generation of a biogas (mostly comprising CH_4 (60–70%) and CO_2 (30–40%)) as well as a stable, pathogen-free, odorless, and nutrient-rich sludge called digestate [15]. Methane production is normally reported as volume of CH_4 per gram of volatile solids (VS), or CH_4 per gram of chemical oxygen demand (COD) [38]. Maximum potential CH_4 emissions from manure is affected by ration, animal type, manure age, quantity, and type of manure addition equipment, but not influenced by digestion temperature [39]. A Canadian study showed that methane produced from beef cattle manure is in the range of 0.19–0.21 m^3 CH_4 per kg of VS, while dairy manure methane production potential is 0.30–0.35 m^3 CH_4 per kg of VS [39]. Other studies have reported methane potential in the range of 0.17–0.33 m^3 CH_4 per kg of VS [39,40]. Captured CH_4 can be used as a clean renewable biofuel. The digestate can be sent to a liquid/solid separator to produce compost or nutrient rich substrate for application as fertilizer in agriculture [32].

Anaerobic digestion is a very complicated process that is highly affected by the type of substrates and operational environmental conditions. Animal manure has high nitrogen content that may inhibit microbial growth [41,42]. Thus, co-digestion between manure and carbon rich lignocellulosic materials is an option to balance C/N ratio for AD and enhance biogas yield [43–48]. For instance, numerous researchers found that co-digestion of cattle manure with biomass increased process stability and methane yield compared with mono-digestion of manure [49,50]. However, the chemical composition of lignocellulosic biomass involving the interaction of cellulose, hemicellulose, and lignin create a structure that is highly resistant AD [43,44]. To overcome this issue and to enhance the digestibility of biomass in the anaerobic process, some thermal and chemical pretreatments (including steam explosion or acid hydrolysis) have been applied to biomass [44,45,51].

2.1.2. Closed-loop system

A closed-loop system is considered a potential strategy in the context of this study for several reasons. Firstly, dry-grind grain-based ethanol production in Canada (Table 1) generates large volumes of dry distiller's grains with solubles (DDGS), which represent a valuable feed