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Abstract

This paper examines the economic and environmental implications of biomass commercialization; that is, converting organic waste into a saleable product, from the perspective of an agri-processor that uses a commodity input to produce both a commodity output and biomass. We characterize the economic value and perform sensitivity analysis to investigate how spot price uncertainty affects this value. We find that commercializing biomass makes the profits more resilient to changes in spot price uncertainty. To examine the environmental implications, we characterize the expected carbon emissions considering the profit-maximizing operational decisions. In comparison with the perception in practice, which fails to consider the changes in operational decisions after commercialization, we identify two types of misconceptions (and characterize conditions under which they appear). In particular, the processor would mistakenly think that commercializing its biomass is environmentally beneficial when it is not, and vice versa. Using a model calibration, we show that the former misconception is likely to be observed in the palm industry. We perform sensitivity analyses to investigate how a higher biomass price or demand (which is always economically superior) affects the environmental assessment and characterize conditions under which these changes are environmentally superior or inferior. Based on our results, we put forward important practical implications that are of relevance to both agri-processors and policy makers.

Keywords: Biomass, Agriculture, Commodity, Sustainability, Emissions, Spot Price Uncertainty, Renewable Energy, Palm Oil

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1 Introduction

Global warming and climate change have created an unprecedented interest in reducing greenhouse gas (GHG) emissions globally, especially in energy production (Kök et al. 2016). Biomass (i.e., organic matter), a renewable energy source, plays a pivotal role in achieving this objective as it can be used as a feedstock in a bioenergy plant replacing fossil fuels to produce energy (e.g., heat, electricity).[1] Our focus in this paper is on agricultural residues as biomass source. In several agricultural industries, including the oilseed industry (e.g., palm, coconut) and the sugar industry, processors convert their residues (e.g., kernel shell for the oilseed industry and bagasse for the sugar industry) into a saleable product and sell it to bioenergy plants. Commercializing agricultural residues is gaining momentum due to increasingly strict standards for renewable energy usage across the globe. For example, as seen in Table 7 of the U.S. Department of Agriculture report (USDA 2018), Japan's import of palm kernel shells has increased nearly by ten-fold since 2013, to more than 1.13 million metric tons in 2017. This volume accounts for approximately US$125 million and according to the same report, it is expected to increase further in the near future as a result of Japan's target of providing at least 22% of its energy needs through renewable sources by 2030. Significant import volumes of palm kernel shells are also reported by several other countries, including South Korea and the U.S. (Jakarta Post 2017). Increasing trend for biomass commercialization is also observed in other agricultural processing industries (see Pearson 2016). These recent developments give rise to a need for processors to better understand the economic and environmental implications of commercializing their biomass.

On the economic implications, there is a nascent operations management literature that studies the value of converting waste stream into a saleable product albeit in the context of other waste streams such as municipal waste (Ata et al. 2012) and excess fresh produce (Lee and Tongarlak 2017). The knowledge base developed in these papers is not directly applicable to the context of agricultural residue because agricultural processors feature unique operational characteristics. Consider, for example, the palm industry. Palm oil mills produce crude palm oil (a commodity output) and palm kernel shell (biomass) from fresh fruit palm bunches (a commodity input). As both the input and the output are commodities, the processors are exposed to prevailing spot prices in buying and selling these commodities and

[1] Among all the renewable energy sources (e.g., wind, solar) energy produced from biomass has the largest share—50% in 2017—in the global renewable energy consumption (International Energy Agency 2018).

these prices exhibit considerable variability (Boyabatlı et al. 2017). Moreover, to counteract against spot price variability, palm oil mills rely on long-term contracts for procurement, as commonly observed in commodity processing industries (Boyabatlı 2015). These unique operational characteristics play critical roles in the economic implications of biomass commercialization. In summary, to our knowledge there is no work that studies the value of biomass commercialization for the agricultural processor. Therefore, there is also no work that examines the effect of key factors (e.g., spot price uncertainty) on this value. Our first research objective is to fill this void.

On the environmental implications, the common perception in practice is that converting waste into a saleable product is environmentally beneficial because it leads to a reduction in GHG emissions owing to lower landfill and replacement of fossil fuel energy source in downstream power plant (Ata et al. 2012). This common perception has been one of the key driving forces behind the increasing popularity of biomass commercialization in agricultural processing industries (see, for example, Pearson 2016). A stream of papers in the industrial ecology literature has refined this perception by highlighting that biomass commercialization requires additional processing (e.g., de-fibring) and transportation activities which may create significant emissions (Iakovou et al. 2010). Although these papers provide a detailed environmental analysis, as also highlighted by Lee (2012), they do not take into account the optimization of operational decisions. Therefore, they fail to incorporate the emissions resulting from the changes in operational decisions (e.g., input processing and procurement volumes, production volumes for each output including biomass) after commercialization. In summary, it is an open question under which conditions the processor can justifiably claim that commercializing its biomass is environmentally beneficial. Moreover, it is also an open question how the environmental assessment is affected by biomass market characteristics. Our second research objective is to develop this knowledge base.

To achieve these objectives, we propose a two-stage model that—in a stylized manner—captures the important operational characteristics of an agri-processor that commercializes its biomass. This model is motivated by our interactions with a coconut processor who aims to commercialize its coconut kernel shell. The firm (processor) procures a single input commodity and sells an output commodity and biomass in a single period to maximize its expected profit. The firm has two sources for input procurement, a contract and an input spot market. The output can be sold to two channels, an output spot market and demand that is characterized by a fixed-price fixed-volume sales contract. The output can also be procured from the spot market to satisfy the demand. The biomass is sold to demand that is characterized by a similar sales contract. In the first stage, the firm chooses the input contract volume to be reserved in the face of the input and the output spot price uncertainties. In the second stage, after these uncertainties are realized the firm decides the quantity to source from the reserved contract volume and the input spot market, the processing volume, the quantity to source from the output spot market, and the quantity of output demand and biomass demand to satisfy.

To delineate the economic and environmental implications of biomass commercialization, we make a comparison with a benchmark model in which the firm sells only the output commodity and biomass goes to landfill. We complement our structural analysis with numerical analysis based on realistic instances. To this end, we calibrate our model to represent a typical palm oil mill located in Malaysia (which accounts for 28.1% of world palm oil production in 2018 (USDA 2019)). We use publicly available data from the Malaysian Palm Oil Board, complemented by the data obtained from the extant literature. Our main findings can be summarized as follows.

Economic Implications. The value of biomass commercialization is given by the difference between the optimal expected profit after commercialization and the same before commercialization. We show that this value can be characterized by the product of biomass demand and an expected biomass margin which captures the effects of spot price uncertainty and firm's optimal decisions. Common intuition may suggest that this expected biomass margin can be characterized based on two possibilities on the spot day before commercialization: processing is profitable so that waste stream is already available for conversion to a saleable product (which brings a margin of biomass price) and processing is not profitable so that there is no waste stream, and hence, no conversion (which brings zero margin). We provide specific conditions under which this intuition holds and extend it by showcasing a third possibility in which processing becomes profitable only after commercialization. More interestingly, we show that when the firm increases its contract procurement volume after commercialization, the biomass margin on the day can become negative or even larger than the biomass price. These results underline the need for conducting a formal analysis in evaluating the value of biomass commercialization.

We conduct sensitivity analyses, both analytically and numerically, to investigate the effects of correlation between input and output spot prices and their respective variability on the value of biomass commercialization. We find that a higher correlation is always beneficial; that is, it increases this value, but a higher (input or output) spot price variability is beneficial only when this variability is low; otherwise, a lower spot price variability is beneficial. The general insight from the literature (see, Plambeck and Taylor 2013 and Boyabatlı et al. 2017) is that a processor's profitability (before and after commercialization) decreases in spot price correlation and decreases (increases) in input or output spot price variability when this variability is sufficiently low (high). Our results indicate that whenever the change in spot price uncertainty has an unfavorable (a favorable) impact on profitability, commercializing biomass reduces this negative (positive) impact. The main takeaway is that biomass commercialization, besides creating a new revenue stream for the processor, makes the processor's profits more resilient to changes in spot price uncertainty.

Environmental Implications. To measure the environmental impact we use total expected carbon emissions—including procurement-, processing-, selling-, and landfill-related emissions—resulting from profit-maximizing operational decisions before and after biomass commercialization. The processor can justifiably claim that commercializing its biomass is environmentally beneficial when the total expected emissions are lower after commercialization. We show that when the changes in operational decisions are ignored, our assessment is consistent with the common perception in practice: commercialization is environmentally beneficial when the landfill emission intensity is higher than the biomass selling emission intensity—which is given by the unit emission associated with additional (processing, transportation, and burning) activities less the unit emission saving obtained by burning biomass instead of fossil fuel. However, when the changes in operational decisions are not ignored, the environmental assessment is more nuanced and we identify biomass selling emission intensity and biomass demand as the two main drivers of this assessment. In particular, we establish two biomass selling emission intensity thresholds where once this emission intensity is lower (higher) than the smaller (larger) threshold, biomass commercialization is environmentally beneficial (harmful); otherwise, biomass commercialization is environmentally beneficial only when biomass demand is lower than a demand threshold. We also find that this demand threshold decreases in the biomass selling emission intensity.

Our results demonstrate that conventional arguments for and against the environmental superiority of biomass commercialization based on such simple proxy as comparison between biomass selling and landfill emission intensities can be misleading. In particular, our analysis highlights two types of misconceptions (and characterizes the specific conditions under which they appear). First, the processor would mistakenly think that commercializing its biomass is environmentally beneficial when it is not. The implication is that agricultural processors, which emphasize conversion of their residue as an argument for the environmental superiority of their business models could be vulnerable to accusations of greenwashing. Second, the processor would mistakenly think that commercializing its biomass is not environmentally beneficial when it is. In this case, an environmentally conscious processor can pass up a profitable investment opportunity (commercializing its biomass) based on an incomplete environmental assessment.

Based on our model calibration, we observe that a typical palm oil in Malaysia can justifiably claim that selling its palm kernel shell (PKS) to a bioenergy plant in Japan to substitute coal in energy production is environmentally beneficial unless biomass demand is larger than a level that is associated with approximately 82% processing capacity utilization. Interestingly, when PKS is used for substituting liquified natural gas, which is a cleaner energy source than coal, PKS commercialization becomes environmentally harmful regardless of the biomass demand. These results have important practical implications. First, care must be taken by palm oil mills to not promote commercializing PKS as environmentally beneficial without qualification. Second, given the current trend in the energy industry that suggests the discontinuation of coal-fired energy production by 2030 (Dempsey 2019), it is important for these mills to take actions to reduce, for example, transportation emissions (by choosing cleaner transportation options or selling biomass locally) to keep biomass commercialization environmentally beneficial. To this end, the on-going industry-wide efforts for reducing the carbon emissions in shipping (Milne 2018) also have an indirect, and potentially a crucial positive environmental impact on agricultural waste-to-energy industry.

To understand the impact of biomass market characteristics on the environmental assessment, we conduct sensitivity analyses to investigate the effects of biomass demand and biomass price on the change in expected emissions after commercialization. We find that an increase in biomass demand is environmentally superior only when biomass selling emission intensity is low; otherwise, it is environmentally inferior. On the other hand, an increase in biomass price is environmentally superior only when biomass selling emission intensity is low or it is moderate and biomass demand is low; otherwise, it is environmentally inferior.

Because a higher biomass demand or price always increases the value of commercialization, these results emphasize that what is economically beneficial is not always environmentally beneficial. This conflict may create challenges in the effectiveness of government policies designed for increasing renewable energy production. For example, in recent years governments have adopted policies (e.g., feed-in-tariff) to promote investment in renewable energy sources (Babich et al. 2019). As a result, there has been a growing number of bioenergy plants leading to an increase in biomass demand for agricultural processors. Our findings demonstrate that this increase may hinder biomass commercialization in an environmentally conscious processor unless its biomass selling emission intensity is low. Therefore, we suggest that governments also devise policies to incent the processors to reduce their biomass selling emission intensity. This can be achieved, for example, by encouraging (through investment subsidies) pelletizing of the biomass before shipment, as is often done in the wood industry, to increase its calorific value so that a larger amount of fossil fuel is substituted.

Another policy implication of our results is relevant for biomass-exporting countries (e.g., Indonesia, Malaysia). Some of these countries have recently started imposing export tax for biomass to encourage the growth of domestic bioenergy industry (see, for example, The Palm Scribe 2018). When biomass is sold locally, all else equal, a processor experiences a higher biomass price due to the absence of export tax (and a lower biomass selling emission intensity due to lower transportation emissions). Our results demonstrate that imposing an export tax is the right move in the growth stage of biomass industry (when biomass demand is relatively low) because a higher price is both economically and environmentally superior leading to processor's voluntary commercialization of its biomass.

The remainder of this paper is organized as follows. §2 surveys the related literature and discusses the contribution of our work. We examine the economic and environmental impacts of biomass commercialization in §3 and §4, respectively. §5 provides a practical application in the context of the palm industry. §6 concludes with a discussion of the limitations of our analysis and future research directions.

2 Literature Review

Our paper's main contribution is to the emerging operations management (OM) literature on by-product synergy. The papers in this literature study the economic implications of converting waste stream into a saleable product by considering the operational characteristics of specific processing environments. For example, Ata et al. (2012) study a waste-to-energy (WTE) firm that collects and processes municipal waste to generate electricity. Lee and Tongarlak (2017) focus on a retail grocer setting and examine the value of using unsold fresh produce to make prepared food items. More recently, Ata et al. (2019) examine another type of by-product synergy in the context of agricultural industries: gleaning operations that deal with collecting unharvested crops on the farmlands to be used in food assistance programs. They study the dynamic staffing problem to schedule volunteers to collect unharvested crops. Different from these papers, Sunar and Plambeck (2016) consider the interplay between by-product synergy and costs associated with the GHG emissions. They model the strategic interaction between a seller and a buyer located in different countries. The buyer incurs a cost associated with GHG emissions of the seller's production activities due to border adjustment. They examine how seller's decision of converting its waste stream into a saleable product has an impact on buyer's operations.

Closest to our work, Lee (2012) studies the economic and environmental implications of converting waste stream into a saleable product in the context of the chemicals and steel manufacturing industries. Motivated by these industries, she focuses on a deterministic model that optimizes production volumes for the main output and the by-product (waste) while considering waste disposal cost, virgin raw material cost and competition in the by-product market. Motivated by our own experience with a coconut processor commercializing its waste stream, we focus on an exogenously given fixed-price fixed-volume sales contract for biomass and do not consider competition in the biomass market. Instead, we consider other important characteristics of agricultural processors (e.g., input and output spot price uncertainties). On the environmental implications, Lee (2012) presents a conceptual framework and makes the critical observation that waste conversion decreases the processing cost which, in turn, increases the production volumes for the outputs (including waste). She conjectures that the increase in total volume could lead to a harmful impact on the environment. Our paper builds on this conjecture and identifies conditions under which biomass commercialization leads to a beneficial or harmful impact on the environment.

Environmental implications of biomass commercialization has also received considerable attention from the industrial ecology literature. We refer the reader to Iakovou et al. (2010) for a comprehensive review. As highlighted by Lee and Tongarlak (2017), the papers in this literature examine the environmental impact without considering the optimization of operations but provide a detailed treatment of GHG emissions related to biomass commercialization. For example, Damen and Faaij (2006) study the emissions associated with using palm kernel shells (PKS) produced in Malaysia to substitute coal in a power plant located in the Netherlands while considering the emissions associated with production, transportation, and consumption of PKS. They neither consider optimization of PKS operations nor take into account uncertainties. Our environmental analysis is motivated by the papers in this literature as it accounts for all emission categories. More importantly, our environmental analysis is based on a more detailed operational framework that not only considers the optimization of processor's decisions but also takes into account the relevant uncertainties. We also provide a model calibration to examine the environmental implications of PKS commercialization in a typical palm oil mill located in Malaysia where PKS is used for substituting coal or liquified natural gas at a power plant located in Japan.

Our paper is also related to the growing OM literature on commodity processing. As reviewed by Goel and Tanrisever (2017), the papers in this literature capture idiosyncratic features of commodity processors in a variety of industries and examine the economic implications of a broad range of operational features, including processing-yield improving technology (de Zegher et al. 2017), procurement flexibility (Martínez-de-Albéniz and Simchi-Levi 2005), and responsive product pricing (Boyabatlı et al. 2011). Within this literature, our work is closely related to the stream of papers that considers input and output (spot) price uncertainties. In this stream, Plambeck and Taylor (2013) study process improvement investment decision in a clean-tech manufacturing setting; Dong et al. (2014) study the value of operational flexibility in a petroleum refinery; Boyabatlı et al. (2017) study the optimal capacity investment decision of an oilseed processor; and Goel and Tanrisever (2017) examine the optimal sales contract choice of a biofuel processor. Similar to these papers, we capture idiosyncratic features of processors in a particular industry (agriculture) facing input and output spot price uncertainties. Different from these papers, we focus on biomass commercialization (another operational feature) and study not only the economic implications but also the environmental implications.

This paper also relates to the rapidly growing literature on sustainable operations—see, Drake and Spinler (2013) for a recent review—due to its focus on the environment. Within this literature, our work is more closely related to the stream of papers that examine the environmental implications of operational decisions that are made by profit-maximizing firms without considering their environmental impact (see, for example, Agrawal et al. 2012, Avcı et al. 2014, and Kök et al. 2016). Kök et al. (2016) is closer to our work because of its focus on energy production. They study the economic and environmental implications of using different electricity pricing policies—peak versus flat pricing—from the perspective of a utility firm. They solve for the optimal profit-maximizing operational decisions and investigate the environmental implications by comparing the total expected carbon emissions of an optimally designed utility under each pricing policy. We study the economic and environmental implications of biomass commercialization from the perspective of an agri-processor. We solve for the optimal profit-maximizing operational decisions and investigate the environmental implications by making a comparison between the total expected carbon emissions of an optimally designed processor before and after biomass commercialization.

3 Economic Implications of Biomass Commercialization

We first describe the economic model (§3.1) and derive the firm's optimal strategy before and after commercialization (§3.2). We then characterize the value of biomass commercialization (§3.3) and examine the impact of spot price uncertainty on this value (§3.4).

3.1 Economic Model Description and Assumptions

The following mathematical representation is used throughout the text: a realization of the random variable $\tilde{y}$ is denoted by y. The expectation operator, probability, and indicator function are denoted by $\mathbb{E}$, $Pr(\cdot)$, and $\chi(\cdot)$, respectively. We use $(u)^+ = \max(u, 0)$. The monotonic relations are used in the weak sense unless otherwise stated. Subscript 0 denotes input-related parameters and decision variables, while subscript 1 (2) denotes the same related to the output (biomass). All the proofs are relegated to §C of the online appendix.

We consider a firm that procures and processes a commodity input to produce and sell a commodity output and biomass in fixed proportions so as to maximize its expected profit in a single selling season. We model the firm's decisions as a two-stage problem: the firm makes its contract procurement decision under input and output spot price uncertainties (stage 1); and the firm makes its contract exercise, spot procurement, processing and selling decisions after these uncertainties are realized (stage 2).

Let $\tilde{S}_0$ and $\tilde{S}_1$ denote the uncertain input and output spot price, respectively. We assume that $(\tilde{S}_0, \tilde{S}_1)$ follow a bivariate distribution with a positive support, bounded expectation (μ_0, μ_1) with covariance matrix $\mathbf{\Sigma}$, where $\mathbf{\Sigma}_{00} = \sigma_0^2$, $\mathbf{\Sigma}_{11} = \sigma_1^2$, $\mathbf{\Sigma}_{01} = \mathbf{\Sigma}_{10} = \rho\sigma_0\sigma_1$, and ρ

denotes the correlation coefficient. We make further assumptions about $(\tilde{S}_0, \tilde{S}_1)$ in §3.4 to study the effect of spot price uncertainty.

The firm has two sources for input procurement, a contract and a spot market. We assume that the firm uses a quantity flexibility contract that is characterized by a unit reservation cost β and a unit exercise cost that is normalized to zero. Let Q denote the contract volume reserved in advance of the spot market (by incurring the unit cost β). On the spot day, the firm decides how much of this contracted volume is delivered. On the day the firm can also source from the input spot market at the prevailing price S_0 to process.

Let z_0 denote the processing volume. We consider a processing capacity K_0 and a unit processing cost c_0. We assume that each unit of processed input yields a_1 and a_2 units of commodity output and biomass, respectively (where $a_1 + a_2 < 1$). In practice, each unit of processed input may also yield other by-products. For example, in the palm industry, processing of fresh fruit palm bunches yields not only crude palm oil (commodity output) and palm kernel shell (biomass) but also other by-products, including palm oil mill effluent and palm kernel. Because our model only considers commodity output and biomass for brevity, it is (implicitly) assumed that unit sale revenue from each of these by-products (if any) is normalized into the processing cost c_0. Hence, we allow c_0 to take negative values.

We consider two channels for commodity output sale, a spot market and a demand which is characterized by a fixed-price fixed-volume sales contract. In particular, we assume that the commodity output can be sold at a unit price p_1 to satisfy demand D_1, and it can be sold to the spot market at the prevailing spot price S_1. The commodity output can also be procured from the spot market at the prevailing price S_1 to satisfy the demand. For biomass sale, we only consider a demand channel which is characterized by a similar sales contract where the firm can sell up to biomass demand D_2 with a marginal sale revenue p_2. Here, p_2 refers to the difference between the unit sale price and the additional unit processing cost incurred (if any) for biomass (e.g., cost for de-fibring). For brevity, thereafter we denote p_2 as the biomass price. We normalize the penalty costs associated with unsatisfied demand for commodity output and biomass to zero. Positive penalty costs can easily be introduced into our model and they do not affect our results. The benchmark model that represents the firm before biomass commercialization can be obtained by setting $D_2 = 0$. Throughout our analysis, to rule out uninteresting cases, we assume $K_0 \geq \max\left(\frac{D_1}{a_1}, \frac{D_2}{a_2}\right)$; otherwise, satisfying the commodity output or biomass demand through processing is not feasible.

In practice, biomass commercialization involves significant fixed costs that are associated with investments in pre-conditioning machines (for removing impurities from the residue and eliminating moisture), storage facility, and transportation assets (for example, conveyor belt or crane for transportation out of the storage facility). These fixed costs require the processors to evaluate the value of biomass commercialization well in advance of the spot day in which the actual conversion of waste into a saleable product takes place. We do not consider the fixed costs in our model as they do not have an impact on our economic analysis. That being said, the significance of these fixed costs reinforces the need for processors to better understand the value of biomass commercialization (which can then be compared with the fixed costs) and also how spot price uncertainty affects this value, the two research questions we answer in §3.3 and §3.4, respectively.

3.2 The Optimal Solution for the Firm's Decisions

In this section, we describe the optimal solution for the firm's decisions after biomass commercialization. The optimal decisions before commercialization can be obtained as a special case. We solve the firm's problem using backward induction.

In stage 1, the firm contracted (reserved) Q units of input. In stage 2, the firm observes the input and output spot price realizations (S_0, S_1). In this stage, constrained by the processing capacity K_0, the firm decides the processing volume z_0, how to source this volume from the available contracted input and spot procurement, the amount of demand to satisfy for the commodity output and biomass, the commodity output volume to sell to the output spot market, and the commodity output volume to buy from the spot market to satisfy demand. Expressing all decisions as a function of the processing volume allows us to formulate the firm's decision problem as a single-variable maximization problem over the processing volume $z_0 \in [0, K_0]$ where the stage 2 objective function is given by

$$\begin{aligned}\Pi(z_0) \doteq & -(z_0 - Q)^+ S_0 - c_0 z_0 + \min(a_2 z_0, D_2) p_2 \\ & + \min(a_1 z_0, D_1)\max(p_1, S_1) + (a_1 z_0 - D_1)^+ S_1 + (D_1 - a_1 z_0)^+ (p_1 - S_1)^+.\end{aligned} \tag{1}$$

In (1), the first term is the input procurement cost from the spot market and the second term is the processing cost. The third term denotes the revenues from biomass demand sale. The remaining terms denote the total revenues from commodity output sales. In particular, for the first $\min(a_1 z_0, D_1)$ units of commodity output, the firm can choose to either satisfy demand at a unit price p_1 or sell to the output spot market at the prevailing price S_1. Therefore, the marginal revenue for these units is $\max(p_1, S_1)$. When all demand is satisfied (i.e., for $(a_1 z_0 - D_1)^+$ units of commodity output), the firm can only sell to the spot market. For the unsatisfied demand over the available commodity output (i.e., for $(D_1 - a_1 z_0)^+$ units), the firm procures from the output spot market to satisfy the demand if it is profitable to do so. Therefore, the marginal revenue for these units is $(p_1 - S_1)^+$.

Proposition 1 characterizes the optimal processing volume z_0^* that maximizes $\Pi(z_0)$.

Proposition 1 *Given a contract volume Q and spot price realizations (S_0, S_1), the optimal processing volume z_0^* is characterized by*

$$z_0^* = \begin{cases} 0 & \text{if } \bar{h}(S_1) \leq 0 \\ \min\left(\frac{D_2}{a_2}, Q\right) & \text{if } \underline{h}(S_1) \leq 0 \leq \bar{h}(S_1) \leq S_0 \\ \frac{D_2}{a_2} & \text{if } \underline{h}(S_1) \leq 0 \leq S_0 \leq \bar{h}(S_1) \\ Q & \text{if } 0 \leq \underline{h}(S_1) \leq \bar{h}(S_1) \leq S_0 \\ \max\left(\frac{D_2}{a_2}, Q\right) & \text{if } 0 \leq \underline{h}(S_1) \leq S_0 \leq \bar{h}(S_1) \\ K_0 & \text{if } S_0 \leq \underline{h}(S_1) \end{cases} \quad (2)$$

where $\bar{h}(S_1) \doteq a_1 S_1 + a_2 p_2 - c_0$ and $\underline{h}(S_1) \doteq a_1 S_1 - c_0$ are unit processing margins when there is unsatisfied biomass demand and no unsatisfied biomass demand, respectively.

The stage 2 objective function $\Pi(z_0)$ in (1) is piecewise linear and concave in z_0. Therefore, the optimal solution occurs at the breakpoints $\left\{0, \frac{D_2}{a_2}, Q, K_0\right\}$ and it is determined by comparing the relevant unit processing margin—that is, the marginal revenue from production minus the processing cost—with the input procurement cost at this stage (which is prevailing spot price S_0 for spot-procured input and 0 for the contracted input).[2] For example, if $\underline{h}(S_1) \leq 0 \leq \bar{h}(S_1) \leq S_0$, then it is profitable to process only when there is unsatisfied biomass demand and only with the contracted input, and thus, $z_0^* = \min\left(\frac{D_2}{a_2}, Q\right)$.

In stage 1, the firm chooses the optimal contract volume $Q^* \geq 0$ with respect to uncertain spot prices so as to maximize the expected profit $\mathbb{E}\left[\pi(Q; \tilde{S}_0, \tilde{S}_1)\right] - \beta Q$, where $\pi(Q; S_0, S_1)$ denotes the optimal stage 2 profit for a given contract volume and spot price realizations.

[2]We note that $\frac{D_1}{a_1}$ is not one of the breakpoints because the marginal revenue from production of commodity output does not change when its demand is satisfied. For $z_0 \leq \frac{D_1}{a_1}$, when $S_1 > p_1$, spot sale is more profitable than satisfying demand and the marginal revenue is $a_1 S_1$. Otherwise (i.e., when $S_1 \leq p_1$), the marginal revenue is again $a_1 S_1$ which is the opportunity gain of not sourcing from the output spot market to satisfy the demand. For $z_0 > \frac{D_1}{a_1}$, only spot sale is possible and the marginal revenue is again $a_1 S_1$.

Proposition 2 *Let* $\underline{\beta} \doteq \mathbb{E}[\min(\tilde{S}_0, (a_1\tilde{S}_1 - c_0)^+)]$ *and* $\bar{\beta} \doteq \mathbb{E}[\min(\tilde{S}_0, (a_1\tilde{S}_1 + a_2p_2 - c_0)^+)]$ *with* $\underline{\beta} < \bar{\beta}$*. The optimal contract volume* Q^* *is given by* 0 *if* $\beta \geq \bar{\beta}$*,* $\frac{D_2}{a_2}$ *if* $\underline{\beta} \leq \beta < \bar{\beta}$*, and* K_0 *if* $0 \leq \beta < \underline{\beta}$*.*

The optimal contract volume is characterized by comparing the unit contract cost β with the expected marginal revenue of an additional unit of contracted input, as given by $\underline{\beta}$ and $\bar{\beta}$. At stage 2, the marginal revenue takes different forms as it depends on the input and output spot price realizations. When the input spot price is less than the relevant unit processing margin, that is $(a_1S_1 + a_2p_2 - c_0)^+$ $((a_1S_1 - c_0)^+)$ when there is (no) unsatisfied biomass demand, it is profitable to source from the input spot market for processing. Therefore, the marginal revenue is given by the opportunity gain of not buying from the spot market; that is, S_0. Otherwise, the marginal revenue is given by the unit processing margin.

Recall that we consider a benchmark model in which the firm only sells the commodity output (and biomass goes to landfill). The firm's optimal decisions in this benchmark model can be obtained from our characterizations by setting $D_2 = 0$. It is important to note that biomass commercialization affects the optimal contract volume. In particular, as follows from Proposition 2, in the absence of biomass the firm optimally procures up to the processing capacity K_0 if $\beta < \underline{\beta}$ and does not procure otherwise. We use this observation in characterizing the value of biomass commercialization in the next section.

3.3 The Value of Biomass Commercialization

The value of biomass commercialization is given by the change in the firm's optimal expected profit due to commercialization; let ΔV denote this value. Because the firm's optimal contracting decision is affected by commercialization and the optimal contract volume is characterized based on the unit contract cost β, we examine the value of biomass commercialization for a given β. In particular, we define $\Delta V(\beta) = V^*(\beta) - V^{nb}(\beta)$ where $V^*(\beta)$ is the firm's optimal expected profit after commercialization (evaluated at the optimal contract volume $Q^*(\beta)$) and $V^{nb}(\beta)$, "nb" stands for no biomass, is the same before commercialization (evaluated at the optimal contract volume $Q^{nb}(\beta)$). Proposition 3 characterizes $\Delta V(\beta)$.

Proposition 3 *The value of commercialization is given by* $\Delta V(\beta) = M(\beta) D_2$ *where*

$$M(\beta) \doteq \begin{cases} \frac{1}{a_2}\mathbb{E}\left[\left(a_2 p_2 - \left(c_0 - a_1\tilde{S}_1\right)^+\right)^+\right] & \text{if } 0 \le \beta < \underline{\beta} \\ \frac{1}{a_2}\left(\mathbb{E}\left[\left(a_2 p_2 + \min\left(\tilde{S}_0, a_1\tilde{S}_1 - c_0\right)\right)^+\right] - \beta\right) & \text{if } \underline{\beta} \le \beta < \bar{\beta} \\ \frac{1}{a_2}\mathbb{E}\left[\left(a_2 p_2 - \left(\tilde{S}_0 + c_0 - a_1\tilde{S}_1\right)^+\right)^+\right] & \text{if } \beta \ge \bar{\beta} \end{cases} \tag{3}$$

with $\underline{\beta}$ *and* $\bar{\beta}$ *as defined in Proposition 2. Moreover,* $M(\beta) \in [0, p_2]$*.*

The value is characterized by the product of biomass demand D_2 and $M(\beta)$ which can be interpreted as the expected biomass margin. This expected margin captures the effects of spot price uncertainty and firm's optimal decisions, and it takes three forms based on the optimal contracting decisions before and after commercialization. The intuition behind each form can be explained based on the *realized biomass margin* on the spot day (stage 2).

Consider the case when the contract cost is high (i.e., $\beta \ge \bar{\beta}$) in which the firm entirely relies on input spot procurement before and after commercialization; that is, $Q^{nb}(\beta) = Q^*(\beta) = 0$. At stage 2, when S_1 is sufficiently small such that it is not profitable to process even in the presence of biomass (i.e., $a_2 p_2 + a_1 S_1 - c_0 \le S_0$), the realized margin is zero. When S_1 is sufficiently large such that it is profitable to process even in the absence of biomass (i.e., $a_1 S_1 - c_0 \ge S_0$), the waste stream is already available, and hence, the realized margin is p_2. For the remaining S_1 realizations, biomass commercialization makes the processing profitable and the realized margin is $p_2 - \frac{S_0 + c_0 - a_1 S_1}{a_2}$. Consider now the low contract cost case (i.e., $\beta < \underline{\beta}$) in which $Q^{nb}(\beta) = Q^*(\beta) = K_0$. In this case, the firm does not rely on input spot procurement and the realized processing margin follows a similar intuition with the high contract cost case after substituting S_0 with 0 (which is the stage 2 procurement cost). The general insights from the high and low contract cost cases are that biomass commercialization does not affect the contract procurement decision and the realized margin at stage 2, which is non-negative, does not exceed p_2.

When the contract cost is moderate (i.e., $\underline{\beta} \le \beta < \bar{\beta}$), biomass commercialization incents the firm to engage in contract procurement where $Q^{nb}(\beta) = 0$ and $Q^*(\beta) = \frac{D_2}{a_2}$. As a result, interestingly, the realized biomass margin at stage 2 can be *negative* and can *exceed* p_2. In particular, when S_1 is sufficiently small such that it is not profitable to process even in the presence of biomass (i.e., $a_2 p_2 + a_1 S_1 - c_0 \le 0$), the realized margin is $-\beta$. In this case, the realized margin is negative because of the contract commitment cost after commercialization. When S_1 is sufficiently large such that it is profitable to process even in the absence of biomass (i.e., $a_1S_1 - c_0 \geq S_0$), the realized margin is $p_2 + \frac{S_0-\beta}{a_2}$. In this case, the realized margin involves the opportunity gain from not sourcing the input from spot market (given by S_0) at a cost of contract commitment (given by β). This realized margin can be larger than p_2 (when the input spot price realization S_0 is larger than β). For the remaining S_1 realizations, biomass commercialization makes the processing profitable and the realized margin is $p_2 + \frac{a_1S_1-c_0-\beta}{a_2}$. Once again, this realized margin can be larger than p_2, specifically when the output spot price realization S_1 is large enough.

The characterization presented in Proposition 3 showcases the complexity of biomass commercialization valuation and emphasizes the need for a formal analysis, as conducted in this paper. As intuition suggests (and as follows from Proposition 3), the value of biomass commercialization cannot be larger than the maximum biomass sale revenue p_2D_2. In the next section we examine how this value is affected from spot price uncertainty.

3.4 Impact of Spot Price Uncertainty

We now conduct sensitivity analyses to study the effects of spot price correlation (ρ) and input and output spot price variabilities (σ_0 and σ_1, respectively) on the value of biomass commercialization $\Delta V(\beta)$. For tractability, we focus on local sensitivity analyses in which the optimal contracting decisions before and after commercialization are not affected by the changes in these parameters—that is, we consider an unaffected ordering of unit contract cost β and the cost thresholds $\underline{\beta}$ and $\bar{\beta}$ given in Proposition 2. With a sufficiently large change in σ_0, σ_1, or ρ, the ordering may be affected because $\underline{\beta}$ and $\bar{\beta}$ depend on these parameters. We consider the effect of such large changes on our results in §5 where we conduct global sensitivity analyses by resorting to numerical experiments.

Throughout this section, we assume $(\tilde{S}_0, \tilde{S}_1)$ to follow a bivariate Normal distribution. We also make two additional assumptions to eliminate unrealistic (and uninteresting) cases: $\rho > 0$ and $a_1\mu_1 > c_0 + \mu_0$—that is, processor has a profitable business (on expectation) before biomass commercialization. Both assumptions are reasonable in the palm industry as we empirically demonstrate in §5. Proposition 4 characterizes the effects of ρ, σ_0, and σ_1 on the value of biomass commercialization $\Delta V(\beta)$.

Proposition 4 *Effects of ρ, σ_0 and σ_1 on $\Delta V(\beta)$ are characterized in Table 1 where $\underline{\beta}$ and $\bar{\beta}$ are as given in Proposition 2:*

Unit Contract Cost β	ρ	σ_0	σ_1
Low: $\beta < \underline{\beta}$	$-$	$-$	$\downarrow$
Moderate: $\underline{\beta} \leq \beta < \bar{\beta}$	$\uparrow$	$\uparrow$ for $\sigma_0 \leq a_1\sigma_1\rho$	$\uparrow$ for $\sigma_1 \leq \sigma_0\rho/a_1$
		$\downarrow$ for $\sigma_0 > a_1\sigma_1\rho$	No analytical result
High: $\beta \geq \bar{\beta}$	$\uparrow$	$\uparrow$ for $\sigma_0 \leq a_1\sigma_1\rho$	$\uparrow$ for $\sigma_1 \leq \sigma_0\rho/a_1$
		$\downarrow$ for $\sigma_0 > a_1\sigma_1\rho$	$\downarrow$ for $\sigma_1 > \sigma_0\rho/a_1$

Table 1: Impact of a Local Increase in Input (Output) Spot Price Variability σ_0 (σ_1) and Correlation (ρ) on the Value of Biomass Commercialization with Bivariate Normal Spot Price Uncertainty: $-$ denotes no change, $\uparrow$ denotes an increase, and $\downarrow$ denotes a decrease.

When the contract cost is low (i.e., $\beta < \underline{\beta}$), $\Delta V(\beta)$ is not affected by changes in ρ and σ_0 because the firm contracts up to the processing capacity K_0 both before and after commercialization, and thus, input spot sourcing is never used. In this case, as follows from Proposition 3, when it is profitable to process after commercialization on the day, the effective marginal sourcing cost of biomass is given by $(c_0 - a_1S_1)^+$ (when $a_1S_1 \geq c_0$, it is profitable to process in the absence of biomass and the effective marginal sourcing cost is zero because waste stream is already available). The influence of σ_1 on $\Delta V(\beta)$ can be explained by its *opposite* effect on the expected marginal sourcing cost $\mathbb{E}[(c_0 - a_1\tilde{S}_1)^+]$. It is well known that this expectation increases in σ_1, and thus, a higher σ_1 decreases $\Delta V(\beta)$.

When the contract cost is high (i.e., $\beta \geq \bar{\beta}$), the firm only uses input spot sourcing before and after commercialization. In this case, as follows from Proposition 3, when it is profitable to process after commercialization on the day, the effective marginal sourcing cost of biomass is given by $(S_0+c_0-a_1S_1)^+$. The sensitivity results in Proposition 4 can be explained based on the opposite of how $\mathbb{E}[(\tilde{S}_0+c_0-a_1\tilde{S}_1)^+]$ changes in ρ, σ_0, and σ_1. It is well known that this expectation increases in the variability of $\tilde{S}_0 - a_1\tilde{S}_1$ which is increasing in the variances of $\tilde{S}_0$ and $a_1\tilde{S}_1$, and is decreasing in the covariance of $(\tilde{S}_0, a_1\tilde{S}_1)$. With a higher ρ, because the covariance increases, the variability of $\tilde{S}_0 - a_1\tilde{S}_1$ decreases, and thus, $\Delta V(\beta)$ increases. With a higher σ_0 (σ_1) both the variance of $\tilde{S}_0$ ($a_1\tilde{S}_1$) and covariance of $(\tilde{S}_0, a_1\tilde{S}_1)$ increase because $\rho > 0$ by assumption. When σ_0 (σ_1) is sufficiently low; that is, $\sigma_0 \leq a_1\sigma_1\rho$ ($\sigma_1 \leq \sigma_0\rho/a_1$), the latter effect outweighs the former and the variability of $\tilde{S}_0 - a_1\tilde{S}_1$ decreases, and thus, $\Delta V(\beta)$ increases. Otherwise, the former effect dominates and $\Delta V(\beta)$ decreases. The impact of spot price uncertainty on $\Delta V(\beta)$ for the moderate contract cost case (i.e., $\underline{\beta} \leq \beta < \bar{\beta}$) can be explained in a similar fashion except for the effect of σ_1. In this case, because the firm only uses input spot sourcing before commercialization but relies on contract after commercialization, $\Delta V(\beta) = \mathbb{E}[(a_1\tilde{S}_1 + a_2p_2 - c_0)^+ - \beta] - \mathbb{E}[(a_1\tilde{S}_1 - \tilde{S}_0 - c_0)^+]$. While the first expectation always increases in σ_1, because the second expectation decreases in the same only when $\sigma_1 \leq \sigma_0\rho/a_1$, the overall impact can only be proven under this condition.

The general insights from Proposition 4 are that the value of biomass commercialization increases in spot price correlation but increases in (input or output) spot price variability only when this variability is low; otherwise, the value decreases in spot price variability.

4 Environmental Implications of Biomass Commercialization

We now investigate the impact of biomass commercialization on the environment. §4.1 describes the environmental model. §4.2 characterizes the conditions under which the firm can justifiably claim that commercializing its biomass is environmentally beneficial and §4.3 examines the impact of biomass market characteristics on the environmental assessment.

4.1 Environmental Model Description and Assumptions

In line with the industry practice and the academic literature (see, for example, Kök et al. 2016), we use carbon emissions to measure the environmental impact and calculate the total expected carbon emissions resulting from profit-maximizing operational decisions before and after biomass commercialization. Echo to our economic model described in §4.1, we consider emissions related to processor's operational activities, including procurement, processing, and selling. To this end, as customary in the literature, we assume a linear emission structure and define a unit emission intensity parameter for each of these activities.

For input procurement, we define $e_0^b > 0$ as the *input buying emission intensity* associated with each input delivered to the processor. This parameter captures the emissions from production (growing) and transportation (to the processor) of the input. We assume that this emission intensity is the same for spot-sourced and contract-sourced inputs which is a reasonable assumption when both inputs are sourced from nearby plantations. Let $e_0^p > 0$ denote the *processing emission intensity* which accounts for the emissions from energy consumption during processing. In our economic model we assume that each unit of input yields other by-products whose revenues are normalized into the processing cost. To capture the emissions associated with these other by-products (for example, emissions related to disposal of palm oil mill effluent), we define $e_3^r > 0$ as the *residue emission intensity* and assume that each unit of processed input yields a_3 units of these by-products (where

$a_3 \leq 1 - a_1 - a_2$). For biomass, paralleling the environmental impact discussed in practice (Ata et al. 2012), we define two emission parameters. For unsold biomass, we define $e_2^l > 0$ as the *landfill emission intensity* which captures the emissions associated with release of methane gas as a result of anaerobic decomposition. For biomass that is sold, we define e_2^s as the *biomass selling emission intensity* which accounts for the emissions associated with additional processing (e.g., de-fibring), transportation, and usage—that is, emissions associated with burning of biomass less the emission savings obtained by substituting fossil fuel for energy production. Although this intensity parameter is unrestricted in sign (because of emission savings), it takes positive values in realistic cases (as empirically verified in §5). For the commodity output, we also define two emission parameters. For the commodity output sold, $e_1^s > 0$ denotes the *commodity output selling emission intensity* which captures transportation (out of the processor) and usage (e.g., refining) emissions. We assume that this emission intensity is the same for output sold to the spot market and output used to satisfy demand. This is a reasonable assumption when both outputs are sold to nearby buyers (e.g., refineries). For the commodity output purchased, $e_1^b > 0$ denotes the *commodity output buying emission intensity* which captures the emissions associated with the production of this output and its transportation to the processor.

To quantify the total expected emissions resulting from profit-maximizing decisions, because the optimal contract volume is characterized based on the unit contract cost β, we define $ECE^*(\beta)$ as the total expected emissions after commercialization for a given β:

$$\begin{aligned} ECE^*(\beta) \doteq & \left(e_0^b + e_0^p + a_3 e_3^r\right) \mathbb{E}\left[z_0^*\left(Q^*(\beta)\right)\right] \\ & + e_1^s \mathbb{E}\left[a_1 z_0^*\left(Q^*(\beta)\right)\right] + \left(e_1^b + e_1^s\right) \mathbb{E}\left[\left(D_1 - a_1 z_0^*\left(Q^*(\beta)\right)\right)^+ \chi(\tilde{S}_1 \leq p_1)\right] \\ & + e_2^s \mathbb{E}\left[\min\left(a_2 z_0^*\left(Q^*(\beta)\right), D_2\right)\right] + e_2^l \mathbb{E}\left[\left(a_2 z_0^*\left(Q^*(\beta)\right) - D_2\right)^+\right]. \end{aligned} \tag{4}$$

In (4), the first term represents the emissions from input sourcing, processing, and residues. The second and third terms denote the emissions associated with commodity output sales and procurement, respectively where the latter emissions are incurred only when it is optimal to source from the output spot market to satisfy demand. The last two terms denote the emissions related to biomass, either from satisfying the biomass demand or waste disposal through landfill.[3] The optimal contract volume $Q^*(\beta)$ can be obtained from Proposition 2 whereas the optimal processing volume $z_0^*(Q^*(\beta))$ can be obtained from Proposition 1 by

[3] We note that $ECE^*(\beta)$ does not include a term directly associated with the optimal contract procure-

substituting $Q^*(\beta)$. The total expected emissions before commercialization, $ECE^{nb}(\beta)$, can be obtained in a similar fashion by setting $D_2 = 0$ and substituting the optimal processing volume $z_0^{nb}(Q^{nb}(\beta))$ in (4).

4.2 Environmental Assessment of Biomass Commercialization

To characterize the impact of biomass commercialization on the environment, we define $\Delta ECE(\beta) \doteq ECE^*(\beta) - ECE^{nb}(\beta)$ as the change in total expected carbon emissions after commercialization. The processor can justifiably claim that commercializing its biomass is environmentally beneficial when it leads to reduction in emissions; that is, $\Delta ECE(\beta) < 0$. When $\Delta ECE(\beta) > 0$, we conclude that biomass commercialization is environmentally harmful. Using $ECE^*(\beta)$ (and $ECE^{nb}(\beta)$) as given in (4), we obtain

$$\begin{aligned}\Delta ECE(\beta) = & \left(e_2^s - e_2^l\right) \mathbb{E}\left[\min\left(a_2 z_0^{nb}(Q^{nb}(\beta)), D_2\right)\right] \\ & + \left(e_0^b + e_0^p + a_3 e_3^r + a_2 e_2^l + a_1 e_1^s\right) \mathbb{E}\left[z_0^*\left(Q^*(\beta)\right) - z_0^{nb}(Q^{nb}(\beta))\right] \\ & - \left(e_1^b + e_1^s\right) \mathbb{E}\left[\left(\left(D_1 - a_1 z_0^{nb}(Q^{nb}(\beta))\right)^+ - \left(D_1 - a_1 z_0^*(Q^*(\beta))\right)^+\right) \chi(\tilde{S}_1 \leq p_1)\right] \\ & + \left(e_2^s - e_2^l\right) \mathbb{E}\left[\min\left(a_2 z_0^*\left(Q^*(\beta)\right), D_2\right) - \min\left(a_2 z_0^{nb}(Q^{nb}(\beta)), D_2\right)\right].\end{aligned} \tag{5}$$

To delineate the intuition behind (5), let us first consider the case where $z_0^*(Q^*(\beta)) = z_0^{nb}(Q^{nb}(\beta))$ for any (S_0, S_1) realization at stage 2—that is, the changes in operational decisions after commercialization are ignored. In this case, only the first term in (5) is relevant. This term captures the expected emissions resulting from converting available waste, which would go to landfill, into a saleable product and using it to substitute fossil fuel in energy production. In this case, consistent with the common perception in practice which also ignores the changes in operational decisions, our analysis reveals that biomass commercialization is environmentally beneficial (harmful) when biomass selling emission intensity is lower (higher) than the landfill emission intensity.

When the changes in operational decisions after commercialization are not ignored, the last three terms in (5) become relevant. Because commercialization creates a new revenue stream, intuitively, for a given contract volume Q, the optimal processing volume for any (S_0, S_1) realization at stage 2 increases (i.e., $z_0^*(Q) \geq z_0^{nb}(Q)$), and thus, the optimal contract

ment volume $Q^*(\beta)$ because we only consider emissions related to input delivered to the processor (and, consistent with industry practice, do not consider emissions related to the reserved but unused input) and we assume that unit input buying emission intensity is the same for spot-sourced and contract-sourced inputs.

volume increases (i.e., $Q^*(\beta) \geq Q^{nb}(\beta)$). As a result, we have $z_0^*(Q^*(\beta)) \geq z_0^{nb}(Q^{nb}(\beta))$ in (5) for any (S_0, S_1) realization. Therefore, the second term in (5) (which captures the emission impact of higher processing volume after commercialization) is always positive—that is, this change is harmful to the environment. Similarly, the third term (which captures the emission impact of lower commodity output procurement volume due to higher output production after commercialization) is always negative—that is, this change is beneficial for the environment. Finally, the last term (which captures the emissions associated with having more waste to be sold as biomass after commercialization) has the same sign with the first term—that is, this change is beneficial (harmful) for the environment when $e_2^s < (>) e_2^l$.

In summary, once the changes in the operational decisions after commercialization are not ignored, environmental assessment is more nuanced. Proposition 5 identifies biomass selling emission intensity and biomass demand as the two main drivers of this assessment.

Proposition 5 *There exist two thresholds $\underline{e}_2^s$, $\overline{e}_2^s$ with $\underline{e}_2^s \leq \overline{e}_2^s$ such that*

(i) if $e_2^s \leq \underline{e}_2^s$, then $\Delta ECE(\beta) < 0$;

(ii) if $e_2^s \geq \overline{e}_2^s$, then $\Delta ECE(\beta) \geq 0$ with equality holding when $e_2^s = \overline{e}_2^s$;

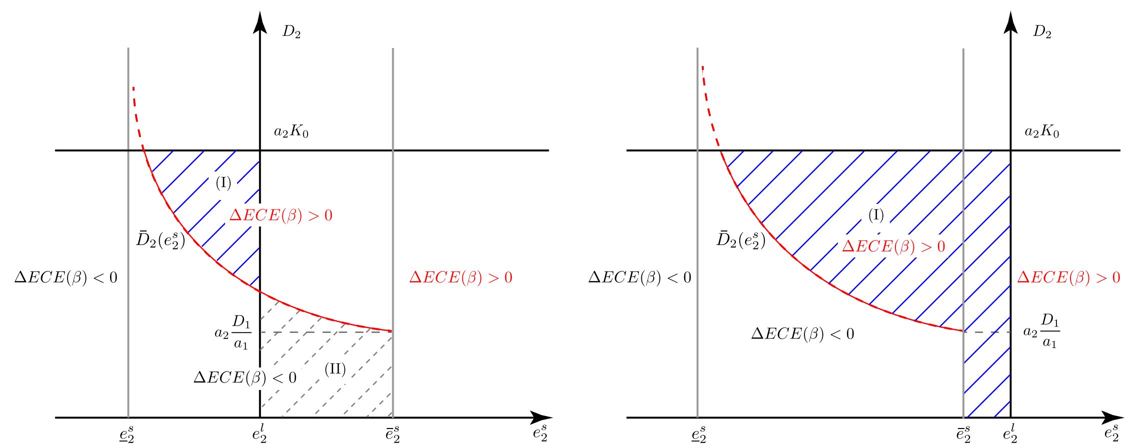
(iii) if $\underline{e}_2^s < e_2^s < \overline{e}_2^s$, then there exists a unique $\bar{D}_2(e_2^s) > a_2 D_1/a_1$ such that $\Delta ECE(\beta) \leq 0$ for $D_2 \leq \min(\bar{D}_2(e_2^s), a_2 K_0)$ with equality holding when $D_2 = \bar{D}_2(e_2^s)$, and $\Delta ECE(\beta) > 0$ for $\min(\bar{D}_2(e_2^s), a_2 K_0) < D_2 \leq a_2 K_0$. Moreover, $\partial \bar{D}_2(e_2^s)/\partial e_2^s < 0$, $\partial^2 \bar{D}_2(e_2^s)/\partial (e_2^s)^2 > 0$, $\lim_{e_2^s \to \overline{e}_2^{s-}} \bar{D}_2(e_2^s) = a_2 D_1/a_1$, and $\lim_{e_2^s \to \underline{e}_2^{s+}} \bar{D}_2(e_2^s) = \infty$.

Proposition 5 establishes two biomass selling emission intensity thresholds $\underline{e}_2^s \leq \overline{e}_2^s$ where once this emission intensity is lower (higher) than $\underline{e}_2^s$ ($\overline{e}_2^s$), biomass commercialization is environmentally beneficial (harmful). When the biomass selling emission intensity is between these two thresholds, biomass commercialization is environmentally beneficial only when biomass demand is lower than a threshold $\bar{D}_2(e_2^s)$ which (convexly) decreases in e_2^s. We defer the discussion of intuition behind how these thresholds are obtained from (5) to the next section (where we discuss how $\Delta ECE(\beta)$ is impacted by the biomass demand D_2).

How does the environmental assessment in Proposition 5 contrast with the common perception in practice? Because this common perception is based on a comparison between biomass selling and landfill emission intensities, we now examine how the emission intensity thresholds established in Proposition 5 compare with the landfill emission intensity.

Proposition 6 *Let $\underline{e}_2^s(e_2^l)$ and $\overline{e}_2^s(e_2^l)$ denote the thresholds defined in Proposition 5 for a given e_2^l. We have $\underline{e}_2^s(e_2^l) < e_2^l$ and there exists a unique threshold $\hat{e}_2^l \geq 0$ such that $\overline{e}_2^s(e_2^l) > e_2^l$ for $0 \leq e_2^l < \hat{e}_2^l$ and $\overline{e}_2^s(e_2^l) \leq e_2^l$ for $e_2^l \geq \hat{e}_2^l$.*

Proposition 6 proves that while the smaller threshold is always lower than the landfill emission intensity e_2^l, the larger threshold is lower than the same only when the landfill emission intensity is small; otherwise, this threshold is higher. Using these results, Figure 1 illustrates the environmental assessment characterization for a given low (panel a) and high (panel b) e_2^l which is set to be the origin of the horizontal axis representing e_2^s.



(a) For a given $e_2^l < \hat{e}_2^l$ (b) For a given $e_2^l \geq \hat{e}_2^l$

Figure 1: When Does Biomass Commercialization Lead to a Reduction (Increase) in Total Expected Emissions; that is, $\Delta ECE(\beta) < 0$ ($\Delta ECE(\beta) > 0$)? Effects of biomass selling emission intensity e_2^s and biomass demand D_2 for a given landfill emission intensity e_2^l.

In comparison with the common perception in practice, Figure 1 highlights two types of misconceptions (and illustrates specific conditions under which they appear). First, in region I, *the processor would mistakenly think that commercializing its biomass is environmentally beneficial when it is not.* In this case, the harmful environmental impact of increasing processing volume after commercialization, the second term in (5), outweighs the other three effects which are beneficial for the environment. Second, in region II, *the processor would mistakenly think that commercializing its biomass is not environmentally beneficial when it is.* In this case, the beneficial environmental impact of decreasing commodity output procurement volume after commercialization, the third term in (5), outweighs the other three effects which are harmful to the environment.

We close this section with an important remark. Recall from Proposition 3 that the value of biomass commercialization is characterized based on three different contract procurement regions (i.e., $\beta < \underline{\beta}$, $\underline{\beta} \leq \beta < \bar{\beta}$, and $\beta \geq \bar{\beta}$). In a particular region because the contract volumes before and after commercialization are independent of β, so is $\Delta ECE(\beta)$, and thus, so are the biomass selling emission intensity thresholds and the biomass demand threshold given in Proposition 5. However, $\Delta ECE(\beta)$ and these thresholds vary across the contract procurement regions. We use this observation in the next section.

4.3 Impact of Biomass Market Characteristics

We now conduct sensitivity analyses to study the effects of biomass demand (D_2) and biomass price (p_2) on the change in total expected carbon emissions after commercialization $\Delta ECE(\beta)$. We say that a change in D_2 or p_2 is environmentally superior (inferior) when it leads to a decrease (increase) in $\Delta ECE(\beta)$. These sensitivity analyses are useful in understanding the environmental consequences of recently implemented government policies (as discussed in the Introduction) that have been devised based on economic consequences.

Although we carry out the sensitivity analyses for any β, for illustration purposes, we focus on the $\beta < \underline{\beta}$ case where the firm contracts up to processing capacity K_0 before and after commercialization. In this case, $\Delta ECE(\beta)$ in (5) can be characterized as follows:[4]

$$\begin{aligned}\Delta ECE(\beta) = &\left(e_2^s - e_2^l\right) D_2\, \mathbb{E}\left[\chi\left(\tilde{S}_1 > \frac{c_0 - a_2p_2}{a_1}\right)\right] \\ &+ \left(e_0^b + e_0^p + a_3e_3^r + a_2e_2^l + a_1e_1^s\right) \frac{D_2}{a_2}\, \mathbb{E}\left[\chi\left(\frac{c_0 - a_2p_2}{a_1} < \tilde{S}_1 \leq \frac{c_0}{a_1}\right)\right] \\ &- \left(e_1^b + e_1^s\right) \min\left(D_1, a_1\frac{D_2}{a_2}\right) \mathbb{E}\left[\chi\left(\frac{c_0 - a_2p_2}{a_1} < \tilde{S}_1 \leq \frac{c_0}{a_1}\right)\chi(\tilde{S}_1 \leq p_1)\right].\end{aligned} \tag{6}$$

The first term in (6) denotes the expected emissions resulting from using available waste of D_2 units, which would go to landfill, to substitute fossil fuel in energy production (which happens on the spot day when processing is profitable after commercialization; that is, $a_1S_1 + a_2p_2 > c_0$). The second term denotes the expected emissions associated with the additional input processing volume D_2/a_2 after commercialization (which happens on the spot day when processing becomes profitable only after commercialization; that is, $a_1S_1 + a_2p_2 > c_0 \geq a_1S_1$). The last term denotes the expected emissions associated with

[4] We relegate the details of this characterization and the characterizations of $\Delta ECE(\beta)$ for the other two cases (i.e., $\underline{\beta} \leq \beta < \bar{\beta}$ and $\beta \geq \bar{\beta}$) to Section B of the online appendix.

the decline in the commodity output spot procurement volume (that is used to satisfy output demand D_1) after commercialization as result of the additional output production volume a_1D_2/a_2 (which happens on the spot day when processing becomes profitable only after commercialization and when it is profitable satisfy the output demand from spot procurement; that is, $p_1 \geq S_1$).

Proposition 7 examines the impact of biomass demand D_2 on $\Delta ECE(\beta)$.

Proposition 7 *Let* $\underline{e}_2^s$ *and* $\overline{e}_2^s$ *as defined in Proposition 5. (i) If* $e_2^s \leq \underline{e}_2^s$*, then* $\partial\Delta ECE(\beta)/\partial D_2 < 0$*; (ii) if* $e_2^s \geq \overline{e}_2^s$*, then* $\partial\Delta ECE(\beta)/\partial D_2 \geq 0$*; (iii) if* $\underline{e}_2^s < e_2^s < \overline{e}_2^s$*, then* $\partial\Delta ECE(\beta)/\partial D_2 < 0$ *for* $D_2 < a_2D_1/a_1$ *and* $\partial\Delta ECE(\beta)/\partial D_2 > 0$ *for* $a_2D_1/a_1 \leq D_2 < a_2K_0$*.*

It follows from (6) that increasing D_2 has a harmful (beneficial) effect on the environment when $e_2^s > (<) e_2^l$ because it increases (decreases) the expected emissions resulting from using available waste. At the same time, it has a harmful effect on the environment because it increases the expected emissions associated with the additional processing volume. Finally, increasing D_2 decreases the expected emissions associated with the decline in the commodity output spot procurement volume, which is beneficial for the environment, only when $D_2 < a_2D_1/a_1$; otherwise, it does not affect these emissions. When the biomass selling emission intensity e_2^s is lower than $\underline{e}_2^s$ (which is smaller than e_2^l as shown in Proposition 6), the beneficial effect associated with using available waste outweighs the harmful effect associated with increasing processing volume without considering the beneficial effect associated with the decline in output spot procurement. As e_2^s increases, the latter effect becomes consequential. In particular, when $\underline{e}_2^s < e_2^s < \overline{e}_2^s$, increasing D_2 continues to be environmentally superior as long as the latter beneficial effect is relevant (i.e., for $D_2 < a_2D_1/a_1$); otherwise, increasing D_2 becomes environmentally inferior. When e_2^s further increases (i.e., $e_2^s \geq \overline{e}_2^s$), the beneficial effect associated with the decline in output spot procurement is always dominated by the combined effects of emissions associated with using available waste and increasing processing volume outweigh, and increasing D_2 is environmentally inferior.

We next examine how changing biomass price p_2 impacts the environmental assessment of biomass commercialization. To avoid uninteresting cases, we restrict our attention to $p_2 < c_0/a_2$ range; that is, biomass revenue itself is not sufficient to justify processing.[5]

[5] Considering $p_2 \geq c_0/a_2$ leads to uninteresting cases. For example, as can be observed from (6), because output spot price $\tilde{S}_1$ is assumed to have a positive support, $\Delta ECE(\beta)$ for $\beta < \underline{\beta}$ is independent of p_2.

Proposition 8 *Assume $p_2 < c_0/a_2$ and let $\hat{e} \doteq e_0^b + e_0^p + a_3 e_3^r + a_2 e_2^l + a_1 e_1^s > 0$. There exist two thresholds $\underline{\underline{e}}_2^s \doteq e_2^l - \frac{\hat{e}}{a_2}$ and $\overline{\overline{e}}_2^s$ with $\underline{\underline{e}}_2^s \le \overline{\overline{e}}_2^s$ such that (i) if $e_2^s \le \underline{\underline{e}}_2^s$, then $\partial \Delta ECE(\beta)/\partial p_2 < 0$; (ii) if $e_2^s \ge \overline{\overline{e}}_2^s$, then $\partial \Delta ECE(\beta)/\partial p_2 \ge 0$; (iii) if $\underline{\underline{e}}_2^s < e_2^s < \overline{\overline{e}}_2^s$, then there exists a unique $\bar{\bar{D}}_2(e_2^s) > a_2 D_1/a_1$ such that $\partial \Delta ECE(\beta)/\partial p_2 \le 0$ for $D_2 \le \min(\bar{\bar{D}}_2(e_2^s), a_2 K_0)$, and $\partial \Delta ECE(\beta)/\partial p_2 > 0$ for $\min(\bar{\bar{D}}_2(e_2^s), a_2 K_0) < D_2 \le a_2 K_0$.*

Proposition 8 demonstrates that the impact of biomass price p_2 is structurally similar to the impact of biomass demand D_2. In particular, when biomass selling emission intensity e_2^s is lower than the threshold $\underline{\underline{e}}_2^s$ (which is also lower than e_2^l), increasing p_2 is environmentally superior. When e_2^s is higher than the threshold $\overline{\overline{e}}_2^s$, increasing p_2 is environmentally inferior. Otherwise (i.e., $\underline{\underline{e}}_2^s < e_2^s < \overline{\overline{e}}_2^s$), increasing p_2 is environmentally superior (inferior) when biomass demand is lower (higher) than $\bar{\bar{D}}_2(e_2^s)$.[6] Although the emission intensity thresholds and the biomass demand threshold are different from the ones in Proposition 7, the intuition behind the characterization of these thresholds is similar. This is because, as can be observed from (6), a higher p_2 affects the emission terms in the same direction with a higher D_2.

It is easy to establish from Proposition 3 that a higher biomass demand or price always increases the value of biomass commercialization $\Delta V(\beta)$. Propositions 7 and 8 demonstrate that a change that is economically beneficial is not necessarily beneficial for the environment.

5 Numerical Analysis: Application to the Palm Industry

In this section, we discuss an application of our model in the context of a palm oil mill processing fresh fruit palm bunches (FFB) to produce crude palm oil (CPO) while generating palm kernel shell (PKS) as organic waste. We calibrate our model parameters to represent a typical palm oil mill in Malaysia selling its PKS to a power plant in Japan. We relegate the description of data and calibration used for our numerical experiments to §A of the online appendix. Using these experiments, we examine the effect of spot price uncertainty on the value of PKS commercialization and the environmental assessment of PKS commercialization where PKS is used for substituting coal or liquified natural gas (LNG).

Throughout this section, $\acute{x}$ denotes the calibrated value for parameter x, "RM" denotes Malaysian ringgit (currency), "mt" denotes metric ton (equal to 1,000 kg), and "CO_2" denotes carbon dioxide which we use for measuring carbon emissions. Table 2 summarizes the calibrated parameter values representing the baseline scenario used in our numerical

[6] We can also prove that the threshold $\bar{\bar{D}}_2(e_2^s)$ (convexly) decreases in e_2^s.

experiments.[7] We use $\acute{\beta} = \underline{\beta} - 0.5\%\acute{\mu}_0 = 98.25\%\acute{\mu}_0$, $\acute{\beta} = (\underline{\beta} + \bar{\beta})/2 = 99.19\%\acute{\mu}_0$, and $\acute{\beta} = \acute{\mu}_0$ to represent the low ($\beta < \underline{\beta}$), moderate ($\underline{\beta} \leq \beta < \bar{\beta}$), and high ($\beta \geq \bar{\beta}$) contract cost cases where $\underline{\beta}$ and $\bar{\beta}$ are calculated based on the calibrated values.

Notation	Description	Value
$\acute{\mu}_0$, $\acute{\mu}_1$	Means of FFB and CPO spot prices	498.77, 2465.20 RM
$\acute{\sigma}_0$, $\acute{\sigma}_1$	Standard deviations of FFB and CPO spot prices	58.60, 255.04 RM
$\acute{\rho}$	Correlation between FFB and CPO spot prices	0.745
$\acute{c}_0$	Unit processing cost (normalized by other by-product revenues)	-39.47 RM/mt
$\acute{K}_0$	Processing capacity	56688.06 mt
$\acute{a}_1$, $\acute{a}_2$	Production yields of CPO, PKS, and residues	19.77%, 5.65%
$\acute{D}_1$	CPO demand	5379.47 mt
$\acute{p}_1$, $\acute{p}_2$	CPO and PKS prices for demand sales	2433.25, 476.40 RM/mt
$\acute{e}_0^b$	FFB buying emission intensity	89.25 kg CO_2/mt
$\acute{e}_0^p$	Processing emission intensity	12.49 kg CO_2/mt
$\acute{a}_3\acute{e}_3^r$	Effective residue emission intensity	209.69 kg CO_2/mt
$\acute{e}_2^l$	PKS landfill emission intensity	1470.00 kg CO_2/mt
$\acute{e}_2^s$	PKS selling emission intensity	151.23 kg CO_2/mt, replacing coal 652.28 kg CO_2/mt, replacing LNG
$\acute{e}_1^s$	CPO selling emission intensity	216.82 kg CO_2/mt
$\acute{e}_1^b$	CPO buying emission intensity	1990.25 kg CO_2/mt

Table 2: Description of the Baseline Scenario Used in Our Numerical Experiments. FFB and CPO spot prices are bivariate normally distributed.

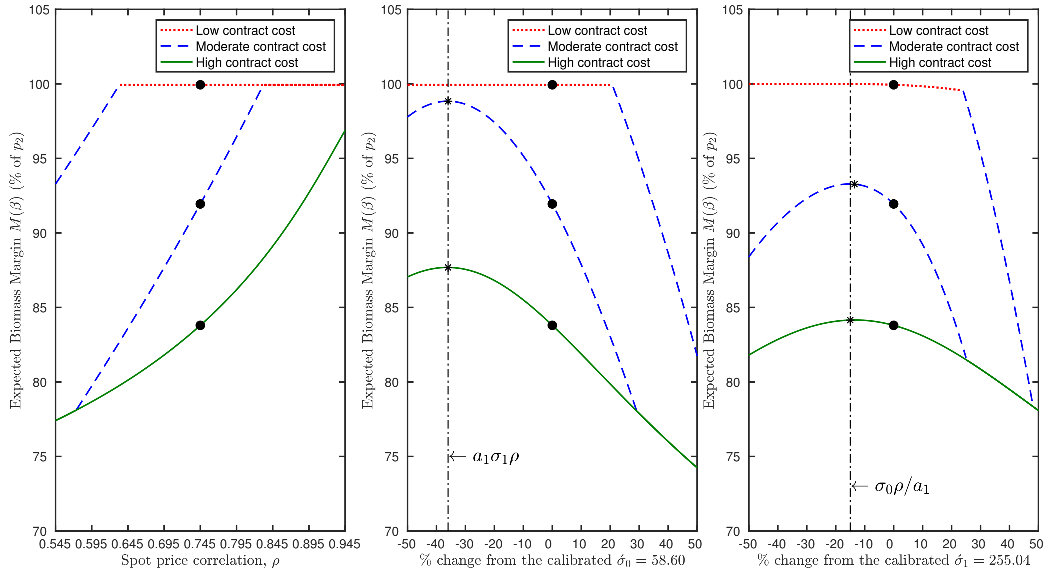
We first examine the effects of FFB and CPO spot price variabilities (σ_0 and σ_1, respectively) and spot price correlation (ρ) on the value of PKS commercialization $\Delta V(\beta)$. Because $\Delta V(\beta) = M(\beta)D_2$ and the influence of these parameters is through their impact on the expected PKS margin $M(\beta)$, Figure 2 plots the effects of changing ρ (panel a), σ_0 (panel b), and σ_1 (panel c) on $M(\beta)$—which is presented as the percentage of the PKS price p_2—in our baseline scenario. Because our model calibration satisfies the assumptions made in §3.4—that is, bivariate Normal distribution of $(\tilde{S}_0, \tilde{S}_1)$ with $\acute{a}_1\acute{\mu}_1 > \acute{c}_0 + \acute{\mu}_0$ and $\acute{\rho} > 0$—we compare our numerical results with the analytical sensitivity results presented in Proposition 4. Our numerical experiments complement the analytical sensitivity analyses in the following two ways. First, they focus on global sensitivity analyses which allow for change in the optimal contracting decisions before and after commercialization. For

[7]There is no $\acute{D}_2$ because our results can be presented without using a calibrated value for biomass demand.

example, as illustrated by dash-dotted line in panel a of Figure 2, when the firm is in the moderate contract cost region ($\underline{\beta} < \beta < \bar{\beta}$) with the calibrated value of $\acute{\rho}$ (represented by $\bullet$), as ρ increases (decreases) there is a transition to low (high) contract cost region $\beta < \underline{\beta}$ ($\beta > \bar{\beta}$). These transitions occur because $\underline{\beta}$ and $\bar{\beta}$ depend on ρ. Second, our numerical experiments examine the effect of σ_1 for an extended range in the moderate contract cost case; Proposition 4 proves this effect only for $\sigma_1 \leq \sigma_0\rho/a_1$. In particular, panel c illustrates that $M(\beta)$ first increases then decreases in σ_1 where the turning point is larger than $\sigma_0\rho/a_1$. This behavior is structurally the same with the high contract cost case. The general insights from Figure 2 parallel the ones from Proposition 4: the value of PKS commercialization increases in spot price correlation but increases in (FFB or CPO) spot price variability only when this variability is low; otherwise, the value decreases in spot price variability.

We next investigate under what conditions a typical palm oil mill in Malaysia can justifiably claim that commercializing its PKS is environmentally beneficial when PKS is used for substituting coal or LNG in the power plant in Japan. To this end, we compute the biomass selling emission intensity thresholds $\underline{e}_2^s$ and $\overline{e}_2^s$, and the biomass demand threshold $\bar{D}_2(e_2^s)$ (as characterized in Proposition 5) in our baseline scenario for the low ($\beta < \underline{\beta}$), moderate ($\underline{\beta} \leq \beta < \bar{\beta}$), and high ($\beta \geq \bar{\beta}$) contract cost cases. Figure 3 illustrates these thresholds for each case where $\bar{D}_2(e_2^s)$ is presented as a percentage of a_2K_0, processing capacity required to satisfy biomass demand, which is no greater than 100% because of our assumption $D_2 \leq a_2K_0$. In each panel the calibrated landfill emission intensity and biomass selling emission intensity with coal (LNG) as the fuel substitute are depicted by $\star$ and $\bullet$ ($\circ$), respectively. Because both biomass selling emission intensities are less than the landfill emission intensity, based on the common perception in practice (which does not consider the changes in operational decisions after commercialization) the palm oil mill would conclude that commercializing its PKS is environmentally beneficial regardless of the fuel substitute.

We observe from panel a that when the contract cost is low, $\underline{e}_2^s = \overline{e}_2^s = \acute{e}_2^l$ and the environmental assessment is consistent with the common perception in practice. In this case, the mill contracts up to K_0 before and after commercialization, and input spot procurement is never used. Because $Pr\left(\tilde{S}_1 > \frac{\acute{c}_0}{\acute{a}_1}\right) \approx 1$ in the baseline scenario; that is, processing is always profitable on the spot day in the absence of PKS revenue, PKS commercialization does not affect the processing volume. Therefore, as follows from (6), $\Delta ECE(\beta) \approx \left(e_2^s - e_2^l\right) D_2$ and PKS commercialization is environmentally beneficial regardless of the fuel substitute

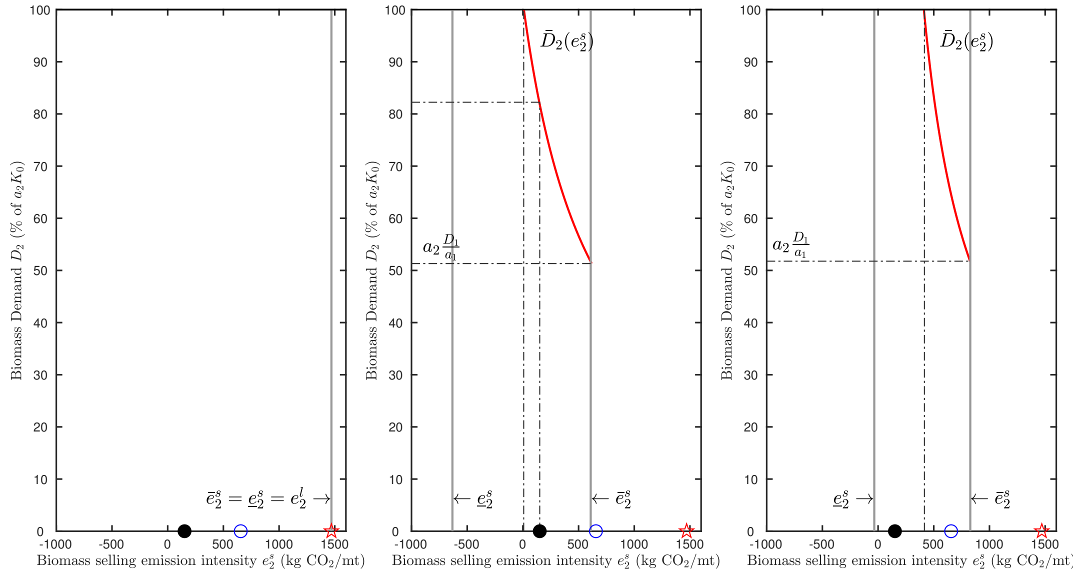


(a) (b) (c)

Figure 2: Effects of Spot Price Correlation ρ (Panel a), FFB Spot Price Variability σ_0 (Panel b), and CPO Spot Price Variability σ_1 (Panel c) on the Expected PKS Margin $M(\beta)$ as a Percentage of PKS Price p_2 in the Baseline Scenario: In panel a, $\rho \in [0.545, 0.945]$ evenly-spaced around the baseline value $\acute{\rho} = 0.745$ with a step size of 0.001 whereas in panel b (panel c), $\sigma_0(\sigma_1) \in [-50\%, 50\%]$ of the baseline value $\acute{\sigma}_0 = 58.60$ ($\acute{\sigma}_1 = 255.04$) with 0.5% increments. In the three panels, baseline scenario for low, moderate, and high contract cost cases are indicated by $\bullet$ aligned horizontally with the baseline value. In panel b (c), $*$ denotes the σ_0 (σ_1) level in which $M(\beta)$ attains its maximum wherever applicable.

because $\acute{e}_2^s < \acute{e}_2^l$. Panel b (c) illustrates that when the contract cost is moderate (high), $\underline{e}_2^s < \overline{e}_2^s < \acute{e}_2^l$ and the environmental assessment may not be consistent with the common perception in practice.[8] For illustration, we focus on the moderate contract cost case which is more representative of a typical palm oil mill because a mixture of contract and input spot procurement is used. In this case (as observed from panel b), the palm oil mill can justifiably claim that commercializing its PKS to substitute coal is environmentally beneficial only when biomass demand is smaller than a level that is associated with approximately 82% processing capacity utilization. Interestingly, when PKS is used for substituting LNG, which is a cleaner energy source, PKS commercialization becomes environmentally harm-

[8]In this case, processing is not always profitable on the spot day in the absence of PKS revenue because input spot procurement is used, and thus, PKS commercialization increases the processing volume.



(a) Low contract cost region (b) Moderate contract cost region (c) High contract cost region

Figure 3: The Environmental Assessment of PKS Commercialization for the Low (Panel a), Moderate (Panel b), and High (Panel c) Contract Cost Cases: In each panel, $\bullet$ ($\circ$) represents the calibrated biomass selling mission intensity e_2^s when PKS is used for substituting coal (LNG) and $\star$ represents the calibrated landfill emission intensity. PKS commercialization is environmentally beneficial when $e_2^s \leq \underline{e}_2^s$ or $\underline{e}_2^s < e_2^s < \bar{e}_2^s$ and $D_2 < \min(\bar{D}_2(e_2^s), a_2K_0)$.

ful regardless of the biomass demand. These results demonstrate that a typical mill may mistakenly think that commercializing its PKS is environmentally beneficial when it is not.

6 Conclusion

This paper studies the economic and environmental implications of biomass commercialization—that is, converting organic waste into a saleable product—from the perspective of agricultural processing firms by incorporating several unique operational features of these firms. On the economic implications, we characterize the value of biomass commercialization and provide insights on how the spot price uncertainty (input and output price variability and correlation) shapes this value. On the environmental implications, we characterize the carbon emission resulting from biomass commercialization and provide guidance on when processors can justifiably claim that commercializing their biomass is environmentally beneficial. We also provide insights on how biomass market characteristics affect this environmental assessment. As summarized in the Introduction, our findings have important practical implications that are of relevance to both agri-processors and policy makers.

In our computational study throughout §5, we calibrated our model to represent a typical palm oil mill in Malaysia. We expect our insights to continue to hold for a palm oil mill in another location (e.g., Indonesia). Because coconut processing and sugarcane processing share common characteristics with the palm processing—for instance, both input and output are commodities, and processing residue is commercialized as biomass—we expect the majority of our findings to be valid for coconut and sugar industries as well. That being said, future research is still needed to verify this conjecture by using our paper's methodology to calibrate the model based on a different agricultural industry.

Relaxing the assumptions made about processing environment gives rise to a number of interesting areas for future research. First, we (implicitly) assume that the processor does not participate in the input spot resale market as a part of its procurement strategy. Second, we normalize the exercise cost of quantity flexibility procurement contract to zero. The availability of spot resale (a positive exercise price) increases (decreases) the profitability before and after biomass commercialization but it is not clear how it would affect the value of commercialization. Finally, based on our interactions with a coconut processor, we assume a fixed-price fixed-volume sales contract for the biomass. Examining the effect of different sales contract forms on our results would be an interesting avenue for future research. For example, the sales contract can be in the form of an index-based contract (Goel and Tanrisever 2017) where the unit biomass price includes a fixed component and a variable component that is indexed on the spot price of the main output.

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