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Optimization Model for the Integration of Biomass into a Conventional Oil Refinery

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Abstract

Using renewable resources such as biomass to produce ethanol and biodiesel to blend into gasoline and diesel, respectively, is becoming popular. It is also possible to integrate biomass into an oil refinery as a feedstock, directly displacing crude oil. This paper investigates the techno-economic viability of using biomass to directly displace crude oil in an existing refinery. Specifically, this paper will identify specific biomasses that could be utilized with corresponding biomass pretreatment methods, determine the points of integration into a refinery, evaluate the economic viability of different integration options, and evaluate the potential to generate energy from biomass. For this purpose an oil refinery mathematical programming model was built and modeled using GAMS and LP. Three main cases were analyzed in this study: Base Refinery, Case II: Ethanol and Biodiesel Blending, and Case III: Direct Biomass Integration. Upon thorough analysis of direct biomass integration options into the refinery model, the use of bagasse in producing pyrolysis oil was best suited for the study as the properties of pyrolysis oil is suitable for direct integration into the existing hydrocracker. In addition, the effect of supply costs, operating costs, and the addition of a hydrocracker to increase plant capacity, were also examined.

Keywords
Biomass, optimization, process integration, petroleum refining.

1. Introduction

Petroleum based gasoline and diesel fuel the cars and trucks, natural gas is used to heat homes and operate commercial furnaces, and petrochemicals are the basis of many plastics. In 2008, the world consumed 85,534,000 barrels of oil per day (Don Hofstrand,2010), and it is projected that demand will rise to 106,600,000 barrels per day by 2030. The rising demand for oil and gas, the decline of cheap, conventional oil, and the governmental and public pressure to reduce pollutants have precipitated the development of “green” and renewable technologies. These technologies strive to achieve the same utility as fossil fuels while leaving a significantly smaller environmental footprint. Gasoline and diesel are the largest petroleum products, totaling 65% of all the products refined from a barrel of oil. Virtually all forms of mechanized transportation relies on these two fuels, so finding cleaner, non-petroleum based fuels can significantly ease the demand on fossil oil and reduce carbon emissions.

This is possible by using biomass which is defined as biological material from any living or recently lived organism. Common examples are sugarcane, corn, switch grass, hemp, and various types of trees. It is commonly converted to energy by simply burning it, usually along with coal, to generate heat and/or electricity (World Factbok,2010). However, biomass can also be converted to fuels or other useful products such as ethanol, syngas, gasoline and diesel.

While alternatives to petroleum fuels are being developed, gasoline and diesel will remain a critical commodity for the near to medium term. Biomass can be an attractive alternative to fossil oil as means of producing transportation fuels. Emerging technologies allow for biomass to be pretreated and integrated directly into an oil refinery to produce bio-petroleum products including bio-gasoline and biodiesel. Crude oil is directly displaced at the source and renewable content in fuels is increased. By adding the ability to produce green fuels into a conventional refinery, the entire fuel production process becomes more streamlined and its integrated nature will allow a more flexible and economic operation.

1.1 Objective

This paper investigates the viability and economics of integrating biomass as a feedstock to displace fossil fuels, including crude oil and coal in a Brazilian refinery. The goal is to formulate a mathematical model based on an optimization framework to provide a practical tool to evaluate and compare different types of biomass that could be utilized. The requisite biomass pretreatment methods were used to determine the points of integration into a refinery and the the economic viability of different integration options were evaluated. The case study in Brazil was chosen for the location of this study due to its vast agricultural and biological capacity and its heavy investment into reducing dependence on crude oil.

1.2 Biomass in Brazil

Brazil is one of the few countries that still has large agricultural growth potential. In the Brazilian Cerrado region which covers 21% of the land area, some 90 million hectares of arable land remains undeveloped (Cerrado,2010), (Ethanol Fuel in Brazil, 2010) Brazil is the world's largest producer of sugarcane, harvesting 558.50 million metric tons in 2007. A full 1% of Brazil's arable land is dedicated to the cultivation of sugarcane which has been historically very important to the economic well being of Brazil and continues to be a core agricultural resource. The next most abundant crop in Brazil is soybean, with a production rate of 51.18 million metric tons in 2005 (UN Data,2010).

One biomass resource that has not been fully utilized in Brazil is bagasse which is the leftover sugarcane material after the sugar has been extracted from the cane. Some of it is currently used for cogeneration at sugar mills, but a significant amount of material still goes to waste. Brazil produced 134.5 million metric tons of bagasse in 2007, about 24% of the total sugarcane harvest by weight (Merchant Research & Consulting, 2010).

1.3 Biofuels in Brazil

1.3.1 Ethanol

In response to the oil crisis of 1973, the Brazilian government implemented its National Alcohol Program in 1975 in order to start phasing out fossil fuel derived automobile fuels. Notably, bioethanol from sugarcane was favoured as an alternative to gasoline. Pure gasoline is no longer available in the country; government regulations mandate that gasoline blends must contain between 20% and 25% ethanol by volume. Neat (100%) ethanol fuels are also available, and about 10% of light duty automobiles in Brazil are capable of running them. The exact amount varies depending on the availability of sugarcane and ethanol. Starting Feb 1, 2010, the Brazilian government has reduced the amount of ethanol blended into gasoline from 25% to 20%, citing supply concerns and high ethanol fuel prices (Agriculture in Brazil, 2010). Ethanol production in Brazil is thoroughly integrated with sugar production and electricity generation produced from sugarcane by-products.

1.3.2 Biodiesel

Recently, Brazil has started to mandate the blending of biodiesel with regular diesel. Biodiesel is created through a transesterification process between vegetable oils and anhydrous ethanol. 95% of the vegetable oil produced in Brazil is from soybean crops. Other possible sources of vegetable oil include sunflower, peanut, castor, and palm. Biodiesel burns significantly more cleanly than fossil diesel. On a well-to-wheel basis, an estimated 78% less carbon dioxide is produced by biodiesel (Agriculture in Brazil, 20108). Brazil first mandated biodiesel blends in 2008, and since then has steadily raised the blend level each year and currently targets a 20% biodiesel blend for big cities and 10% in rural areas by 2015. The most recent increase came into effect January 1, 2010 and raised the biodiesel blend from 4% to 5%. Brazil's annual biodiesel production capacity of 3.6 billion liters is well in excess of the 2.4 billion litres that will be required in 2010 to meet the 5% biodiesel blend mandate (Brazil's Biodiesel Rush, 2010), (Food and Agriculture, 2010), (The Lipid Library,2010)

2.0 Biomass Integration

Integrating biomass into a refinery reduces dependence on crude oil by substituting it with a bio-oil that can be processed in a similar fashion to fossil oils. Depending on the amount of biomass fed to the refinery, it may be possible to achieve the mandated biodiesel level without additional blending at the end. By integrating biodiesel production into the refinery, the costs associated with purchasing it from a biodiesel refiner and transporting it to the blending site can be eliminated. Cogeneration is also possible, thereby reducing dependence on coal and natural gas. Using biomass to produce ethanol on site at the refinery is also an option. These integration pathways are summarized in Figure 1 and explained in further detail in Section 3.0.

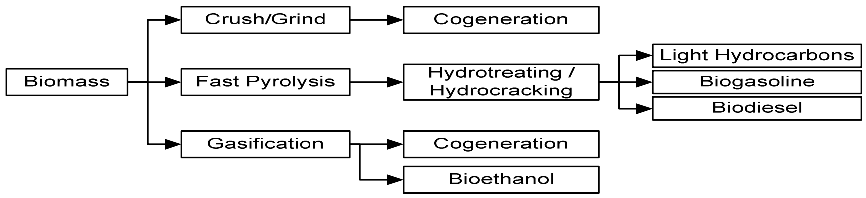

Figure 1: Summary of Integration Pathways of Biomass Into a Refinery

2.1 Biomass Selection

In order to achieve a sustainable, long term solution, the selection of biomass is very important. Domestic or agricultural wastes are examples of biomass that may be used without negative impact on food prices.

2.1.1 Bagasse

After sugarcane is pressed and juiced, the remaining plant matter is known as bagasse. In Brazil, bagasse is a large source of agricultural waste that has not yet been utilized. Net availability of bagasse in Brazil for 2007 was 75.84 million metric tons, 56% of the gross bagasse production that year (Matter Network, 2010).

The total production of some of Brazil's largest crops for 2005-2007 is shown in Table 1. The amount of bagasse available is extremely great, by mass surpassing the total production of any other crop except sugarcane, from which bagasse comes. Since sugarcane is already closely tied to the fuels industry, and the availability of bagasse is proportional to the sugarcane harvest, its production will never be outpaced by the growing sugarcane or ethanol production for fuels.

Table 1: Total Production of Brazil's Major Crops and Bagasse for the Years 2005-2007 (Matter Network, 2010)

	Total Production (thousands of metric tons)						
Year	**Corn**	**Rice**	**Soybean**	**Wheat**	**Sugarcane**	**Sugarcane Bagasse**	**Net Available Bagasse**
2005	35,113	13,193	51,182	4,659	422,957	106,470	61,430
2006	42,662	11,526	52,465	2,485	477,411	121,150	71,646
2007	52,112	11,061	57,857	4,114	549,707	134,550	75,840

2.1.2 Soybean oil

Soybean oil is one of the world's major edible vegetable oils. In 2002-2003, soybean oil accounted for about half the worldwide production of edible vegetable oil production (R. Jorapur and A.K. Rajvanshi, 1997). Brazil produced 6.1 million tonnes of soybean oil in 2008 (Gasification, 2010).

2.2 Cogeneration

Cogeneration refers to the simultaneous production of heat and electricity. Cogeneration also reduces the load on the country's power grid and reduces the need for centralized power plants. In typical cogeneration units, coal or natural gas is burned, and electricity is produced via a steam turbine, gas turbine, gas engine. The leftover heat from producing electricity is recovered. Bagasse can be fired instead of coal or natural gas to achieve the same result.

In Brazil, bagasse is already used as a fuel for cogeneration facilities. Many sugar/ethanol production facilities are totally energy self-sufficient and can even sell electricity back to the grid. Compagnie Thermique de Savannah in Mauritius operates a bagasse fired cogeneration facility in which 74.5MW of electricity and 140 tonne/hour low pressure steam are produced. 65MW is put into the grid. The facility achieves an electrical efficiency of 40%-45%, which is typical of a thermal power plant, and a thermal efficiency of about 85%, which is excellent.

To replace coal or any other solid fuel in a cogeneration facility, bagasse must first be dried to less than 10% moisture and crushed or ground. Dry ash free bagasse has a heating value of 19,400kJ/kg (Brazil's Biodiesel Rush,

2010) and compares reasonably with coal. Bagasse releases 2 to 4 time less particulate emissions than coal (Brazil's Biodiesel Rush, 2010).

To replace natural gas in a cogeneration facility, bagasse will need to undergo a gasification process. After being reduced to a particle size of less than 5cm and approximately 10% moisture, bagasse is subjected to temperatures above 700 C under controlled oxygen and/or steam conditions (Biomass Co-processing and co-firing,2006). The chemistry of the gasification process may be summarized in four steps (FAOSTAT, 2009).

1. Devolatilization – under high temperatures, all the volatile components is released, leaving behind a char
2. Combustion – some of the char reacts with oxygen to form carbon monoxide or carbon dioxide
3. Gasification – char reacts with carbon dioxide and steam to produce carbon monoxide and hydrogen
4. Water gas shift reaction – balances the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen according to $CO + H_2O \leftrightarrow CO_2 + H_2$

Under the high temperature conditions of a gasifier, this reaction reaches equilibrium very quickly. The syngas produced in the gasifier can be used to fire furnaces for cogeneration, among other uses. As a fuel, it is desirable to maintain an H_2/CO ratio between 1 and 2. Syngas typically has a heating value between 100 and 450 btu/scf, compared to a value of 1000 btu/scf for natural gas. Red Lion, an American company, claims that it can produce a syngas with a heating value of at least 350 btu/scf by using rice straw and rice hulls with an efficiency of 70% (Biomass Co-processing and co-firing,2006).

3.0 Modeling

3.1 Linear Programming

Linear programming is often used in refineries for investment planning, operations planning over an extended period, and also day-to-day plant scheduling. With the use of linear programming, the profit of a refinery can be maximized by deducing the most optimal route to generate products, based on current operating costs, product profits, and feed costs.

Biomass integration into a refinery is a relatively new concept. As such, technical and analytical information is not readily available. The detailed chemistry and engineering behind biomass pretreatment and integration into a refinery is not accessible. The primary objective of this investigation is to obtain a general overview of how much biomass can be directly integrated into a conventional refinery. Our primary concern lies in the operating costs of additional units required for biomass integration, as well as the cost for the biomass base feed stock. Since the overview of this objective is broad in nature, linear programming is sufficient to capture the main details of a refinery while allowing for the manipulation of additional process streams and units.

General Algebraic Modeling System (GAMS) is the mathematical programming tool used to model the refinery in this project. GAMS is designed to model a multitude of systems including linear, nonlinear and mixed-integer optimization problems. As such, this tool is very applicable to refinery problems as the chemistry and mathematics behind the engineering is generally non-linear in nature. GAMS allows the linear model utilized in this investigation to be optimized quickly and efficiently.

3.2 Refinery Model

Here,the model developed by Allen (1971), has been adapted and utilized. The main refining processes in this model are focused on the crude distillation unit and the catalytic cracker. The model is able to simulate the distillation unit (physical separation) and the catalytic cracker (chemical reactions) through conversion ratios. Crude oil is the main feed into the plant while gasoline, naphtha, diesel, jet fuel, heating oil and fuel oil are produced as products. Products such as gasoline, diesel, heating oil, and fuel oil are obtained through blending.

The main constraints in this model include the capacity of the distillation unit and the catalytic cracker, along with the demands of the produced products. These are both listed in Table 2 and Table 3. The main objective of the linear program is to maximize the overall profit. This equation is shown below:

Profit = Product Revenue – (Feed Cost + Operating Cost)

$$profit = \sum_j \left(p_j - C_j \right)$$

Table I: Capacity of the Main Operating Units in the Refinery Model

Unit	Capacity (Tonne/day)
Primary Distillation	15,000
Catalytic Cracker	2,500

where p_j is the profit of stream j, c_j is the operational and purchasing cost of producing stream j, and x_j is the production flow rate for stream j. Product profits along with crude oil costs were also obtained and factored into the linear program. The following table summarizes the cost of crude oil and profits obtained from each product produced from crude oil.

Table II: Cost and Profit of Crude Oil and Refined Crude Oil Products (A. Leiras, personal com., March 2, 2010)

Product	Cost/Profit ($/tonne)
Crude Oil	422
Gasoline	692
Naphtha	299
Diesel	669
Jet Fuel	600
Heating Oil	680
Fuel Oil	180

The LP optimizes and maximizes plant profit by altering crude and product flow rates. As such, the solution to the linear program will provide results such as the total flow of crude oil into the refinery and product flow rates.

3.2.1 Base Refinery Model

The base refinery model used is essentially the Allen's model (Oil, 2010) which has been updated in terms of operating costs, crude and product prices, and the product conversion ratios. Figure 2 illustrates the base refinery model, which was used as the main reference for comparison in the study. Here, the main products are obtained from processing crude in the primary distillation tower and in the hydrocracker. Gasoline, diesel, heating oil and fuel oil are obtained through blending of other crude products at a fixed ratio.

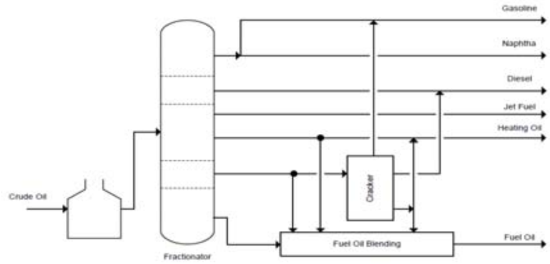

Figure 2: Base Refinery Process Flow Diagram

3.2.2 Case II – Blending of Biomass

The second case considered is the blending of ethanol and biodiesel into the product gasoline and diesel stream respectively. Blending is done to meet and achieve the standards set by government regulations. Currently, ethanol and biodiesel are produced offsite of the refinery and shipped into the plant. Product blending is essentially completed during the last stages of gasoline and diesel production.

In the investigation performed, ethanol and biodiesel are produced on site and blended. By doing so, transportation costs are reduced. Ethanol is produced through the fermentation of sugar and molasses whereas biodiesel is produced through the trans-esterification of a vegetable oil with a short chain alcohol such as methanol or ethanol. In Brazil, biodiesel is produced mainly from soy oil, and as such, soy oil is utilized as a feedstock here. Figure 3 illustrates the flow diagram for the blending of ethanol and biodiesel into the product gasoline and diesel streams.

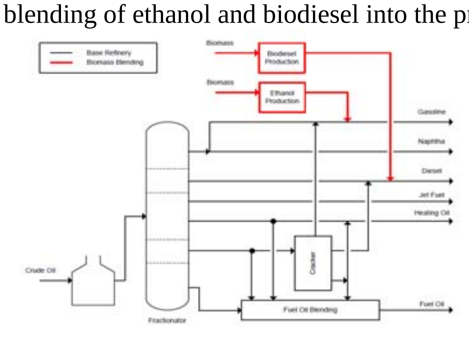

Figure 3: Case II - Blending of Biomass

3.2.3 Case III – Direct Integration of Biomass into Refinery Model

As discussed earlier, there are various locations in a refinery that are optimal for biomass integration. However, integration locations for biomass in the refinery model are limited to the units available. The model utilized in this investigation is simplistic in nature, containing only a primary distillation unit and a catalytic cracker. From the technical evaluation of the options available, it has been found that the chemical properties and composition of pyrolysis oil make it viable for direct integration into a hydrocracker. The main products obtained from the hydrocracking of biodiesel are gasoline, diesel, water, and light end hydrocarbons. Sucrose is extracted from the cane and the resulting cellulosic waste, bagasse, is normally burned to produce electricity. As an alternative to combusting bagasse for energy, this material could be used as an abundant feedstock into a refinery.

In this investigation, bagasse is purchased and treated at the refinery. Bagasse is first converted into a bio-oil through pyrolysis and then fed into the current hydrocracker in the model. The pyrolysis of bagasse generates 60 - 70 wt% pyrolysis oil, with the remainder being waste and solid-char (Gary, J. H., & Handwerk, G. E., 2001). The conversion of pyrolysis oil in a hydrocracker into its petroleum products have been inputted into the refinery model as 30 wt% gasoline, 8 wt% diesel and the remainder being water and light ends (Gary, J. H., & Handwerk, G. E., 2001).

The direct integration of biomass into a refinery could potentially be the next step a refinery takes to reduce its dependence on crude oil to produce petroleum products. Ethanol and biodiesel blending has already been incorporated into most refineries in Brazil. As such, the current investigation of direct biomass integration into a refinery will include the original blending of ethanol and biodiesel produced through sugarcane and soy oil. Gasoline and diesel produced from hydrocracked pyrolysis oil will also contribute to the total blending requirements of gasoline and diesel. Figure 4 illustrates the process flow diagram for direct biomass integration into the refinery model.

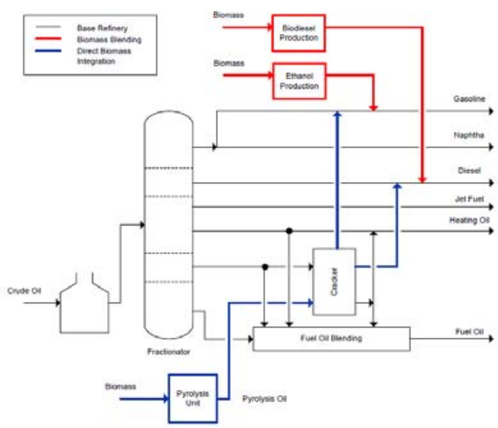

Figure 1: Case III – Direct Integration of Biomass into the Refinery

4.0 Results Discussion

4.1 Case Comparison

The base case along with Case II, blending, and Case III, direct biomass integration, scenarios were evaluated in GAMS and the resulting optimized solutions were compared. The main purpose of the base refinery in this investigation is to provide a basis to compare the scenarios evaluated in Case II and Case III. Figure 5 compares the revenue, costs, and profit obtained from the three cases investigated. The first observation to note is the sharp increase in profit for Case II and Case III compared to the base refinery. The capacity of the refinery to process crude is basically capped at 86.1% of the total distillation tower capacity. The product demands, type of crude oil and the conversion ratio of crude oil to petroleum products constrain the amount of crude oil processed in the refinery. As such, no additional crude oil is processed in the refinery in Case II and Case III compared to the base refinery model. The maximum capacity of the distillation tower will only be fully utilized if the product demands are increased from their current values.

The same observation is observed for the operation of the hydrocracker. From the optimized results for the base refinery and Case II, it is observed that 65.7% of the capacity of the hydrocracker is utilized. Once again, the type of crude oil, the product demands, and the conversion ratios of crude oil to petroleum products reflect the capacity of the hydrocracker utilized. However, once the pyrolysis oil stream is integrated into the hydrocracker in Case III, it

is observed that 100% capacity of the hydrocracker is utilized. This outcome is understandable as additional feed, the pyrolysis oil, is introduced into the hydrocracker to be processed.
A 62.5% increase in profit is obtained from the blending of ethanol and biodiesel into the crude product streams compared to the base refinery case. In Case III, a 79.1% increase in profit is attained by directly integrating pyrolysis oil into the hydrocracker, compared to the base case. As explained above, the capacity of the refinery is reached in the base case and the addition of biomass in Case II and III does not increase the volume of crude oil processed in the refinery. The increase of profit comes from the increased volume of gasoline and diesel produced through the blending of ethanol, biodiesel, and gasoline produced from pyrolysis oil.
There is only a 10.2% profit increase in Case III compared to Case II. This profit increase comes from the slightly cheaper production means of bio-gasoline and biodiesel from pyrolysis oil. The 10.2% profit increase indicates that the direct integration of biomass into a refinery may not be a significantly profitable project as the initial capital investment on the pyrolysis unit is not taken into account in this investigation.

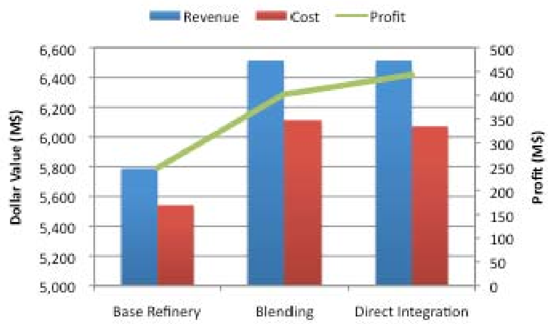

Figure5: Comparison of Revenue, Cost and Profit for the Cases Investigated

Figure 6 compares the yield of gasoline obtained in each of the three cases investigated. As shown, the production of gasoline from conventional crude oil is unchanged from the base refinery, to Case II and Case III. The additional gasoline yield is obtained from the blending of bio-fuels generated from biomass. In Case II, the E-25 blending requirements are met by the production of ethanol and biodiesel from sugarcane only. However, once direct integration of pyrolysis oil into the hydrocracker is introduced in Case III, it is noted that the blending requirements in gasoline is also contributed by the bio-gasoline produced from pyrolysis oil. Ethanol produced from the fermentation of sugarcane, contribute to 70.7% of the E-25 blending requirements while bio-gasoline produced from the pyrolysis of bagasse, contributes 29.3% to the remainder of the blending requirement.
Similarly, Figure 7 illustrates the yield of diesel in each of the three cases investigated. Once again, it is noted that the production of diesel from conventional crude oil is capped in all three of the cases. This observation is understandable as the production capacity of the distillation tower and hydrocracker is met in all three cases.

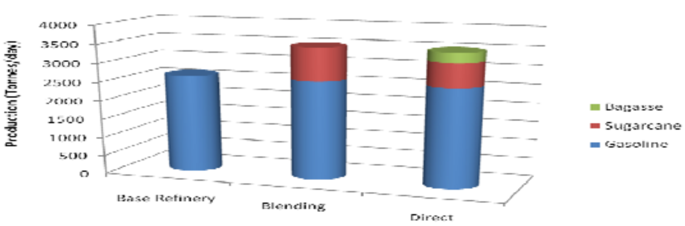

Figure 6: Case Comparison of Gasoline Yields

The additional yield in diesel is obtained through the blending of biodiesel produced from soy oil and the pyrolysis of bagasse. As shown, in Case II, the B-5 blending requirement is met by the biodiesel produced from soy oil. However, once pyrolysis oil is integrated into the existing hydrocracker in the refinery, biodiesel generated from bagasse also contributes to the B-5 blending requirements. In Case III, biodiesel produced from soy oil supplies 65.6% of the blending requirement while biodiesel produced from bagasse contributes 34.4%.

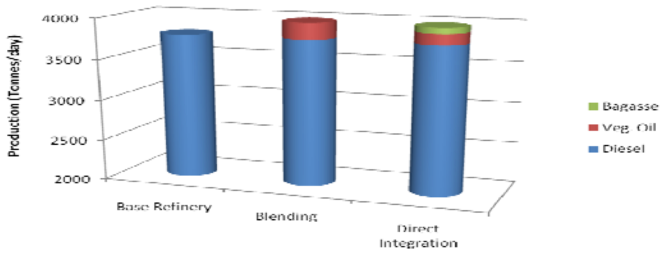

Figure 7: Case Comparison of Diesel Yields

4.2 Electrical Energy Consumption

The electrical energy consumption of both the primary distillation unit and the catalytic cracker for three models in question was also compared. Table 4 shows basic economic values for utilities used in a typical refinery.

Table III. Basis for economic calculations (modified from (Maples, 1993))

Utilities	Dollar per unit
Electric Power	0.06 per Kwh
Fuel	3.00 per MMBTU
Steam (low to high pressure)	3.00-4.50 per M lb

Considering that the primary unit operates at atmospheric pressure, correlations indicate that 0.05 Kwh/bbl, 100 kBtu of fuel /bbl, and 25 lb of steam/bbl are required during normal operation (Bradley, D., 2006). In comparison, the hydrocracker is a much more energy intensive unit as it breaks down heavy hydrocarbons (C_{20} to C_{50}) into lighter hydrocarbons chains, usually being C_{20} and lighter (Bradley, D., 2006). That being said, it was estimated that the catalytic cracker consumes approximately 2,000 scf of hydrogen/bbl. A summary of the operating requirements for each unit can be found in Table 5.

Table 5. Operating Requirements for Refinery Units [18]

	Electricity	Fuel	Steam	Hydrogen
Primary Unit	0.05 kwh/bbl	100 kBtu/bbl	25 lb/bbl	-
Hydrocracker	13.1 kwh/bbl	213.9 kBtu/bbl	-	2,000 scf

Electricity costs are in Table 6. Both the base case and the blending case have the same energy consumption as the flow rates processed by each unit are equal. However, given that the catalytic cracker feed increased when the pyrolysis oil stream was added for the direct integration model, an increase in cost is evident.

Table 6. Energy Consumption for all Models

Unit	Base Model		Blending of Biomass		Direct Integration of Biomass	
	KWh/day	$/day	KWh/day	$/day	KWh/day	$/day
Primary Unit	47,345	2,841	47,345	2,841	47,345	2,841
Catalytic Cracker	157,789	9,467	157,789	9,467	240,058	14,403
Total	205,134	12,308	205,134	12,308	287,402	17,244

4.3 Effect of Crude Oil Prices

Based on the fact that crude oil price is one of the main variables in the model, due to its coefficient value, it was evident that the impact of crude oil prices on the viability of biomass blending and direct integration was worth investigating.

It is evident that both the second case and the third case can produce higher profits at a particular crude oil price versus the base case, where no biomass is integrated. For example, at a crude oil price of $230/tonne, the blending of ethanol and biodiesel into the crude product streams yields an increase of 5.5% in profit against the base refinery model case.

4.4 Fluctuating Vegetable Oil Prices

The lowest, highest, and average prices of soyoil used are $694.6/tonne, $1635.3/tonne, and $1177/tonne, respectively. The results obtained from the linear program based on these price levels can be found in Figure 10. It is observed that both the blending and the direct integration scenarios exhibit the same trend. An increase in profit as the vegetable oil prices decreased is observed.

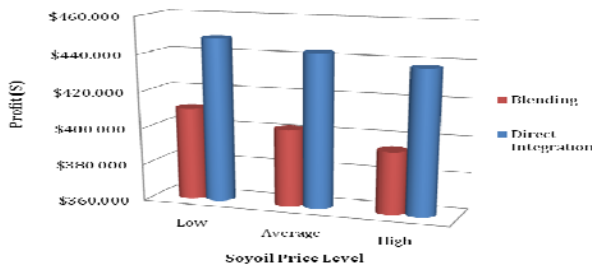

Figure10: Effect of Soyoil Price Levels on Profit

4.5 Operating Cost of Bagasse Unit

Converting bagasse into pyrolysis oil is still a relatively new concept and technology. For that reason, most studies have been done based on bench scale and pilot plant experiments, yielding very little information on the actual cost of the bagasse processing unit. For our model, the bagasse processing unit was estimated to have an operating cost of $75 per tonne processed, which is equivalent to 15 times more expensive than the cost of the primary distillation unit. Considering that this estimate might not be the most accurate value, an investigation of the operating cost of the unit was launched.

For this investigation, the cost of the processing unit was varied from $5 per tonne to $150 per tonne. The impact of the unit processing costs on the refinery profit can be found in Figure 11. First of all, it can be said that the bagasse unit operating cost affects the profit in a linear manner, as this is a linear optimization problem. Next, by determining the slope of the diagram, it was found that a dollar increase in the operating cost will reduce the profit by approximately $1428.

A closer look at Figure 11 shows the highest operating cost for the bagasse processing unit that the model can handle is $103.75 per tonne. At this value, the operating cost for the bagasse unit is approximately 20.75 times more expensive than the primary distillation unit operating cost. It was noted that higher values would result in biomass blending as the preferred method for incorporating biomass into the refinery.

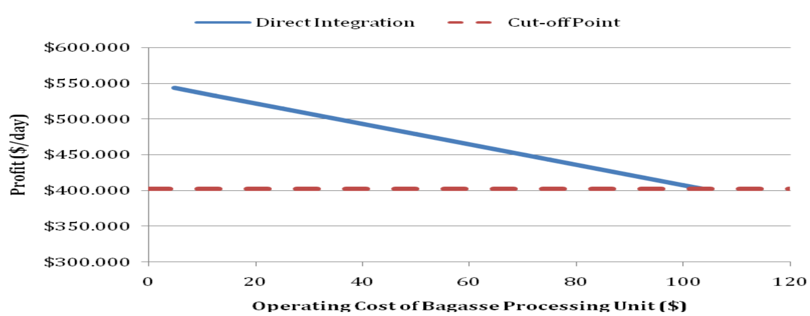

Figure 2: Effect of Bagasse Processing Unit Cost on Refinery Profit

5.0 Conclusions

It was concluded that fast pyrolysis is currently the most efficient method of integrating biomass into a refinery. The benefit of fast pyrolysis is that it uses bagasse as a feedstock, which is not only relative cheap but it also allows for its direct addition into existing catalytic crackers. Moreover, it was found that the refinery profitability was highly increased through direct integration of biomass. Biomass blending was also able to increase the profitability of the refinery but to a lower degree in comparison to the direct integration scenario. In addition, the direct integration model had the added benefit of being less susceptible to crude oil fluctuations and even biomass price fluctuations.

The investigation of fluctuating biomass feed prices found that the highest profitability was obtained when the price of vegetable oil was the highest and the price of sugarcane was the lowest. The main reason being that sugarcane volumes greatly exceed those of vegetable oil; as such the profit is more sensitive to changes in sugarcane prices.
In addition, the investigation of processing costs for the bagasse unit indicated that costs greater than $103.75 per tonne would render the direct integration method uneconomical. Moreover, it was found that a dollar increase in the operating cost would cause a reduction in profit of approximately $1428.
In terms of generating energy from biomass, it was determined that this would be feasible if pyrolysis oil was being produced. It was found that the non-condensable gas stream produced during the conversion of bagasse to pyrolysis oil could be recycled and combusted offsetting as much as 89% of the total electrical energy consumption.

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