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Techno-economic Modelling of a Sugarcane Biomass Torrefaction Plant Producing an Alternative Solid Fuel for Coal-Fired Power Plants in the Philippines

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While most of the world is decarbonizing its energy mix, the Philippines has become more coal-intensive. Coal-fired power dominated the generation mix in the Philippines at 58 % in 2021, up from 26 % in 2008. Taking a cue from countries such as India, which pursued the torrefaction of local agricultural residues to replace coal, while recognizing the Philippines’ 4,450 MW of non-food biomass resource availability, technical and economic modeling of a local torrefied biomass production facility was undertaken to determine the viability of its product as an alternative fuel. Geographic market analysis matched biomass resource availability with coal fleet location, arriving at the selection of sugarcane residues as raw material, the Negros Island as facility location, and power plants in Central Philippines as target off-takers. Aspen Plus™ was used to model a scaled-up production facility based on laboratory-scale kinetic data of sugarcane residue torrefaction. Economic analysis shows that a 5-10 % co-firing rate of torrefied sugarcane biomass is achievable in 6 power plant units in Central Philippines with a total capacity of 627 MW, and the levelized fuel price at 12 % IRR is 20 % less than the average Newcastle prices in 2021-2022. With uncertain coal price trends due to geopolitical factors that influence international fuel supply and with 91 % of local coal usage reliant on imports, local biomass torrefaction can open a pathway towards decarbonizing recently built coal power plants and strengthening the country’s energy self-sufficiency.

1. Introduction

From renewables having more installed capacity than coal in 2008, the growth of fossil fuel in the Philippines has tremendously eclipsed that of renewables – coal alone is at 1.47 times the combined installed capacity of renewables in 2021. The generation mix shows a worse outcome; from contributing a quarter of the country's energy needs in 2008, coal has dominated the mix at 58 % by 2021. During the same period, the contribution of renewables in the generation mix has shrunk from a third to just over a fifth of the total energy mix, despite the law’s target of having renewables generate a minimum of 35 % (Department of Energy Philippines, 2017).

On the other hand, the utilization of biomass, a baseload renewable energy resource, has remained low. The Philippines as an agricultural country is gifted with abundant biomass resources. An inventory conducted by the Department of Energy and the United States Agency for International Development showed a total biomass potential of 4,450 MW (Senate of the Philippines 19th Congress, 2016). With only 489 MW or roughly 10 % installed out of the potential as of 2021 (Department of Energy Philippines, 2022), the growth remains promising.

In investigating biomass utilization, torrefaction can be seen as a viable pathway. It involves the slow heating of biomass in a low-oxygen environment to produce biofuels which can replace coal in various industrial applications (Gent et al., 2017). A similarly agricultural country, India, with a likewise high percentage of coal at 72.5 % of the power generation mix in 2020 (International Energy Agency, 2021), has required coal power plants to meet a minimum of 5 % co-firing with torrefied biomass pellets by October 2022 (Modi, 2022). This is intended to meet the climate targets and valorize residues that are improperly disposed of through open burning.

In the Philippines, a moratorium was issued on constructing new coal-fired power plants (Chavez, 2020). The country however does not intend to phase out these power plants since most existing ones are new; the

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possibility of converting them to use renewable fuels such as biomass is being investigated (Domingo, 2021). In this study, a novel process for torrefied biomass production was designed, following assessments of biomass resource availability, potential off-takers, process synthesis, simulation, and economic analysis were undertaken to evaluate torrefied biomass as an alternative fuel in local coal-fired facilities.

2. Methodology

2.1 Biomass resource availability and potential local coal power plant off-takers

The local biomass residues whose availability is estimated are rice husk, rice straw, coco husk, coco shell, corn cob, corn stalk, corn leaves, bagasse, and sugarcane leaves and tops. Data from the Philippine Statistics Authority (2022) was used, particularly from the year 2019 as data from 2020-2021 are not representative of long-term yields due to contraction from COVID-19. The tonnages of resource availability are presented in terms of location in geographic clusters of regions: (1) North Luzon; (2) South Luzon; (3) Visayas; and (4) Mindanao. Data from the Department of Energy Philippines (2022) were used to analyze the Philippine coal fleet by age and by the same geographic clusters used for mapping biomass resources. For age, the plants are classified based on commercial operations date (COD), i.e., 2010-present, 2000-2009, or before 2000. The priority off-takers are those built recently as economic returns are not yet reached given the typical 25 to 30-y plant life.

2.2 Process development, synthesis, simulation modeling, and economic analysis

For process synthesis, the literature survey resulted in the general input-output structure that is reflected in Figure 1 for the eventually chosen resource, sugarcane leaves and tops (SLT). The basis for process simulation was formed from relevant physicochemical data and thermodynamic property models, following reactor optimization and separation process sequencing. The process was simulated using Aspen Plus^{TM} and through material and energy balance calculations. Table 1 shows the correlations involving heat effects and thermodynamic properties (Manouchehrinejad and Mani, 2019) used in the Aspen Plus^{TM} flowsheet in Figure 2.

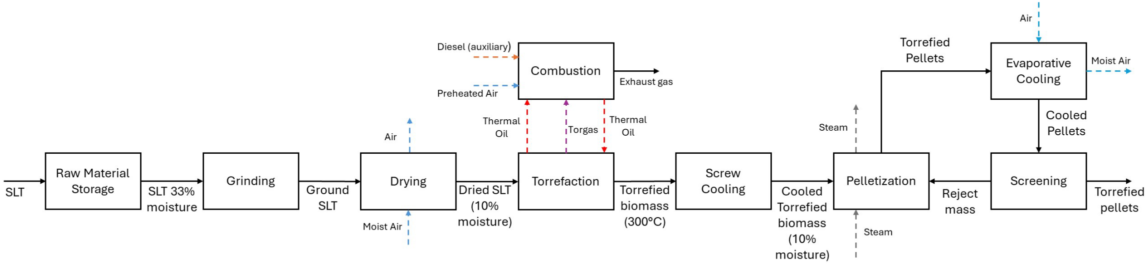

Table 1: Thermodynamic properties and calculation methods.

Solid thermodynamic property	Calculation method	Component attributes
Enthalpy model	HCOALGEN	Ul, Pr, Su[a]
Heat of combustion (HHV)	Boie correlation	Ul, Pr, Su
Standard heat of formation (H_f)	The heat of combustion-based correlation	Ul, Su
Heat capacity (c_p)	Kirov correlation (1965)	Pr
Solid thermodynamic property	Calculation method	Component attributes

a. Ul: Ultimate analysis, Pr: Proximate analysis, Su: Sulfur analysis

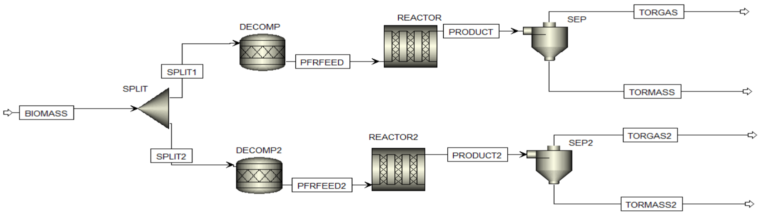

Figure 2: Process flow diagram of the torrefaction reactor system in Aspen Plus^{TM}

Conag et al. (2018) developed a kinetic model of the eventual chosen resource, sugarcane leaves. Reactions are as follows which proceed with pseudo-1st order kinetics, where some volatile matter (VM) transforms to torrefied gas (torgas) or gaseous volatile matter and fixed carbon (FC) simplified through three parallel reactions:

$$VM_{solid} \rightarrow VM_{gas} \qquad r_{VM,\,gas} = k_1 Y_{VM} \tag{1}$$

$$VM_{solid} \longrightarrow VM_{gas} \qquad r_{FC} = k_2 Y_{VM} \tag{2}$$

$$VM_{solid} \longrightarrow FC \qquad r_{VM,\,solid} = -k_1 Y_{VM} - k_2 Y_{VM} = -K' Y_{VM} \tag{3}$$

Each rate constant is associated with a different Arrhenius constant and activation energy. The kinetics parameters are shown in Table 2 and were used as inputs in the process simulation of the scaled-up facility.

Table 2: Kinetic parameters of SLT torrefaction under minimized oxidative pressure (Conag et al., 2018)

Biomass/Component	k_0 (min^{-1})	E (kJ/mol)	r^2 (experimental data with rate equation)
VM gas formed, $k_1 = K' - k_2$	1278.96	51.63	0.95
Solid VM, K'	1045.34	50.44	0.95
Fixed carbon, FC, k_2	0.39	27.59	0.92

Equipment costs were computed and adjusted through the Chemical Engineering Plant Cost Index (CEPCI) and used to determine capital costs. Revenue was based on the Newcastle price (Australian Government Department of Industry, Science and Resources, 2023), the benchmark used by potential coal power plant off-takers. It was reduced by a factor of 0.88 considering the ratio of torrefied biomass with a Higher Heating Value (HHV) of 22 MJ/kg (Conag et al., 2018) to the Newcastle coal HHV which is 25.1 MJ/kg (International Energy Agency, 2022). Major costs of production namely raw material and electricity were estimated based on industry information (Energy Regulatory Commission, 2022) as well as published rates from utility providers in the chosen facility location (Central Negros Electric Cooperative, 2022). US dollar (USD) to Philippine Peso (Php) exchange rate of 54.4738 Php/USD on December 20, 2022 was used for all computations.

3. Results and discussions

Results in Tables 3 and 4 show the highest % of coal power plants in Visayas being recently constructed and sugarcane leaves and tops (SLT) constituting the largest amount of residue in the geographic cluster. Therefore, the hypothetical torrefaction plant was placed in this location and modeled based on an SLT feedstock.

Table 3: Biomass resource availability in different regions in the Philippines in tonnes (t)

Biomass Resource	North Luzon		South Luzon		Visayas		Mindanao	
	t	%	t	%	t	%	t	%
Rice Husk	1,728,894	12.7	553,777	8.8	640,224	4.3	840,071	5.6
Rice Straw	8,644,469	63.7	2,768,883	44.2	3,201,122	21.5	4,200,354	27.9
Coco Husk	82,099	0.6	1,288,377	20.5	720,900	4.8	3,076,394	20.4
Coco Shell	28,148	0.2	441,729	7.0	247,166	1.7	1,054,764	7.0
Corn Cob	443,825	3.3	63,745	1.0	74,067	0.5	615,189	4.1
Corn Stalk	1,479,418	10.9	212,485	3.4	246,890	1.7	2,050,630	13.6
Corn Leaves	650,944	4.8	93,493	1.5	108,632	0.7	902,277	6.0
Bagasse	224,692	1.7	367,830	5.9	4,193,284	28.1	1,015,595	6.7
SLT	293,303	2.2	480,150	7.7	5,473,733	36.7	1,325,715	8.8
Total	13,575,792	100	6,270,469	100	14,906,018	100	15,080,988	100

Table 4: Installed capacity of coal-fired power plants in the Philippines, segmented by geography and COD

Commercial Operations Date	North Luzon		South Luzon		Visayas		Mindanao	
	MW	%	MW	%	MW	%	MW	%
Before 2000	1,998.0	38.2	1,364.0	40.2	66.3	4.7	0.0	0.0
2000 to 2009	52.0	1.0	511.0	15.1	0.0	0.0	232.0	11.8
2010 to present	3,175.5	60.8	1,518.1	44.7	1,348.2	95.3	1,727.5	88.2
Total	5,225.5	100	3,393.1	100	1,414.5	100	1,959.5	100

Negros Occidental in Visayas was selected as the feedstock source since it yields most of the country's sugar (Philippine Statistics Authority, 2019). After accounting for current users, the available raw material is 1,638,789 t/y which is the basis of plant sizing for this study. Up to 2,319 t/d of the torrefied pellet can be produced based on 0.73 product conversion (dry basis), 33 % feed moisture, and 5 % product moisture (Go and Conag, 2019).

For off-takers, the coal-fired power plants consisting of 6 units located east of Negros have been particularly considered in this study. According to estimates (Department of Energy Philippines, 2015), these plants have a total coal demand of 9,326 t/d. Studies showed that a 5-10 % co-firing ratio is advised, which agrees with India's policy to use this blend (Kassi, 2023). The demand is projected at 466-932 t/d, easily met by the supply. The rotary kiln reactor was selected over the moving bed, fluidized bed, torbed, and microwave reactor due to a literature survey on reactor technology (Batidzirai et al., 2013). As in Figure 2, two units were considered, influenced by the scenario that one can operate in a low-demand case. In Aspen Plus^{TM}, the reactor is modeled by an RStoic block which simulates the decomposition step of biomass to its defined components, followed by an RPlug block for sizing and optimization, followed by a separation block to obtain the flow rates of torrefied biomass and torgas. A Fortran block was incorporated as a system optimizer with constraint inputs in Table 5.

Table 5: Range of values for optimization based on Conag et al. (2018)

Process Variables	Range of Values
Temperature	250 to 350 °C (base case: 300 °C)
Length	0.1 m to 18 m (base case: 18 m)
Diameter	0.1 m to 3 m (base case: 3 m)

From the 250-350 °C range, higher conversion to torgas is observed as temperature increases. The temperature significantly affects the residence time required to reach the target composition, with 1.6 h at the lowest torrefaction temperature of 250 °C. Conag et al. (2018) cite the optimum temperature and residence time as 300 °C and 45 min, respectively. This study predicted an optimum value near this point, at 300 °C and 39 min. The conversion to torgas increases from a minimum of 0.14 to an observed maximum of 0.40 at the maximum reactor length. For diameter, a similar trend as with length was observed, with conversion and residence time increasing with increasing diameter at base case conditions. Since the material flow through a PFR is along its length with a larger magnitude, the two process variables optimized are temperature and reactor length.

An initial profit function is used by subtracting raw material cost, annualized equipment installation cost, and operating cost from product revenue. Beyond the 5 m reactor length, profit increases as more products are obtained at higher throughput. Deciding on an optimum temperature and reactor length, the 15 m length is chosen. The ideal residence time for SLT torrefaction ranges from 30 to 60 (Conag et al., 2018), narrowing the optimal temperature range from 280 to 320 °C. The chosen optimum temperature is 300 °C, consistent with the temperature that yields an ideal residence time. Figure 3 shows the 3D surface plot of the two variables versus profit. The optimized dimensions are 15 m by 3 m, with a length-to-diameter (L/D) ratio of 5. Heuristics show that kilns generally have an L/D ratio of 2 to 8 (Haggar, 2010), which the value of the simulation falls within.

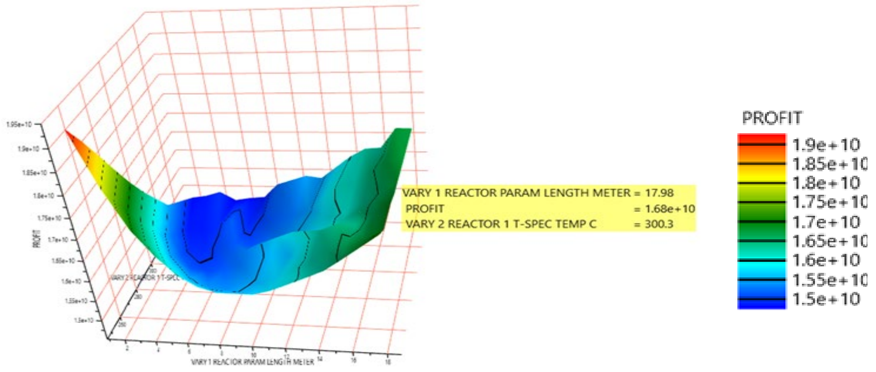

Figure 3: 3D surface plot of reactor temperature and length versus profit.

Overall, as in Figure 1, the simulated scaled-up production of torrefied biomass pellets from SLT is divided into feed handling, torrefaction, pelletization, heating utility, cooling utility, and storage and product handling. The total equipment cost is estimated at Php 565 million, while the fixed capital investment is Php 2.7 billion. Figure 4 breaks down the purchased equipment costs and fixed capital investment.

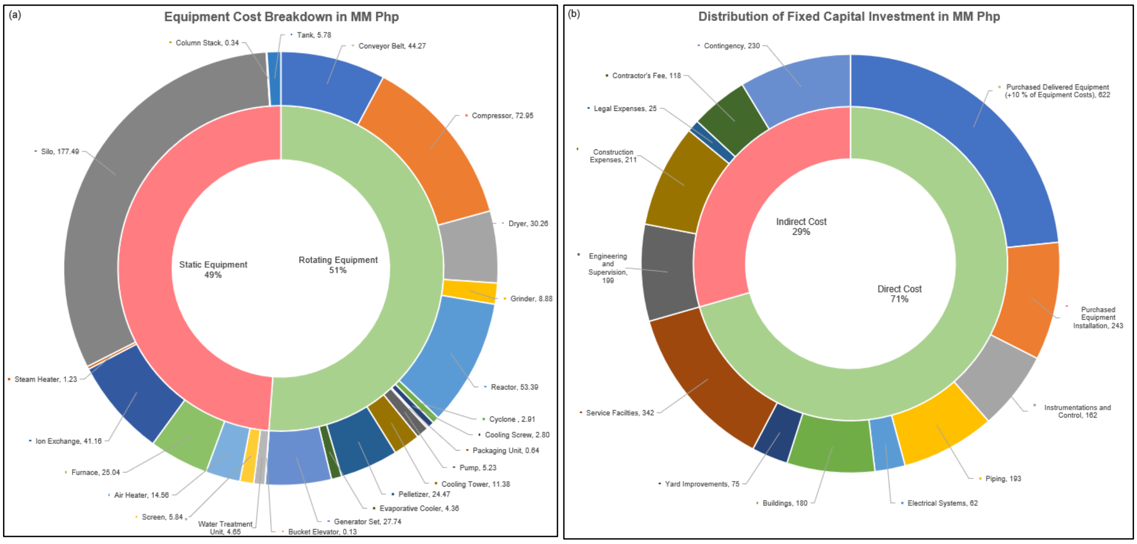

Figure 4: Equipment cost (a) and fixed capital investment (FCI) (b) estimates for the torrefaction facility

A 60,000 t/y plant using a moving bed reactor requires a capital investment of Php 308 to 373 million (Bergman et al., 2005). Considering the CEPCI difference, the FCI for the proposed plant would be around Php 2.3 billion, Php 400 million lower than the calculated Php 2.7 billion. The higher capital cost may be attributed to splitting the plant into two operating lines and adding auxiliary units such as ion exchangers. The total cost of production (TCOP) is determined as the sum of variable and fixed costs. Variable costs encompass raw materials, electricity, water, and diesel. Fixed cost is composed of labor, maintenance, and overhead. The proposed plant's TCOP is Php 6,968/t of torrefied pellet, significantly higher than the estimated Php 2,355 to 3,297/t in 2005 (Bergman et al., 2005). The difference is due to inflation and the inclusion of the raw material price in the proposed estimate, which contributed a variable cost of Php 4,370/t.

In evaluating the long-term profitability, two indicators, NPV and IRR, were examined. The 25-y IRR is 43.5 % with an NPV of Php 16.8 billion. The project is economically viable due to the increase in the Newcastle price in 2022. The critical value for product price that results in an acceptable IRR of 12 % is Php 9,179/t. This is 20 % less than the HHV-adjusted Newcastle price in 2021-2022 at Php 11,527/t. This highlights that economically, torrefied SLT can serve as an alternative fuel to coal-fired power plants, with a project developer able to expect a 10-y payback at a 12 % IRR levelized costing which competes very well with market prices from 2021-2022.

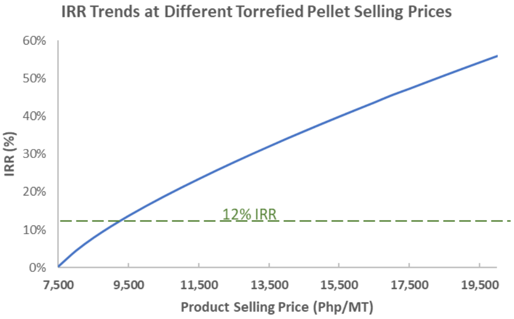

Figure 5. Internal Rate of Return (IRR) trends for the torrefaction facility at different selling prices (Php/t)

4. Conclusions

This study explored how indigenous biomass can transition coal plants towards solid biofuels. Techno-economic analysis showed that a hypothetical torrefaction facility in Negros Occidental generates 1,000 t/d of torrefied pellets which can be fired as an alternative fuel in 627 MW of existing coal plants in Central Philippines, at a replacement rate of 5-10 % and at a levelized price that competes with 2021-2022 market rates.

It is recommended that studies be pursued on various biomass residues such as coco husk, rice straw, and corn residues, whose availability may be matched with coal fleets located in other geographic clusters of the country. This may form the basis to mandate biomass co-firing targets in coal facilities in the Philippines, akin to similarly coal-dependent India, especially for the plants that cannot be shut as payback remains to be reached.

If pursued, this will stimulate the rural agricultural economy with additional baseload low-carbon energy that complements the fledgling additions of the variable renewable energy solar and wind to the Philippine grid.

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