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Energy Sufficiency of Biomass and Wastewater in Closed Process of Sago Starch Production

Kecukupan Energi Berbasis Biomassa dan Limbah Cair Dalam Proses Tertutup Produksi Pati Sagu

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Abstract

Sago grows in lowland and peat swamp regions that are relatively isolated due to limited basic infrastructures, including energy supply, especially electricity. These limitations constraining the development of sago starch production and industry. The sago starch production process generates by-products such as sago bark waste, pith waste, and wastewater which are potentially used as an energy source. This paper discusses a closed system model of an energy-independent sago starch production process from the utilization of by-products and wastewater. A mass balance model was developed to calculate the energy potency of by-products and waste to construct a closed system for the sago starch production process. The model's output showed that the by-product from processing 1,000 tons of sago stems per day with an optimal yield of 14% potentially generates 90,562 kWh of energy. This energy potency can meet the 26,070 kWh energy needed for sago starch production, making it possible to develop into a closed production system. Further research is needed to determine the site-specific aspects that affect energy sufficiency.

Keywords: closed system, energy sufficiency, sago starch

Abstrak

Kawasan hutan sagu berada di dataran rendah dan rawa-rawa yang relatif terisolasi karena keterbatasan infrastruktur dasar, termasuk pasokan energi, terutama listrik. Keterbatasan tersebut menyebabkan produksi dan industri pati sagu sulit berkembang. Proses produksi pati sagu mempunyai hasil samping berupa kulit, ampas, dan limbah cair yang dapat dimanfaatkan sebagai sumber energi. Artikel ini membahas model sistem tertutup proses produksi pati sagu yang mandiri energi dari pemanfaatan hasil samping dan limbah cair. Model kesetimbangan massa dikembangkan untuk menghitung potensi energi dari hasil samping dan limbah untuk membangun sistem tertutup proses produksi pati sagu. Luaran model menunjukkan bahwa hasil samping dari pengolahan 1.000 ton batang sagu per hari dengan rendemen optimal 14% berpotensi membentuk energi sebanyak 90.562 kWh. Potensi energi ini dapat memenuhi kebutuhan energi yang diperlukan dalam pengolahan sebanyak 26.070 kWh, sehingga produksi pati sagu dapat dikembangkan menjadi sistem produksi tertutup. Penelitian lanjutan perlu dilakukan untuk mengetahui aspek spesifik lokasi terhadap kecukupan energi.

Kata kunci: *kecukupan energi, pati sagu, sistem tertutup*

INTRODUCTION

Indonesia's sago processing industry is predominantly small-scale, relatively slow developed, and even underdeveloped. Large-scale sago industries are generally located in Riau, Papua, Java, and Sulawesi. The technology application in Indonesia's sago starch production is increasing, even though its production quantity is still limited. According to the Indonesian Directorate General of Plantations, Indonesia produced 359,838 tons of sago starch in 2019 (Direktorat Jenderal Perkebunan, 2020). Sago starch production requires energy equivalent to 2,000-3,000 kWh per ton of sago starch (Wan et al., 2016) and 20 tons of water per ton of sago starch produced (Awg-Adeni et al., 2013).

The by-products of sago starch production are sago pith waste, sago bark, sago stem powder, and wastewater. The waste contains cellulose and starch, potentially used as carbon sources (Amin et al., 2019). The ratio of starch to sago pith is 1:6

(Nuraini, 2015). The amount of sago bark and sago pith waste is 26% and 14% (Budiman & Ismayana, 2016; Amin et al., 2019), or in general, the sago bark is around 17–25% of the sago stem total weight (Lai et al., 2013). The wastewater produced is 16–20 m^3 per ton of sago starch produced and contains a lot of carbohydrates (Sathya et al., 2011; Siruru et al., 2019), forming a total of 75–83% sago pith waste and wastewater (Lai et al., 2013; Narmatha et al., 2017).

Sago pith contains 65.7% starch, crude fiber, crude protein, fat, and ash. That by-product contains 21% lignin, 20% cellulose, and the rest is extractive substances and ash. Sago bark contains more cellulose (57%) and lignin (38%) than sago pith (Santoso, 2018). The extraction process is essential because it affects the sago starch yield produced. Relatively large amounts of water are used to produce much wastewaters. Wastewater generated from the extraction process is generally disposed of without treatment. This waste still contains solids such as sago starch and pith. Solid waste and wastewater from sago starch production can be energy source. Sago bark, stem powder, and pith waste can make briquettes (Denitasari et al., 2011). Sago pith waste can also be used as a substrate for bioethanol production (Asben et al., 2012). Sago starch wastewater can be used as a biogas-producing substrate (Anuar et al., 2014).

This paper aims to calculate the potential of sago starch production waste as an energy source and its sufficiency in fulfilling the production needs. If the potential is greater than the need, the production of sago starch can be developed into a closed production system. The by-product of sago starch production is expected to be used as an energy source to build a sago starch closed production system.

METHODS

System Limitations

The sago starch production process comprises five main stages compartmentalized in the model. Those are the stripping station, grating station, extraction station, washing station, and drying station. Each production process station can consist of several compartments. The primary input material assumption is 1,000 tons of sago stems per day and 2,918 tons of water per day. The main product of this production process is sago starch, and the by-products are sago bark, stem powder, wastewater, sago pith waste, and water vapor. The output from each compartment is sago bark on stripping, sago stem powder on cutting, sago pith waste on extraction, and wastewater from washing to drying.

Model Description

The mass balance model was developed to describe an actual production process that relates input as a free variable with output as a dependent variable using the efficiency coefficients of both based on the principle of linear equations (Bantacut & Pasaribu, 2015). Mass balance modeling uses the flow basis of sago starch production with a capacity of 1,000 tons of sago stems per day. The calculation results estimate the potential by-products as a source of energy to fulfill the production process needs.

Mass Balance

The mass balance model follows the production process's compartment, then builds a mass balance equation that relates the input (sago stems and water) to the output (sago starch and by-products). The efficiency equation was identified using secondary data regarding the mass flow of the sago starch production process. After the mass balance and efficiency equations are formulated, the efficiency factor and mass balance value can be determined.

Energy Potency of Sago Starch Production By-product

Based on the mass balance model results that correspond to the actual and accurate sago starch production process, the by-product energy potential can be calculated using equation (1).

$$\text{Energy Potency (kcal)} = \text{Mass (kg)} \times \text{Calorific value (kcal/kg)} \qquad (1)$$

The calorific value for each by-product uses available reference data. The by-product mass is obtained from the mass balance model calculation. Wastewater energy can be obtained through biogas production and jointly used to heat the boiler (co-generator).

Mass Balance Model of Sago Starch Production

The mass balance model has 4 independent variables as the mass input and 16 as the process output. The independent variables consist of I_1, I_3, I_4, and I_5, while the dependent variables are X_1, X_2, X_3, X_4, X_5, X_6, X_7, P_8, W_1, W_2, W_4, $W_{5.1}$, $W_{5.2}$, W_6, W_7, and W_8. Formed equations are used to calculate the dependent variable so 16 equations are needed consisting of 8 mass balance equations and 8 efficiency equations (see Figure 1 and Table 1 for symbols and their definition). Depending on the required detail level, one or more compartments can be grouped into a station.

The station I is the sago bark stripping process (W_1) using a Ring Debarker machine to produce peeled sago stems (X_1). The bark percentage of sago stems reaches 17% (Chong et al., 2014; Supu et al., 2017; Tenriawaru et al., 2018). These process results are sago peeled stem and sago bark.

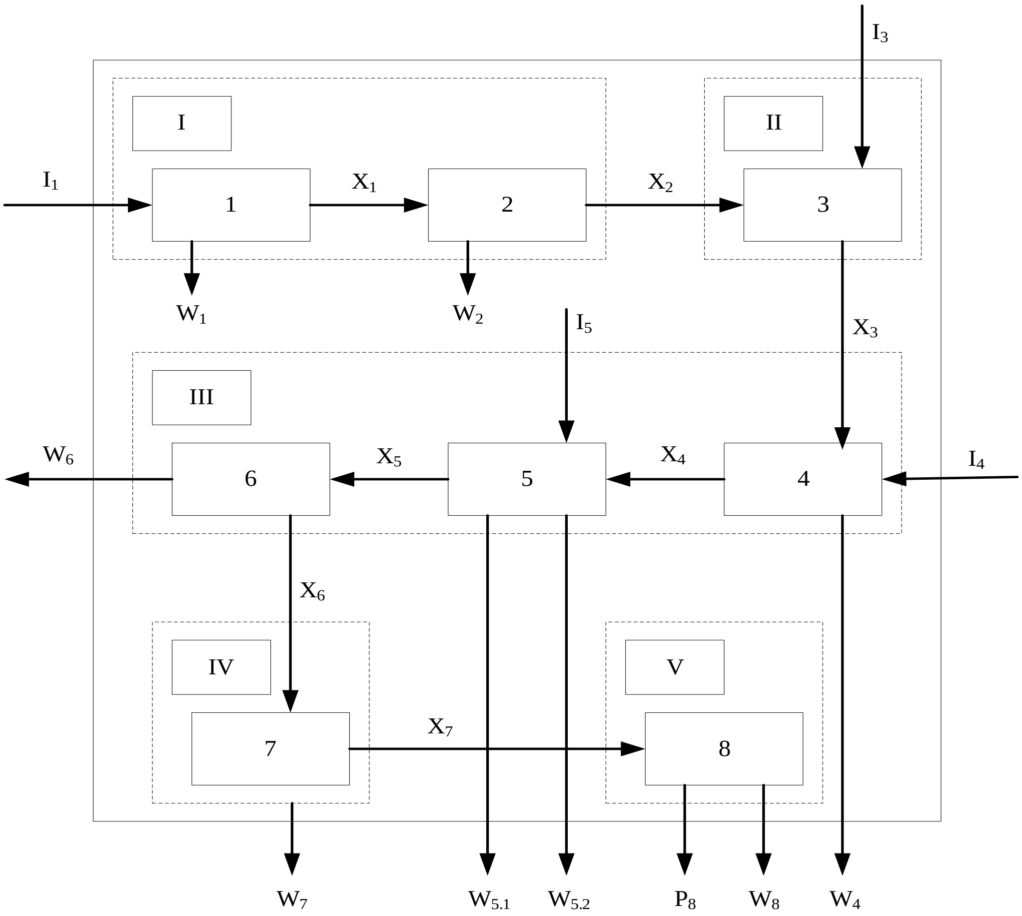

Figure 1. Mass Balance Model

Table 1. Symbol description of the mass balance model

Symbol	Description	Symbol	Description
	Station I	X_1	Peeled sago stem
1	Bark Stripping Compartment	X_2	Cut sago stem
2	Cutting Compartment	X_3	Sago slurry
	Station II	X_4	Starch solution from extraction
3	Grating Compartment	X_5	Starch solution from washing
	Station III	X_6	Concentrated starch slurry
4	Extraction Compartment	X_7	Wet starch
5	Washing Compartment	W_1	Sago bark
6	Sedimentation Compartment	W_2	Sago stem powder
	Station IV	W_4	Wastewater
7	Dewatering Compartment	$W_{5.1}$	Sago pith waste
	Station V	$W_{5.2}$	Wastewater
8	Drying Compartment	W_6	Wastewater
I_1	Sago stem	W_7	Wastewater
I_3	Water for extraction station	W_8	Water vapor
I_4	Water for washing sago sediment	P_8	Sago starch
I_5	Water for sago sediment further washing		

Station II is the sago stem cutting process to facilitate the grating process. The cutting process uses the Slicer on the Ring Debarker. Waste from the cutting process is sago stem powder (W_2). Then belt conveyor moves the small sago stem size (X_2) to the next process.

Station III is a grating process facilitated with water addition (I_3). The grating process is assumed to produce no waste, except for the added water splash. The grating uses Rasper, which has thorns to shred the sago stems to a smaller size.

Station IV is the first extraction process with sufficient added water (I_4). The extraction process generates wastewater (W_4). Extraction carries out by mixing the grated sago pith with water. This mixture is called sago slurry (X_3). The sago slurry is added with water to extract the starch content (X_4) while stirring using the rotary sieve bends machine. The mixture result is then filtered by vibrating filtering to separate the wastewater.

Station V is starch slurry (X_5) washing, the final starch extraction process. Separation carries out by adding water (I_5) to wash starch. This process generates wastewater ($W_{5.1}$) and sago pith waste ($W_{5.2}$). The next process is sedimentation. The sedimentation process (VI) purpose is to process the concentrated starch slurry (X_6), separated between sago starch (X_7) and wastewater ($W_{5.2}$).

The next process is dewatering (VII), using a filter press to discard the wastewater (W_7). This process output is wet starch (X_7). The last process in compartment VIII is drying. Dryers that can be used are ovens or rotary vacuum drum driers (Ehara et al., 2018). The main result products from the drying process are dry sago starch (P_8) and water vapor (W_8). The mass balance model is shown in Figure 1, and the symbol description is in Table 1.

Mass Balance Equation

Mass balance equations are made for each process stage in the compartment. Especially processes that produce outputs and by-products, so that the eight mass balance equations are obtained as follows:

Compartment 1: $I_1 - X_1 - W_1 = 0$ (2)
Compartment 2: $X_1 - X_2 - W_2 = 0$ (3)
Compartment 3: $X_2 + I_3 - X_3 = 0$ (4)
Compartment 4: $I_4 + X_3 - W_4 = 0$ (5)
Compartment 5: $I_5 + X_4 - X_5 - W_{5.1} - W_{5.2} = 0$ (6)
Compartment 6: $X_5 - W_6 - X_6 = 0$ (7)
Compartment 7: $X_6 - X_7 - W_7 = 0$ (8)
Compartment 8: $X_7 - W_8 - P_8 = 0$ (9)

Efficiency Equation

The equation needed to calculate the dependent variable value is made by creating an efficiency equation. The efficiency coefficient value between the variable are obtained based on previous research as follows:

1. Production efficiency of peeled sago stems
   The sago stems stripping process produces 17% sago bark waste from sago stems (Chong et al., 2014; Supu et al., 2017; Tenriawaru et al., 2018). Peeled sago stems yield is 83% of the total sago stem. Efficiency value $a_1 = 0.83$.

$$a_1 = \frac{X_1}{I_1} = \frac{\text{peeled sago stem}}{\text{sago stem}} \tag{10}$$

2. Production efficiency of cut sago stems
   Peeled sago stems are then cut to facilitate the next process. The percentage efficiency of cut sago stems is 99% (Budiman & Ismayana, 2016; Yusuf et al., 2019). The remaining 1% is sago stem powder waste. The coefficient a_2 value is 0.99.

$$a_2 = \frac{X_2}{X_1} = \frac{\text{cut sago stem}}{\text{peeled sago stem}} \tag{11}$$

3. Production efficiency of starch solution from extraction
   Wan et al. (2016) calculated that the extraction process produced 91.3 tons of starch solution, 98.4 tons of sago slurry, and 87 tons of water, so the efficiency coefficient value of $a_3 = 0.49$.

$$a_3 = \frac{X_4}{X_3 + I_4} = \frac{\text{starch solution from extraction}}{\begin{array}{c}\text{sago slurry + water for}\\ \text{washing sago sediment}\end{array}} \tag{12}$$

4. Production efficiency of sago pith waste
   The percentage of wet starch in the starch slurry is 14% (Flach, 1997; Budiman & Ismayana, 2016; Amin et al., 2019). The coefficient a_4 value = 0.14.

$$a_4 = \frac{W_{5.1}}{X_3} = \frac{\text{sago pith waste}}{\text{sago slurry}} \tag{13}$$

5. Production efficiency of starch solution from washing
   The starch solution produced from the second extraction or washing is 90.1 tons from 91.3 tons of the first extraction's starch slurry. The water addition is 120 tons, so it has an efficiency of 42% (Wan et al., 2016). The coefficient a_5 value = 0.42.

$$a_5 = \frac{X_5}{X_4 + I_5} = \frac{\text{starch solution from washing}}{\text{starch solution from extraction + water for sago sediment further washing}} \quad (14)$$

6. Production efficiency of starch slurry
   The production of concentrated starch slurry has an efficiency value of 33%, so the a_6 coefficient value is 0.33 (Wan et al., 2016).

$$a_6 = \frac{X_6}{X_5} = \frac{\text{concentrated starch slurry}}{\text{starch solution from washing}} \quad (15)$$

7. Wet starch production efficiency
   The percentage of wet starch in the starch slurry is 41% (Wan et al., 2016). The coefficient value of a7 is equal to 0.41.

$$a_7 = \frac{X_7}{X_6} = \frac{\text{wet starch}}{\text{concentrated starch slurry}} \quad (16)$$

8. Sago starch production efficiency
   After drying, 12.5 tons of wet starch can produce 12 tons of sago starch. The efficiency of sago starch production is 96% (Wan et al., 2016). The coefficient a_8 has a value of 0.96.

$$a_8 = \frac{P_8}{X_7} = \frac{\text{sago starch}}{\text{wet starch}} \quad (17)$$

RESULTS AND DISCUSSION

Mass Balance and Energy Potency Model

The sago starch yield obtained from the mass balance model is 14.01%. After comparing the model with different research results, the model can be used to calculate the final output of the material flow and production process. The mass balance is shown in Table 2 and Figure 2.

Energy Potency in Sago Starch Processing Waste

Sago bark waste contains 57% cellulose and 38% more lignin than sago pith (Santoso, 2018). Sago pith contains 54.6% starch, 31.7% cellulose and hemicellulose, 3.3% lignin, 2.1% crude protein, and 1.8% fat (Husin et al., 2019; Tiro et al., 2018; Neethu & Murugan, 2021). Sago pith and sago bark contains high calories (Table 3). Waste calories can be converted into steam using a high-pressure boiler to turn a turbine and generate electrical energy. Wołowicz et al. (2012) stated that the efficiency of converting electrical and thermal energy using condensing steam turbine co-generation could reach 43.5% (Table 4).

Wastewater from sago starch production is treated by anaerobic digestion to produce biogas (methane). Wastewater from sago starch production is assumed to be similar to tapioca wastewater. This wastewater contains nutrients (nitrogen, carbon, phosphorus, potassium, calcium, magnesium, sulfur, zinc, manganese, copper, iron, and sodium) (Racho & Pongampornnara, 2020; Haryanto et al., 2020). The carbon, nitrogen, and phosphorus ratio is 24: 0.14: 1. This content supports the *Spirulina platensis (Arthrospira)* growth for methane formation. The value of COD removal from wastewater also affects methane gas production. COD removal of sago starch wastewater is 65% (Sabri et al., 2018).

Based on the measurement results of anaerobic ponds gas emissions, every m^3 of sago liquid waste can produce 10.77 kg of biogas or 6.46 kg of methane, which has a methane calorific value of 13,384.34 kcal/kg (Lam & Lee, 2011). Methane gas can be converted into electricity through combustion in a boiler with an efficiency of 80% (Li et al., 2011). The hot steam produced is flowed into a turbine to drive a generator to produce an electric current. The single-stage conversion turbine will convert 20 kg of steam into 1 kW of electrical energy (Bantacut & Pasaribu, 2015). The electrical energy obtained from the sago wastewater conversion is 2,065 kWh per 1,000 tons of sago stems.

Table 2. Mass balance of sago starch production process

Material	%	Tons/Day
Input		
Sago stem (I_1)		1,000
Water (I_3, I_4, I_5)		2,918.43
Total input		3,918.43
Output		
Sago starch (P_8)	14.01[a]	140.17
Sago bark and stem powder (W_1 and W_2)	17.83[a]	178.3
Sago pith waste ($W_{5.1}$)	17.61[a]	175.61
Wastewater ($W_{5.2}$, W_6, W_7)	87.3[b]	3,424.35
Total output		3,918.43
Yield	14.01	
System efficiency	100	

[a] per 1.000 tons sago stems; [b] per total input

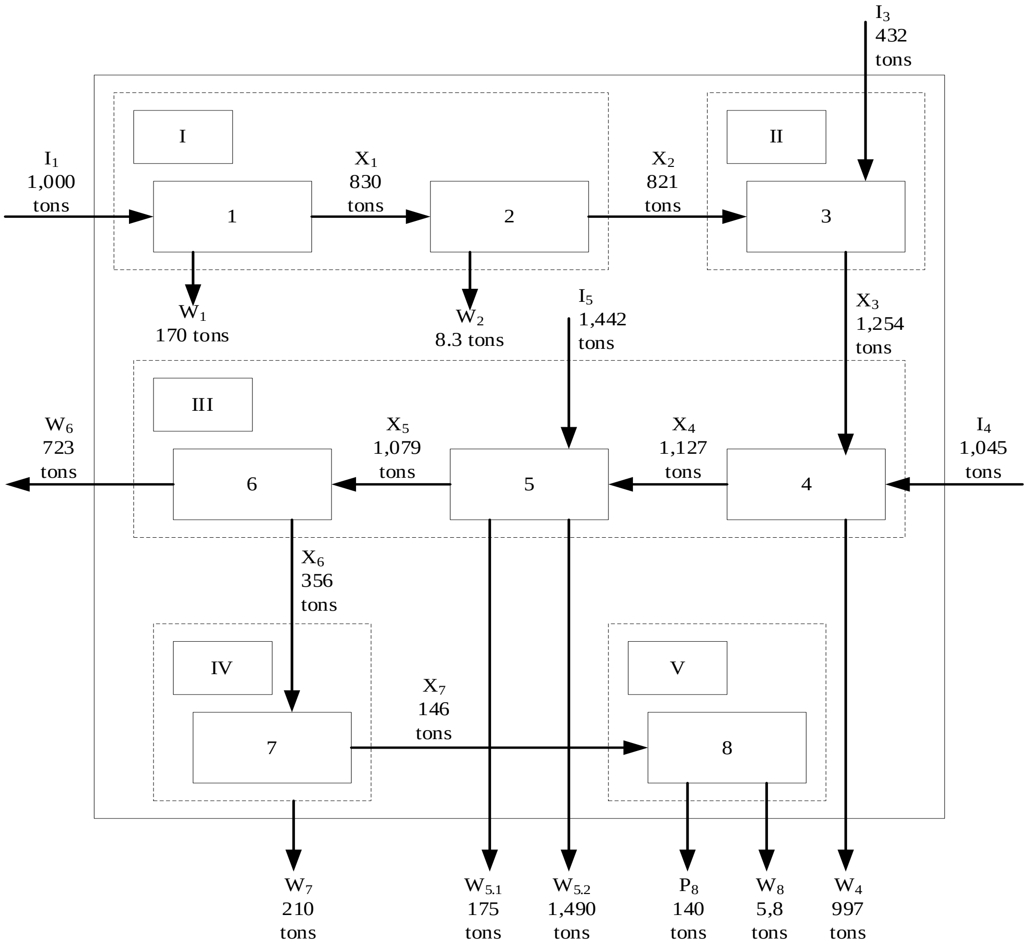

Figure 2. Mass Balance Flow of Sago Starch Production

Table 3. The by-product calorific value contained from sago starch production

By-products	Mass (tons)	Calorific Value (kkal/kg)	Energy Potency (kkal)	Reference
Sago bark and sago stem powder	178.30	4,674.95	833,543,585.00	(Chong et al., 2014)
Sago pith waste	175.61	3,693.52	648,638,744.00	(Fretes et al., 2013)

Table 4. Conversion calculation from biomass to electrical energy

	Waste Type		Quantity (ton/day)	Energy Content/kg Biomass (kcal/kg)	Total Biomass Energy (kcal)	Steam Produced (kg/day)	Actual Steam (kg/day)	Electrical Power Total Output (kWh)
Steam Generate from Solid Waste	Sago bark and sago stem powder		178.30	4,674.95	833,543,585.00	1,244,224.00	995,379.00	
	Sago pith waste		175.61	3,693.52	648,638,744.00	968,218.00	774,575.00	
	Total				1,482,182,329.00	2,212,442.00	1,769,954.00	88,497.00
							Surplus	
	Volume (tons/day)	**Methane Potential (kg/m^3)**	**Calorific Value (kcal/kg)**	**Electrical Output (kWh)**	**Total Electricity (kWh)**	**Processing Electricity Consumption (kWh)**	**(kWh)**	**(kW)**
Electricity Generate from Wastewater	3,424.35	6.46	13,384.34	103,300	191,797	26,070	127,305	5,304

Assumption:
Factory capacity 1,000 tons/day
The heat energy required to produce 1 kg of steam at 30 bar and saturated temperature = 669.93 kcal/kg
Average boiler efficiency 80%
Steam conversion in turbine 20.00 Kg steam/kWh

Closed System Production of Sago Starch

The production system generates by-products: sago bark, pith waste, wastewater, and water vapor. The by-products such as sago bark and pith waste contain energy then reused as energy sources, but not all by-products can be reused because of the high-water content or water vapor. Water vapor generated from the drying process can be reused through condensation (condenser) to produce water potentially reused as an input in the extraction process. Wastewater generated from the extraction process can be reused as material for biogas production, then converted into electrical energy. A closed production system of sago starch is shown in Figure 3.

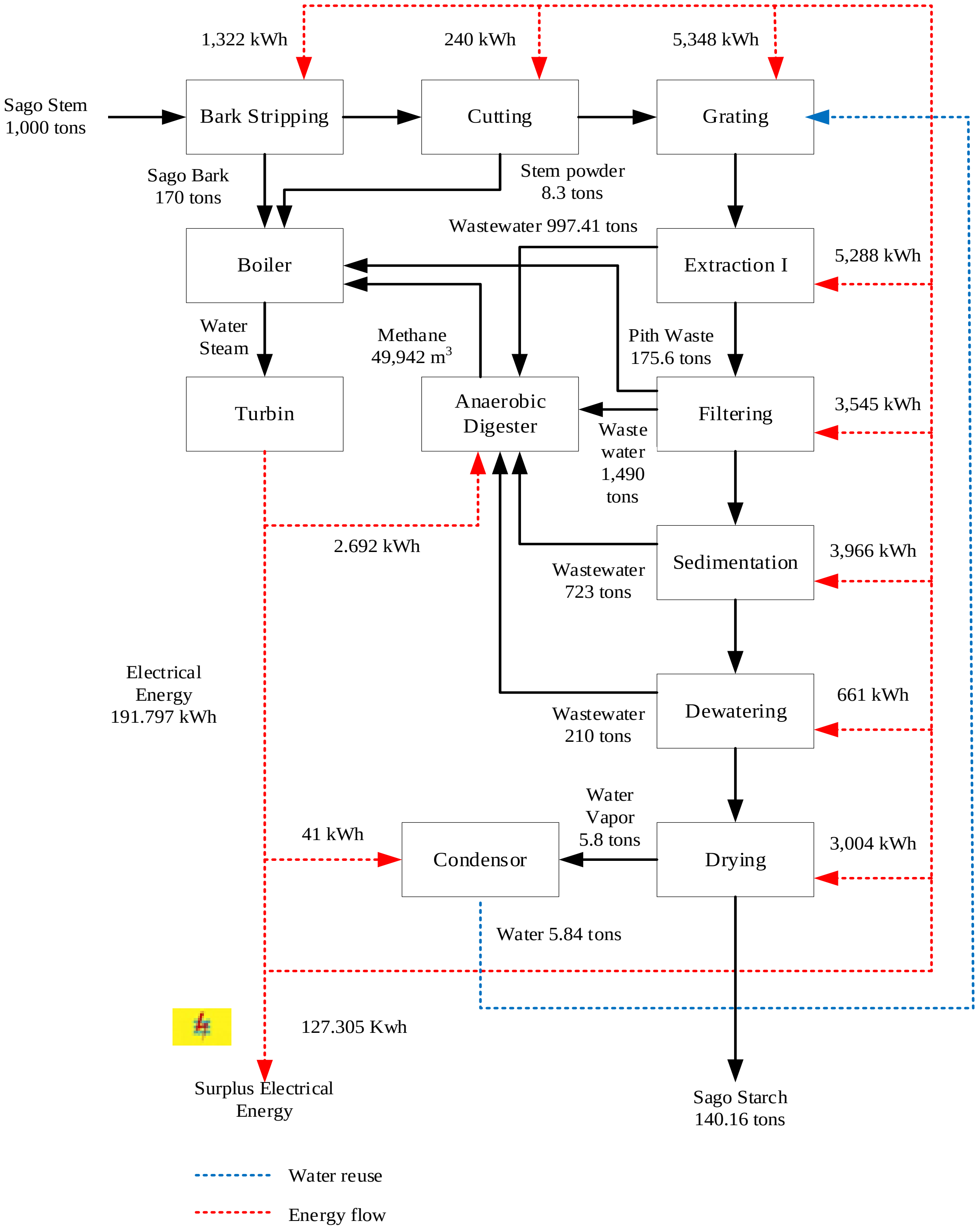

Figure 3. Sago Starch Closed System Production

CONCLUSIONS

Sago bark, pith waste, and wastewater have potency to produce energy. The sago starch production with a capacity of 1,000 tons of sago stems per day produces 178.3 tons of sago bark and sago stem powder, 175.61 tons of sago pith waste, and 3,420.75 tons of wastewater. The sago barks and sago pith waste can produce 88,497 kWh of electrical energy per day, while the wastewater can produce 103,300 kWh of electrical energy per day. The sago starch processing factory needs 26,070 kWh per day to be energy-independent, so there is still an energy surplus of 127,305 kWh per day, equivalent to a 5.3 MW of electrical energy. The energy-independent production model in this paper can be developed into an energy-independent sago starch production system. Sago starch production can be developed into a closed system industry. Water vapor condensation can be reused as a grating station water source.

Further research in implementing this system is needed to adjust energy requirements, such as the energy required to process by-products. This adjustment is needed because each industry has different machine operations and specifications, so the energy requirements will also be different. Sago starch's closed system production application can be used in small to large industries.

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