Article

Techno-Cost-Benefit Analysis of Biogas Production from Industrial Cassava Starch Wastewater in Thailand for Optimal Utilization with Energy Storage

Chatree Wattanasilp ^{1,*}, Roongrojana Songprakorp ² , Annop Nopharatana ³ and Charoenchai Khompatraporn ⁴

¹ Division of Energy Management Technology, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, 126 Pracha Uthit Rd., Bang Mod, Thung Khru, Bangkok 10140, Thailand

² Division of Energy Technology, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, 126 Pracha Uthit Rd., Bang Mod, Thung Khru, Bangkok 10140, Thailand; roongrojana.son@kmutt.ac.th

³ Excellent Center of Waste Utilization and Management (EcoWaste), Pilot Plant Development and Training Institute, King Mongkut's University of Technology Thonburi, (Bangkuntien) 83 Moo 8 Thakham, Bangkuntien, Bangkok 10150, Thailand; ponna_65@hotmail.com

⁴ Production Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, 126 Pracha Uthit Rd., Bang Mod, Thung Khru, Bangkok 10140, Thailand; charoenchai.kho@kmutt.ac.th

* Correspondence: wattanasil2@hotmail.com

Abstract: This paper applied the optimization model of the biogas utilization pathway with the biogas utilization availability assessment to examine the effect of biogas system parameters on biogas utilization. The model analyzes the biogas utilization pathway availability and maximum profit to value added and productivity in biogas from industry wastewater in Thailand. The results showed that profit and availability of biogas utilization reduce biogas loss to flare, that it entails several conversion processes. The scenario for the biogas utilization pathway and storage with biogas production technology improves. Evaluated are operation time, waste and energy demand to the cassava starch usage during the production for 50–1000 tons per day. Five mature biogas production technologies were benchmarked evaluated based on the chemical oxygen demand removal efficiency and biogas yields. Subsequently, low-, medium-, and high-pressure storages and a battery storage were considered and discussed in this paper as suitable energy storage for each desired biogas plant operation. Five biogas utilization pathways, including converting biogas into thermal energy, generating electricity, and upgrading biogas to compressed biogas, were then compared. Those improved options in the scenario select suitable biogas technologies, storage, and application for value-added, reduce the environmental problems and renewable energy production from wastewater.

Keywords: biogas technology; cassava starch; renewable energy; storage; utilization pathway; wastewater

Citation: Wattanasilp, C.; Songprakorp, R.; Nopharatana, A.; Khompatraporn, C. Techno-Cost-Benefit Analysis of Biogas Production from Industrial Cassava Starch Wastewater in Thailand for Optimal Utilization with Energy Storage. *Energies* **2021**, *14*, 416. <https://doi.org/10.3390/en14020416>

Received: 14 December 2020

Accepted: 4 January 2021

Published: 13 January 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Biogas technology was implemented to replace aeration treatment ponds of factories in Thailand. Initially, most biogas systems were primarily for wastewater treatment rather than alternative energy production. The Energy Policy and Planning Office (EPPO), Ministry of Energy, Thailand, promoted biogas technology by launching the “Biogas Promotion Project for Industry” (BPPI) since 2008–2015. The project provided an investment subsidy for a biogas plant in agro-industry [1]. The Energy Research Institute (ERI), Chulalongkorn University, Thailand, organized the program. The project involved 227 factories from five relevant agro-industries: cassava starch, palm oil refinery, ethanol, food, and rubber. Among those factories registered in the program, 53 cassava starch factories produced biogas from wastewater processing.

Additionally, there were five biogas technologies which were implemented in Thailand, including up-flow anaerobic sludge blanket (UASB), anaerobic covered lagoon (ACL),

and continuously stirred tank reactor (CSTR), anaerobic fixed film reactor (AFFR), and hybrid reactor (HBR). Those technologies attribute different efficiencies and investments, which are essential factors. They are also related to wastewater odor, methane emission, and fuel prices. However, some plants wasted biogas by flaring without any benefit. That was due to the oversized or non-optimal design of the biogas system and the storage system. Furthermore, discontinuous raw materials caused unbalanced thermal energy utilization.

In terms of the cassava starch process, relevant literature was reviewed, including Tran et al. [2], who presented the energy, water usage, and carbon footprints of cassava starch production in Thailand, Vietnam, and Colombia. The study introduced and demonstrated an environmental indicator, such as greenhouse gas (GHG) emissions, to evaluate whether the project was feasible and useful [3]. Anyanwu et al. showed that the successful program of cassava yield and biogas production could reduce cassava peel and wastewater [4]. Ghimire et al. studied baseline GHG emissions, and waste management to the cassava starch industry is energy. The result presented that biogas has the highest energy recovery with GHG alleviation potential [5].

In the biogas technology sector, some researchers developed the efficiency of biogas technology, including Lu et al. who studied methane that can be produced through anaerobic digestion using cassava starch wastewater [6]. The critical process parameters in an UASB reactor for wastewater treatment, operated by the days factor, were determined to comprehensively evaluate the performance. Phowan and Danvirutai presented a result, the highest efficiency of chemical oxygen demand COD removal, hydrogen yield, and methane yield compared with one-stage and two-stage CSTR processes [7]. Cavaleiro et al. showed the performance of an anaerobic hybrid sludge bed-fixed film reactor and used a neural network model and the fuzzy logic control performance [8].

Although the biogas production process is relatively continuous and stable, the biogas consumption rate can cause the system to be unbalanced. Therefore, storage is essential for balancing the biogas utilization. It determines the optimal size. In the study of Poul Alberg Stergaard, the effects of heat storage, biogas storage, and electricity storage on the performance of a fully renewable energy scenario [9] were studied. Furthermore, a high-pressure type of room was studied by Guan et al. [10]. Regards to methane sorption on a volumetric rig, with higher pressure, Castello et al. studied the behavior of different carbon materials in methane storage to obtain the best carbon material adsorption capacity by unit volume of adsorbent [11]. Kapdi et al. studied gas storage [12]. The biogas upgrading for the vehicle to extend the potential of biogas production with animal waste. Rios et al. modeled a cylindrical stainless-steel vessel filled with granular activated carbon as a natural gas storage system [13]. The hydrogen sulfides gas (H_2S) removal unit was essential before using biogas. F. Osorio and J.C. Torres studied the removal of H_2S for biogas from the digesters of a pilot plant with chemical gas scrubbing technology [14]. Pipatmanomai et al. conducted a feasibility study on a biogas-to-electricity system with and without H_2S removal by activated carbon, as the H_2S adsorbent [15]. Further, relevant to H_2S removal technologies, includes the work of Waewsak et al. [16].

The optimization method is mainly employed to solve technical problems in the industry [17]. There are numerous optimization tools available in which the non-linear binary program (NLBP) [18] found as a solution to the reliability of an electric distribution system [19]. However, optimization tools explicitly designed for biogas utilization pathways were the cost-benefit of electricity [20]. As an evaluation of biogas plant economics, [21] analyzed the economic performance of electricity production and compared the NPV and PB of the cost. Using GIS data for the investment model, the pricing, and optimization of natural gas storage in the competitive natural gas markets, they also reviewed that the estimated and optimum gas storage process eases the gas market impacts on the model [22], and optimization energy storage arrangement with a wind turbine, the analysis on cost, size, and technology [23]. Dominkoi et al. focused on investment management for a biomass tri-generation system combined with pit thermal energy storage (PTES) [24].

Therefore, this study aims to thoroughly investigate the key factors of operation cassava starch manufacturing, efficiency and cost of the biogas system. The possible options of biogas utilization pathways are explored for enhancing the biogas production efficiency and improving the renewable energy performance of the cassava starch industry. The optimization scheme using NLBP for maximum-profit biogas utilization pathway is the production of seasonal yield, conversion, storage technologies, and together with the biogas utilization availability assessment (BUAA). The study focuses mainly on biogas utilization, reduction in flare loss, and energy conservation. Results from implementation to real-world agriculture industries plants are shown in terms of a techno-cost-benefits as cleaner energy production and firm renewable energy plants.

2. Materials and Methods

2.1. Cassava Starch Factory

The biogas supply chain from cassava starch factories defined the seasonal yield, which was operating 5–12 months from providing the raw material. The plants are classified into three sizes (capacity), as shown in Figure 1. The data analysis from survey 53 cassava starch factories for the model uses different operation time, energy, and waste. The scenario contains vital data with a high impact variable by working day and energy demand. The raw materials impact the number of operations, which was an advantage and a high profit for financial analysis. The medium and large factory has a farmer cooperative system for a continuous supply of raw material.

Figure 1. Categorized sizes of cassava starch plants.

In contrast, small factories could not buy raw material to follow market prices that cause less workday. The low energy demand provides various utilization of biogas and value-added. Likewise, small factories are less likely to choose a high investment of the biogas system because of less of a working day and high energy demand. Therefore, the critical data were significant for the scenario model.

In the process, 1 ton of cassava starch requires 3.91–5.03 tons of cassava roots (26.9% starch). They were cleaned by washing grime from the rind tapioca peel, including soil and sand. The fresh roots were then chopped into small pieces using a grinding machine before rasping to be a slurry, comprising starch, water, fibrous residue, and impurities. After dewatering in a decanter machine, protein separation, and dehydration took place, and the product was packaged. For the drying process, hot air was used from a hot-oil boiler or steam boiler. The energy demand and wastewater discharge from the process is shown in Figure 1.

2.2. Analysis of Biogas Production

There are five technologies considered in this work: UASB, ACL, CSTR, AFFR, and HBR. Among those production technologies, UASB was used to generate biogas. The UASB reactor comprises a built-in three-phase precipitator for the effective separation of gas, liquids, and solids (sludge). The wastewater was pumped into the UASB tank at the bottom of the reactor and it flowed to the top. It mixed the sludge granules of the microorganisms. Figure 2a shows a diagram of the UASB system.

(a)

(b)

(c)

Figure 2. Cont.

(d)

(e)

(f)

Figure 2. (a–e) Process diagrams of the biogas digester technologies considered (f) COD removal efficiency, biogas production yield, and investment cost corresponding to biogas production technologies. (a) UASB. (b) ACL. (c) CSTR. (d) AFFR. (e) HBR. (f) Main parameters attributed by technology.

The ACL is popular in livestock farms in Thailand. This kind of digester requires a large area, which can be in-ground or lined. The lagoon is covered with flexible or floating gas-tight materials. The retention time is usually 30–45 days or longer, depending on design. Figure 2b presents a diagram of a covered lagoon system. The difference of ACL with UASB is that, in ACL, the biogas kept on top of the holder is wastewater. This simple passive digester can produce methane from wastewater with low maintenance and cost, improving efficiency given in Figure 2f.

The CSTR diagram is shown in Figure 2c. The steel digester tank comprises a motor which is an agitator for the mixing of solid waste. The agitator motor operates for a given period. The methane produced is fed directly to a generator or boiler without the biogas holder for some plants. Therefore, for the methane production design, the equipment capacity must properly match the size.

The AFFR process is associated with the attached biological growth, take the filter media in the reactor tank. Ideally, the press will usually provide a thin microorganism film with contact wastewater. The most common type of filter media includes plastic sheet media (vertical and crossflow). Stationary media may also include submerged media, detailed in Figure 2d which shows an AFFR system that is similar to the UASB system, the only difference of the filter media is in the reactor.

The HBR is a combined system of each technology for the highest yield of methane production. Figure 2e shows a sample of a hybrid system matching two techniques between a covered lagoon and CSTR. For this system, the ACL has a high volume of storage, and the CSTR has an agitator for mixing bacteria, which reduces bacteria settlement on the ground of the digester.

Data of the five technologies from 227 biogas plants were analyzed for COD removal efficiency, the ratio of biogas production, and investment, as shown in Figure 2f. The radar plot shows the COD removal efficiency in blue, the production yield in red, and the green investment cost. It is noted that while all the technologies meet the COD removed requirements and give the same amount of production yield, the CSTR is the cost that is far more expensive than the others. However, in the next section, more details in examining the biogas utilization pathway are described.

Five biogas technologies, UASB, ACL, CSTR, AFFR, and HBR, are considered in the paper. Among those production technologies, data of the five biogas technologies from 227 biogas plants were analyzed for COD removal efficiency, the ratio of biogas production, and investment, as shown in Figure 2f. The graph plot shows the COD removal efficiency, the production yield, and the investment cost. It is noted that while all the technologies meet the COD removed requirements and give the same amount of production yield, the CSTR is the cost that is far more expensive than the others. However, in the next section, more details in examining the biogas utilization pathway are described.

2.3. Biogas Production

The investigated biogas production technologies are effects on biogas utilization pathways, five biogas technologies considered in the optimization model for methane production. Equations (1) and (4) calculate the volume of methane production in a unit of normal cubic meters (Nm³) per year and hour. The COD is input with the averaged value of 15,000 mg L⁻¹, as obtained from 53 factories is data:

$$COD_{loading\ n} = C_n \times D_n \times W_n \times COD, \quad (1)$$

$$COD_{removal\ i,\ n} = COD_{loading\ n} \times Effr_{i,\ n}, \quad (2)$$

$$Cap_{i,\ n} = COD_{removal\ i,\ n} \times Me_{i,\ n}, \quad (3)$$

$$Br_i \leq Cap_{i,\ n}. \quad (4)$$

Biogas System Investment Cost

The investment costs are calculated by the study in calculating the linear cost function. The cost price cover the range of factory sizes in Thailand (50–400 tonnes per day). The profit of the study has a minimum value that has been beneficial for the financial model. The large size model checks and adjusts costs before calculating Equation (5), (9), (12), (14), (16), (18), (21), and (24). These data were the average value from the actual implement of BPPI.

The investment cost (Inv_i) of the biogas systems for the five technologies studied, defined as USD kg⁻¹ COD_{removal}, is used for Equation (5), and listed in Figure 2f:

$$Inv_i = COD_{removal\ i,\ n} \times CB_{i,\ n}. \quad (5)$$

2.4. Storing Biogas and Energy

A gas vessel comprises a covered lagoon direct to stored methane gas. Typically, the scenario classifies three pressure levels: low-, medium-, and high-pressure systems.

2.4.1. Low-Pressure Storage: T_1

A biogas plant mainly uses low-pressure storage, as in covered lagoon technology. A high-density polyethylene (HDPE) is stored in the methane gas. It is the thickness of 0.75–2 mm and stores a high volume, up to approximately 100–100,000 Nm³. The investment cost of low-pressure storage is significantly lower than medium- and high-pressure systems. The cover of a lagoon pond was installed and used for UASB, CSTR, AFFR, and HBR systems.

The design used for the scenario I, which used biogas for the cassava process is thermal energy for three factory sizes and the surplus biogas converted to electricity. A scale of low-pressure biogas storage is given by Equation (6). The capacity storage for thermal energy and electricity sales of the whole day:

$$T_1 \text{ for } S_1 \quad T_{11} = V_{k0} \text{ (if } V_{k0} < De), \quad (6)$$

$$T_1 \text{ for } S_2 \quad T_{12} = V_{k1} = V_{k0} - De. \quad (7)$$

The size of the storage for the boiler and on-peak period is given by Equation (8), for which biogas' capacity is kept for off-peak hours, from 10 p.m. on Friday to 9 a.m. on Monday, ~59 h of storage:

$$T_1 \text{ for } S_3 \quad T_{13} = 59 \times (V_{k3}/H_o). \quad (8)$$

$$T_{13} = 59 \times (V_{k3}/H_o). \quad (8)$$

The investment cost of the low-pressure system:

$$CT_{1,3} = 6.94 \text{ USD} \times T_{L1,2,3}. \quad (9)$$

2.4.2. Medium-Pressure Storage: T_2

Medium-pressure storage is typically used for small systems, for approximately 100 Nm³/day at 7 bar, with a steel tank. The biogas from the food waste system is used to store, which reduces the plant area, and the gas can be delivered long distances. The investment cost is more than double that of low-pressure systems—the volume of storage is given by Equations (10) and (11):

$$T_2 \text{ for } S_2 \quad T_{22} = V_{k2}/P_c, \quad (10)$$

$$T_2 \text{ for } S_3 \quad T_{23} = (59 \times (V_{k3}/H_o))/P_c. \quad (11)$$

The investment cost of medium-pressure storage is calculated as 90.55 USD per m³ (including the compressor unit):

$$CT_{21,2,3} = 90.55 \text{ USD} \times T_{M1,2,3}. \quad (12)$$

2.4.3. High-Pressure Storage Used for Compressed Biogas after Upgrading: T_3

High-pressure storage, typically at 200 bar, is suitable for storing compressed biogas (CBG) used for vehicle fuel. This CBG system has a high methane content, usually of more than 95%, and a tank volume of approximately 10–10,000 Nm³. Regularly, the high-pressure tank removes CO₂ before compressing the methane.

The calculated size of T_3 :

T_3 for S_5

$$T_3 = V_{k5}/H_o/0.552, \quad (13)$$

The investment cost calculate $24.14 \text{ USD Nm}^{-3}$

$$CT_3 = 24.14 \text{ USD} \times T_3. \quad (14)$$

2.4.4. Battery Storage: T_4

In addition to storing biogas in pressure vessels to accommodate fluctuations and peaks, biogas can feed directly into electricity and is stored in a battery. In this form, there is no need for gas-tight containers or dome for storage facilities.

Battery systems were usually in renewable energy systems like solar cells and wind turbines. There are many types of variable costs per W-h. Among these, lead-acid battery is a mature technology and generally has a low investment cost. Technically, a large capacity is discharged. However, this may not necessarily be the only option.

For whole-day case—No use:

T_4 for S_4

$$T_4 = (V_{k4} \times B_e)/D_n \times B_t. \quad (15)$$

As per data from suppliers in Thailand, the investment cost of the battery system was 905.52 USD per 1000 Ah:

$$CT_4 = 905.52 \text{ USD} \times (T_4/1000). \quad (16)$$

Equations (6)–(14) determine the sizes of biogas storage and energy storage. The size of biogas storage depends on the scenarios analyzed. As an indicator of pressure tank storage, three levels, low, medium, and high, categorize the pressure. Moreover, as energy storage, a battery was chosen for the scenario of converting biogas to electricity for selling whole day or on-peak periods. In this regard, different capacities of biogas storage and sizes of the battery are considered for the optimal utilization pathways in terms of economics and revenue.

2.5. Gas Preparation and Biogas Utilization Pathway Analyses

H_2S is typically associated with biogas from the digester. It is harmful and strongly caustic to many types of steel. H_2S burns, it forms a sulfur oxide, and acid matter, and rusts iron, such as the biogas engine. Practically, biogas contains 100–500 mg Nm^3 of sulfur dioxide. Technically, there are three leading solutions to remove H_2S from biogas: biological, chemical, and physical. The H_2S removal system costs around 286.74 USD Nm^3 of biogas. Meanwhile, the price of a gas humidity unit is 63.89 USD Nm^{-3} of biogas. For this study, defining five biogas utilization scenarios of cassava industries are examined as follows.

2.5.1. Thermal Energy for Drying Process: S_1

The preliminary energy was the supply for the drying. The biogas was a replacement for the heavy oil, pricing at approximately 0.452 USD l^{-1} . The thermal energy demand mainly depends on the production of the factory. Cassava factory size categories are recalled in Figure 1.

The size of the burner was calculated, subject to a maximum capacity of cassava starch processing. Here, the consumption of biogas was approximately 50–100 $\text{Nm}^3 \text{ ton}^{-1}$:

$$BUs = V_{k0}/H_o. \quad (17)$$

A biogas burner replaces the existing oil burner. The investment cost was 301.84 USD $\text{Nm}^3 \text{h}^{-1}$. It includes a pipe system:

$$Buc = 301.84 \times Bus. \quad (18)$$

The energy of biogas used for S_1 to calculate the low heating value of biogas that replaced heavy oil is:

$$E_{k0} = V_{k0}/0.526. \quad (19)$$

2.5.2. Electricity Generation via the Gas Engine to the Grid for the Whole Day: S_2

With the given assumption that a cassava starch factory has excess biogas, after on-site use, the surplus biogas was converted to electricity to a grid operator, for a whole day, as $0.0721 \text{ USD kWh}^{-1}$. This scenario allows a biogas plant as a simple operation with a low investment cost and small-size systems.

The calculation of the S_2 scenario includes the generator size and cost and provides equipment and energy value.

The size of biogas engine-alternator set (kW) for selling electricity on the whole day:

$$GW_{size} = (V_{k1} \times B_e)/H_w. \quad (20)$$

Investment cost of S_2 :

$$GW_{cost} = 0.953 \text{ USD} \times GW_{size}. \quad (21)$$

The energy to convert biogas to electricity, likely of scenarios S_2 , S_3 , and S_4 :

$$E_{k(2,3,4)} = (V_{k2,3,4} \times B_e). \quad (22)$$

2.5.3. Electricity Generation via the Gas Engine to the Grid during On-Peak Hours: S_3

Medium-to-large starch processing plants typically have large-size systems, which can be the biogas for selling electricity during the peak periods at $0.0884 \text{ USD kWh}^{-1}$. The on-peak hours in Thailand cover 9 a.m.–10 p.m. Monday–Friday. With the capacity, the excess gas production matched the operating time of 13 h per day.

2.5.4. Electricity Generation via Gas Engine and Store in the Battery for On-Peak Period Selling: S_4

The on-peak period requires a large volume of storing gas. An alternative approach was saving electrical energy in the cell for later on-peak. Considering the safety aspect, high-volume biogas stored at low pressure has the potential risk of explosion.

For electricity only in on-peak periods:

$$GP_{size} = (V_{k5} \times B_e)/H_{on}. \quad (23)$$

Investment cost of S_4 :

$$GP_{cost} = 0.953 \text{ USD} \times GP_{size}. \quad (24)$$

This system is investment cost, including the gas engine-alternator set and electricity distribution, which was approximately $0.953 \text{ million USD MW}^{-1}$ for all methods. The electricity on-peak period with the battery was calculation treated as the same as that of the electricity on-peak period scenario.

2.5.5. Upgrading to Bio-Methane for Vehicle Fuel: S_5

In this scenario, the biogas needed CO_2 removal to obtain a calorific heat value suitable for the vehicle, priced at approximately $0.392 \text{ USD per kg-CBG}$. As a result, the gas volume reduces typically by 40%. There are many processes to remove CO_2 with various costs, consumptions, and efficiencies, e.g., absorption in water both physically and chemically, adsorption with pressure or vacuum changes with zeolite or carbon separation, and cryogenic process, among others. The quality of methane was enhanced such that the compactness of biogas with methane was more than 95%. Hence, the investment cost was

approximately 6942.35 USD Nm⁻³ of biogas (including shipping and installing of the plant to Thailand):

$$E_{k5} = V_{k6}/0.552. \quad (25)$$

2.6. Mathematical Formulation

The model formulation has established a base on the constructed system.

Objective Function

The maximize annual profit formulated the objective function. The revenue of biogas is minus the equipment system is investment costs and biogas digester per year for 15 years. Figure 3 shows the conceptual boundary optimization model of biogas utilization:

$$\text{Maximize profit} = (P_0 E_{k0} - \text{inv}_0) + \sum_{k=1}^6 (P_k E_k - \text{inv}_k) I_k - \sum_{i=1}^5 (\text{inv}_i I_i).$$

Figure 3. Conceptual pathways of biogas utilization in the optimization model.

Subject to

$$\sum_{i=1}^5 I_i = 1$$

$$\sum_{k=1}^6 I_k = \begin{cases} S_k (V_k - De) & \text{if } V_k > De \\ 0 & \text{otherwise} \end{cases}$$

$$V_k = \sum_{i=1}^5 B_{ri} U_i I_i$$

$$V_k \leq \max\{cap_i I_i\}$$

For $k = 0$

$$E_k = S_1 V_i \text{ if } V_i < De$$

For $k = 1, 2, 3, 4, 5, 6$

$$E_k = \begin{cases} S_k (V_k - De) & \text{if } V_k > De \\ 0 & \text{otherwise} \end{cases}$$

And $I_i = \text{binary } I = 1, 2, \dots, 5.$

$I_k = \text{binary } k = 1, 2, 3, 4, 5, 6.$

Binary coding was applied to manage the algorithm in NLBP. It is the ability to dispose of both integer variables quickly and contuously simple. The calculation has three solution parts with constraints. In the first part, selecting one of the five technologies constrain biogas production, as below.

The maximizing volumetric biogas generates from five technologies (U_i). The subscript i denotes each technology:

$$U_1 + U_2 + U_3 + U_4 + U_5 = 1.$$

The utilization part deals with the storage and combines the application of the scenarios, as detailed in Table 1.

Table 1. Utilization biogas with storage model.

No.	Utilization Pathway	Description	Storage	Model
1	k_0	Use biogas to the boiler	Low-pressure	$T_1 S_1$
2	k_1	Use biogas to electricity the whole day if $V_k > De$	Low-pressure	$T_1 S_2$
3	k_2	Use biogas to electricity the whole day if $V_k > De$	Medium-pressure	$T_2 S_2$
4	k_3	Use biogas to electricity on-peak periods if $V_k > De$	Low-pressure	$T_1 S_3$
5	k_4	Use biogas to electricity on-peak periods if $V_k > De$	Medium-pressure	$T_2 S_3$
6	k_5	Use biogas to electricity on-peak periods if $V_k > De$	Battery	$T_4 S_4$
7	k_6	Use to upgrade CBG if $V_k > De$	High-pressure	$T_3 S_5$

3. Results

The proposed NLBP model was formulated in Microsoft Excel. To solve the objective function, the cost-benefit ratio corresponds to each scenario. The input variables included working days, ranging from 150 to 300 days per year. They are depicted in Table 1 and Figures 1 and 3.

The results of small factories. The capacity ranging from 50 to 250 tons of production per day is shown in Figure 1 for all five digesters (U_1 — U_5). In the first utilization pathway, the biogas produced was supplied to the boiler. The volume of biogas was just enough to cover conventional Fuel for ~90%. There was no biogas left for other pathways. At the minimum, the working day has a maximum profit of 44.78 USD per ton-COD loading. Biogas is produced from the ACL with low-pressure storage. ($T_1 S_2$). It appears that the ACL has low investment and can store biogas in the digester. However, its disadvantages, as low efficiency and the need for a large area for the plant, become a limitation for higher revenue. The high-performance operation of a plant for 180–300 days. The UASB with low-pressure storage gave maximum profits of approximately 52.48 to 55.42 USD per ton-COD loading, respectively, shown in Figure 4.

Figure 4. Optimization results of small cassava starch factories for biogas utilization.

Figure 5a shows the investment per ton-COD loading of a biogas plant; ACL has low investment costs while CSTR is high. Figure 5b presents the investment cost regarding the application and storage; ACL has low investment cost because it self-stores biogas, which is advantageous. Figure 5c and d show the profit analysis per investment and ton-COD loading of biogas-to-boiler with low- and medium-pressure (k_1 and k_2 , respectively), ACL has the highest value.

Figure 5. (a) Investment cost of all biogas plants; (b) Investment cost of application, storage, operating, and maintenance; (c) Profit per investment of k_1 ; (d) Profit per investment of k_2 .

For medium-size factories, the left volume of biogas, approximately 15% produced, was available for other pathways. The maximum profit solution is for 150–210 working days. The ACL used in S_1 and S_3 results in about 44.97, 47.77, and 49.77 USD per ton-COD loading, respectively. The UASB can obtain the maximum profit value for the plant working on 240–300 days with low-pressure storage. The resulting biogas is used in S_1 and S_3 . The maximum profits are 51.62, 53.62, and 55.21 USD per ton-COD loading, respectively. Although UASB has the disadvantages of high investment and storage added, it is highly efficient, as shown in Figure 6. Figure 7 shows the different investment values per ton-COD of biogas plants; ACL has the lowest investment, and CSTR has the highest. Figure 8a shows the analysis result of the profit of the five biogas technologies on the k_3 scenario; CSTR cannot produce the biogas cover thermal demand, while ACL technology has a high value because of its low investment, but uses a large amount of land for installing the system. The new potential option was to generate electricity on peak time with battery energy storage, which reduces the investment cost of the battery before and after by approximately 50%, compared with the low-pressure storage of three biogas technologies (which have no storage in the digester), as shown in Figure 8b–d.

Figure 6. Optimization results of medium cassava starch factories for biogas utilization.

Figure 7. Investment of all biogas plants.

(a)

(b)

(c)

(d)

Figure 8. (a) Profit per investment of k_3 from five biogas technologies; (b) Profit per investment of k_3 from three biogas technologies; (c) Profit per investment of three biogas technologies on k_5 before reduced battery cost; (d) Profit per investment of three biogas technologies on k_5 after reduced battery cost by 50%.

For large-size factories, there is 450–1000 tons of produce per day. After substituting for conventional fuel, there was 1–19% excess biogas for other utilization pathways. It considered the maximum profit solution for the 150–240 working day plants. The ACL used for k_3 has the highest profits of approximately 46.49, 49.11, 50.98, and 52.38 USD per ton-COD loading. For the plants operating for 270–300 days per year, the UASB technology provided the maximum profit value with the k_3 . The maximum profit was in the range of 53.52–55.15 USD per ton-COD loading, as shown in Figure 9. Comparing to similar profit figures, the covered lagoon can be a potential candidate for UASB. Figure 10 shows the different investment values per ton-COD of biogas plant; ACL has the lowest investment, and CSTR has the highest investment. CSTR technology has a profit per investment because of low demand energy. The profit per investment on k_3 and k_5 pathways that compare profit before and after battery cost reduce by about 50%. It has a high potential for the future benefit of biogas utilization on the k_5 pathway, as shown in Figure 11a–d.

Figure 9. Optimization results of large cassava factories for biogas utilization.

Figure 10. Investments of all biogas plants.

Figure 11. (a) Profit per investment of five biogas technologies on k_3 ; (b) Profit per investment of four biogas technologies on k_3 ; (c) Profit per investment of four biogas technologies on k_5 before reduced battery cost; (d) Profit per investment of four biogas technologies on k_5 after reduced battery cost by 50%.

4. Discussion

The effects of five different biogas technologies were used to develop the result. The multiplication of the efficiency COD removal and biogas yields define the indicator of the digester as the multiplication of the energy demand. The evaluation proposes the best solution. The result shows that for the small factories requiring thermal energy demand of about 2.30 PJ/ton, the indicator value should be greater than 0.432 and effective energy conservation. For the plants in which the thermal energy demands are about 1.285 PJ/ton, the indicator value higher than 0.342 is the best practice with any biogas production technology.

More than that, the research work presented the biogas model for available implementation to real-world agriculture industries and which was an added benefit of the clean technology project [3]. The calculation of the scenario focuses on the financial benefit, not including the availability—the availability technologies concept for a link to the notion of liberation and enrichment. They are available to user lives without imposing burdens upon users. That has become effortless, creating an availability assessment for the biogas model. The BUAA evaluation is available for all systems with the four sides. The first, “Instants” was considered for energy demand as random. Second, we were assessed on “Safe” in all spatial and temporal contexts. Third, “Everywhere” was all-encompassing, with no exclusion. The last “Easy” mechanics of technology become invisible to users, as shown in Appendix A. The results of BUAA were k_3 and k_5 pathways of medium-size factories. This was the first and secondary benefit; the battery has a full score of more than low-pressure storage on-peak. The battery storage was an advantage technology as instant technologies for electricity demand, safety for use and operation of the plant, small area for installation, and smooth process for renewable energy source, as presented in Figure 12. Besides, the biogas plant was applied to the local grid or island grid system that was to investigate another kind of storage and integrate the energy demand side. The sustainability renewable energy source is likewise research of Amiryar and Pullen [25].

Figure 12. BUAA of UASB technologies on $k3$ and $k5$ scenarios.

5. Conclusions

This paper presents the option biogas value-added which was an optimization model. The scenario showed a techno-cost-benefit evaluation of the biogas utilization pathway. First of all, the essential indicator of the cassava starch manufacturers was the energy demand and some operating days. That has an impact on the diversity of biogas utilization. Likewise, the two key indicators of biogas production of digester were benchmarked based on efficiency COD removal and methane generate yields. Secondary, the kind of storage was significant on a renewable energy source and location to constrain. It is a variable of cost and value-added advantage. Finally, the proposed optimization scheme for biogas utilization pathways with BUAA can be applied to evaluate project implementation of biogas power plants fed with any industrial wastewater. Hence, it can achieve energy sustainability and smart power generation systems.

Author Contributions: Conceptualization; methodology; formal analysis; data curation; writing—original draft preparation; visualization C.W. validation, C.W.; R.S.; writing—review and editing, C.W.; R.S.; supervision, R.S.; C.W.; R.S.; A.N.; C.K. have investigation, read and agreed to the published version of the manuscript.

Funding: “The EPPO, Ministry of Energy, Thailand”.

Acknowledgments: The EPPO, Ministry of Energy, Thailand, and ERI, Chulalongkorn University, support this work.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

B_e	Ratio convert biogas to electricity about (2.185 kWh/Nm ³)
Br_i	Biogas produce from five biogas technologies (N-m ³ /mgCOD _{removal})
B_t	Ratio of converting electric energy to size of battery about (1 kWh/1.95 Ah)
BU_c	Investment cost of biogas burner (USD/ N-m ³ /hour)
BU_s	Size of biogas burner (N-m ³ /hour)
$Cap_{i,n}$	Capacity of biogas generated from five biogas technologies (N-m ³ /Year)
C_B	Battery size (Ah)
C_n	Production capacity of cassava factory (Ton/Day)
$CB_{i,n}$	Cost of biogas system (UASB, ACL, CSTR, AFFR, HBR) (USD/mgCOD _{loading})
COD	Chemical oxygen demand fixed at approximately (15,000 mg/L)
$COD_{loading\ n}$	COD Volume of wastewater load to the biogas digester (kgCOD/Day)
$COD_{removal\ i,\ n}$	COD Volume of wastewater removal of biogas digester (kgCOD/Day)
$ConS_k$	Constant parameter convert biogas to energy (MJ/N-m ³)
$CT_{1,I}$	Investment cost of the low-pressure system (USD/N-m ³)
$CT_{2,I}$	Investment cost of the medium-pressure system (USD/N-m ³)
CT_3	Investment cost of the high-pressure system (USD/N-m ³)
CT_4	Investment cost of the battery storage system (USD/Ah)
De_l	Biogas boiler demand of large size cassava factories (MJ/Ton)
De_m	Biogas boiler demand for medium size cassava factories (MJ/Ton)
De_s	Biogas boiler demand of small size cassava factories (MJ/Ton)
D_n	Working days of cassava factory (Day/Year)
$E_{k=0}$	Ratio biogas convert to energy 1 Nm ³ = 20.93 MJ/LHV heavy oil 39.77 (MJ/L)
$E_{k=1.2,..,5}$	Biogas 1 Nm ³ = 2.185 (kWh/Year)
$E_{k=6}$	Biogas 1 Nm ³ = 0.552 (kgCBG/Year)
$Effr_{i,n}$	COD removal efficiency of five biogas technologies (%)
GP_c	Generator cost for selling electricity only in on-peak periods (MW)
GP_s	Generator size for selling electricity only in on-peak periods (MW)
GW_c	Generator cost for selling electricity the whole day (MW)
GW_s	Generator size for selling electricity the whole day (MW)
H_c	Hour continue of off-peak (Hour/Day)
H_o	Operating hours (Hour/Day)
$Ho_{i,n}$	Operating hours per year (Hour/Year)
H_{on}	65 h on peak per week (Hour/Week)
H_w	24 h of whole day (Hour/Day)
$Inv_{i=1}$	Investment cost of UASB (USD)
$Inv_{i=2}$	Investment cost of ACL (USD)
$Inv_{i=3}$	Investment cost of CSTR (USD)
$Inv_{i=4}$	Investment cost of AFFR (USD)
$Inv_{i=5}$	Investment cost of HBR (USD)
inv_o	Investment cost of equipment k_0 scenario (USD)
$inv_{k=1}$	Investment cost of equipment k_1 scenario (USD)
$inv_{k=2}$	Investment cost of equipment k_2 scenario (USD)
$inv_{k=3}$	Investment cost of equipment k_3 scenario (USD)
$inv_{k=4}$	Investment cost of equipment k_5 scenario (USD)
$inv_{k=5}$	Investment cost of equipment k_5 scenario (USD)
$inv_{k=6}$	Investment cost of equipment k_6 scenario (USD)
k_0	Scenario utilization pathway biogas to the boiler
k_1	scenario utilization pathway biogas to the boiler with low-pressure storage and electricity the whole day withS low-pressure storage
k_2	Scenario utilization pathway biogas to the boiler with low pressure and electricity a whole day with medium pressure storage
k_3	Scenario utilization pathway biogas to the boiler with low pressure and electricity on-peak periods with low-pressure storage

k_4	Scenario utilization pathway biogas to the boiler with low pressure and electricity on-peak periods with medium pressure storage
k_5	Scenario utilization pathway biogas to the boiler with low pressure and electricity on-peak periods with battery storage
k_6	Scenario utilization pathway biogas to the boiler with low pressure and upgrade biogas to compress biogas with a high-pressure storage
$Me_{i,n}$	Ratio of methane generated per $COD_{removal}$ ($N\text{-m}^3/\text{mg}COD_{removal}$)
P_0	Price of biogas converted to the boiler (USD)
$P_{k=1,2}$	Price of biogas converted to electricity whole day (USD/kWh)
$P_{k=3,4,5}$	Price of biogas converted to electricity on peak (USD/kWh)
$P_{k=6}$	Price of biogas converted to CBG (USD/kg)
P_c	7 bar pressure compress (Bar)
S_1	Use biogas to boiler
S_2	Use biogas to electricity the whole day
S_3	Use biogas to electricity on-peak period
S_4	Use biogas to electricity on-peak period with battery storage
S_5	Use biogas to upgrade CBG
$T_{1,i}$	Size of low-pressure storage ($N\text{-m}^3$)
$T_{2,i}$	Size of medium pressure storage ($N\text{-m}^3$)
$T_{3,i}$	Size of high-pressure storage ($N\text{-m}^3$)
T_4	Size of battery storage (Ah)
$V_{i,n}$	Volume of biogas generated per hour from five biogas technologies ($N\text{-m}^3/\text{h}$)
V_k	Volume of biogas from five technologies ($N\text{-m}^3/\text{Day}$)
W_n	Consumption of wastewater per ton of production (m^3/Ton)

Appendix A

Biogas Utilization Availability Assessment : BUAA				
1. Technologies Instant on demand				
1.1 Instant on methane generate of Biogas technologies				
Characteristic	Score			Note
	Actual		Max	
Hydraulic Retention Time of transfrom waste to Biogas P	3	3	3	3 = Hydraulic Retention Time ($HRT < 15\text{day}$), UASB, CSTR, AFFR 2 = Hydraulic Retention Time ($HRT > 15 < 30\text{day}$) 1 = Hydraulic Retention Time ($HRT > 30\text{day}$) ACL 0 = Not biogas reactor
Total score	3	3	3	
1.2 Instant on demand Storage system				
Characteristic	Score			Note
	Actual		Max	
Can respond on demand	1	3	3	3 = Low pressure + Battery 2 = Low+Medium-High pressure 1 = Low pressure only 0 = Not storage
Total score	1	3	3	
1.3 instant on utilization system				
Characteristic	Score			Note
	Actual		Max	
convert biogas to high value	3	3	3	3 = To Combustion in Boiler+ To Generator on 2 = To Combustion in Boiler+Upgrade methane, To Combustion in Boiler + Generator 24h 1 = To Combustion in Boiler (1 application) 0 = To flare
Total score	3	3	3	

Figure A1. Cont.

2. Safety of system				
2.1 Safety of Biogas technologies				
Characteristic	Score			Note
	Actual		Max	
Digester system control by sensor	1	3	3	3 = Control on sensor : UASB, AFFR, CSTR 2 = Semi control hand and sensor : HBR 1 = UN sensor control : ACL 0 = Not
Total score	1	3	3	
2.2 Safety Storage system				
Characteristic	Score			Note
	Actual		Max	
Storgae system and volume risk of fire	1	3	3	3 = Battery 2 = Medium-High pressure and Low pressure low volume 1 = Low pressure high volume 0 = Not storage
Total score	1	3	3	
2.3 Safety Utilization system				
Characteristic	Score			Note
	Actual		Max	
Safety energy srouce	3	3	3	3 = To Combustion in Boiler+ To Generator on peak 2 = To Combustion in Boiler+Upgrade methane, To Combustion in Boiler + Generator 24h 1 = To Combustion in Boiler (1 application) 0 = To flare
Total score	3	3	3	
3. Every where operation of system				
3.1 Every where biogas technologies				
Characteristic	Score			Note
	Actual		Max	
area of biogas technologies	1	3	3	3 = Compact area, UASB, CSTR, AFFR 2 = Semi compact area HBR 1 = Large Area :ACL 0 = Not biogas reactor
Total score	1	3	3	
3.2 Every where Storage system				
Characteristic	Score			Note
	Actual		Max	
less area for install system	1	3	3	3 = Battery 2 = Medium-High pressure and Low pressure low volume 1 = Low pressure high volume 0 = Not storage
Total score	1	3	3	
3.3 Every where Utilization				
Characteristic	Score			Note
	Actual		Max	
less limit	3	3	3	3 = To Combustion in Boiler+ To Generator on peak 2 = To Combustion in Boiler+Upgrade methane, To Combustion in Boiler + Generator 24h 1 = To Combustion in Boiler (1 application) 0 = To flare
Total score	3	3	3	

Figure A1. Cont.

4. Easy operation**4.1 Easy operation of biogas technologies**

Characteristic	Score			Note
	Actual		Max	
Performance operate system of biogas technologies	1	3	3	3 = Automatic control, UASB, CSTR, AFFR 2 = Semi automatic control HBR 1 = handle :ACL 0 = Not biogas reactor
Total score	1	3	3	

4.2 Energy Easy use of Storage

Characteristic	Score			Note
	Actual		Max	
lesstime for discharge	1	3	3	3 = Battery 2 = Medium-High pressure and Low pressure low volume 1 = Low pressure high volume 0 = Not storage
Total score	1	3	3	

4.3 Easy Utilization system

Characteristic	Score			Note
	Actual		Max	
low maintainace time	3	3	3	3 = To Combustion in Boiler+ To Generator on 2 = To Combustion in Boiler+Upgrade methane, To Combustion in Boiler + Generator 24h 1 = To Combustion in Boiler (1 application) 0 = To flare
Total score	3	3	3	

Shape BUAA	Description	Diagnosis
All characteristic Score more than 70%	Excelllant Availability of plant
All characteristic Score less than 50%	Poor Availability of plant
A single characteristic is significantly high than the rest	A single side of availability analysys and has potentail to development
one side score more than 50%	Not Availability of plant must develop system
A single characteristic is significantly low than the rest	Low score of group show weaknesses of utilization
A single side has score less than 50%	Development on low score for avaibility of plant
Two side or more than by high or low thane 50%	Development on low score for avaibility of plant

Figure A1. Biogas Utilization Availability Assessment.**References**

1. Annual Report 2015 EPPO, Energy Policy and Planning Office (EPPO). Available online: http://www.eppo.go.th/images/Infomation_service/EPPOAnnualReport/EPPOAnnualReport2015.pdf (accessed on 2 March 2016).
2. Tran, T.; Da, G.; Moreno-Santander, M.A.; Velez-Hernandez, G.A.; Giraldo-Toro, A.; Piyachomkwan, K.; Sriroth, K.; Dufour, D. A comparison of energy use, water use and carbon footprint of cassava starch production in Thailand, Vietnam and Colombia, Resources. *Conserv. Recycl.* **2015**, *100*, 31–40.
3. Chavalparit, O.; Ongwandee, M. Clean technology for the tapioca starch industry in Thailand. *J. Clean. Prod.* **2009**, *17*, 105–110.

4. Anyanwu, C.N.; Ibeto, C.N.; Ezeoha, S.L.; Ogbuagu, N.J. Sustainability of cassava (*Manihot esculenta* Crantz) as industrial feedstock, energy and food crop in Nigeria. *Renew. Energy* **2015**, *81*, 745–752.
5. Ghimire, A.; Sen, R.; Annachhatre, A.P. Biosolid management option in Cassava Starch Industries of Thailand: Present practice and future possibilities. *Procedia Chem.* **2015**, *14*, 66–75.
6. Lu, X.; Zhen, G.; Estrada, A.L.; Chen, M.; Ni, J.; Hojo, T.; Kubota, K.; Li, Y.Y. Operation performance and granule characterization of up-flow anaerobic sludge blanket (UASB) reactor treating wastewater with starch as the sole carbon source. *Bioresour. Technol.* **2015**, *180*, 264–273.
7. Phowan, P.; Danvirutai, P. Hydrogen production from cassava pulp hydrolysate by mixed seed cultures: Effect of initial pH, substrate and biomass concentrations. *Biomass Bioenergy* **2014**, *64*, 1–10.
8. Cavaleiro, A.J.; Alves, M.M.; Mota, M. Microbial and the operational response of an anaerobic fixed bed digester to oleic acid overloads. *Process. Biochem.* **2001**, *37*, 387–394.
9. Stergaard, P.A. Comparing electricity, heat and biogas storage impacts on renewable energy integration. *Energy* **2012**, *37*, 255–262.
10. Guan, C.; Loo, L.S.; Wang, K.; Yang, C. Methane storage in carbon pellets prepared via a binderless method. *Energy Convers. Manag.* **2011**, *52*, 1258–1262.
11. Lozano-Castello, D.; Alcaniz-Monge, J.; de la Casa-Lillo, M.A.; Cazorla-Amoros, D.; Linares-Solano, A. Advance in the study of methane storage in porous carbonaceous materials. *Fuel* **2002**, *81*, 1777–1803.
12. Kapdi, S.S.; Vijay, V.K.; Rajesh, S.K.; Prasad, R. Biogas scrubbing, compression and storage: Perspective and prospectus in the Indian context. *Renew. Energy* **2005**, *30*, 1195–1202.
13. Rios, R.B.; Bastos-Neto, M.; Marcelo, R.A., Jr.; Eurico, A.; Torres, B. Experimental analysis of the efficiency on charge/discharge cycle in natural gas storage by adsorption. *Fuel* **2011**, *90*, 113–119.
14. Osorio, F.; Torres, J.C. Biogas purification from anaerobic digestion in a wastewater treatment plant for biofuel production. *Renew. Energy* **2009**, *34*, 2164–2171.
15. Pipatmanomai, S.; Kaewluan, S.; Vitidsant, T. Economic assessment of biogas-to-electricity generation system with H₂S removal by activated carbon in a small pig farm. *Appl. Energy* **2009**, *86*, 669–674.
16. Waewsak, C.; Nopharatana, A.; Chaiprasert, P. Neural-fuzzy control system application for monitoring process response and control of anaerobic hybrid reactor in wastewater treatment and biogas production. *J. Environ. Sci.* **2010**, *22*, 1883–1890.
17. Ferreira, G.D.; Bretas, A.S. A non-linear binary program model for electric distribution system reliability optimization. *Electr. Power Energy Syst.* **2012**, *43*, 384–392.
18. Sharma, S.; Rangaiah, G.P.; Cheah, K.S. Multi-objective optimization using MS Excel with an application to design of a falling-film evaporator system. *Food Bioprod. Process.* **2012**, *90*, 123–134.
19. Albernas-Carvajal, Y.; Corsano, G.; Kafarov, V.V.; Cortés, M.G.; Suárez, E.G. Optimal design of pre-fermentation and fermentation stage applying non-linear programming. *Energy Convers. Manag.* **2014**, *87*, 1195–1201.
20. De Jong, Y. Gas storage valuation and optimization. *J. Nat. Gas. Sci. Eng.* **2015**, *24*, 365–378.
21. Upadhyay, S.; Sharma, M.P. Development of the hybrid energy system with cycle charging strategy using particle swarm optimization for a remote area in India. *Renew. Energy* **2015**, *77*, 586–598.
22. Johnston, L.; Diaz-Gonzalez, F.; Gomis-Bellmunt, O.; Corchero-Garcia, C.; Cruz-Zambrano, M. Methodology for the economic optimization of energy storage systems for frequency support in wind power plants. *Appl. Energy* **2015**, *137*, 660–669.
23. Mudasser, M.; Yiridoe, E.K.; Corscadden, K. Cost-benefit analysis of grid-connect wind-biogas hybrid energy production, by turbine capacity and site. *Renew. Energy* **2015**, *80*, 573–582.
24. Dominkovic, D.F.; Cosic, B.; Medic, Z.B.; Duic, N. A hybrid optimization model of biomass trigeneration system combined with pit thermal energy storage. *Energy Conserv. Manag.* **2015**, *104*, 90–99.
25. Amiryar, M.E.; Pullen, K.R. Assessment of the carbon and cost savings of a combined diesel generator, solar photovoltaic, and flywheel energy storage islanded grid system. *Energies* **2019**, *12*, 3356–3371.