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Economics of Distributed Power Generation via Gasification of Biomass and Municipal Solid Waste

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Abstract: More than one billion people worldwide still lack access to electricity. Rural electrification via gasification has the potential to satisfy electricity access and demand. This study conducts an economic evaluation of rural electrification through gasification of biomass and municipal solid waste (MSW) using a 60 kW downdraft gasifier, developed at Oklahoma State University. The effects of feedstock cost, electricity selling price, feed-in-tariff, tipping fee, tax rate, and the output power are evaluated using major financial parameters: the net present value, internal rate of return, modified internal rate of return, simple payback period, and discounted payback period, and sensitivity analysis. Results show that the downdraft gasification power system offers a payback period of 7.7 years, while generating an internal rate of return, modified internal rate of return, and net present value of 10.9%, 7.7%, and $84,550, respectively. Results from a sensitivity analysis indicate that the feed-in-tariff has the greatest positive contribution to the project's net present value. Using MSW, the gasification power system potentially reduces carbon dioxide, nitrogen oxides, and sulfur dioxide emissions as compared to direct combustion and landfill. The technology provides a promising future for rural electrification utilizing biomass and MSW whilst offering economic and environmental benefits for local communities.

Keywords: gasification; biomass; municipal solid waste; power generation; economic analysis

1. Introduction

The year 2015 set records for world clean-energy investment, with renewable energy sources increasing by twice as much global capital as fossils fuels [1]. Investment reached over $350 billion [2]. At the same time, access to electricity is becoming more critical in modern life and economic development. A recent report from the International Energy Agency (IEA) revealed that, by 2030, around 675 million people (8% of the global population) will still lack access to electricity and 90% of them live in sub-Saharan Africa [3]. In the same period, about 2.3 billion people will still use biomass, coal, and kerosene for cooking, slightly reduced from 2.8 billion today [3]. This makes them vulnerable to harmful indoor air pollution, which potentially causes lethal poisoning and is considered associated with 2.8 million premature deaths per year [3].

One of the clean technologies that can address the aforementioned issues while expanding access to electricity is gasification of locally forestry products (i.e., biomass) and municipal solid waste (MSW). Gasification is becoming more popular as it can utilize any carbonaceous feedstocks, such as coal, biomass, and municipal solid waste [4]. Syngas, the main product of gasification, consists mainly of carbon monoxide (CO) and hydrogen (H_2), and small fractions of methane (CH_4) and heavier hydrocarbons. Syngas is generated through multiple reactions by the conversion of carbonaceous feedstocks at a temperature range from 500 °C to 1400 °C [5], with an efficiency of 75–80% [6]. Heavier components, including contaminants of the feedstock, are collected as ash and slag. After being cleaned of contaminants, syngas can directly feed internal combustion engines (ICEs) comprising spark ignition and compressed ignition engines, gas turbines (GTs), or fuel cells (FCs), resulting in an electrical efficiency from about 21% [7] to 65% [8] with a minimum service life of 20 years [9].

With the prospect of increasing natural gas prices, syngas can contribute a positive role in the future energy economy. As an illustration, in China, and in Indonesia and other Southeast Asian countries, due to the increased demand for liquefied natural gas (LNG), the current prices of natural gas for the industrial market has recently reached $10–15/MMBtu, with predictions to steadily increase in the coming years [10]. The LNG chain demands high capital expenditures (CAPEX) and operating expenses (OPEX), especially for the steps of liquefaction and cryogenic overseas transportation, consequently resulting in high "landed prices" [10]. In comparison, syngas production cost from wood biomass is about $0.042 kWh (~$12.3/MMBtu) [11], while $0.02 kWh (~$5.9/MMBtu) from MSW [12].

In terms of capacity, electricity generation systems derived from gasification can be flexible and suitable for distributed application while supporting rural development as the size of the gasifier can range from kW-scale to MW-scale. Current total electric capacity of distributed and dispersed (independently operating) generation (with a generator size < 1 MW) in the U.S. reached 5407 MW in 2015, with still-increasing predictions in coming years [13], while the global net electricity generation of 23.4 trillion kilowatt hours (kWh) in 2015 is projected to increase to 34.0 trillion kWh in 2040 [3]. Emissions of CO_2 and SO_2 equivalents during power generation from biomass were also reported 67 and 18 times lower, respectively, than those from fuel oil [14]. In addition, biopower generation can generate negative greenhouse gas emissions (GHGs) ranging from 600 to 650 g CO_2-eq/kWh when waste materials are used [15].

Studies on evaluating the economic performance of biopower generation using sensitivity and capital budgeting analyses have been reported [16,17]. Using sensitivity analysis, at a feedstock cost of $34/ton, a discount rate of 6–8%, and a projected life of 30 years, for the 10 and 20 MW plants, Moriarty [16] found positive net present values (NPVs) at breakeven electricity rates of about $142 and $123/MWh, respectively. However, other key financial parameters, such as the internal rate of return (IRR), were not included in the analysis. At a larger scale (>50 MW), Nderitu et al. [17] analyzed the feasibility of biopower generation throughout states in the U.S. using sensitivity analysis at a feedstock price of $40/ton, a discount rate of 10%, and a life of 20 years. When state-level renewable portfolio standards and incentives (i.e., feed-in-tariff (FIT), tax credit, and new federal subsidies) were not applied and selling electricity into the marketplace was the only source of revenue for the biopower plant, the authors found that the electricity sales need to be (at least) 25% higher than the base case to make the project economically feasible. However, the NPV and payback period (PP) were not presented. In a more recent study of distributed power generation, Buchholz et al. [18] reported an economic analysis of a 250 kW downdraft gasifier to replace one of the diesel generators (200 kW in capacity) that supported a tea estate processing utility. The gasifier used fuelwood (cut 10 × 10 × 10 cm) with a constant feeding rate of 320–400 kg/h. Equipped with an ash removal system, a syngas cleaning system, and a 250 kW syngas engine, the gasification system successfully replaced the use of a 200 kW diesel fuel generator. When the internal load was supplied by the gasifier, the gasification power system offered an IRR and PP of 11% and 8 years, with the diesel fuel savings of 149,000 L/year. The electricity production and avoided diesel costs were correspondingly achieved at $0.18/kWh and $93,631/year. However, the project NPV and sensitivity analysis on factors impacting the economic performance of the gasification power system were not presented. In addition, using Monte Carlo analysis, Campbell et al. [19] investigated four production pathway scenarios, including the use of pyrolysis for biofuel product and gasification technology for making wood pellets (scenario 1 and 2), for the conversion of beetle-killed pine to bioenergy and bioproducts in the Rocky Mountains with the feed rate of 9–10 ton/hour and a plant lifetime of 20 years. They found that these scenarios (1 and 2) provide the highest possible return, resulting in a positive NPV of $76 million and $22.4 million, respectively; meanwhile, a negative NPV of $8.3 million was found for electricity production (scenario 4). However, this study is based on a technological concept, not based on experimentation. Except for the study reported by Buchholz et al. [18], the aforementioned studies were based on the combustion technology for electricity production; thus, the results could vary significantly with the gasification technology. In addition, none of these studies have reported the use of MSW for electricity production via gasification technology.

Unlike previous studies taking advantage on using commercially available units of gasifier, this paper presents an economic analysis of a 60 kW downdraft gasification system, developed at Oklahoma State University (OSU), which has the capability to treat biomass and MSW for supporting rural electricity production. The gasifier unit is not only an upscale unit that has been used for years [20] but also equipped with modifications that can increase the efficiency of carbon conversion. Key financial parameters, including the NPV, IRR, modified internal rate of return (MIRR), PP, and discounted payback period (DPP), with the analyzed period of 20 years, are selected to investigate the economic viability of the project. A sensitivity analysis investigating factors that impacts the economic performance is included and the results are then compared with a similar type of gasifier with a 250 kW size reported by Buchholz et al. [18]. To support the economics of the gasification power system, an environmental evaluation is added to compare with direct combustion and landfill as two conventional treatments of biomass and MSW.

2. Methodology

The performance of power generation systems developed at OSU has been reported previously [7,21]. The major equipment includes a reactor (a downdraft gasifier), a belt conveyor, a cyclone separator, an ash collecting system equipped with a screw conveyor, a water-acetone syngas cleaning system, and an ICE, as its schematic diagram shown in Figure 1.

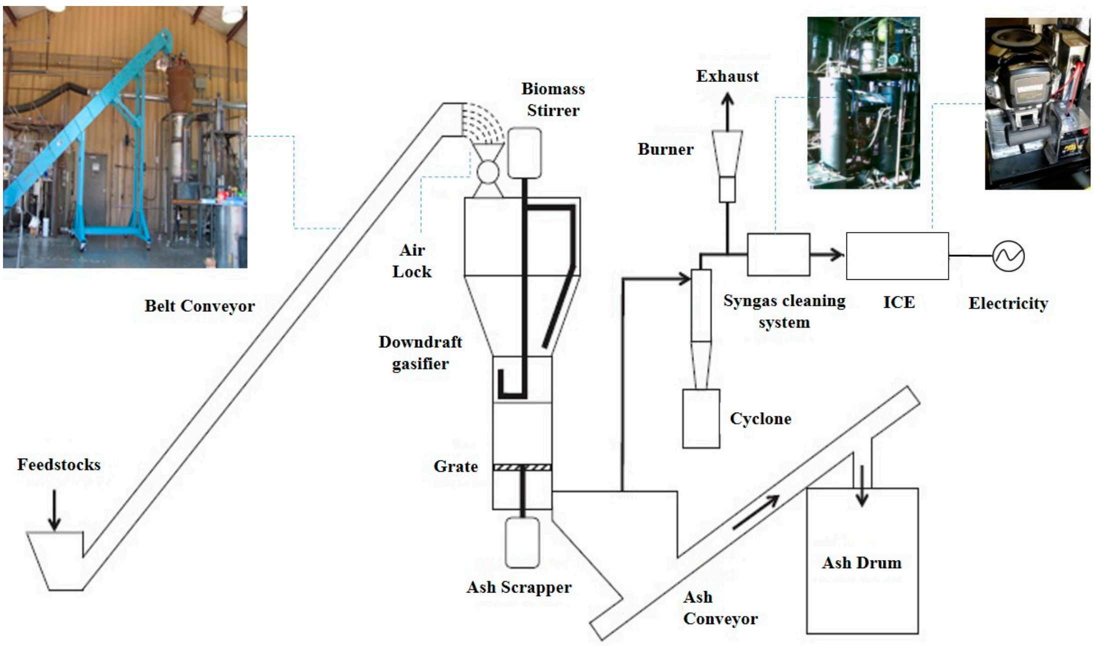

Figure 1. Simplified process diagram of high-temperature gasification, developed at Oklahoma State University, reproduced with permission from [22], published by Elsevier.

A sensitivity analysis is used to assess the main economic parameters, including the feedstock (biomass) cost, electricity selling price, FIT, output power, tax rate, tipping fee, and the labor cost.

The NPV and IRR, two major investment analysis and capital budgeting decision tools [23,24], are used to determine the feasibility of the project, as expressed below:

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{\mathrm{CF}_t}{(1+k)^t} \tag{1}$$

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{\mathrm{CF}_t}{(1+\mathrm{IRR})^t} = 0 \tag{2}$$

where CF is cash flow; k is the discount rate; t is the corresponding year; n is the total year of the analysis. In addition to NPV and IRR, PP, DPP, and MIRR are calculated to further observe the project's economic performance. PP refers to the length of time it takes for the original cost of an investment to be recovered from its expected cash flows, while DPP, the next level of PP where the cash flows are discounted before calculating the period of payback, is used to present more accurate results as it includes the time value of money [23,24]. MIRR refers to the discount rate at which the present value of a project's cost is equal to the present value of its terminal value; the terminal value is found as the sum of the future values of the cash inflows compounded at the required rate of return. MIRR is included to reinforce the analysis as it correctly assumes reinvestment at the project's cost of capital and that the initial expenses are financed at the project's financing cost; thus, the problem of multiple IRRs can be circumvented. The PP, DPP, and MIRR can be expressed as the following [24]:

$$\mathrm{PP} = A + \left(\frac{B}{\mathrm{CF}_t}\right) \tag{3}$$

$$\mathrm{DPP} = ln\left(\frac{1}{1-\frac{\mathrm{CF}_0 \times k}{\mathrm{CF}_t}}\right) : ln(1+k) \tag{4}$$

$$\text{PV of cash out flows} = \frac{\mathrm{TV}}{(1+\mathrm{MIRR})^n} \tag{5}$$

where A is the number of years before full regaining of initial investment; B is the amount of initial investment that is unrecovered at the start of the recovery year; CF_0 is the initial investment; CF_t refers to the cash flow in year t; k is the discount rate; TV is the terminal investment.

2.1. Gasifier Characteristics

The 60 kW downdraft gasifier [7,21,25] is used in the current study since it has several advantages over other types of gasifiers. The gasifier generates syngas that has low tars (<3 mg/Nm^3) and high calorific value (4–6 MJ/Nm^3), thus providing a high cold gas efficiency (CGE) (85–90%) [26]. In addition, the gasifier is easy to set-up and control during operation and capable of treating different feedstocks (including biomass and MSW) with stable performance [25,27]. The gasifier is also capable of generating power up to 5 kW from a 10 kW internal combustion engine using syngas flow of about 15 m^3/h; the gasifier produces a total syngas flow of more than 150 m^3/h [7,21], thus, its ability to generate an output power of approximately 60 kW is within reach, following its rating capacity [21,25]. Due to the unique design of the reactor, the downdraft gasifier is generally only suitable for a small to medium power scale (up to 10 tons/day (tpd) of feed stream with an output power of approximately 1 MW) [26], as shown in Figure 2.

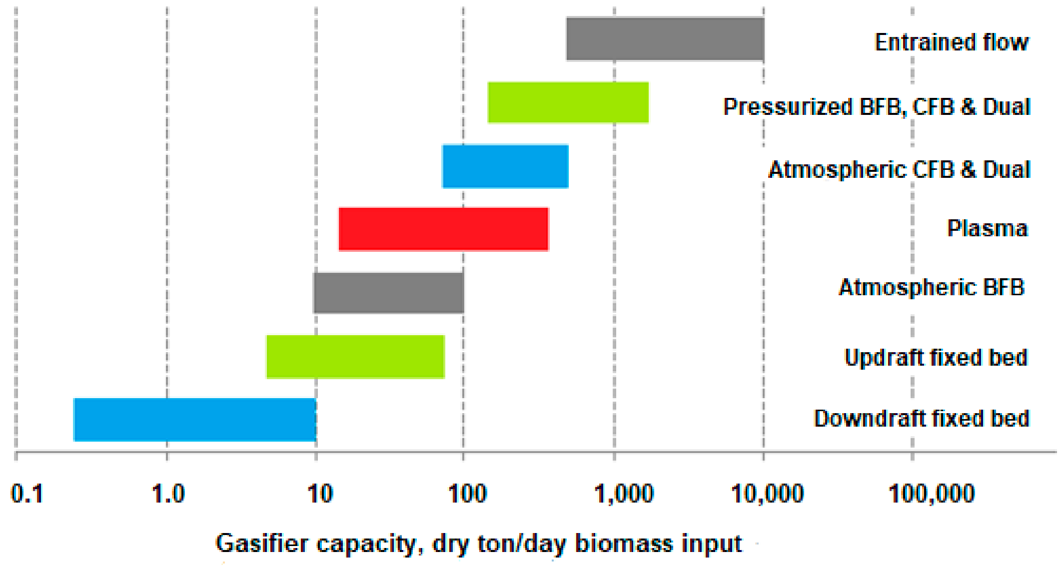

Figure 2. Gasifier technology versus capacity range [28].

2.2. Basic Key Economic Inputs

Basic key economic inputs are the main parameters that directly influence the economic performance of a project. Some inputs can either refer to the practical situation or the assumptions based on literature. In this study, the key economic inputs include total capital costs, total operating and maintenance (O&M) costs, biomass feedstock cost and tipping fee, weighted average cost of capital (WACC), plant availability, plant lifetime, salvage value, depreciation rate, electricity price, FIT, marginal tax rate, and contingencies.

2.2.1. Total Capital Cost

The total capital cost, including basic equipment and materials for the 60 kW downdraft gasifier, is $112,500, as shown in Table 1.

Table 1. Equipment and materials of the downdraft gasifier.

Equipment	Cost	Remarks
Reactor, cyclone separator, and control system	$60,000	
Belt conveyor	$10,000	Bunting Magnetic Co.
Ash removal system (ash drum, screw conveyor, electric motor)	$10,000	
Air compressor	$10,000	Sullair air compressor
Gas scrubbing system (double gas scrubber, pump)	$4,500	The gas cleaning system consisted of water-acetone solution [29]
Power generation unit (natural gas ICE)	$18,000	An ICE of 100 kW is used to accommodate total volume of syngas flow with an assumed capital cost based on a detailed specification in [30]
Total	$112,500	

2.2.2. Total O&M Cost

The total O&M costs (including fixed and variable costs) consist of labor, supporting equipment (i.e., pumps, compressors, and electric motors—commonly known as the balance of plant (BOP)) and utilities, and chemicals are shown in Table 2 with major operating costs shown in Figure 3. With the total output power of 60 kW (about 43,800 kWh/month), the total O&M costs are consequently $0.196/kWh.

Table 2. Operation and maintenance costs of the 60–kW downdraft gasifier.

Description	Amount, $/month [1]	Remarks	References
Operational costs			
Fixed			
Labor	4640	1 operator/shift; four shifts in total. @$7.25/person/hour	[31]
Variable			
Electricity for BOP			
Air Compressor, 28.4 kW	393	4146.4 kWh/month (in average), operating at 20% capacity.	(Sullair, Model 2209AC, Sullair LLC., Michigan City, IN, USA)
Electric heaters, 5 pcs @360W	121	1314 kWh/month (average energy consumption)	
Chiller, 1.5 hp	75	815.8 kWh/month (average energy consumption)	(Schreiber, Model 300 AC, Engineering Corporation, Cerritos, CA, USA)
Water pump, 0.5 hp	25	543.9 kWh/month (average energy consumption)	
Belt conveyor, 1 hp	50	543.9 kWh/month (average energy consumption)	(Bunting Magnetics Co., Newton, KS, USA)
Air log motor, 1 hp	50	543.9 kWh/month (average energy consumption)	(Grainger, Roanoke, TX, USA)
Ash scrapper, 1 hp	50	543.9 kWh/month (average energy consumption)	(Grainger, Roanoke, TX, USA)
Ash conveyor, 1 hp	50	543.9 kWh/month (average energy consumption)	(Dayton, Model 2MXT4A, Dayton Electric Mfg. Co., Lake Forest, IL, USA)
Syngas cleaning system (i.e., acetone)	2142	5 gal/day is used, with a retail price of $14.28/gal	Water-acetone based, mixable with renewable filters [32,33]
Disposal cost of liquid waste (i.e., acetone)	225	5 gal/day is used, with a disposal cost of $0.23/lb and density 784 kg/m^3	Hazardous Materials Management Facility, Boulder County [34]
Propane gas	16	4.7 gal cylinder with a retail price of $3.44/gal	
Maintenance costs			
Fixed			
Tools	25		
Sealant and insulations	20		
Air lock fins, 8pcs	200		
Spare electric motor	17		
Variable			
Charcoal	480	2 packages/day with a retail price of $8/package	
Total O&M costs, $/month	8580		

Note: [1] Calculated using electricity rate of $9.48/kWh [35].

Labor cost, representing 54% of total operating cost, is critical because it directly affects the total O&M cost of the power generation system. A labor cost of $7.45/hour is considered as current minimum wage in the state of Oklahoma in 2018 [31]. Syngas cleaning system, the second largest contributor of total operating cost, uses water-acetone solution as a commercially proven method to remove syngas tar and other contaminants. An additional cost to dispose of the solution is required to maintain the removal efficiency, assumed at $0.23/lb., following a typical disposal rate of hazardous waste in a neighboring area [34].

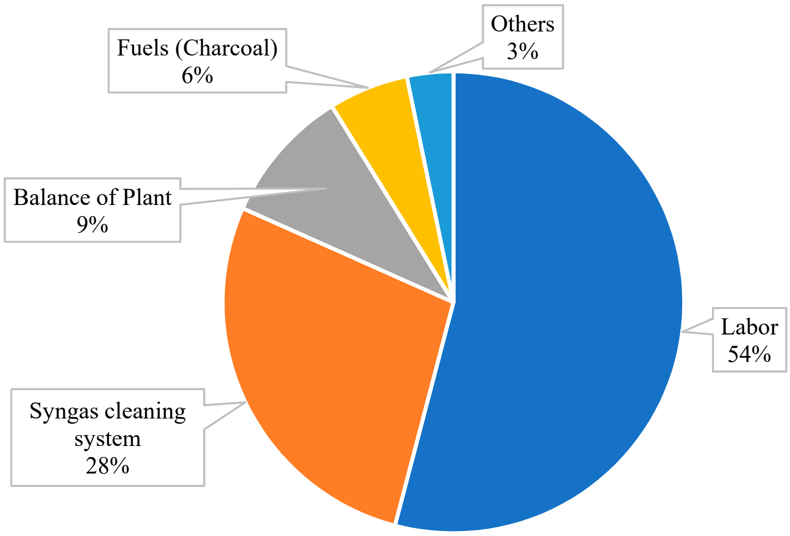

Figure 3. Major operating costs of the downdraft gasification power system.

2.2.3. Feedstock Cost

Biomass feedstock greatly impacts the economics of power generation [36]. Biomass feedstock cost, including production, harvesting, and delivery, is considered to be $20/ton as it uses local agricultural sources, which are close to the plant, thus, the delivery cost can be neglected. The considered cost closely agrees with the one reported previously (about $25/ton) if the delivery cost is negated [37]. In Central Oklahoma, a higher economic value of the power generation can be achieved by using non-edible feedstocks, such as switchgrass (*Panicum virgatum*) and eastern redcedar (*Juniperus virginiana*), because these feedstocks are readily present, considerably decreasing transportation cost as one of the major costs associated with biomass feedstock [25]. The eastern redcedar has particularly been a major issue in the local region; considered an invasive plant, its growth rate of 380 ha per day results in a negative impact on the ecology. If action is not taken, problems caused by the cedar invasion could cost more than $450 million in upcoming years [38]. The key economic factor of current economic study is the successful operation of OSU's downdraft gasification system in converting various organic feedstocks, including biomass (e.g., switchgrass, eastern red cheddar) and MSW, into electricity generation with stable performance [21]. This outcome becomes a significant advantage in achieving a greater economic return because of potential tipping fees of MSW disposal. In this study, a tipping fee of $55.11/ton was used as referred to in 2017-data [39]. In addition, the downdraft gasification system uses air as the gasification medium, offering a simple operation and low operational costs [40], while still generating a high energy syngas, 4–7 MJ/Nm^3 [7,26].

Total direct costs typically include the capital cost, general contractor and subcontractor, materials, and labor [41]. Based on the construction activities during 2015–2016, the general contractor and subcontractor costs of downdraft gasifiers were considered to be nearly 30% of the total capital cost; a range of 45–53% was commonly used in commercial projects [41].

2.2.4. WACC

Using WACC as the discount rate is recently preferred in economic evaluation. The WACC is a reliable tool that helps a company evaluate investment opportunities and the economic value of a project, as it blends all capital sources of the company, including common shares, preferred shares, bonds, and any other long term debt, generating a fair value for the company's equity [42]. In this study, a WACC of 5.9% is adopted from the Bloomberg database as an average value of WACCs taken from four public companies which develop a small to medium scale biofuel production Aventine Renewable Energy (6.1%), GEVO (4.4%), Renewable Energy Group (6.5%), and Verenium (6.4%) [43].

2.2.5. Plant Availability, Lifetime, and Salvage Value

Even though the availability of the biomass gasification power plant could reach 99% in practical operation [44], the availability of power generation is targeted to reach 90% (best case). Potential disturbances during operation may include the reactor leaks, the jammed stirrer due to agglomeration of the bed materials caused by either the high moisture or the high ash content of the feedstock, and other potential disturbances of supporting equipment, such as leaky gaskets of air compressors and gas cleaning systems. Hence, 60% and 75% of plant availability were considered as the worst and base case scenarios based on historical experiences of the gasification power system at OSU.

The life of the facilities is assumed 20 years, following a typical standard for a biomass combined heat and power plant [9], and the salvage value is considered 15% as a common use for estimating the power plant economics [45].

2.2.6. Depreciation Rate

Since biopower generation uses combined heat and power from renewable energy sources, and to account for the cost of wearing down the equipment over a 20-year period, a 50% first-year bonus depreciation provided by the IRS Modified Accelerated Cost-Recovery System (MACRS) is used to better estimate the economics of the project [46,47]. Of six columns, calculated columns refer to columns c, e, and f. Column c is equal to 50% × column b, while column e refers to the summation of columns c and d. Finally, column f is equal to column e × (total equipment/capital + installation cost), considering total capital cost of $112,500 (Table 1) and installation cost of $32,500 (i.e., general contractor/subcontractor, material and labor). Refer to Table 3 for details.

Table 3. Depreciation details considering the 50% first-year bonus depreciation.

Depreciation Details					
MACRS Table:	**Normal Table**	**Normal Table ×50%**	**Year 1 Additional 50%**	**Total (Modified Table)**	**Tax Depreciation**
(a)	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**
1	14.29%	7.15%	50.00%	57.15%	−82,860
2	24.49%	12.25%	0%	12.25%	−17,755
3	17.49%	8.75%	0%	8.75%	−12,680
4	12.49%	6.25%	0%	6.25%	−9055
5	8.93%	4.47%	0%	4.47%	−6474
6	8.92%	4.46%	0%	4.46%	−6467
7	8.93%	4.47%	0%	4.47%	−6474
8	4.46%	2.23%	0%	2.23%	−3234

2.2.7. Electricity Price, FIT, Tax Rate, and Contingencies

A local electricity price of $9.48 cent/kWh is used as referred to current local electricity price (all sectors) in the state of Oklahoma in 2017 [35], while a FIT of $0.15/kWh is used following the normal scheme of financial support for biogas and biomass based power generation [48]. In the U.S., FIT policies provide a guarantee of payment for power plants using renewable energy sources for typically 15–20 years [49]. A marginal tax rate of 30% is used and the contingencies, which include contractor overhead costs, fees, profit, and construction, are assumed 15% as referred to earlier [41].

The basic key economic inputs and assumptions used in the present study are summarized in Table 4. As seen, the capacity of the gasifier is 100 kg/h (~2.4 tpd), producing an output power of 60 kW with the capability to treat biomass and MSW at 40 wt%. Feedstock (biomass) cost, electricity selling price, FIT, tipping fee, tax rate, and the output power are key economic inputs that are selected to investigate the project economics. Their impacts on the project economics will be presented in the next section. For instance, building the facility close to areas where the feedstock can be collected easily is paramount. Additionally, it should be noted since assumptions used in this study refer to local economics and current technological advances, the results presented in the next sections may vary from one case to another.

Table 4. Key economic inputs used in this study.

No.	Parameters	Downdraft
A	Feed rate/Capacity, tpd	2.4
B	Total output power, kW	60
C	Availability, %	90
D	Feedstock cost, $/ton	20/−10 [b]
E	Total capital cost [a]	$112,500
F	General contractor and labor	$30,000
G	Sub-contractor material & labor	$2500
H	Total direct cost	$145,000
I	Indirect cost, %	25
J	Total Indirect cost	$36,250
K	Total direct and indirect cost	$181,250
L	Contingency, %	15
M	Contingency	$27,188
N	Start-up and training, %	2
O	Start-up and training	$2900
P	Total project investment	$211,338
Q	WACC, %	5.9
R	Total O&M costs, $/kWh	0.196
S	Lifetime, years	20
T	Salvage value, %	15
U	Depreciation rate, %	See Table 3
V	Electricity price, $/kWh	0.0948
W	FIT, $/kWh	0.15
X	Marginal tax rate, %	30

Note: [a] Capital cost includes equipment and materials, [b] The downdraft gasifier was designed to treat MSW 40 wt% (maximum ratio) [21], with the feedstock costs of biomass and MSW, $20/ton and –$55.11/ton, respectively.

2.3. Environmental Performance

The deployment of gasification technology provides significant advantages to the environment due to its lower emission, compared to direct combustion. In addition, gasification technology prevents soil contamination due to leachate as compared to conventional landfill. Gasification involving MSW typically generates 31 g of NO_x and 9 g of SO_2 per ton of waste converted, while landfill releases 68 g of NO_x and 53 g of SO_2 per ton, and direct combustion emits more than 192 g and more than 94 g, respectively [50]. Moreover, in terms of CO_2 emission, MSW gasification generates only about 1 kg CO_2-eq/kWh of generated power, while landfill produces about 2.75 kg CO_2-eq/kWh and direct combustion about 1.6 kg CO_2-eq/kWh [50]. Due to carbon-containing feedstock being converted into syngas (mainly H_2 and CO) and unconverted carbon-rich products accumulating in the ash/slag collector, MSW gasification can produce electricity without releasing greenhouse gas emissions (GHGs) or harmful pollutants, such as methane, dioxins, and furans (PCDDs/PCDFs) in the atmosphere [51] and can reduce the landfill volume by over 88% [52], which is closely equal to the use of direct combustion in reducing the original volume of solid waste by 90% [53]. Based on performance of several commercial MSW gasification and direct combustion plants, the emission levels of heavy metals generated from MSW gasification plants comply with the relevant standards and are overall lower than those of the direct combustion plants, especially for mercury emissions [54,55].

The unique process of gasification allowing the unconverted carbons, heavy metals, and char accumulated in the gasifier base being removed through the ash/slag collection system, reducing their presence in the flue-gas stack, is a critical advantage. Hence, based on the recent experimental findings above, the environmental mitigation factors can be summarized in Table 5. These factors could be different from one study to another depending on the assumptions taken during the analysis.

Table 5. Positive environmental factors of MSW gasification.

Emissions	Gasification	Direct Combustion	Landfill
CO_2, kg CO_2-eq/kWh	1.0	1.6	2.8
NO_x, g/ton waste converted	31	192	68
SO_2, g/ton waste converted	9	94	53
Landfill area factor	12%	10%	100%

In addition, char as a major byproduct of the gasifier can further be used for various applications, such as soil enhancement, gas adsorbent, activated carbon and catalyst [56], which can potentially increase the economics of the entire gasification power system. An earlier report by Qian et al. [57] investigating the properties of the char derived from gasification of switchgrass will be added to complete the environmental analysis.

3. Results and Discussion

The economic evaluation of generating electricity and power via gasification of biomass and MSW using the downdraft gasification system is analyzed using a sensitivity analysis. The main factors considered affecting the project economics, including the feedstock cost, electricity selling price, FIT, tipping fee, tax rate, labor cost, and the output power, are evaluated in detail. The results are then compared to a 250 kW downdraft gasification power generation system as reported by Buchholz et al. [18]. The main findings are presented in detail in the following sections.

3.1. Downdraft Gasification Power System

The downdraft gasification system has the capability to co-feed biomass and MSW (at maximum 40 wt%) for electricity production, as reported in detail earlier [21]. The technology provides a positive NPV of $84,550 and a PP and DPP of 7.7 and 11.0 years, and generates an IRR and MIRR of 10.9% and 7.7%, respectively. These results show that the downdraft gasification power system is economically viable as it results in a positive NPV and the IRR generated is higher than the considered WACC (5.9%).

Figure 4 shows the sensitivity analysis of seven key economic inputs, including the feedstock (biomass) cost, electricity selling price, FIT, tax rate, tipping fee, labor cost, and output power, on the project economics (i.e., NPV) in a spider diagram. The magnitude of changes for each key economic input will directly be reflected to the project's NPV, making the spider diagram an effective tool in sensitivity analysis. The NPV is selected because it is considered a robust tool in determining accept-or-reject of a project as it employs more realistic reinvestment rate assumptions than the IRR. In case when IRR and MIRR methods return conflicting results under certain project conditions, the NPV is also better than the MIRR [58]. Among these parameters, the FIT provides the greatest impact, followed by the electricity selling price, the output power, and the tipping fee. In contrast, the labor and feedstock cost and the tax rate negatively affect the project's NPV.

Labor cost has a steep negative slope in the sensitivity analysis. A 15% increase in the labor cost will decrease the project's NPV by nearly 72% ($60,845). However, the project's NPV will be greater if the gasifier's operation can be automatically run as it reduces the labor requirement. Thus, for the stakeholders, to provide a higher economic return, it is critical to consider both the automation of the system and the project location. For instance, regions having locally low labor cost, such as in developing countries, could be the primary option.

The biomass cost also demonstrates a negative impact to the project's NPV. A 15% increase in the biomass cost will decrease the project's NPV from $84,550 to $73,063 (~13.5% reduction). If the feedstock only depends on biomass, a slight change of the feedstock cost will greatly impact the project viability, which will eventually prolong the PP. However, with the gasifier's capability in treating MSW with 40 wt%, the presence of the MSW negates the sensitivity of biomass feedstock. The cost associated with biomass feedstock is assumed at $20/ton, negating costs associated with transportation as the project location is within the area of biomass harvesting. Therefore, for the stakeholders, to provide a higher economic return, it is critical to consider the project's location and types of biomass. Building the facility close to the source of feedstock is beneficial as it reduces costs associated with storage and transportation, while using low density biomass such as switchgrass (used in this study) reduces the preprocessing costs. In the U.S, the biomass cost generally ranges from $40 to $80/ton [59], which is contributed by harvesting, storing, and transporting; with preprocessing, the cost can increase to the level of $83–150/ton [60]. The tax rate also negatively impacts the project's NPV at similar magnitude with the biomass cost.

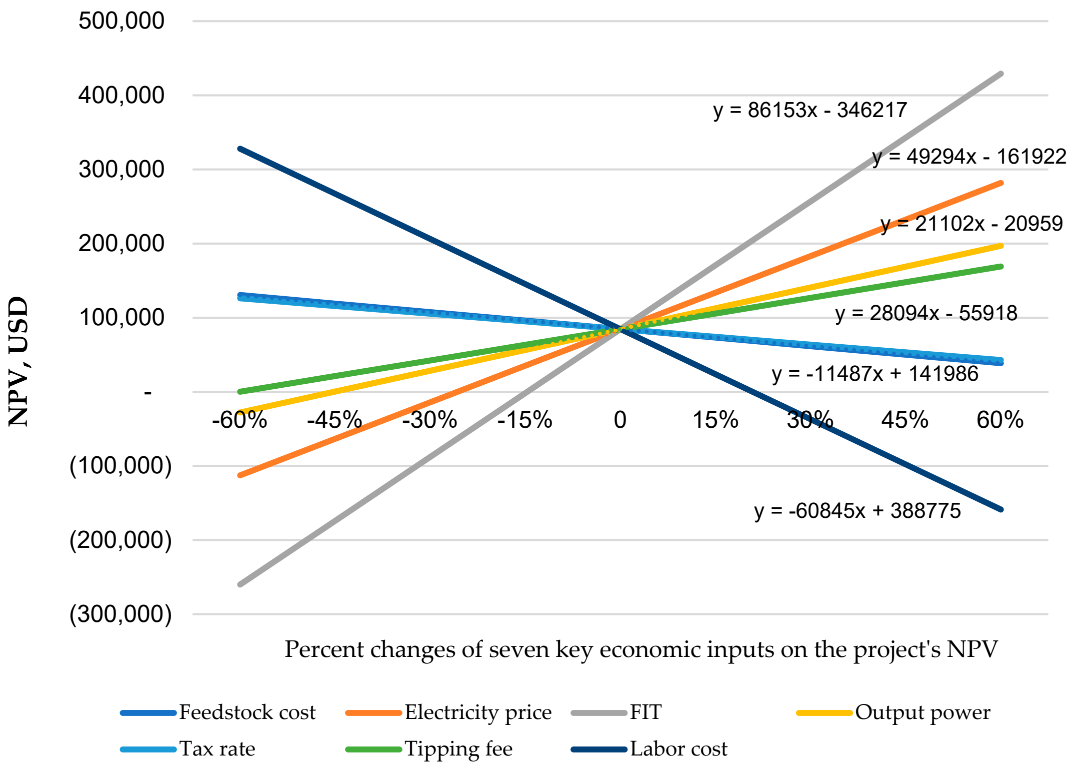

Figure 4. Major factors impacting on the project's NPV of the downdraft gasification power system.

As shown, the FIT has a steep positive slope in the project's NPV; thus, it greatly increases the project's viability, making it a critical key economic input that needs to be considered by the stakeholders; FIT in renewable energy projects is always paramount. In this study, an increase or a decrease of the FIT by 30% will consequently change the project's NPV by 204% ($172,307). FIT policies can benefit ratepayers, renewable energy (RE) developers, and society at large. However, some drawbacks have been reported regarding FITs, such as they do not directly include the high initial cost of RE development [48]. FIT payments can essentially be constructed by three mechanisms: based on the actual price of levelized cost of electricity generation, based on the utility avoided cost, and based on a fixed price incentive; thus, its magnitude may vary from one region to another [48].

The electricity selling price also greatly affects the project's economics. An increase or a decrease of the electricity price by 30% will change the project's NPV by 117% ($98,589). Similar to FITs, the electricity price varies from one region to another, depending on local electricity supply and demand. As an example, from January 2011 to April 2018, an average retail price of electricity across the U.S. varied from $0.0948/kWh to $0.1103/kWh [35]. Thus, the project's location is critical key economic input that needs to be considered by the stakeholders. Projects located in regions with high electricity selling prices will provide a greater economic return. For instance, in 2018, the average electricity prices for industrial, commercial, and residential customers in Alaska reached $0.1710, $0.1858, and $0.2194 per kWh [35], the second highest in the country.

The output power also has a significant impact on the project's NPV. A fluctuation of $56,187 (about 66.5%) on the NPV was observed when the output power changed by 30%. A greater output power can only be achieved when the feeding rate and the reactor capacity are augmented. However, increasing the design of output power will also increase the capacity of the syngas cleaning system, as the second largest cost component after the capital cost and labor (Figure 3).

In addition, the tipping fees positively contribute to an increased project's NPV. A 30% increase in the tipping fee raises the project's NPV by nearly $42,204 (about 50%). As MSW generation steadily increases in recent years, it is recognized that tipping fees will continue to increase every year. An increase from $51.82/ton in 2017 to $55.11/ton in 2018 at a national level was recently observed [39].

Among the major parameters, output power is the only one related to the system performance. In the current study, a reduced output power by 15% (51 kW) and 30% (42 kW) was considered. As shown in Figure 5, a reduction of output power from 60 to 42 kW directly increases the PP from 7.7 years to 9.8 years, with a decrease in IRR from 10.9% to 7.7%. The project's NPV also decreases from $84,550 to $28,363. In turn, when the output power can only be generated at 51 kW, compared to maximum rating of generation, the project's PP consequently increases from 7.7 years to be 8.7 years, while the IRR decreases from 10.9% to 9.3%.

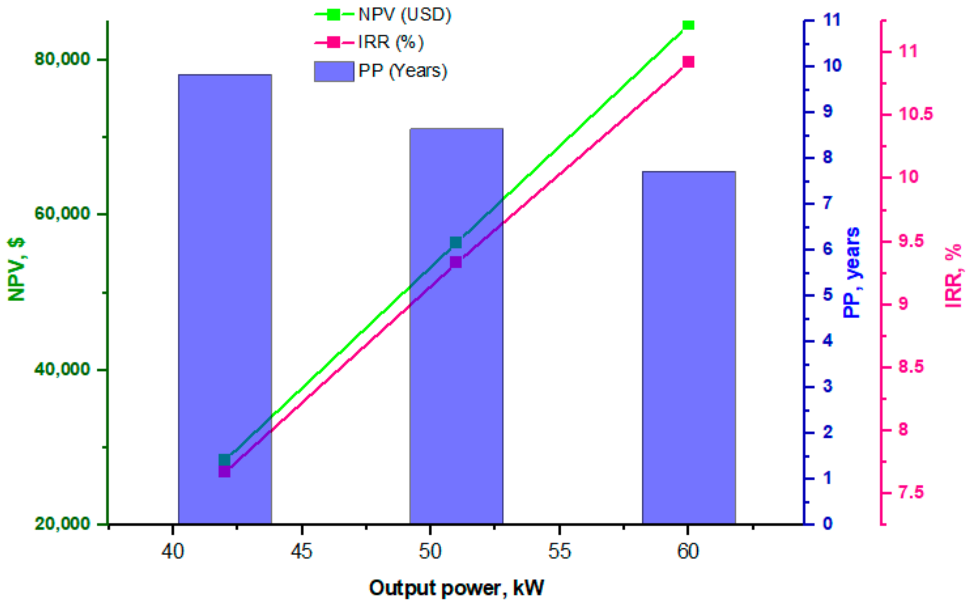

Figure 5. Impact of output power on the NPV, IRR, and PP of the downdraft gasification power plant.

The output power is a function of the operational performance and availability of the power generation system, including potential operational disturbances (i.e., reactor leak, air supply disruption, etc.) that can restrict the output power. For illustration, Table 6 presents three scenarios that could occur in the gasification power system in terms of operational availability: worst, base, and best case. Operational challenges and disturbances may cause the plant to operate at availability of 60% (where the project still generates a marginal positive NPV with IRR = WACC, considered the worst case scenario), or 75% (where the project generates a positive NPV with IRR > WACC of 5.9%, considered the base case scenario) from its operational targeted availability of 90% (best case scenario) throughout the year. However, the availability of the plant for distributed power plant is not as critical as the one connected to the grid as the power plant only affects the local electricity network.

Table 6. Example scenarios that can occur during operation.

Parameter	Worst Case	Base Case	Best Case
Plant availability, %	60	75	90
PP, years	11.4	9.2	7.7
DPP, years	18.1	13.8	11.0
NPV, $	753.9	42,652	84,550
IRR, %	6.0	8.5	10.9
MIRR, %	5.9	6.9	7.7

3.2. Comparison to Commercial Downdraft Gasification Power Plant

The economics of power generation using the 60 kW downdraft gasification technology are compared to those using a commercial 250 kW downdraft gasification technology as reported by Buchholz et al. [18]. The gasification power plant was constructed to support the Muzizi Tea Estate processing utility in Uganda.

Table 7 presents the comparison of the major economic parameters between the two gasification technologies that can be used for distributed power application. Although the downdraft gasification power generation in this study is at a smaller scale compared to the Muzizi plant, it performed better economically, with a shorter PP, a comparable IRR, and a lower production cost. However, economic analyses are based on the local conditions. For instance, labor cost is a major cost component that impacts the total O&M (as shown in Figure 4). When the technology is applied in other regions having a lower labor rate, the economic viability of the system will consequently be higher. It should be noted that the authors, however, did include costs associated with the feedstock handling. Hence, compared to gasification system in this study, the gasification power plant in the Muzizi included a higher number of workers but at a lower labor rate.

Table 7. The comparison of economics performance between two gasification power plants.

No.	Parameters	OSU	Muzizi Plant
A	Installed capacity, kW	60	250
B	Capital costs, $	112,500	442,198
C	PP, years	7.7	8.0
D	DPP, years	11.0	n.a
E	IRR, %	10.9	11.0
F	MIRR, %	7.7	n.a
G	NPV, $	84,550	n.a
H	Labor costs, $/year	55,680 (four persons)	17,497 (six persons)
I	Electricity production costs, $/kWh	0.18	0.18

In a more recent study, Elsner et al. [61] presented an economic analysis of a 75 kW downdraft gasification power system in Poland. The study used a discount rate of 7%, annual plant availability of 7000 h, and a plant lifetime of 20 years with a total capital cost of $325,635. At $1.1/Euro, local electricity and heat selling prices of $0.0154/kWh and $13.75/GJ were also observed. Considering FITs (i.e., green and yellow certificates) of 77 cent/kWh and the recommended feedstock composition (wood pellet 40 wt% and sludge waste 60 wt%), if all electricity and heat produced were sold to the grid, the project resulted in an IRR of 4.8% and a negative NPV. However, if all electricity and heat produced were internally consumed, the project would generate an IRR of 13% and a positive NPV of $156,700 with a PP of slightly more than eight years. However, the labor costs were only considered on a part-time basis, accounting for about $11,686/year.

According to the economic evaluation presented above, besides offering flexibility of the feedstocks, the current gasification power system offers positive economic benefits with a positive IRR, MIRR and NPV, making the project highly viable to execute. Additionally, with the project's PP of 7.7 years, the project is within a typical range of PP (5–10 years) of biofuel projects [62].

To further increase the project economics by means of reducing the O&M costs, the syngas cleaning system can also be improved using a more advanced technology that is chemical-free (i.e., to avoid the use of chemical sorbent (i.e., acetone)) with a low energy consumption, such as an advanced hot filtration system. In a practical distributed application, replacing the acetone solution during operation could be a major challenge, especially where the product availability and supply chain are not well established. Thus, reducing risks associated with these concerns is critical to ensure the project's economics.

3.3. Environmental Performance

The capability of a 60 kW downdraft gasifier in treating MSW brings substantial positive impacts to the environment. Based on the performance of the downdraft gasification system having ability to treat MSW stream of 40 kg/h and positive environmental factors presented in Table 5, the gasifier could generate 60 kg CO_2-eq emission (mostly driven by the use of power generation unit to generate the electricity, not the gasification process), 29 g/day of NO_x emission, and 8.6 g/day of SO_2 emission, and potentially reduce CO_2, NO_x, and SO_2 emissions by 37.5%, 83.9%, and 90.4%, respectively, as compared to direct combustion. This reduction of emissions can further bring substantial economic benefits when mitigation cost of these emissions are considered [63,64]. In terms of PCDDs/PCDFs and heavy metals emissions, using latest advanced gas cleaning systems, which are normally employed in modern direct combustion plants, the difference of these emissions between gasification and direct combustion is currently minor [54,55].

In addition, when the gasification system is compared to the landfill, it can reduce CO_2, NO_x, and SO_2 emissions by 63.6%, 54.4%, and 83%, respectively. It should be noted that these potential environmental benefits still exclude the impacts of leachate that contaminates the soil as commonly found in the landfill areas. Additionally, using MSW gasification, a potential reduction of landfill area (about 88%) can be achieved, as described earlier.

4. Conclusions

An economic evaluation of utilizing biomass and MSW for power production via gasification was performed at a feed rate of 2.5 tpd and an output power of 60 kW. Results show that, among seven major economic parameters being evaluated (i.e., the feedstock (biomass) cost, electricity selling price, FIT, output power, tax rate, tipping fee, and the labor cost), FIT has the greatest impact on the project's NPV, followed by the electricity selling price, the output power and the tipping fee, while the labor and feedstock cost and the tax rate generate a negative impact for the power generation.

The downdraft gasification power system offers a PP of 7.7 years, while an IRR, MIRR, and NPV of 10.9%, 7.7%, and $84,550, respectively, are achieved. In comparison with a 250 kW downdraft gasification power plant, the OSU downdraft gasifier had a shorter PP and a higher IRR. However, the economic results may vary significantly depending on the assumptions made regarding local economics and technological advances. Results also show that a 60 kW downdraft gasification system has an economic potential that is competitive with a larger scale downdraft gasification system in supporting distributed power applications.

Finally, the 60 kW downdraft gasification system potentially reduces CO_2, NO_x, and SO_2 emissions of 37.5, 83.9, and 90.4% and 63.6, 54.4, and 83%, respectively, as compared to direct combustion and landfill, respectively. Moreover, using this downdraft gasification system, a reduced landfill area can potentially be achieved and soil contamination by leachate can be avoided. Thus, the technology provides a promising future and flexibility in utilizing locally forestry products, including biomass and waste sources, whilst offering economic and environmental benefits for local communities.

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was prepared by N.I. and edited by B.S., A.K., and R.L.H. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

BOP	Balance of plant
CAPEX	Capital expenditures
CF	Cash flow
CGE	Cold gas efficiency
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2 eq	Carbon dioxide equivalent
DPP	Discounted payback period
FC	Fuel cell
FIT	Feed-in-tariff
GT	Gas turbine
H_2	Hydrogen
ICE	Internal combustion engine
IRR	Internal rate of return
IRS	Internal Revenue Service
kWh	Kilowatt-hours
LNG	Liquefied natural gas
MACRS	Modified Accelerated Cost-Recovery System
MIRR	Modified internal rate of return
MSW	Municipal solid waste
MW	Megawatt
NPV	Net present value
NO_x	Nitrogen oxides
O&M	Operating and maintenance
OPEX	Operating expenses
OSU	Oklahoma State University
PP	Payback period
PCDDs	Polychlorinated dibenzo-p-dioxins
PCDFs	Polychlorinated dibenzo-furans
PV	Present value
RE	Renewable energy
SO_2	Sulfur dioxide
TV	Terminal investment
WACC	Weighted average cost of capital

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