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**DOI**
10.3390/en17174416

**Publication date**
2024

**Document Version**
Final published version

**Published in**
Energies

energies

MDPI

*Article*

# Improving the Economic Feasibility of Small-Scale Biogas-Solid Oxide Fuel Cell Energy Systems through a Local Ugandan Biochar Production Method

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**Abstract:** A small-scale (up to 5 kWe) biogas-solid oxide fuel cell (SOFC) energy system is an envisioned system, which can be used to meet both electrical and thermal energy demand of off-grid settlements. SOFC systems are reported to be more efficient than alternatives like internal combustion engines (ICE). In addition to energy recovery, implementation of biogas-SOFC systems can enhance sanitation among these settlements. However, the capital investment costs and the operation and maintenance costs of a biogas-SOFC energy system are currently higher than the existing alternatives. From previous works, $H_2S$ removal by biochar was proposed as a potential local cost-effective alternative. This research demonstrates the techno-economic potential of locally produced biochars made from cow manure, jackfruit leaves, and jack fruit branches in rural Uganda for purifying the biogas prior to SOFC use. Results revealed that the use of biochar from cow manure and jack fruit leaves can reduce $H_2S$ to below the desired 1 ppm and substitute alternative biogas treatments like activated carbon. These experimental results were then translated to demonstrate how this biochar would improve the economic feasibility for the implementation of biogas-SOFC systems. It is likely that the operation and maintenance cost of a biogas-SOFC energy system can in the long run be reduced by over 80%. Also, the use of internal reforming as opposed to external reforming can greatly reduce the system capital cost by over 25% and hence further increase the chances of system economic feasibility. By applying the proposed cost reduction strategies coupled with subsidies such as tax reduction or exemption, the biogas-SOFC energy system could become economically competitive with the already existing technologies for off-grid electricity generation, like solar photovoltaic systems.

**Keywords:** biogas-SOFC; cost; biochar; techno-economic analysis

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**Citation:** Wasajja, H.; Champatan, V.; Verhorst, R.; Lindeboom, R.E.F.; van Lier, J.B.; Aravind, P.V. Improving the Economic Feasibility of Small-Scale Biogas-Solid Oxide Fuel Cell Energy Systems through a Local Ugandan Biochar Production Method. *Energies* **2024**, *17*, 4416. https://doi.org/10.3390/en17174416

Academic Editor: Peter V. Schaeffer

Received: 21 April 2024
Revised: 26 July 2024
Accepted: 22 August 2024
Published: 3 September 2024



## 1. Introduction

The world is in dire need of decarbonizing energy systems and reducing the dependence on natural gas and other fossil fuels, while providing a robust and stable electrical and thermal energy supply. In the short term, a transition away from the roughly 80% global dependence of fossil fuels, will require more than the metal resource-intensive solar PV and wind combined with battery storage systems. The solid oxide fuel cell (SOFC), due to its versatility and high electrical efficiency, and waste-derived biogas could be a welcome complement. SOFCs are preferred to other types of fuel cells due to the added advantage of relatively higher tolerance to fuel impurity and flexibility [1]. However, they have a number of constraints.

Staffell et al. [2], reported that fuel cells have been "*forever five years away from commercialization*" hence lagging behind as compared to other domestic technologies. They further reported that although cost predictions for an SOFC was USD 500 per kWe with an additional USD 500–1000 for a complete micro-combined heat and power (CHP) system, the actual costs of SOFC have not yet met this target and the goals have been changed to realistic values. It is assumed that mass production of small-scale systems for domestic applications could accelerate their move from laboratory to commercialisation. In fact, it is reported that production volumes are a dominant factor in determining early SOFC manufacturing costs and hence highly influence the overall SOFC costs [3]. For instance, production costs of fuel cells can potentially drop from USD 500/kWe to less than USD 100/kWe if production can be increased from 100 to 50,000 systems per year [4]. The same authors [2] also reported that over 10,000 domestic micro-CHP units were already operating in Japan in 2011 and annual sales were expected to double by 2012, mostly on natural gas. And as of 2021, 300,000 CHP units and back up-power systems had been installed in Japan, and the target is to install 5 million systems by 2050 [5]. Although promising from a capital investment point of view, this trajectory will keep the fuel cell systems out of reach for the majority of the world. Moreover, the operational costs will remain highly dependent on the price of the fuel gas, i.e., the natural gas used.

Electricity generation from biogas plants is of growing interest to meet the energy needs of off-grid communities in resource-constraint societies. A number of pilot projects with this objective have been carried out by different organizations, like the German Corporation for International Cooperation (GIZ) and the Netherlands Development Organization (SNV) in East Africa [6–8]. Some countries, like South Africa, consider electricity generation from biogas as a low hanging fruit [9]. According to the same source, a potential of 93 MWe is feasible in medium term to be generated from wastewater treatment plants (WWTPs), contributing to cover 20% of the total electricity generation potential from biogas in South Africa. As solid oxide fuel cells (SOFCs) are thermodynamically more efficient energy converters which can use biogas as a fuel to generate both thermal and electrical energy, they can further enhance electricity production from biogas. Our previous work explored a biogas-SOFC energy system to meet both thermal and electrical energy needs for the rural and off-grid population from an experimental and techno-economic perspective. The main advantages highlighted in our previous work [10–12] are summarized and explained in more detail below:

- sanitation becomes source of fuel and dependence on purchase of fossil fuel is reduced or made obsolete entirely
- SOFC are efficient at small scale
- $CO_2$ in biogas allows internal dry reforming and omits the need for large gas upgrading units
- local additives for in situ $H_2S$ removal are feasible in a rural digester context.
- low-cost digesters are cost effective if minor changes and operational strategies can enable biogas quality and quantity improvement.

Biogas from anaerobic digestion (AD) is an attractive source of fuel to utilise in a biogas-SOFC energy system since it involves the use of already existing wastes to recover energy and omits the needs to purchase (fossil) fuel. A major advantage of the proposed system to other alternatives is the capability of waste utilization. Furthermore, the anticipated waste heat from such energy systems can be utilised to optimise the AD process and/or sterilise the digestate. Moreover, thermal energy in excess may be used for drinking water production, which may contribute to improved health conditions, while also increasing the economic returns of SOFCs. Biogas-SOFC energy systems are considered attractive since they also contribute to controlled organic waste stabilisation, which would otherwise result in sanitation-related diseases, hence reducing sanitation related diseases which is becoming an increasing problem to rural people [13]. At the same time, thermal stabilisation unlocks the use of digestate as a substitute for fossil-fuel derived fertilisers for agricultural applications [14,15].

It has been reported that small-scale biogas plants for direct gas use are economically viable in some sub-Saharan countries, like Uganda, with a payback period of approximately 1 year for a 16 $m^3$ digester volume of plant capacity [16]. In the case where the biogas would be converted to electricity, the conventional-based internal combustion engine is limited by the Carnot efficiency [17], while the SOFC is not. Especially at the small scales, the required electrical conversion efficiency is thus a major SOFC advantage. Moreover, another advantage of SOFCs is that they can work in modulation ranges of 50–100%. This ability enables SOFCs to work on variable gas flow rates, which is typical for small-scale digesters that are often installed without gas storage [18].

Next to this, SOFCs may not require high methane and low water content in biogas, like the conventional gas and diesel engines, if both water and carbon dioxide are utilised for biogas reforming [8]. This fuel quality flexibility is expected to result in further cost advantages. However, SOFCs do require highly cleaned gas from trace impurities.

From this perspective, previous work demonstrated that addition of cow-urine to dilute cow-manure, if properly utilised, is a practice that could without major operational costs contribute to lower trace impurities, like $H_2S$ in the biogas [10]. Also, it has been reported that biochar could be used as a polishing technique to meet the SOFC fuel quality requirement [19]. Since biochar can be produced locally, this could further reduce operational expenditures.

Recently a few companies started manufacturing small-scale SOFC systems with capacities up to 5 kWe on a commercial scale [20,21]. Such a small-scale SOFC system can perfectly match with a small-scale biogas system hence forming a biogas-SOFC energy system for rural energy supply. However, as far as the authors are aware no integrated biogas-SOFC economic feasibility study has been described in the literature taking into account the above mentioned technical integration benefits.

From this perspective, it is important to note that the cost of small-scale digesters in Uganda has been well described in the literature. In 2006, the international network for sustainability, reported the cost for 1–6 $m^3$ daily capacity of biogas production as USD 1800–3900 [22]. This would imply that the installation cost per 1 $m^3$/day of biogas production capacity was about USD 650–1800 by then. The installation cost per 1 $m^3$/day of biogas production capacity would definitely be lower for plants of higher capacity. According to Lutaaya [23], the fixed dome cost of a 6 $m^3$ digester volume ranged between USD 1000–1200. Savings per annum for a family with a 10 $m^3$ digester volume, as reported by the same author [23], was Ugandan shillings (UgSh.) 780,000 (USD 629 (*Available online: https://data.worldbank.org/indicator/PA.NUS.FCRF?locations=UG (accessed on 31 August 2023), Exchange rate in 1998 was 1 USD = 1240 UgShs*)) due to the reduced purchase of solid biomass (firewood and charcoal). When adjusting this amount with an average inflation rate of 6.4% from 1998 to date, the value is today equivalent to 1,119,000 (USD 320 (*Exchange rate as per 21 January 2022, 1 USD = 3500 UgShs*)) [24]. SNV reported biogas reactor investment costs in the order of UgSh 950,000 (USD 271 (*Exchange rate as per 21 January 2022, 1 USD = 3500 UgShs*)) for a 6 $m^3$ digester volume with a biogas production capacity of 2 $m^3$/day [25], which agrees with approximately USD 180 per cubic meter daily biogas production. It can be therefore deduced from the literature that the average installation costs per $m^3$ of biogas production per day is between USD 180 and 1800 whereas the cost per kWe is USD 100–500 for an SOFC system, as stated earlier. However, the cost of an SOFC system per kWe is higher than this range when it comes to small systems of less than 5 kWe [26].

For the biogas-SOFC system, the costs will not only depend on the initial investment costs of a digester and an SOFC, but also on the operation and maintenance costs plus the additional costs required for fuel conditioning, like a biogas cleaning unit. It has been reported that the costs for gas purification can represent up to 20% of the electricity benefits for a biogas-SOFC plant of 300 kWe capacity [27]. The fixed operational costs, such as changing the stacks in the SOFC, were reported as the major barrier for integration of SOFCs in the energy mix.

With the above-described advantages of a biogas-SOFC energy system, it is important to analyse the biogas-SOFC energy system costs and compare them with existing technologies such as the biogas-internal combustion engine (ICE) system and the various $H_2S$ removal technologies reported in Table 9 of our previous works [12]. This will help in making informed decisions of integrating a biogas-SOFC energy system in an off-grid energy mix from the economic point of view. The major hindrance of the use of fuel cells in off-grid energy supply has been the high CAPEX. Our present research, therefore, focuses on how these advancements and integration from a local perspective, such as using locally produced biochar as a cleaning adsorbent, as opposed to commercial alternatives like activated carbon, can affect the overall capital exploitation cost (CAPEX) and operational exploitation costs (OPEX), including maintenance, of the biogas-SOFC energy system. In addition, the effect of changing electricity prices in relation to decentralized (micro) grid management subsidies in terms of tax exemptions on both the CAPEX and OPEX is investigated, as well as the effects of system modifications, such as using internal reforming as opposed to external reforming. The biogas-SOFC system costs are then compared with biogas-ICE systems and solar-based systems to justify its market readiness. Overall, the research focuses on how frugal innovation can accelerate economic feasibility of advanced biomass-based energy systems such as biogas-SOFCs.

## 2. Material and Methods

### *2.1. Biochar Experiment*

#### 2.1.1. Description of the Studied Site and System

The envisioned studied system is located in Kijonjo monastery, Kyotera district in Uganda. The monastery currently has a 75 $m^3$ biogas digester. This biogas digester is fed with cow dung from a farm of over 130 cows. With a capacity of 9–15 kg of dung per day per cow [28], the gas capacity of this farm can go up to 35 $m^3$ of biogas per day when adding farm projected growth into consideration [29]. Also, the farm has 10 pigs and 100 chickens which can produce an additional 1.5 $m^3$ of biogas per day. Additionally, sewage from the residents can also be used as co-feedstock to the digester and has a daily biogas production of 0.5 $m^3$. The power capacity requirement is estimated at 1 kW to power 40 rooms of the residents, security lights, and phone charging. Based on the available gas and power requirement, a 5 kWe capacity of a biogas-SOFC can be assumed for this site. If future growth is anticipated and extra gas is needed for the biogas-SOFC system, an additional digester can be installed.

#### 2.1.2. Local Biochar Production

Negative value organic residues were taken as feedstock and were carbonised using a locally made carbonizer in Uganda (Figure 1). The process which uses combustion of a part of the organic feedstock to raise the temperature, does not need any further operational input, while reaching a carbonisation temperature of above 400 °C as measured by a thermal camera (Figure 2) and infra-red thermal gun (Colemeter, Hong Kong, China). Jackfruit tree branches were cut from a single tree and leaves were separated from branches and left to semi dry under the shade. Fresh cow dung was also collected from a farm and left to semi dry under the shade. Leaves, branches, and cow dung were carbonised as shown in Figure 2. Samples of biochar from leaves, tree branches, cow dung, and activated carbon were prepared following the same procedure as described by Wasajja et al. [10]. Element composition of the sample analysis was carried out using ICP-OES 128 5300DV (Perkin Elmer Optima, Waltham, MA, USA) following the procedure described by Wasajja et al. [10]. pH was measured using a pH meter (Greisinger G 1500 series, Regenstauf, Germany with pH resolution of 0.01 and temperature of 1 °C). The surface porous structure of carbonised biochar was characterised by nitrogen sorption at 77 K using the NOVATouch gas sorption analyser from Quantachrome (Quantachrome Instruments, Boynton Beach, FL, USA). Prior to the measurements, the samples were degassed at the degas station of the same instrument, using either 60 or 130 °C under vacuum for 16 h. The specific Brunauer–Emmet–Teller (BET) theory was used for the determination of the BET surface area of biochar, determined and based on the adsorption isotherm input data. This calculation was standardized within the TouchWin version 1.2 (www.quantachrome.com, 21 August 2024) software of Quantachrome and provided a linear fit with a correlation coefficient of 0.99.

**Figure 1.** Photo of biochar carbonisation.

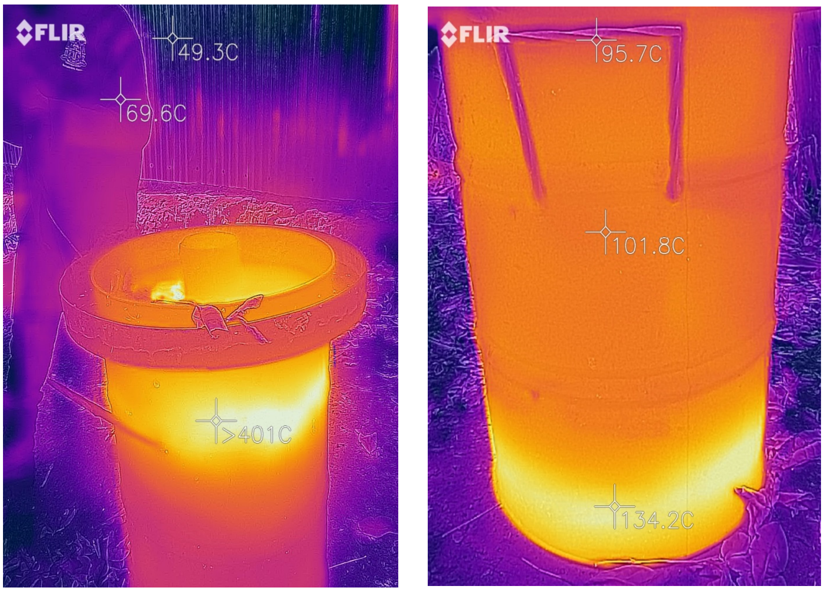


**Figure 2.** Temperature profile in °C of biochar carbonisation taken by thermal camera (taken at different times).

### 2.1.3. $H_2S$ Breakthrough Experiments

$H_2S$ breakthrough tests were performed in duplicate, using three different types of locally produced biochars and activated carbon, to determine their respective $H_2S$ adsorption capacities. Biochar made from cow dung (CB), jackfruit tree leaves (LB), jackfruit tree branches (TB), and activated carbon (AC) was used. The experimental set-up is shown in Figure 3. The experiments were performed using a polymer column with a column height of 20 cm and an internal diameter of 0.59 cm. For each type of biochar the adsorption bed height was set to 2 cm, which corresponds to a ~0.55 $cm^3$ bed volume. For CB, LB, TB, and AC this is equivalent to 0.265, 0.160, 0.075, and 0.330 g of adsorbent, respectively. Glass beads with a diameter of 1 mm were placed both underneath and on top of the adsorption bed to fill the volume above the mesh and prevent bed floatation. The inlet gas tube was connected to a 25 L Tedlar bag (Dupont, Wilmington, DE, USA) containing a gas mixture of 56% methane, 37% carbon dioxide, 7% nitrogen, and 100 ppm hydrogen sulfide. The flowrate was controlled by a peristaltic pump (Marlow Watson, Falmouth, UK) and was calibrated for a nominal flow rate of 1500 mL $h^{-1}$ (Ritter, Schwabmünchen, Germany). The outlet of the column was connected to a 0.02 M $Na_2CO_3$ solution to capture outgoing $H_2S$, after which the gas was dissipated into a fumehood.

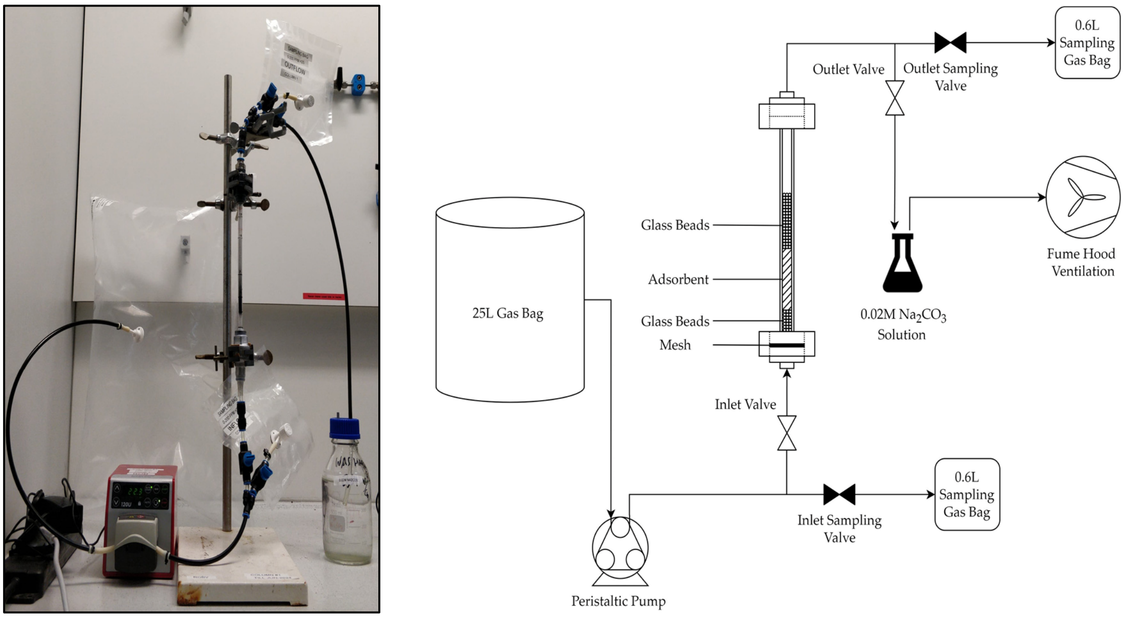


**Figure 3.** Set-up $H_2S$ breakthrough experiments.

Both inlet and outlet of the column had a two-valve system to take $H_2S$ samples. $H_2S$ was sampled and measured by using a gas hand sampling pump (Dräger accuri, Luebeck, Gemany) fixed with a Dräger tube (Dräger, Luebeck, Germany) of two different ranges: 0.2–6 ppm and 0–200 ppm. At the start of each experiment, and after every Tedlar bag refill, the input $H_2S$ was measured. $H_2S$ random measurements were done to determine the $H_2S$ content in the outlet gas of the column ($H_2S$_out). Experiments were performed at room temperature while the relative humidity was monitored (range 32–48%). Experiments were stopped when outlet $H_2S$ reached 90 ppm, which corresponds to roughly 90% of the biochar's adsorption capacity being reached. The adsorption capacity is therefore in this case defined as total milligrams adsorbed $H_2S$ per gram of adsorbent at 90% total adsorption capacity. It was calculated by subtracting the surface area underneath the breakthrough curve from the total $H_2S$ that passed through the column. The surface area was approximated using the trapezoidal rule as the method.

Additional $H_2S$ breakthrough tests with a nominal flow rate of 600 mL $h^{-1}$ (Ritter, Germany) were conducted in quadruplicate to evaluate the consistency of the results under different flow conditions. For these tests, the biochar that exhibited the highest adsorption capacity was used.

### *2.2. Economic Analysis of the System*

The economic analysis was carried out based on both the CAPEX and OPEX of the biogas-SOFC system. For comparison, a similar system of biogas-ICEs was designed, and its economic analysis was also carried out. Analysis of the economic viability of the systems was done, using the net present value (NPV) and payback period. NPV was specifically chosen because the predicted energy price is likely to be constant in the next coming years and the projects analysed are mutually exclusive [30,31]. NPV reflects the value of an investment throughout its life time depreciated to present value. NPV was calculated using Equation (1):

$$NPV = \sum \frac{Cash\ flow}{(1+i)^t} - initial\ investiment \quad (1)$$

where $i$ is the depreciation rate and $t$ is the time period in years. The payback period, which is the time required to recover the initial investment, was calculated using Equation (2):

$$Payback\ period = \frac{Initial\ investiment}{Cash\ flow\ per\ year} \quad (2)$$

The future value of money was calculated using Equation (3):

$$Future\ Value = \frac{Present\ Value}{(1+i)^n} \quad (3)$$

where $i$ is the interest rate and $n$ is the number of time periods (years).

Sensitivity analysis was carried out based on projected cost reduction, resulting from the use of locally available materials such as biochar as opposed to activated carbon for biogas cleaning. Also, system modifications such as the use of internal reforming as opposed to external reforming coupled with tax exemption were considered during the sensitivity analysis.

## 3. Results and Discussion

### *3.1. Experimental Results Using Locally Produced Biochar and Activated Carbon*

#### 3.1.1. Produced Biochar Characterization

The elemental analysis of biochar is as shown in Figure 4. It followed that biochar from leaves had the highest amount of metal element content whereas biochar from tree branches had the least metal content. It was observed that generally biochar had more metal content as compared to activated carbon. Also, the BET analysis of biochar from cow dung, tree leaves, and tree branches is as shown in Figure 5. Results from BET analysis show that activated carbon has a surface area of over 1100 $m^2g^{-1}$ surface area as compared to biochar of which the highest among the three categories was that of cow dung at 27 $m^2g^{-1}$.

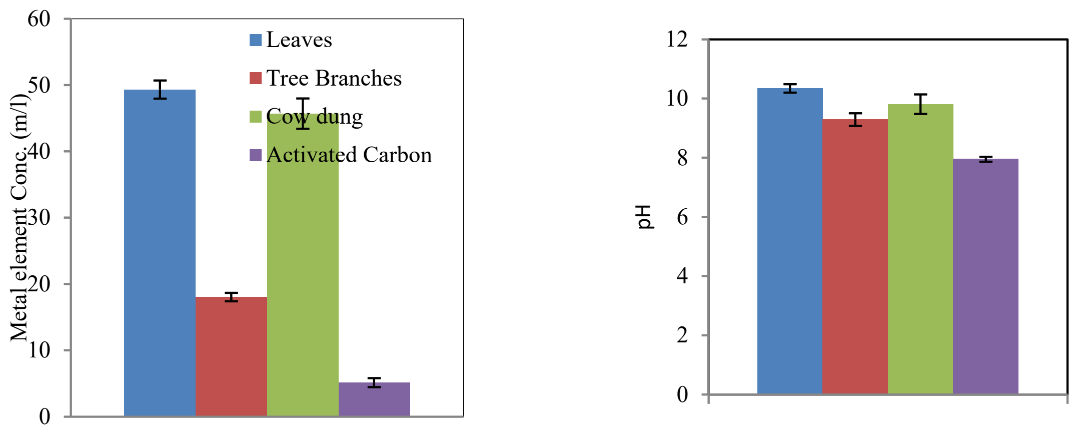


**Figure 4.** Metal element content in biochar from leaves, tree branches, cow dung, and activated carbon. (1.5 mg of sample diluted up to 50 mL).

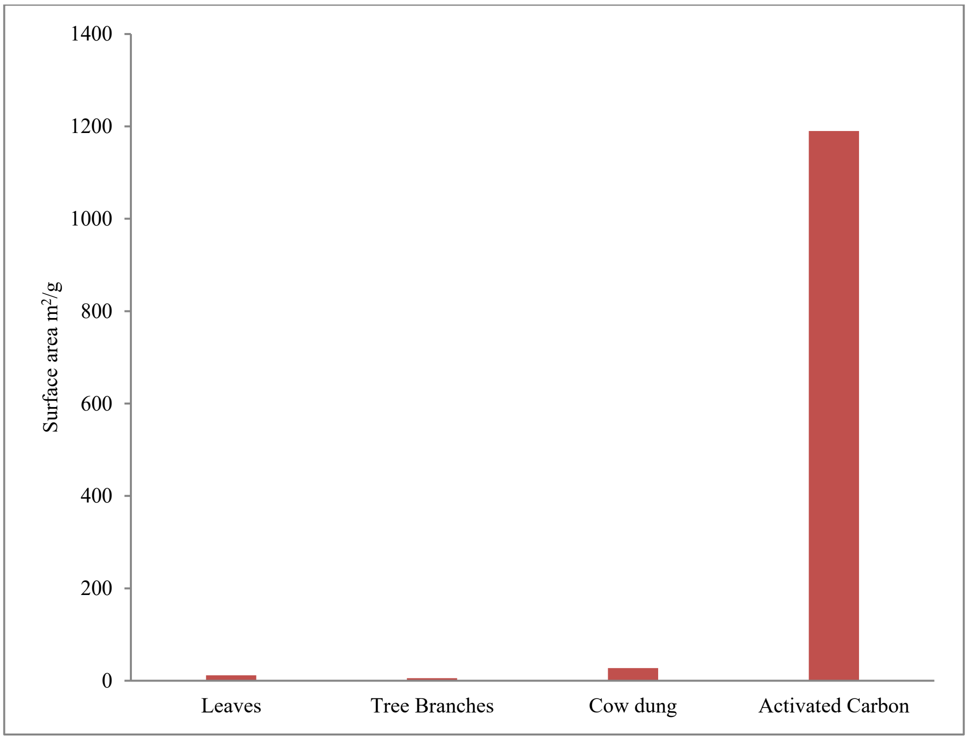


**Figure 5.** BET surface area biochar from leaves, tree branches, cow dung, and activated carbon, Section 2.1.2.

3.1.2. Experimental Results

It was observed that biochar made from cow dung (CB), jackfruit tree leaves (LB), jackfruit tree branches (TB), and activated carbon (AC) performed differently in terms of $H_2S$ adsorption. Figure 6 shows the $H_2S$ breakthrough curves of each of these biochars in duplicate. An immediate breakthrough of the 1 ppm $H_2S$ SOFC threshold was observed in biochar CB1 and both LB and TB duplicates. For biochar CB2, AC1, and AC2, this threshold value was reached at 06:20, 06:35, and 14:33, respectively. On average, the 90 ppm $H_2S$-threshold was reached for CB, LB, and TB, at 61:20, 13:04, and 04:49, respectively. For AC, 90 ppm on the outlet was not reached within 60 h. An overview of the resulting average adsorption capacities is given in Table 1.

The 1 ppm breakthrough tests with a 600 mL $h^{-1}$ flowrate showed that cow dung biochar can effectively clean the gas to 0 ppm $H_2S$, see Figure 7. The 1 ppm breakthrough times for the quadruplicates were 03:41, 04:42, 07:11, and 19:36 h, which correspond to adsorption capacities of 1.103, 1.511, 2.146, and 6.482 mg $H_2S$/g biochar, respectively. On average this is 2.810 mg $H_2S$/g biochar, which is slightly higher than the 1.977 mg found in the previous experiment for cow dung biochar and lower than 6.698 mg for activated carbon (Table 1).

In conclusion, all biochars and activated carbon were observed to remove $H_2S$ from biogas, but their adsorption capacities differed. Overall, biochar made from cow dung showed a better 90% $H_2S$ removal capacity than biochar made from jackfruit tree leaves and branches. For activated carbon this could not be deduced from the experiments. However, even after 20–60 h the activated carbon was observed to keep absorbing $H_2S$.

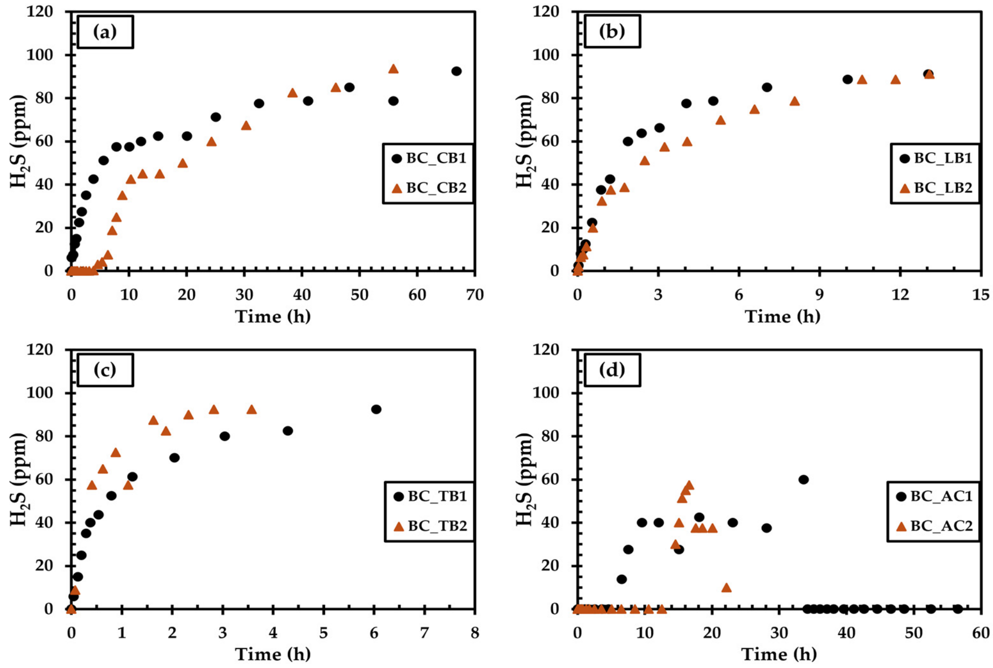


**Figure 6.** $H_2S$ breakthrough tests with biochar made from cow dung (**a**), jackfruit tree leaves (**b**), jackfruit tree branches (**c**), and activated carbon (**d**). Flowrate = 1500 mL $h^{-1}$.

**Table 1.** Average adsorption capacities of biochar and activated carbon.

| Adsorbent | Average Adsorption Capacity [mg $H_2S$/g Adsorbent] | |
|---|---|---|
| | **1 ppm Threshold** | **90 ppm Threshold** |
| Cow Dung Biochar | 1.977 | 18.37 |
| Jackfruit Tree Leaves Biochar | 0.000–0.058 * | 5.63 |
| Jackfruit Tree Branches Biochar | 0.000–0.163 * | 3.92 |
| Activated Carbon | 6.698 | ** |

* 1 ppm breakthrough occurred in between measurements at t0 and t1. ** Experiment did not reach 90 ppm.

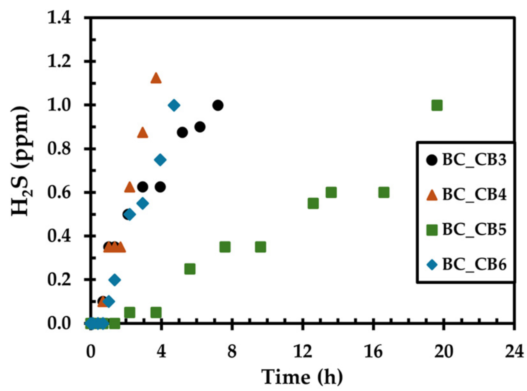


**Figure 7.** 1 ppm breakthrough tests with cow dung biochar. Flowrate = 600 mL $h^{-1}$.

Furthermore, only cow dung biochar and activated carbon showed the ability to clean the biogas to 0 ppm $H_2S$. For biochar made from jackfruit tree leaves and branches the results were inconclusive since the first measurements were already >1 ppm. Activated carbon outperformed cow dung biochar by roughly a factor of three in terms of its average 1 ppm breakthrough adsorption capacity.

### 3.2. Economic Analysis of Biogas-SOFC Energy System

The economic analysis was based on the current economic conditions of Uganda, applying an interest rate of 17% [32];, this is based on historical trend and forecasted values of Uganda lending interest rates [33], although the average lending rate for the past 10 years has been 22% [33]. The lowest interest rate was used, since due to oil discovery, Uganda is expected to register GDP growth in the nearby future driven mainly by the oil sector [34]. And an exchange rate of 3500 Uganda Shillings (UgShs) for 1 US dollar (USD) was used. Table 2 lists the assumptions for the conducted economic analysis. It is assumed that the already available cow dung would be used to generate biogas before being used as fertilizer, hence the savings of fertilizer costs is also considered as an income. Digestate fertilisers are considered to be of higher quality as compared to undigested manure [35].

**Table 2.** Assumptions during economic analysis.

| Item | Assumptions |
|---|---|
| Interest rate | 17% |
| Dollar rate (USD 1) | UgShs 3500 |
| Project duration | 20 years |
| Energy selling price | Assumed constant throughout the project duration |
| Source of income | Electricity and fertilizer purchase savings |

#### 3.2.1. Capital Costs and Operations Costs

From 2009 to 2017, fuel cell CAPEX costs have dropped by 70% and OPEX costs have dropped by approximately 57% [36]. For a fuel cell system, balance of plant (BoP) is composed of auxiliary systems such as cleaning units, power conditioning systems, etc. BoP can be a dominant cost driver for the overall SOFC system costs and should not be overlooked, especially for small-scale SOFC systems of less than 5 kWe capacity [4]. Therefore, future cost reduction should also focus on non-stack system components. The costs per kWe of manufacturing small SOFC systems like 10 kWe can be as high as three times more as compared to the costs of manufacturing a relatively big SOFC system of around 250 kWe, both at a production capacity of 100 systems per year [4]. However, if the production capacity is increased to more than 50,000 systems per year, these costs could be almost comparable [4]. Photovoltaic (PV) inverters and SOFC inverters could share some key traits like DC voltage inversion to AC, anti-islanding protection, frequency synchronization, and feed of sine wave current. However, their costs may not be necessarily similar. SOFC inverters are assumed to be cheaper than PV inverters, since some functionalities such as maximum power point tracking are not required [26].

The costs of a 1kWe SOFC was between USD 21,000–31,000 in 2016 [26]. The price of a 5 kWe SOFC was between USD 6000–8500 per kWe installed (manufacturing costs and installed price analysis of stationary fuel cell systems), which in total amounts to USD 30,000–42,500 for a 5 kWe system. Considering the prevailing inflation rate, the costs of a 1 kWe and 5 kWe system amounts to USD 24,000–36,000 and USD 33,000–47,000, respectively (*interest rate of i = 0.25–2.25 according to the interest bank rate of country of origin of this information*) [27]. It should be noted that the biogas-SOFC labour installation cost per kWe is USD 12,000 and USD 2,500 for a 1 kWe and 5 kWe SOFC, respectively [26]. For small SOFC systems of less than 5 kWe, the BoP hardware accounts for 60% of the total system cost [37]. It has been reported that 80% of the BoP plant cost is due to the required fuel processing, i.e., biogas cleaning and reforming [37]. Therefore, eliminating the fuel cleaning unit and the reformer could have a high impact on the overall SOFC CAPEX and OPEX [2]. For a small-scale system, the costs of installation take the biggest percentage of the total installed system costs. However, this is likely to be different in developing countries where the cost of labour is low [26]. It is assumed that the SOFC inverter cost will be comparable to the typical PV inverter cost [38]. The SOFC system costs summary is presented in Table 3.

**Table 3.** Indicative SOFC system costs summary.

| Sn. | Description | Cost per kWe for a 1 kWe (USD) | Cost per kWe for a 5 kWe (USD) | 5 kWe Total Costs (USD) | Ref |
|---|---|---|---|---|---|
| 1 | SOFC system | 24,000–36,000 | 6500–9500 | 32,500–47,500 | [26] |
| 2 | Installation cost of SOFC system | 12,000 | 2500 | 12,500 | [26] |
| 3 | BoP cost of SOFC system @60% of total system cost | 14,000–21,500 | 3900–5600 | 19,500–28,000 | [37] |
| 4 | Fuel processing of SOFC system @80% of BoP | 11,500–17,500 | 3000–4500 | 15,000–22,500 | [2] |

OPEX for SOFC includes payment for the workers, cost of changing the absorber, costs for changing fuel cell stacks, amongst others. The operational fixed cost, such as changing stacks, has been reported as the major barrier for integration of SOFCs in the energy mix [39]. Therefore, a distinct reduction in OPEX is a key factor to enable an economic breakthrough of small-scale biogas-SOFC systems. Table 4 presents the envisaged OPEX of a biogas-SOFC system.

**Table 4.** CAPEX and OPEX of a biogas-SOFC energy system.

| No. | Item | Cost (USD) | Comment |
|---|---|---|---|
| 1 | Fuel cell (5 kW) | 33,000 * | |
| 2 | Inverter | 2000 | |
| 3 | Other electrical accessories | 500 | |
| 2 | Biogas digester | 10,500 | |
| 3 | Gas supply system and storage | 1000 | |
| 4 | Gas cleaning equipment | 3000 | |
| 5 | Design and installation | 0 | included in SOFC cost |
| | **Sub-Total 1** | **50,000** | |
| 6 | Miscellaneous cost (5% of the investment) | 2500 | |
| 8 | Taxes | 12,000 | |
| | **Total installation costs** | **64,500** | |
| | **Annual running costs** | | |
| 7 | Labours costs | 1000 | |
| 8 | Cost of adsorbent | 5000 | With activated carbon used as adsorbent |
| 10 | **Annual miscellaneous** | | |
| | Total running costs per year | 6000 | |
| | **Other fixed costs** | | |
| 11 | Spare parts/cost of changing the cells | 6000 | changed every after three years |
| | **Annual miscellaneous cost** | | |
| 12 | Income from fertilisers | 1000 | |
| 13 | Income from electricity using assumed cost of electricity@ 0.21 USD/kWh | 8300 | |
| | **Total income per year** | **9300** | |

* The approximate minimum cost of a 5 kWe is considered with assumption that the cost is decreasing with time.

3.2.2. System Cost Analysis

For assessing the overall cost analysis, the current economic conditions of Uganda were considered. The envisaged biogas-SOFC system was considered to have a total installed power level of 1–5 kWe and a life span of 20 years. The interest rate in Uganda was estimated at 17–20% [32], whereas it is 0.25–2.25% in the USA [40]. The current cost of the fuel cell was taken to be USD 24,000 to 36,000 for a 1 kWe and USD 33,000 to 47,000 for a 5 kWe SOFC system (installed costs) [26]. However, it is expected that the costs will decrease to about USD 21,500 for a 1 kWe and USD 30,000 for a 5 kWe with mass production of 10,000 to 50,000 units per year [26]. These costs include the installation costs and the BoP costs, which account for over 60% of the SOFC system cost [26]. The costs of the biogas cleaning system are part of the BoP and are considered to be USD 100–250. The cost of biochar adsorbents was assumed to be lower than that of commercial adsorbents such as activated carbon which costs more than USD 4.8 per kg of $H_2S$ adsorbed, according to literature [12], with experimental results indicating 142 kg AC to be procured per kg $H_2S$ adsorbed. Following experimental results, biochar can be prepared in a local biochar drum from cow manure. This can further reduce the final cost of biochar. Therefore, the cost of biochar is expected to be below USD 4.8 per kg of $H_2S$ adsorbed [12]. The consumption of adsorbents can be minimized if in situ cleaning techniques are used, such as the use of urine for cattle dung dilution to increase the digester pH for enhanced $H_2S$ solubilisation and to induce $H_2S$ precipitation as metal sulphides during AD [10]. It was assumed that the cells would be replaced after every 5 years, and the costs were assumed as USD 1900–6000 for a 1 kWe and USD 4000–7500 for a 5 kWe SOFC system. Table 4 summarises the CAPEX and OPEX parameters considered.

The costs of installation of the digester per $m^3$ of biogas produced per day were assumed to be between USD 180–1800 based on literature and price quotations from selected biogas plant installers (Appendix A). The observed costs varied distinctly between private companies, which can be partly attributed to the fact that some suppliers promote biogas plants on a subsidised basis from international donors. Nonetheless, the typical commercial costs without any subsidy would lie within the range based on price quotations from private companies in Uganda.

OPEX would ideally include the salaries of the operators. It was assumed that one employee would be enough to operate the envisaged system on a part time basis. The cost for this labour according to the Uganda scale was assumed to be 300,000 UgShs (USD 86 (*Exchange rate as per 21 January 2022, 1 USD = 3500 UgShs*)). Other running costs would be the changing of adsorbents and the changing of the cell stacks which are listed in Table 4. Other expenses such as the annual maintenance cost and annual spare parts were estimated to be 6% of the annual OPEX [26], whereas annual miscellaneous expenses were 12% of the annual OPEX [26]. Since most of the required spare parts are imported from abroad, it was assumed that they would be taxed on importation. Taxes were assumed to be 34.5% [41–43]. Taxes include value added tax, levy and withholding tax according to the Uganda tax laws. For the base scenario, income is generated from selling the digestate as fertilisers and electricity was assumed at current market prices of USD 1000 and USD 8300.

With the above parameters, the NPV is less than –USD 50,000 for an operational period of 20 years and therefore the system is economically not feasible.

### *3.3. Sensitivity Analysis*

3.3.1. Effect of Mass Production on SOFC System Costs on NPV

It was assumed that the costs of the SOFC system would drop with mass production. A cost reduction analysis (Figure 8) showed that the envisaged biogas-SOFC system would become economically feasible at a price of approximately USD 10,000 for the entire system. However, Table 3 indicates that the costs of other equipment, such as the biogas cleaning equipment is about 60% of the total costs of a biogas-SOFC energy system. Therefore, for attaining economic feasibility of the envisaged biogas-SOFC energy system, other cost components, such as the digester itself, should be reduced as well.

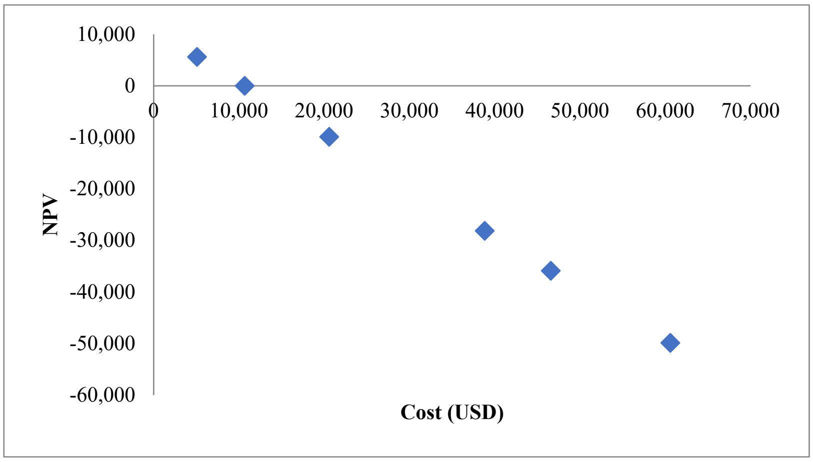


**Figure 8.** Sensitivity analysis of SOFC system cost (USD) on net present value (NPV).

It should be noted that the cost target for a small-scale SOFC is USD 1000–1700/kWe [4]. This implies that the target price for a 5 kWe biogas-SOFC system is around USD 5000 and thus, cost reduction of other equipment, such as a cleaning unit and biogas digester, is required.

#### 3.3.2. Effect of Locally Available Materials on the Economic Feasibility of a Biogas-SOFC Energy System

With activated carbon as adsorbent, the operation cost per year was estimated to be over USD 6000 based on the cost of adsorbent per kg of $H_2S$ adsorbed [12]. However, using biochar as adsorbent, the operational costs were reduced to approximately USD 1000 per year since biochar can be carbonised on site from the already existing biomass. It was assumed that the cost of carbonisation of biochar is insignificant and can be incorporated in the labour cost and in miscellaneous costs. The estimated current CAPEX of the proposed system is approximately USD 65,000 (Table 4). When activated carbon is used as adsorbent, the negative NPV value becomes zero, indicating economic feasibility, when the costs are reduced to USD 12,500 (cost of the entire biogas-SOFC system). When biochar is used, the operational costs will be reduced to USD 1000 and thus, the NPV value would increase. In the latter case, the negative NPV value becomes zero when the costs of the biogas-SOFC system are reduced to USD 40,500 (Figure 9). This implies that if biochar is used as adsorbent, higher future costs of the biogas-SOFC are allowed, i.e., up to USD 40,000, to become economically feasible. Whereas, if activated carbon is used, the future costs of a biogas-SOFC energy system needs to drop to at least USD 12,000 to become economically feasible (Figure 9). The latter value seems unrealistic since the costs of solely the digester are about USD 10,000 (Table 4) and it is unlikely that these costs will further decrease, since AD is a mature technology. Moreover, if also other cost reduction strategies are considered, such as utilisation of internal reforming as opposed to external reforming, subsidies and tax exemption, and mass production, the proposed use of biochar as alternative adsorbent can realistically accelerate the economic feasibility of the proposed biogas-SOFC energy system.

From Figure 9, it is observed that for the same capital investment cost, the biochar payback period is distinctly shorter because of the lower operating cost for using biochar as an adsorbent instead of activated carbon. The calculated differences in yearly operational costs provide opportunities to invest in a more expensive SOFC system.

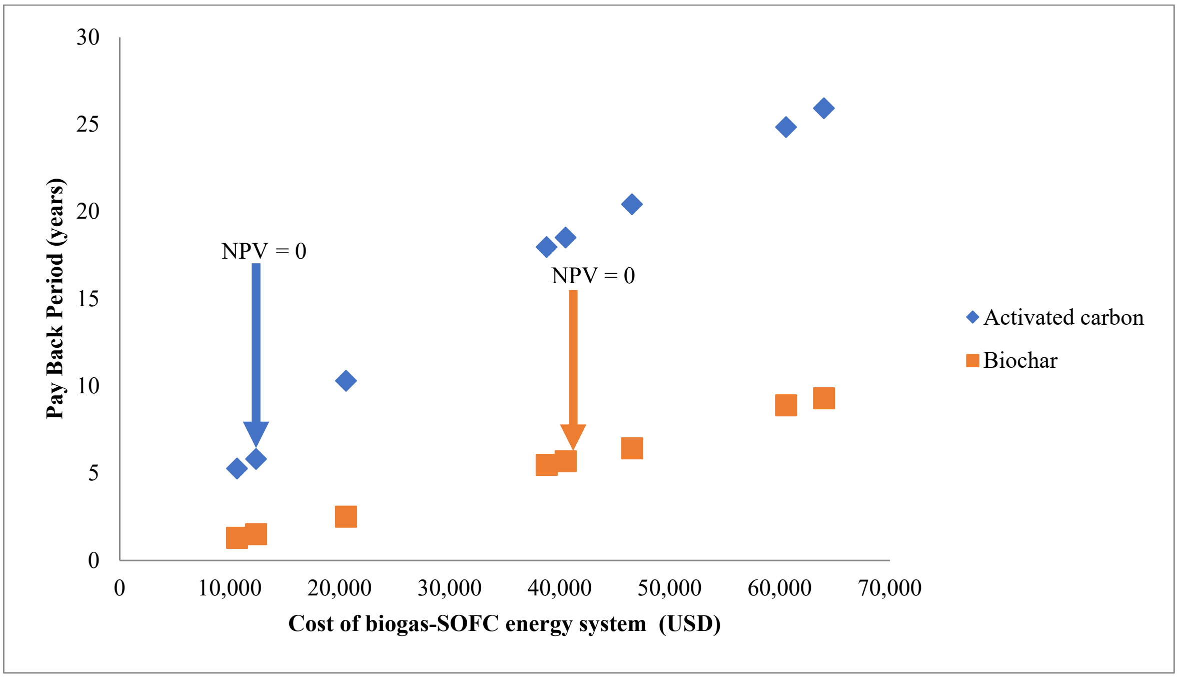


**Figure 9.** Foreseen payback period as a function of biogas-SOFC energy system costs, using either activated carbon or biochar as gas cleaning adsorbent. Arrows indicate at what system costs the NPV reaches zero, using either of the two adsorbents.

When using activated carbon as an adsorbent, even if the cost of the SOFC system only (without the cost of biogas digester) is reduced to USD 1000, the NPV is −USD 15,500 (Scenario B in Figure 10). It was assumed that the cost of other parts, like the biogas system in Table 3, may not reduce with time and were assumed to be constant. This implies that despite a drastic reduction in the SOFC costs, the biogas-SOFC system would not be economically viable, at least in the near future. However, if biochar is considered as an adsorbent, the biogas-SOFC starts to be economically viable when the cost of the whole biogas-SOFC system can be reduced to USD 7000, indicated by a positive NPV in Figure 10 (scenarios E and F).

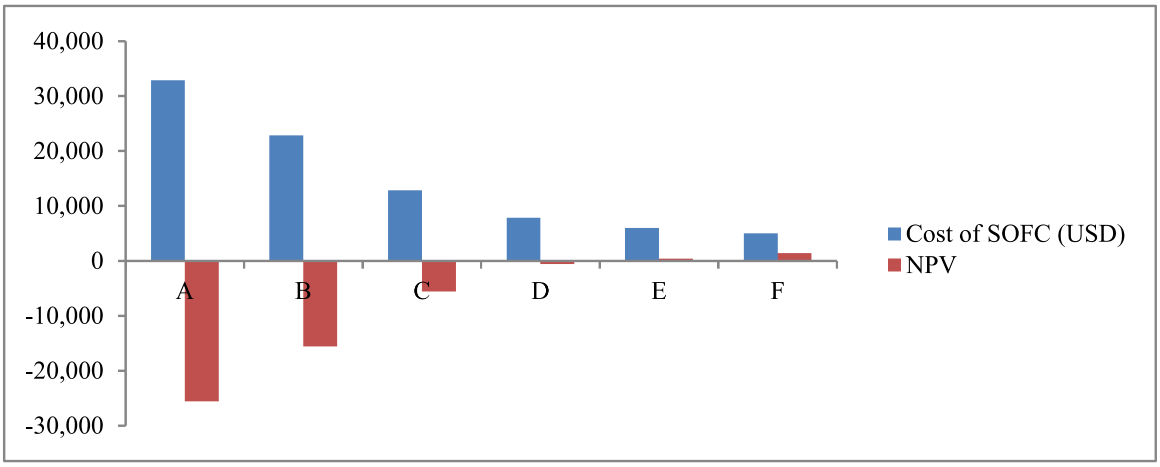


**Figure 10.** Predicted cost reduction of SOFC system with corresponding NPV values using locally produced biochar as adsorbent. NPV is negative from A to D and positive from E to F.

### 3.3.3. Internal vs. External Reformer

Francesco [44] analysed the exergy and energy efficiency of internal and external dry reforming of a small-scale SOFC of 5 kWe capacity using a cycle tempo simulation software tool. Results showed that both types of reforming have comparable efficiencies. Apparently, internal reforming does not negatively affect the exergy and thermal efficiency of an SOFC. As indicated in Table 3, for a small-scale SOFC, BoP accounts for 60% of the costs of an SOFC system [37], although, this may not be the case with the projected fuel cell cost reduction. Of this 60%, the fuel processing system accounts for 80%. The fuel processing system can be eliminated if dry reforming is envisaged. From Table 4, it follows that a 5 kWe SOFC system costs about USD 33,000. This implies that the fuel processing system costs approximately USD 16,000. With this reduction, the NPV is USD 38,400 and for the system which uses biochar as an adsorbent, the NPV will further increase to USD 10,300. With subsidies in terms of tax exemption, the NPV with activated carbon and with the use of biochar is USD 26,400 and USD 1,600, respectively (Figure 10, scenario F). These calculations showed that a 5 kWe biogas-SOFC system is currently economically feasible if internal reforming is applied, biochar is used as adsorbent, and subsidies are applicable.

For the influence of the inflation rate on NPV in the sensitivity analysis, two scenarios were considered, i.e., scenario 1 and 2, of which scenario 1 does not consider the inflation rate. For scenario 2, the average inflation rate for Uganda for the past ten years of 6.25% was considered [40]. The interest rate was chosen as the sensitive parameter in the sensitivity analysis for the two scenarios since it varies with time, and it is country dependent. It should be noted that the interest rate of 17% in Uganda was relatively high as compared to the interest rate of 3% in the USA, where the SOFC was produced. The current costs of a biogas-SOFC energy system of USD 64,000 was considered (Figure 11).

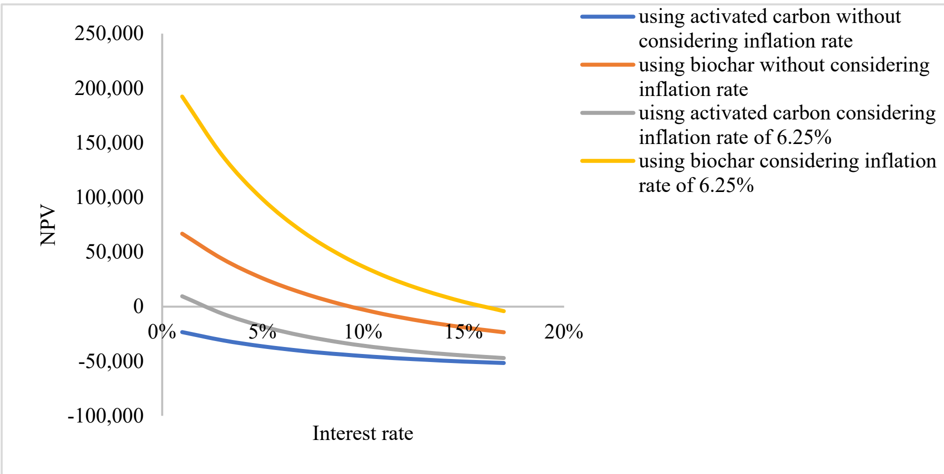


**Figure 11.** NPV as a function of interest rate, with and without inflation rate of 6.25%.

The lowest NPV values were observed with scenario 1, using activated carbon as the gas cleaning adsorbent without considering the inflation rate. The corresponding NPV values started at USD 51,608 at 17% interest rate with a payback period based on energy and fertiliser income of approximately 26 years. When using biochar as adsorbent, a payback period of approximately 9 years and NPV value of USD 23,400 is realised. This trend is similar to scenario 2 when an inflation rate of 6.25% was considered using activated carbon as the gas cleaning adsorbent and the NPV values started from USD 47,000 at 17% interest rate and a payback period of approximately 19 years. For using biochar, the NPV value started from USD 4000 with the payback period of approximately 7 years. It was observed that in both scenarios, the use of biochar will accelerate the economic feasibility of the biogas-SOFC energy system. However, when extrapolating these results to a different local context, securing a stable biochar supply chain is critical. It is worth noting that the production process of biochar can affect its physicochemical properties and final cost [45], and hence further studies on both the cost and energy effectiveness of local biochar production are also recommended.

### *3.4. Influence of Assumptions on Fertiliser and Electricity Value on NPV*

Next to the costs of the system, the income from both fertiliser and electricity will be sensitive to future developments and the exact local conditions. All across the planet, electricity prices have responded with high volatility due to the increased dependence on weather-dependent renewables, and Europe's sudden shift in the sourcing strategy of natural gas. Next to that, nitrogen fertiliser is typically produced from natural gas through the Haber Bosch process, while potassium and phosphorus require energy intensive mining. Therefore, income from both fertiliser and electricity can be expected to fluctuate with volatility in the global markets.

Local integrated energy systems, combined with an energy hub may play a major role in determining the price of electricity and heat [46], and thus also fertilizer. On island economies these effects may even be more pronounced, and the grid would benefit from the presence of a stabilizing variable load through, for example, diesel generators [47]. Biogas-SOFCs could then particularly be seen as a more renewable substitute, that moreover is interesting from a waste-providing prosumer bi-level heat–electricity integration point of view as described by Liu et al. [48]. But it should be noted that when the reliability of supply is at stake [49], it should be taken into account that the decision to invest in a biogas SOFC should not only be NPV dependent.

### *3.5. Comparison of a Similar System of 5 kWe PV and ICE System*

An economic comparison was made between the biogas-SOFC energy system, a biogas-ICE system and a solar PV system. The CAPEX cost for the biogas-ICE was USD 13,500 and that of a solar PV system USD 37,000 based on quotations from private companies in Uganda. It was also assumed that the ICE would be replaced every three years at a cost of USD 2000 [50], which increases the CAPEX cost of the biogas-ICE energy system. All three energy systems were designed for a power capacity of 5 kWe and identical full load hours. For the purpose of comparison, both real and full load operation hours were included in Figure 12, although this may not be very practical, especially for the biogas-ICE engine. Results revealed that biogas-ICE and biogas-SOFC have a negative NPV value and hence, they are currently not economically feasible at least for the Uganda situation. However, as reported before, the biogas-SOFC energy system starts to be economically feasible at a system capital cost of less than USD 40,000 if a cheap adsorbent for biogas cleaning such as locally produced biochar is used. From Figure 12, it can be deduced that with subsidies in terms of tax exemption and using biochar, the biogas-SOFC energy system is economically competitive with already existing biogas-ICE systems. Figure 12 illustrates that a small-scale biogas-SOFC energy system might become economically feasible if operation costs are reduced, e.g., by using biochar for gas cleaning purposes. Also, it is to be noted that tax exemption can contribute to more than 30% of the SOFC system costs, since most of the parts are imported. It is further of note that if subsidies are applied, biochar is used, and fuel processing is eliminated by applying dry reforming, the biogas-SOFC energy system has a positive NPV value and becomes economically feasible (Figure 12). Under the afore mentioned conditions, the NPV is approximately equivalent to that of currently applied solar PV systems. With a further cost reduction in SOFC manufacturing, the NPV further increases. It can be observed that biochar can potentially accelerate the economic breakthrough of a biogas-SOFC energy system. However, future research should properly investigate the biochar characteristics in terms of element composition and surface area to guarantee adsorption capacity of a given quantity, as is the case for activated carbon. Also, subsidies in terms of tax exemptions can contribute greatly to economic feasibility of the biogas-SOFC energy system. Therefore, just like other technologies such as solar, SOFCs also need to be considered in the Ugandan and other sub-Saharan Africa countries policies for tax waiving.

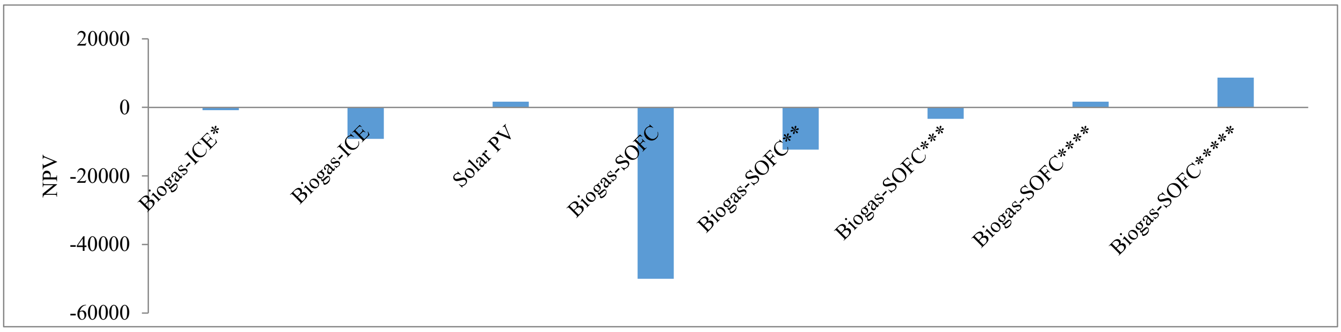


**Figure 12.** NPV of biogas-ICE and solar PV energy systems and that of biogas-SOFC at different scenarios. * Biogas-ICE operated at full load for 24 h. ** Biogas-SOFC system with subsidies and using biochar. *** Biogas-SOFC system without subsidies, using biochar and with SOFC projected cost of USD 1000/kWe. **** Biogas-SOFC system with subsidies, without fuel processing and uses biochar. ***** Biogas-SOFC system with subsidies, using biochar and with SOFC projected cost of USD 1000/kWe.

## 4. Conclusions

Predictive calculations showed that locally available materials such as biochar may have a distinct positive effect on the economic feasibility of the biogas-SOFC energy system. Materials like biochar adsorbent can be used to reduce the operation cost by over 80%. This can significantly bring down the overall system cost and hence accelerate the economic feasibility of a biogas-SOFC energy system. Considering the Uganda interest rate of 17%, the current economic status of the proposed biogas-SOFC energy system is very high, as compared to other alternatives like solar PV. However, with forecasted costs of USD 1000/kWe, the biogas-SOFC energy system is economically feasible when subsidies and/or tax exemption are applied, the costs of fuel processing are reduced (utilizing a cheap adsorbent), and internal reforming is used as opposed to external reforming. It is observed specifically that when biochar as a gas cleaning adsorbent is used, the economic feasibility of a biogas-SOFC energy system will be considerably accelerated. Although lessons for improving economic feasibility for large scale systems can be drawn from this study, the results of the current case study are directly applicable to and representative for small scale (<5 kWe) in the east African context, characterised by many tier 1–3 households.

**Author Contributions:** Validation, V.C.; Formal analysis, V.C., R.V. and P.V.A.; Investigation, H.W, V.C., R.V. and P.V.A.; Writing—original draft, H.W.; Writing—review & editing, H.W., R.V., R.E.F.L., J.B.v.L. and P.V.A.; Supervision, R.E.F.L., J.B.v.L. and P.V.A.; Project administration, J.B.v.L.; Funding acquisition, R.E.F.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by TU Delft Global initiative, grant number 15DGF214.

**Data Availability Statement:** Data is contained within the article.

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

## Nomenclature

| | |
|---|---|
| AD | Anaerobic Digestion |
| ADG | Anaerobic Digestion Gas |
| CAPEX | Capital Investment Cost |
| GIZ | German Corporation for International Cooperation |
| ICEs | Internal Combustion Engines |
| NPV | Net Present Value |
| OPEX | Operation and Maintenance Cost |
| SNV | Netherlands Development Organization |
| SOFC | Solid Oxide Fuel Cell |

## Appendix A

**Table A1.** Below shows costs of different biogas plants. However, these costs may vary depending on the region where the biogas is installed. (Exchange rate 4240.1).

| Plant Capacity/Size | Type | Gas Production Capacity | Cost (UGX) for Company 1 | Cost (UGX) for Company 2 | Cost (UGX) for Company 3 | Cost (UGX) for Company 4 * | Company 3 HS Green Energy | Average Cost (UGX) | Cost (EUR) | Cost per Cubic Meter |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 $m^3$ | Fixed Dom | 2 | 3,490,500 | 2,851,000 | | | | | | |
| 6 $m^3$ | Tubular | | | | 2,516,000 (USD 680) | | | | | |
| 9 $m^3$ | Fixed Dom, Pig Dung | 3.5–4 | 4,512,500 | 3,427,000 | | 6,004,100 ** | | | | |
| 9 $m^3$ | Tubular | | | | 3,034,000 (USD 820) | | | | | |
| 13 $m^3$ | Fixed Dom | | 5,309,500 | 5,309,500 | | | | | | |
| 20 $m^3$ | Fixed Dom | | 7,507,500 | | | | | | | |
| 26 $m^3$ | Fixed Dom, Cow and Human waste | | 11,808,000 | | | | | | 2784.84 | 107.11 |
| 30 $m^3$ | Fixed Dom | | 8,623,500 | | | | | | | |
| 30 $m^3$ | Bio-Toilet | | | 15,177,150 | | | | | | |
| 30 $m^3$ | Tubular | | | 9,840,000 | | | | | | |
| 45 $m^3$ | Fixed Dom | | 9,960,000 | | | | | | | |
| 65 $m^3$ | Fixed Dom | | 15,121,000 | | | | | | | |
| 75 $m^3$ | Fixed Dom | | | | | | 37,000,000 | | | |

* Quotation from the receipt of plant owner. ** Year of quotation is 2016.

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