Energy Recovery Potential from Effluents in the Process Industry: System Dynamics Modeling and Techno-economic Assessments

Supplementary Materials

I

Energy Recovery from Biogas Model Documentation

ac1=
60.1
Units: Nm3/gVS

ac2=
111.5
Units: Nm3/gVS

Acetogenesis and Methanogenesis= INTEG (
(hydrolyzable carbon-CH4-CO2-"CO2*")*T,
0)
Units: Nm3/gVS

alpha=
0.839
Units: Nm3/gVS

Am=
257.2
Units: Nm3/gVS

batch time=
10
Units: Day

capacity factor=
0.8
Units: Dmnl

CH4=
DELAY3(Acetogenesis and Methanogenesis/(Am*Km), batch time)
Units: Nm3/gVS
CO2=
Hydrolysis and Acidogenesis/(kc1*ac1)
Units: Nm3/gVS

"CO2*"=
Acetogenesis and Methanogenesis/(kc1*(ac1+ac2))
Units: Nm3/gVS
concentration of methane=
60
Units: Dmnl

daily total biogas production=
CH4+"CO2*"
Units: Nm3/gVS

effluent from beer production=
4805.77
Units: m3/Day
Effluents: Cassava - 9554 Sugar - 2767 Beer - 4805.77

effluent from cassava flakes production=
9554
Units: m3/Day
Effluents: Cassava - 9554 Sugar - 2767 Beer - 4805.77

effluent from sugar production=
2767
Units: m3/Day
Effluents: Cassava - 9554 Sugar - 2767 Beer - 4805.77

effluents in=
(effluent from beer production+effluent from cassava flakes production +effluent from sugar production
)*(initial solid carbon
)*k*Time
Units: m3

electrical energy potential=
(capacity factor*hours of operation*power generation potential)/(electrical Energy unit adjustment
)
Units: GWh/Day

electrical Energy unit adjustment=
10^6
Units: KW/GWh

electricity Efficiency Energy Conversion=
33
Units: KW/MJ

heat Energy Unit Adjustment=
1
Units: Day/m3
heat generation potential=
((lower calorific value of methane*capacity factor*thermal Efficiency Energy Conversion *daily total biogas production*purification rate
)/(heat Energy Unit Adjustment*10^6))
Units: GWh/Day

hours of operation=
24

Units: 1/Day

Hydrolysis and Acidogenesis= INTEG (
((alpha*effluents in*unit Adjustment)-(CO2-hydrolyzable carbon))*T,
0.588*0.1*0.6)
Units: Nm3/gVS

hydrolyzable carbon=
Hydrolysis and Acidogenesis*kh
Units: Nm3/gVS

initial solid carbon=
0.588*0.1*0.6
Units: m3

k=
0.1
Units: 1/m3

kc1=
0.18
Units: gVS/Nm3

kh=
0.22
Units: Dmnl

Km=
0.039
Units: gVS/Nm3

lower calorific value of methane=
5.5
Units: KWh/m3

lower Heating Value of methane=
35.5
Units: MJ/m3
power generation potential=
(lower Heating Value of methane*electricity Efficiency Energy Conversion*daily total biogas production
*concentration of methane
*purification rate)/power unit adjustment
Units: KW

power unit adjustment=
31536
Units: 1/m3

purification rate=
0.9

Units: gVS/Nm3

T=
1
Units: 1/Day
Conversion factor

thermal Efficiency Energy Conversion=
45
Units: GWh/KWh

unit Adjustment=
1
Units: 1/m3

II

Table S1. Life cycle Assessment of generated effluents

	Beer Effluent	Cassava Effluent	Sugar Effluent
Average Electricity generation potential /day (GWh/day)	0.03	0.05	0.02
Electricity generation potential/year (GWh/yr)	7.74	15.3902	4.4576
Emission avoided (tCO2eq/yr)	3068.30	6099.644137	1766.693981
LCA (tCO2 eq)	76707.48	152491.1034	44167.34952
Average Heat generation potential/day (GWh/day)	0.127925	0.254311	0.073658
Heat generation potential /year (GWh/yr)	35.819	71.20708	20.62424
Emission avoided (tCO2eq/yr)	14196.25173	28221.71564	8174.066912
LCA (tCO2 eq)	354906.2932	705542.8909	204351.6728
Total Avoided Emissions/Year	17,264.55	34,321.36	9,940.76

III

Table S2. Cost and Revenue generated as well as Levelised cost of Electricity for Reciprocating Internal Combustion engine – (CHP system)

Price of 1USD @ 500₦

	Item description	Estimated Unit cost ($)	Estimated cost ($)
Investment cost	Cryogenic equipment		70,000.00
	CHP system (reciprocating IC engine)		10,400,000.00
	Land cost and site construction		30,000.00
	storage tank farm		200,000.00
	labor (skilled and Unskilled)	10,000	2,000,000.00
	Stainless steel 9.6 m3 tanks	2,000	2,000,000.00
	Different sizes of connecting tubes	2.00	2,000.00
	Different sizes of valves	10.00	1,000,000.00
Total Investment cost			15,900,000.00
Annual O & M for AD			87,500.00
Annual Operating and maintenance cost of CHP			311,098.54
Total cost			16,298,598.54
Salvage Cost			1,000,000.00
Potential Revenue from Electricity Generated	28.28	1,032,179.13	
	(GWh/yr)	Price of electricity @ 0.05/kWh	
Potential Revenue from Heat Generated	130.85	6,631,084.45	
		Price of LPG @ 1.25/kg	
		Price of Heat @ NGN0.08/kWh	
Annual Revenue			7,663,263.58
Levelised cost of electricity	282,816,852.15	0.06	

Table S3. Cost and Revenue generated as well as Levelised cost of Electricity for Micro turbine – (CHP system)

Price of 1USD @ 500₦

	Item description	Estimated Unit cost	Estimated quantity
Investment cost	Cryogenic equipment		$ 70,000.00
	CHP system (micro turbine engine)	Price of USD @ 500#	$ 16,640,000.00
	Land cost and site construction		$ 30,000.00
	storage tank farm		$ 200,000.00
	labor (skilled and Unskilled)	$ 10,000.00	$ 2,000,000.00
	Stainless steel 9.6 m3 tanks	$ 2,000.00	$ 2,000,000.00
	Different sizes of connecting tubes	$ 2.00	$ 200,000.00
	Different sizes of valves	$ 10.00	$ 1,000,000.00
Total Investment cost			$ 21,140,000.00
Annual O & M for AD			$ 87,500.00
Annual Operating and maintenance cost of CHP			$ 367,661.91
Total cost			$ 21,595,161.91
Salvage Cost			$ 1,000,000.00
Electricity sales	28.28	$ 1,357,673.18	
	(GWh/yr)	$ 0.08	/kWh
Heat sales	130.85	$ 6,631,084.45	
		Price of LPG @ 1.25/kg	
		$ 0.08	/kWh
Annual Revenue			$ 7,988,757.64
Levelised cost of electricity	$ 282,816,852.15	$ 0.08	

Table S4. Cost and Revenue generated as well as Levelised cost of Electricity for Gas turbine – (CHP system)

Price of 1USD @ 500₦

	Item description	Estimated Unit cost	Estimated quantity
Investment cost	Cryogenic equipment		$ 70,000.00
	CHP system (Gas turbine engine)	Price of USD @ 500#	$ 11,830,000.00
	Land cost and site construction		$ 30,000.00
	storage tank farm		$ 200,000.00
	labor (skilled and Unskilled)	$ 20.00	$ 2,000,000.00
	Stainless steel 9.6 m3 tanks	$ 2,000.00	$ 2,000,000.00
	Different sizes of connecting tubes	$ 2.00	$ 200,000.00
	Different sizes of valves	$ 10.00	$ 1,000,000.00
Total Investment cost			$ 17,330,000.00
Annual O & M for AD			$ 87,500.00
Annual Operating and maintenance cost of CHP			$ 313,926.71
Total cost			$ 17,731,426.71
Salvage Cost			$ 1,000,000.00
Electricity sales	$ 28.28	$ 1,118,533.83	
	(GWh/yr)	$ 0.06	/kWh
Heat sales	$ 130.85	$ 6,631,084.45	
		Price of LPG @ 1.25/kg	
		$ 0.08	/kWh
Annual Revenue			$ 7,749,618.28
Levelised cost of electricity	$ 282,816,852.15	$ 0.07	

Table S5. Cost and Revenue generated as well as Levelised cost of Electricity for Fuel cell-CHP system

Price of 1USD @ 500₦

	Item description		Estimated Unit cost	Estimated quantity
Investment cost	Cryogenic equipment			$ 70,000.00
	CHP system (Gas turbine engine)		Price of USD @ 500#	$ 14,600,000.00
	Land cost and site construction			$ 30,000.00
	storage tank farm			$ 200,000.00
	labor (skilled and Unskilled)		$ 10,000.00	$ 2,000,000.00
	Stainless steel 9.6 m3 tanks		$ 2,000.00	$ 2,000,000.00
	Different sizes of connecting tubes		$ 2.00	$ 200,000.00
	Different sizes of valves		$ 10.00	$ 1,000,000.00
Total Investment cost				$ 20,100,000.00
Annual O & M for AD				$ 87,500.00
Annual Operating and maintenance cost of CHP				$ 1,131,267.41
Total cost				$ 21,318,767.41
Salvage Cost				$ 1,000,000.00
Electricity sales		28.28	$ 1,445,042.96	
	(GWh/yr)		$ 0.06	/kWh
Heat sales		130.85	$ 6,631,084.45	
			Price of LPG @ NGN1.25/kg	
			$ 0.08	/kWh
Annual Revenue				$ 8,076,127.41
Levelised cost of electricity	$ 282,816,852.15		$ 0.09	

IV

Table S6. Cash flow for Gas turbine

Cash flow	Year 0	1	2	3	4	5	6	7	8	9	10
Initial Investment	$17,330,000.00										
Operating and maintenance cost		$401,426.71	$401,426.71	$401,426.71	$01,426.71	$401,426.71	$401,426.71	$401,426.71	$401,426.71	$401,426.71	$401,426.71
PV of Cash Outflow	$17,330,000.00	$313,614.61	$245,011.42	$191,415.17	$149,543.10	$116,830.55	$91,273.87	$71,307.71	$55,709.15	$43,522.77	$34,002.16
Cumulative Cashflow	$17,330,000.00	$17,643,614.61	$17,888,626.03	$18,080,041.20	$18,229,584.30	$18,346,414.85	$18,437,688.72	$18,508,996.42	$18,564,705.57	$18,608,228.34	$18,642,230.50
Net Annual Cashflow		$(11,589,225.33)	$(7,104,245.12)	$(3,600,354.33)	$(862,939.65)	$1,275,665.56	$2,946,450.89	$4,251,751.93	$5,271,518.36	$6,068,210.89	$6,690,626.93

Column1	Manual	NPV Fx
NPV of Project	$6,798,001.11	$6,798,001.11
IRR	41%	
ROI	36%	
Profitability index (Cost-Benefit ratio)	1.39	
Payback period	6.63	

Table S7. Cash flow for Microturbine

Cash outflow	Year	0	1	2	3	4	5	6	7	8	9	10
Initial Investment		$21,140,000.00										
Operating and maintenance cost			$455,161.91	$455,161.91	$455,161.91	$455,161.91	$455,161.91	$455,161.91	$455,161.91	$455,161.91	$455,161.91	$455,161.91
PV of Cash Outflow		$21,140,000.00	$355,595.24	$277,808.78	$217,038.11	$169,561.02	$132,469.55	$103,491.84	$80,853.00	$63,166.40	$49,348.75	$38,553.71
Cummulative Cashflow		**$21,140,000.00**	**$21,495,595.24**	**$21,773,404.02**	**$21,990,442.13**	**$22,160,003.16**	**$22,292,472.71**	**$22,395,964.54**	**$22,476,817.54**	**$22,539,983.94**	**$22,589,332.70**	**$22,627,886.41**
Net cashflow			**$**(15,254,378.34)	$(10,656,236.41)	$(7,063,938.03)	$(4,257,454.93)	$(2,064,890.00)	$(351,948.65)	$986,286.78	$2,031,783.21	$2,848,577.30	$3,486,697.68

Column1	Manual	NPV Fx
NPV of Project	$3,594,071.86	$3,594,071.86
IRR	34%	
ROI	16%	
Profitability index (Cost-Benefit ratio)	1.17	
Payback period	8.09	

Table S8. Cash flow for Reciprocating Internal Combustion turbine

Cash outflow / Year	0	1	2	3	4	5	6	7	8	9	10
Initial Investment	$15,900,000										
Operating and maintenance cost		$398,599	$398,598.54	$398,598.54	$398,598.54	$398,598.54	$398,598.54	$398,598.54	$398,598.54	$398,598.54	$398,598.54
PV of Cash Outflow	$15,900,000	$311,405	$243,285	$190,067	$148,490	$116,007	$90,631	$70,805	$55,317	$43,216	$33,763
Cumulative Cashflow	**$15,900,000.00**	**$16,211,405.11**	**$16,454,690.35**	**$16,644,756.94**	**$16,793,246.47**	**$16,909,253.91**	**$16,999,884.72**	**$17,070,690.05**	**$17,126,006.71**	**$17,169,222.85**	**$17,202,985.46**
Net cash flow		$(10,224,480.44)	$(5,790,480.78)	$(2,326,418.54)	$379,880.08	$2,494,175.87	$4,145,969.47	$5,436,433.21	$6,444,608.01	$7,232,244.57	$7,847,585.63

Column1	Manual	NPV Fx
NPV of Project	$7,954,959.82	$7,954,959.82
IRR	45%	
ROI	46%	
Profitability index (Cost-Benefit ratio)	1.50	
Payback period	6.09	

Table S9. Cash flow For Fuel Cell

Cash outflow	Year	0	1	2	3	4	5	6	7	8	9	10
Initial Investment		$20,100,000										
Operating and maintenance cost			$1,218,767	$1,218,767.41	$1,218,767.41	$1,218,767.41	$1,218,767.41	$1,218,767.41	$1,218,767.41	$1,218,767.41	$1,218,767.41	$1,218,767.41
PV of Cash Outflow		$20,100,000	$952,162	$743,877	581,154	$454,026	$354,708	$277,116	$216,497	$169,138	$132,139	$103,234
Cumulative Cashflow		**20,100,000**	**21,052,162**	**21,796,038.63**	**22,377,192.22**	**22,831,218.46**	**23,185,926.46**	**23,463,042.08**	**23,679,538.67**	**$23,848,676.62**	**$23,980,815.65**	**$24,084,049.26**
Net Annual Cashflow			($14,742,687.50)	($10,557,287.11)	($7,287,443.06)	($4,732,877.39)	($2,737,122.96)	($1,177,939.81)	$40,172.02	$991,821.89	$1,735,298.35	$2,316,139.33

Column1	Manual	NPV Fx
NPV of Project	$2,423,513.52	$2,423,513.52
IRR	32%	
ROI	10%	
Profitability index (Cost-Benefit ratio)	1.12	
Payback period	7.69	