the Energy to Lead

AQMD Contract #: 13432

BIOGAS CLEANUP SYSTEM COST ESTIMATOR TOOLKIT TRAINING AND USER INSTRUCTION MANUAL

Version 2
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The purpose of the toolkit is to provide a starting point in the process of identifying potential biogas treatment technologies for landfills and wastewater treatment plants. Treatment technologies may be subject to site-specific contaminants and concentration variability, so facilities are encouraged to perform site-specific research to validate the effectiveness of biogas treatment systems. Accordingly, cost estimates provided by the toolkit should be deemed as an initial rough estimate, which will require refinement for a particular project.

This project relied primarily upon vendor surveys. As a validation process, biogas facilities should consider performing a second phase of this study where actual costs and the operational performance of biogas cleanup systems can be assessed

Program Installation

In order to install the spreadsheet on a new computer, the following file should be copied:

SRSC.xls

The spreadsheets are currently unprotected and no macros are used.

Program Operation

The program consists of three Excel worksheets: two input worksheets (represented by Table 1), one for siloxane-only and the second for all-contaminant removal systems and a third to obtain engine cost savings realized by implementing a siloxane removal system (see Table 4).

INPUTS

A sample input section of the toolkit worksheet is shown in Table 1. The input spreadsheet format is identical for both the siloxane-only and the all-contaminant removal systems.

The red highlighted values indicate inputs while those in black are default or calculated values. The main input is the biogas flowrate. It is entered in the first line of the spreadsheet along with its units (SCFM) from which the spreadsheet calculates the corresponding engine power in kW and BHP. Alternatively, the engine power can be entered along with its units (either BHP or kW) and the spreadsheet will calculate the required flowrate (see the calculational scheme below). Values for the biogas HHV and engine efficiency can be also be input; the default values are 500 and 32%.

The spreadsheet toolkit methodology provides generic cost categories and default assumptions to estimate the installed costs of the siloxane removal systems. Direct costs are required for certain key elements, such as the capital and O&M costs. Other costs, such as system installation, are then estimated from a series of input percentages or factors (in red font) applied to the purchased equipment costs, as shown in Table 1. The spreadsheet provides various percentage factors as default values (column 3) in Table 1, but users may enter their own values (into column 2). The default percentages used in the spreadsheet were taken from those used by industy as presented in the EPA Air Pollution Control Cost Manual[1] and shown in Appendix A. The methodology is sufficiently general to be used with retrofit systems as well by inputting a retrofit factor (see Appendix A). This methodology provides rough order-of-magnitude-level cost estimate; the only input required for making this level of estimate is the biogas volumetric flow rate (or equivalent engine power). The precision could be improved with more detailed cost data.

Based on the inputs provided the calculational scheme involved to obtain the output is presented below in the following sections.

CALCULATIONAL SCHEME

In order to facilitate estimation of the vendor cost data for use in the toolkit, a best-fit regression analysis was performed of the capital and O&M vendor cost data versus flow rate to obtain correlation equations for use in the toolkit. These equations are then applied to the user input biogas flow data in the spreadsheet using the calculational scheme shown in Table 2 for estimation of the system capital and O&M costs. The siloxane removal system equipment cost (SRSEC) for a siloxane-only removal system is calculated in the spreadsheet as follows:

$$\text{SRSEC (\$)} = 35{,}064 \times (\text{Flow rate, SCFM})^{0.375}$$

And for the all-contaminant removal system by:

$$\text{SRSEC (\$)} = 1741.5 \times (\text{Flow rate, SCFM}) + 635{,}374$$

The siloxane-only removal system O&M cost is calculated in the spreadsheet by:

$$\text{O\&M (\$)} = 2047 \times (\text{Flow rate, SCFM})^{0.399}$$

And the all-contaminant removal system O&M cost (SRSEC) is calculated in the spreadsheet by:

$$\text{O\&M (\$)} = 306.1 \times (\text{Flow rate, SCFM})^{0.952}$$

The conversion between input engine BHP and kW power is performed in the spreadsheet as follows:

$$\text{BHP} \times 0.7457 = \text{kW}$$

The equivalent biogas volumetric flowrate in SCFM from engine kW is calculated as follows:

$$\text{SCFM} = \text{kW} \times 3414/(60 \times \text{HHV} \times \text{Engine Efficiency}/100)$$

in the EPA Air Pollution Control Cost Manual and shown in Appendix A for reference. The methodology is sufficiently general to be used with retrofit systems as well by inputting a retrofit factor (see Appendix B).

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[1] EPA Air Pollution Control Cost Manual, Sixth Edition EPA/452/B-02-001, January 2002, United States Environmental Protection Agency Office of Air Quality Planning and Standards Research, Triangle Park, North Carolina 27711, EPA/452/B-02-001

OUTPUTS

In addition to estimating the capital (purchased equipment) and O&M costs for the siloxane removal system, the following cost categories are used to describe the annual cost as per the scheme in Table 2:

1. Total Equipment Costs (TEC), which include the capital costs of the siloxane removal system and auxiliary equipment, instrumentation, sales tax, and freight;
2. Direct Installation Costs (DIC), which are the construction-related costs associated with installing the control device;
3. Indirect Capital Costs (ICC), which include installation expenses related to engineering and start-up;
4. Direct Operating Costs (DOC), which include annual increases in operating and maintenance costs due to the addition of the control device; and
5. Indirect Operating Costs (IOC), which are the annualized cost of the control device system and the costs due to tax, overhead, insurance, administrative burdens and capital recovery.

From these costs is estimated the Total Annual Cost (TAC), which is the sum of the Direct Operating and Indirect Operating Costs. The methodology is sufficiently general to be used with retrofit systems as well by applying a retrofit factor (Appendix A).

Two output spreadsheets are included in the Excel toolkit workbook:

1. Siloxane-only removal system costs
2. All-contaminants removal system cost.

A sample output based on the calculational scheme is shown in Table 3.

An estimate for the reduction in engine maintenance costs resulting from implementation of a siloxane removal system was developed for this toolkit based on literature data,[2,3,4] and interviews and personal communications with biogas engine operators and manufacturers. The estimated savings are expressed in payback years (i.e., the ratio of the siloxane system capital cost to the annual engine cost savings) in Table 4 and range from one-half year to three years at the highest (>60 ppmv) and the lowest (<9 ppmv) biogas siloxane concentrations. Table 4 is incorporated into the Excel toolkit workbook as a separate spreadsheet from which the user can determine payback years for their biogas siloxane concentration by simply looking up the value in the table.

Also included in this manual are brief descriptions of the potential biogas cleanup system technologies for those vendors providing cost data (Appendix B).

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[2] "Best Practices to Select Internal Combustion Engines and Maximize the Success of Methane to Electricity Projects," Mauricio Lopez, Electric Power Gas Division, Caterpillar, Inc., presented at Methane Expo 2013 Vancouver, Canada.

[3] "Total Biogas Quality Management," November 7, 2007, presented at Intermountain CHP Workshop on Siloxanes and Other Harmful Contaminants: Their Importance In Biogas Utilization.

[4] "Glendale Energy Siloxane Removal at a Small Landfill Gas to Electrical Energy Facility in the Arizona Desert," presented at the 17th Annual LMOP Conference and Project Expo, Baltimore, MD, January 21-23, 2014.

Table 1. Sample Spreadsheet Input Section

	Value	Units
Input Value and Units	**1,000**	**SCFM**
Biogas Higher Heating Value (HHV)	**500**	Btu/ft^3
Engine Efficiency	**32**	%
Inlet Flow Rate	1,000	SCFM
Engine Power	2,813	kW
Engine Power	3,773	bhp

Input either SCFM, kW or BHP.

Input either flowrate or engine power.

CALCULATOR		
Cost Items	**Factor**	**Default Factor**
DIRECT CAPITAL COSTS (DCC):		
(1) Siloxane Removal System Equipment Cost (SRSEC)		
(2) Auxiliary Equipment	**5.0%**	5%
(3) Freight	**5.0%**	5.0%
(4) Sales Tax	**10.0%**	10.0%
Subtotal: **Total Equipment Cost (TEC)**		
(3) Direct Installation Costs		
(a) Foundation and Structural Support	**8.0%**	8.0%
(b) Handling & Erection	**14.0%**	14.0%
(c) Electrical	**4.0%**	4.0%
(d) Piping	**2.0%**	2.0%
(e) Insulation	**1.0%**	1.0%
(f) Painting	**1.0%**	1.0%
Subtotal: **Total Direct Installation Costs (DIC)**		
Total DCC:		
INDIRECT CAPITAL COSTS (ICC):		
(1) Indirect Installation Costs (IIC)		
(a) General Facilities	**5.0%**	5.0%
(b) Engineering and Home Office Fees	**10.0%**	10.0%
(c) Process Contingency	**10.0%**	10.0%
(2) Other Indirect Costs (OIC)		
(a) Siloxane Monitor	**$75,000**	75,000
(b) Startup and Performance Testing	**1.0%**	1.0%
(c) Spare Parts	**1.0%**	1.0%
(d) Contractor Fees	**10.0%**	10.0%
Total ICC:		
PROJECT CONTINGENCY	**15.0%**	15.0%
RETROFIT COSTS	**0.0%**	0.0%
TOTAL CAPITAL INVESTMENT (TCI):		
DIRECT OPERATING COSTS (DOC):		
(1) Operating Labor		
(a) Operator		
hr/shift	**0.5**	0.5
Pay Rate	**$40**	$40
Operating Hours	**8760**	8760
(b) Supervisor	**15.0%**	15.0%
(2) Maintenance (labor and material)	**1.5%**	1.5%
(3) Siloxane Removal System Media Replacement + Energy Requirement		
(4) Siloxane System Periodic Testing	**$24,000**	$24,000
Total DOC:		
INDIRECT OPERATING COSTS (IOC):		
(1) Overhead	**60.0%**	60.0%
(2) Property Taxes	**1.0%**	1.0%
(3) Insurance	**1.0%**	1.0%
(4) Administration	**2.0%**	2.0%
(5) Capital recovery costs (CRC)		
Capital recovery factor (CRF)		
Interest rate	**7.0%**	7.0%
Annualization years	**10**	10
Total IOC:		
Recovery Credits (RC)	**$0**	$0

Table 2. Calculational Scheme in Toolkit Spreadsheet

SILOXANE REMOVAL SYSTEM CAPITAL AND ANNUAL COSTS CALCULATOR	
Cost Items	**Cost Factors**
DIRECT CAPITAL COSTS (DCC):	
(1) Siloxane Removal System Equipment Cost (SRSEC)	Calculated by program (see calculational methodology section)
(2) Auxiliary Equipment	Percent input x SRSEC
(3) Freight	Percent input x SRSEC
(4) Sales Tax	Percent input x (SRSEC+auxiliary + freight)
Subtotal: **Total Equipment Cost (TEC)**	(1) + (2) + (3) + (4)
(3) Direct Installation Costs	
(a) Foundation and Structural Support	Percent input x TEC
(b) Handling & Erection	Percent input x TEC
(c) Electrical	Percent input x TEC
(d) Piping	Percent input x TEC
(e) Insulation	Percent input x TEC
(f) Painting	Percent input x TEC
Subtotal: **Total Direct Installation Costs (DIC)**	(a) + (b) + (c) + (d) + (e) + (f)
Total DCC:	
INDIRECT CAPITAL COSTS (ICC):	
(1) Indirect Installation Costs (IIC)	
(a) General Facilities	Percent input x TEC
(b) Engineering and Home Office Fees	Percent input x TEC
(c) Process Contingency	Percent input x TEC
(2) Other Indirect Costs (OIC)	
(a) Siloxane Monitor	Enginnering Estimate ($)
(b) Startup and Performance Testing	Percent input x TEC
(c) Spare Parts	Percent input x TEC
(d) Contractor Fees	Percent input x TEC
Total ICC:	IIC+OIC
PROJECT CONTINGENCY	Percent x (DCC+ICC)
RETROFIT COSTS	Percent x TIC
TOTAL CAPITAL INVESTMENT (TCI):	DCC+ICC+Project Contingency+Retrofit Costs
DIRECT OPERATING COSTS (DOC):	
(1) Operating Labor	
(a) Operator	
hr/shift	User estimated labor hours/shift
Pay Rate	User estimated pay rate ($/hr)
Operating Hours	User estimated operating hours/year
(b) Supervisor	Percent x operating labor cost (1)
(2) Maintenance (labor and material)	Percent x TCI
(3) Siloxane Removal System Media Replacement + Energy Requirement	Calculated by program (see calculational methodology section)
(4) Siloxane System Periodic Testing	Enginnering Estimate ($)
Total DOC:	(a) + (b) + (2) + (3) + (4)
INDIRECT OPERATING COSTS (IOC):	
(1) Overhead	Percent x [operating labor cost (1)+ maintenance cost (2)]
(2) Property Taxes	Percent x TCI
(3) Insurance	Percent x TCI
(4) Administration	Percent x TCI
(5) Capital Recovery Costs (CRC)	Calculated by program (CRF x TCI)
Cost Recovery Factor (CRF)	Calculated by program (see calculational methodology section)
Interest Rate	Interest rate in percent
Annualization years	Annualization period in years
Total IOC:	(1) + (2) + (3) + (4) + (5)
Recovery Credits (RC)	Enginnering Estimate ($)
TOTAL ANNUAL COST (TAC):	DOC + IOC - RC
TOTAL ANNUAL COST PER kWh	(DOC+IOC)/(kWh/yr)
TOTAL ANNUAL COST PER MMBtu	(DOC + IOC)/(MMBtu/yr)
TOTAL ANNUAL COST PER MSCF	(DOC + IOC)/(MMBtu/yr)

Table 3. Sample Spreadsheet Output of Siloxane Removal System Cost Calculation

	Value	Units
Input Value and Units	**1,000**	**SCFM**
Biogas Higher Heating Value (HHV)	**500**	Btu/ft^3
Engine Efficiency	**32**	%
Inlet Flow Rate	1,000	SCFM
Engine Power	2,813	kW
Engine Power	3,773	bhp

Input either SCFM, kW or BHP.

Input either flowrate or engine power.

SILOXANE-ONLY REMOVAL (SOR) SYSTEM CAPITAL AND ANNUAL COSTS CALCULATOR				
Cost Items	**Cost Factors**	**Factor**	**Removal System Cost ($)**	**Default Factor**
DIRECT CAPITAL COSTS (DCC):				
(1) Siloxane Removal System Equipment Cost (SRSEC)	Calculated by program		467,586	
(2) Auxiliary Equipment	5% of equipment cost (SRSEC)	**5.0%**	23,379	5%
(3) Freight	5% of SRSEC	**5.0%**	23,379	5.0%
(4) Sales Tax	10% of (SRSEC+auxiliary+freight)	**10.0%**	46,759	10.0%
Subtotal: **Total Equipment Cost (TEC)**	(1) + (2) + (3) + (4)		561,103	
(3) Direct Installation Costs				
(a) Foundation and Structural Support	8% of TEC	**8.0%**	44,888	8.0%
(b) Handling & Erection	14% of TEC	**14.0%**	78,554	14.0%
(c) Electrical	4% of TEC	**4.0%**	22,444	4.0%
(d) Piping	2% of TEC	**2.0%**	11,222	2.0%
(e) Insulation	1% of TEC	**1.0%**	5,611	1.0%
(f) Painting	1% of TEC	**1.0%**	5,611	1.0%
Subtotal: **Total Direct Installation Costs (DIC)**	(a) + (b) + (c) + (d) + (e) + (f)		168,331	
Total DCC:	TEC + DIC		729,434	
INDIRECT CAPITAL COSTS (ICC):				
(1) Indirect Installation Costs (IIC)				
(a) General Facilities	5% of TEC	**5.0%**	28,055	5.0%
(b) Engineering and Home Office Fees	10% of TEC	**10.0%**	56,110	10.0%
(c) Process Contingency	10% of TEC	**10.0%**	56,110	10.0%
(2) Other Indirect Costs (OIC)				
(a) Siloxane Monitor	Engineering Estimate	**$75,000**	75,000	75,000
(b) Startup and Performance Testing	1% of TEC	**1.0%**	5,611	1.0%
(c) Spare Parts	1% of TEC	**1.0%**	5,611	1.0%
(d) Contractor Fees	10% of TEC	**10.0%**	56,110	10.0%
Total ICC:	IIC+OIC		282,608	
PROJECT CONTINGENCY	15% of (DCC+ICC)	**15.0%**	151,806	15.0%
RETROFIT COSTS	0% of TIC	**0.0%**	0	0.0%
TOTAL CAPITAL INVESTMENT (TCI):	DCC+ICC+Project Contingency+Retrofit Costs		1,163,849	
DIRECT OPERATING COSTS (DOC):				
(1) Operating Labor				
(a) Operator			21,900	
hr/shift		**0.5**		0.5
Pay Rate		**$40**		$40
Operating Hours		**8760**		8760
(b) Supervisor	15% of operator cost	**15.0%**	3,285	15.0%
(2) Maintenance (labor and material)	1.5% of TCI	**1.5%**	17,458	1.5%
(3) Siloxane Removal System Media Replacement + Energy Requirement	Calculated by program		27,164	
(4) Siloxane System Periodic Testing	Engineering estimate	**$24,000**	24,000	$24,000
Total DOC:	(a) + (b) + (2) + (3) + (4)		93,807	
INDIRECT OPERATING COSTS (IOC):				
(1) Overhead	60% of (operator labor (1) + maintenance (2))	**60.0%**	25,586	60.0%
(2) Property Taxes	1% of total capital investment	**1.0%**	11,638	1.0%
(3) Insurance	1% of total capital investment	**1.0%**	11,638	1.0%
(4) Administration	2% of total capital investment	**2.0%**	23,277	2.0%
(5) Capital recovery costs (CRC)	CRF x TCI		165,732	
Capital recovery factor (CRF)	0.1424			
Interest rate		**7.0%**		7.0%
Annualization years		**10**		10
Total IOC:	(1) + (2) + (3) + (4) + (5)		237,872	
Recovery Credits (RC)	Engineering Estimate	**$0**	0	$0
TOTAL ANNUAL COST (TAC):	DOC + IOC - RC		331,679	
TOTAL ANNUAL COST PER kWh			0.013	
TOTAL ANNUAL COST PER MMBtu			1.26	
TOTAL ANNUAL COST PER MSCF			0.63	

Table 4. Engine Cost Savings Information

Category	Siloxane Level, ppmv	Payback Years
Moderate	0.5 - <9	3.0
Heavy	>9 - <25	2.0
Severe	>25 - <60	1.0
Extreme	>60 - 140+	0.5
Savings Include (based on siloxane levels)		
Spark plugs: increase life 3x to 4x		
Engine re-build from 5000 to 40,000 hours		
Exhaust heat boiler re-tube: increase life by 3x to 4x		
Power Savings / Availability: increase of 75 to 92%		
Oil changes increase interval: 500 to 1440[5] hours		
Pre-chamber and pre-chamber check valve by 2x to 6x		

Assumptions-

1. Gas already meets engine OEM gas cleanliness standards
2. Lean Burn Engines

[5] Title 40, Part 63, Subpart ZZZZ-National Emissions Standards for Hazardous Air Pollutants for Stationary Reciprocating Internal Combustion Engines.

APPENDIX A

TOOLKIT COST FACTORS AND DEFINITIONS OF COST CATEGORIES[6]

[6] EPA Air Pollution Control Cost Manual, Sixth Edition EPA/452/B-02-001, January 2002, United States Environmental Protection Agency Office of Air Quality Planning and Standards Research, Triangle Park, North Carolina 27711, EPA/452/B-02-001

TOTAL CAPITAL INVESTMENT ELEMENTS

Total capital investment (TCI) includes:

- All costs required to purchase equipment needed for the siloxane removal system (total equipment costs or TEC)
- Costs of labor and materials for installing that equipment (direct installation costs or DIC)
- Costs for site preparation and buildings,
- Other costs (indirect installation costs or IIC)
- Costs for land, working capital, and off-site facilities.

Equipment installation may also require land, but as most add-on control systems take up little space this cost would be relatively small. For those systems that do require larger quantities of land for the equipment, chemicals storage, and waste disposal, especially when performing a retrofit installation, space constraints can significantly influence the cost of installation and the purchase of additional land may be a significant factor in the development of the project's capital costs.

Direct installation costs include:

- Costs for foundations and supports, erecting and handling the equipment, electrical work, piping, insulation, and painting.

Indirect installation costs include:

- Engineering, construction and field expenses (i.e., costs for construction supervisory personnel, office personnel, rental of temporary offices, etc.);
- Contractor fees (for construction and engineering firms involved in the project);
- Start-up and performance test costs (to get the control system running and to verify that it meets performance guarantees);
- Contingencies such as redesign and modification of equipment, escalation increases in cost of equipment, increases in field labor costs, and delays encountered in start-up. Contingencies are not the same thing as uncertainty and retrofit factor costs, which are treated separately below.

Initial operational costs (the initial costs of fuel, chemicals, and other materials, as well as labor and maintenance related to startup) are included in the operating cost section of the cost analysis instead of in the capital component. Routine operation of the control does not begin until the system has been tested, balanced, and adjusted to work within its design parameters. Until then, all utilities consumed, all labor expended, and all maintenance and repairs performed are a part of the construction phase of the project and are included in the TCI in the "Startup" component of the Indirect Installation Costs.

TOTAL ANNUAL COST ELEMENTS

Total Annual Cost (TAC) has three elements: direct operating costs (DOC), indirect operating costs (IOC), and recovery credits (RC), which are related by the following equation:

$$TAC = DOC + IOC - RC$$

The one-year basis allows time for siloxane monitoring and is directly usable in the financial analyses.

Direct Operating Costs (DOC): DOC can include costs for raw materials (media, reagents), utilities (steam, electricity, process and cooling water), waste treatment and disposal, maintenance materials (greases and other lubricants, gaskets, and seals), replacement parts, and operating, supervisory, and maintenance labor. If collected waste cannot be recycled or sold, it must be landfilled or disposed of in some other manner. Disposal costs are site-specific, but run $33 per ton for the Ox Mountain site, exclusive of transportation. Hazardous disposal costs will vary depending on the composition of the media but per the cost manual can be $150 per ton or more (1998 dollars).

Indirect Operating Costs (IOC): Indirect or “fixed” costs include such categories as administrative charges, property taxes, insurance, and capital recovery. The system capital recovery cost (CRC) is based on the equipment lifetime and the annual interest rate employed. The default values used in the toolkit for estimating the CRC were an estimated 10-year equipment life and an interest rate of 7 percent, which results in a calculated capital recovery factor (CRF) of 0.1424. The toolkit then estimates the CRC by multiplying the CRF by the TCI.

Recovery Credits: Direct and indirect annual costs are reduced by recovery credits, taken for materials or energy recovered by the contaminant removal system, which may be sold, recycled to the process, or reused elsewhere at the site. The value of the credits are net of any associated processing, storage, transportation, and any other costs required to make the recovered materials or energy reusable or resalable. The materials recovered, however, may be of small quantity or of doubtful purity, resulting in their having less value than virgin material.

Siloxane monitoring cost section: Critical factors in selecting the type of analyzer or monitor for a particular application include gas concentration, ambient temperatures and the presence of contaminants that could damage or interfere with the sampling or analyzer systems. Other issues such as data availability requirements may influence analyzer selection or drive the need for two analyzers with one in a backup capacity. These issues impact equipment selection and can substantially impact capital, operating and maintenance costs. As manufactures overcome past limitations, monitors and gas analyzers are becoming more versatile. The selection of a monitor and the cost analysis should be performed on a site-specific basis.

Retrofit Cost Considerations: The installation factors used in the spreadsheet and listed in the cost manual apply mainly to systems installed in new facilities. These factors must be adjusted whenever a control system is sized for, and installed in (i.e.,"retrofitted") an existing facility. However, because the size and number of auxiliaries are usually the same in a retrofit situation, the purchased equipment cost of the control system would probably not be much different from the new plant purchased cost. Some kinds of system modifications and additional cost considerations in a retrofit could include the need for additional ductwork, piping, insulation, painting, site preparation, engineering, and lost production during shutdown. To estimate the unanticipated additional installation, the cost of the system (i.e., TCI) can be multiplied by a retrofit factor. In the cost manual the retrofit factor ranges from 1.3 to 1.5, with the multiplier selected based on the relative difficulty of the installation.

Table 5. Range of Cost Factors from the EPA Cost Control Manual

Cost Item	Cost Factor Range, %
Total Equipment Costs (TEC)	
Auxiliary equipment	10-50
Sales taxes	0-8
Freight	1-10
Direct Installation Costs (DIC)	
Foundations & supports	4-12
Handling & erection	14-50
Electrical	1-8
Piping	2-30
Insulation	1-7
Painting	1-10
Indirect Installation Costs (IIC)	
Engineering	10-20
Construction and field expenses	5-20
Contractor fees	0-10
Start-up	1-2
Model study	2-3
Performance test	1
Contingencies	3
Retrofit	10-50

APPENDIX B

DESCRIPTIONS OF THE POTENTIAL BIOGAS CLEANUP SYSTEM TECHNOLOGIES

Willexa Energy

The biogas treatment system provided by Willexa Energy (Figure 1) utilizes polymeric media cassettes (designated as PpTek BGAK) for siloxane removal. The system is regenerated automatically on-site for continuous gas treatment. Media lasts at least five years before needing replacement.

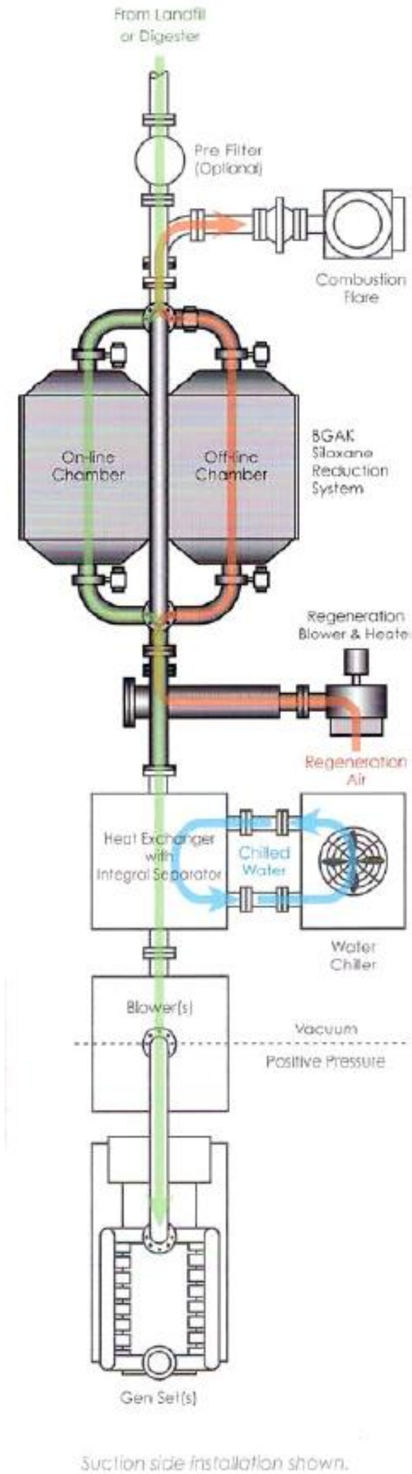

Figure 1. Willexa Biogas Treatment System

DCL America

An example of DCLs' SRT System for siloxane removal is shown in Figure 2. Proprietary/selective and regenerable removal media (not activated carbon or silica gel) with lifespan of 7+ years, claimed to remove up to 99% or more of heavy siloxanes.

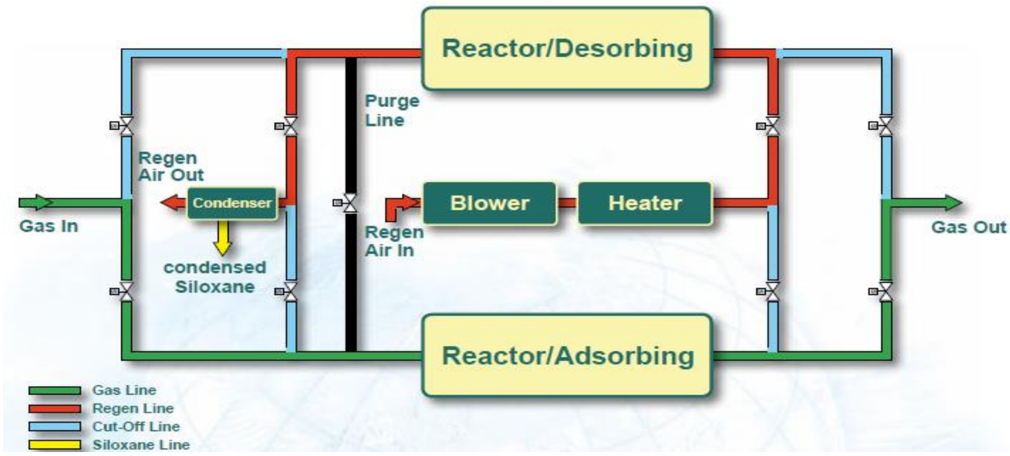

Figure 2. DCL Biogas Treatment System

Pioneer Air Systems

Pioneer Air Systems' Total Contaminant Removal (TCR) System (Figure 3), is claimed to remove siloxanes, sulfur, halide compounds, and other contaminants from biogas by chilling the gas to sub-zero temperatures of -10ºF/-23ºC pressure dew point. (PDP). Most contaminants either condense or dissolve in the condensed fluids.

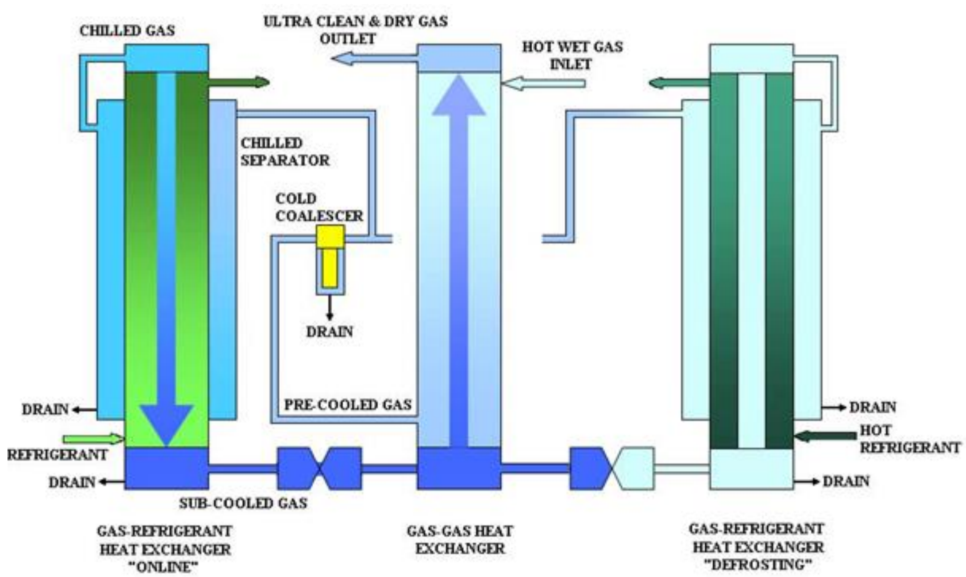

Figure 3. Pioneer Total Contaminant Removal (TCR) System

For applications that require gas cleaning to ppb levels, e.g., for SCR or fuel cells, Pioneer offers catalytic carbon adsorbers in series with TCR where the adsorbers function as polishing filters.

Environmental Systems and Composites Inc. (ESC)

ESC's multi-stage gas treatment system, which includes their regenerable CompHeet system for VOCs and siloxane removal, can consist of one or more of the following (per their website) based on the biogas/system specifications:

1. Inlet raw gas coalescer
2. H_2S/organic sulfur removal
    a. Bioscrubber or
    b. Iron sponge or
    c. SulfaTreat adsorbent
3. Particulate filters
4. Blower(s) or compressors
5. Moisture removal system (to <40°F)
    a. Compressor
    b. Recirculation pump
    c. Condenser
6. Water droplet coalescer
7. Two-stage siloxane removal system (regenerative and polishing systems)
8. Final particulate filter

Over 90% of the chemical contaminants, including siloxanes and VOCs, in the biogas are removed in the first regenerable stage of the two-stage siloxane removal system. The remaining contaminants are removed in the second stage using non-regenerable activated carbon. Regeneration of the activated carbon is accomplished using hot 400-450°F gases generated by the system. The contaminant-containing gas is cleaned and recycled in another reactor. The exhaust gases from the system are mainly carbon dioxide and water vapor. The residue from the removed biogas contaminants are periodically removed (about every 6 months) as a dry solid, which is disposed in a landfill.

ESC's is the only self-contained regenerable biogas treatment system permitted to operate in the SCQAMD in the state of California. ESC apparently specializes in systems for fuel cells–they have provided biogas treatment systems for the 600- and 320-SCFM fuel cell systems at Inland Empire Utilities Agency Water Recycling Plant in Ontario, CA, and at the Water Pollution Control Plant of the City of San Jose, CA.

Quadrogen

Quadrogen's Integrated Biogas Clean-up System (IBCS) is claimed to remove all sulfur species, siloxanes, chlorides, water, oxygen and other impurities from biogas to the ppb level suitable for engines, microturbines, fuel cells and pipeline quality methane. Figure 4 is a schematic flow diagram taken from Quadrogen's patent (US 2013/0209338 Al) illustrating a preferred embodiment of their biogas cleaning system for removing the above contaminants to ppb levels, and a pre-cooling stage to remove a majority of water and VOCs.

As stated in the patent, while it is generally preferable that the biogas be cooled to -10°F in the process in order to condense out the majority of the siloxanes and some of the volatile organic compounds, this low temperature does not necessarily need to be reached in some cases, to be effective. Because some biogas sources such as agricultural digesters do not have high levels of siloxanes or volatile organic compounds impurities, in these cases it may be sufficient to reduce the temperature of the biogas to around 40°F in order to only remove most of the water. This is also the case if the siloxane levels in the biogas are very low, for instance less than approximately 1 ppm, where it would be possible to simply capture most of the siloxanes economically with the downstream siloxane removal bed.

Quadrogen, demonstrated their IBCS in a recent installation at California's Orange County Waste Water Treatment Plant configured to supply clean biogas to Fuel Cell Energy's DCF-300 (300-kW) fuel cell. Independent customer validation indicated that the system continues to remove all specified contaminants (siloxanes, sulfur species, halides, and VOCs) to levels below the 30 ppb required by the project. As is the case with ESC, Quadrogen's current market appears to be more applicable and directed towards fuel cells and pipeline-quality methane.

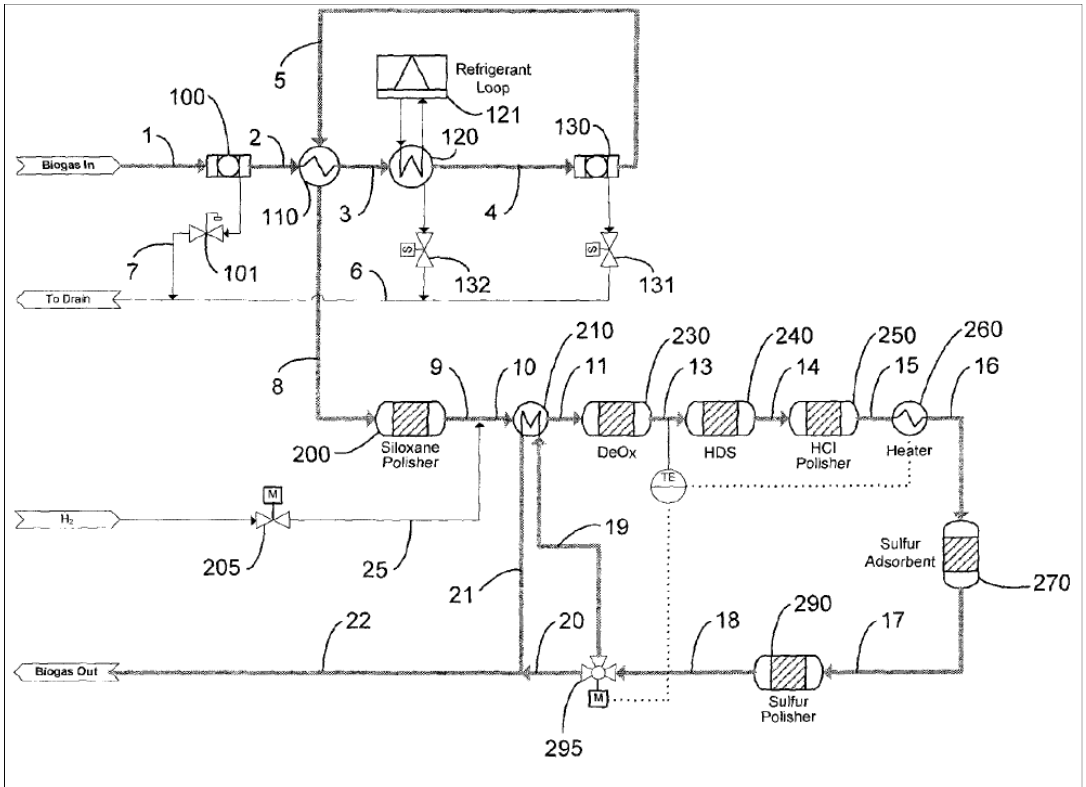

Figure 4. Quadrogen Biogas Cleanup System in Patent

Acrion Technologies

The Acrion biogas cleaning unit (Figure 5) consists of a CO_2 wash column that operates at increased pressures (300 psig) and reduced temperatures (-65°F). Dried and compressed biogas enters the bottom of the column and is cooled by a liquid CO_2 wash that is able to strip out all contaminants from the incoming biogas feed stream with the exception of the H_2S species. At the top of the column, the temperature is reduced such that some of the CO_2 condenses, and this condensed CO_2 is used to wash and cool the incoming dry LFG. The liquid CO_2 stream exiting from the bottom of the wash column is concentrated with contaminants and must be flared. The standard Acrion unit does not produce a liquid CO_2 product although the unit can be retrofitted in order to do so. For removal of the sulfide species, a commercially available system can be used upstream of the Acrion base unit. For the gas stream coming from the outlet of the Acrion base unit, the CO_2 content in the raw biogas is expected to be reduced by only ~5 vol%, with proportionate increases in the oxygen, nitrogen, and methane contents.

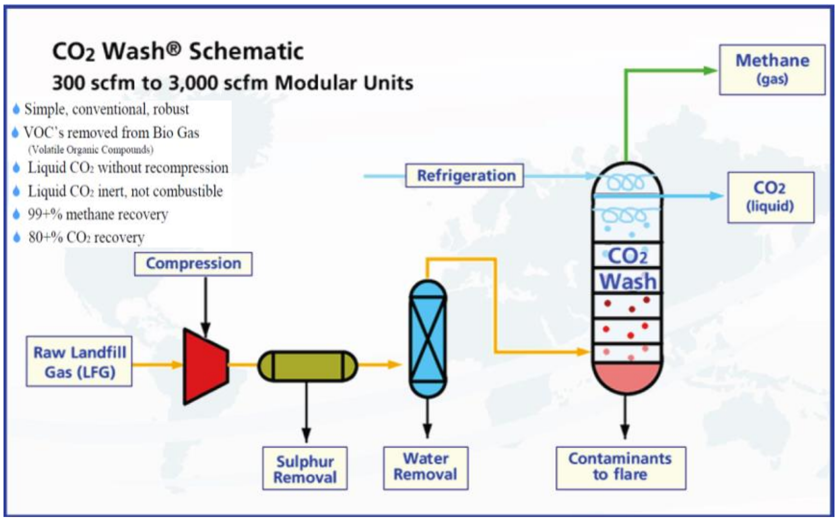

Figure 5. Acrion Gas Treatment System

In 2001, Acrion operated their CO2 Wash demonstration unit at the New Jersey EcoComplex. During one hundred hours of continuous operation the unit recovered contaminant-free methane-carbon dioxide (800 BTU/MCF) and food grade liquid to levels shown in Table 6.

As with ESC and Quadrogen, Acrion's biogas treatment system is geared more towards fuel cells and biomethane production.

Table 6. Acrion Cleaned Gas Composition

Methane Product (700 - 800 BTU/scf)	
Siloxane Compounds	Below detection limit of 5 ppb
Chlorinated Hydrocarbons	Below detection limit of 10 ppb
Total Sulfur Compounds	100 ppb

Nrgtek

Nrgtek has developed a unique technology for siloxane removal from biogas, based on a continuous liquid scrubber with nanofiltration/pervaporation membranes, claimed to be capable of removing siloxanes from 25-40 ppm to less than their detectable limits (0.02 ppm). The Company is currently working on a 1,000 SCFM prototype, after having proven its concept on 10 SCFM and 100 SCFM (Figure 6) pilot plant systems. At this time they do not have a product available in the commercial marketplace.

Figure 6. Nrgtek 100-SCFM Siloxane Removal System

Venture Engineering and Construction

- Venture offers single-stage or two-stage system configurations (dual-swing bed adsorption skid Figure 7), depending on the specification, biogas matrix and budget.
- For maximum contaminant removal efficiency (<100 ppbv), Venture incorporates selective adsorption using a variety of media, including activated alumina, silica gels, and in some instances, molecular sieves in the first stage adsorption skid, followed by activated carbon adsorption in the second stage. Two-stage systems may be required to attain the low contaminant levels required for post-engine catalyst systems.
- Selective adsorption upstream of carbon accomplishes: 1) economic removal of moisture from the raw biogas that competes for activated carbon surface area, 2) removal of a significant portion of the siloxanes (99%+ removals of total siloxanes, or $<1 mg/m^3$), and 3) a reduction in the size of the activated carbon system.
- Both the selective and carbon systems are regenerated on-site. For IC engine or turbine plants, a combination of cleaned LFG gas (slip stream) and low-watt density electric heating elements provide the regeneration for the off-line vessels.
- Standard effluents are <100ppb, siloxane concentration below $0.5 mg/m^3$ and 80% removal of NMOCs. The system also removes H_2S and water.
- The media is specified to last at least 1 year in between replacements, based on a 24-hour regeneration cycle. To date, proven media life is greater than 12 months at all of Venture's installations. The spent solid media typically can be disposed of as non-hazardous.
- The system described above is completely modularized and designed to remove siloxanes from raw biogas with an inlet flowrate of up to 4000 SCFM (modules in increments of 1000 SCFM) and inlet siloxanes concentration of 75 ppmv or less to an outlet concentration of 1.0 ppmv or less. This assumes that total gaseous non-methane organics (NMOCs) does not exceed 6000 ppmv (as ppm methane), and hydrogen sulfide equal to 35 ppmv. Higher NMOCs and/or hydrogen sulfide will affect the size of the system. In instances where hydrogen sulfide concentrations are significantly higher (>100 ppmv), it

may be more economical to employ a hydrogen sulfide removal step ahead of the selective adsorption skid.

Figure 7. Example of a Venture Engineering Gas Conditioning Skid

Parker NLI

The Parker regenerative GES siloxane removal system is shown in Figure 8 and includes particulate and aerosol filtration, VOC reduction and dehydration in addition to siloxane removal.

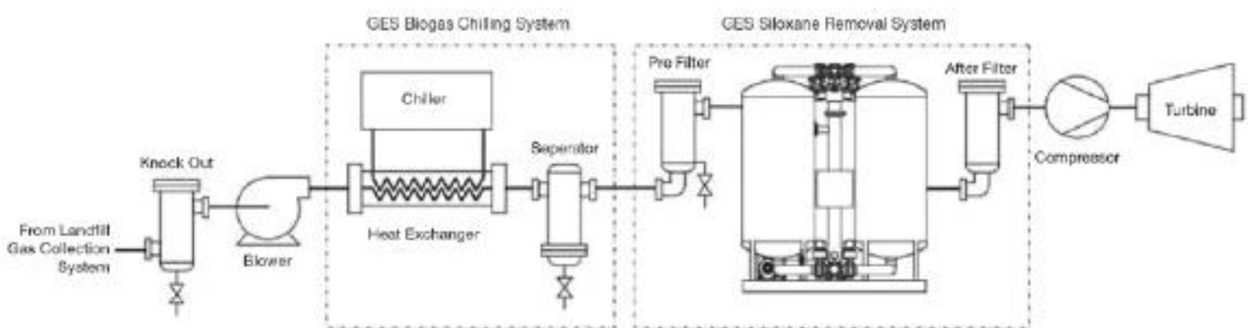

Figure 8. Typical Parker GES Landfill Gas Flow Schematic