Energy and Emissions Savings and Potential in Wastewater Treatment Facilities

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Overview

- ❑Industrial Assessment Center at ASU
- ❑Water Energy Nexus
- ❑Wastewater Treatment Plants (WWTP)
- ❑Biogas Composition
- ❑Combined Heat and Power
- ❑Case Study

Acknowledgement

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The IAC Program

- The US Department of Energy, Advanced Manufacturing Office, currently supports 31 Industrial Assessment Centers (IACs) at universities across the US.
- These Centers provide free evaluations of small and medium-sized manufacturing facilities to reduce costs by increasing energy efficiency, improving productivity, and decreasing waste.
- **IACs train the next-generation of energy savvy engineers**, more than 60 percent of which pursue energy-related careers upon graduation.

Industrial Assessment Center
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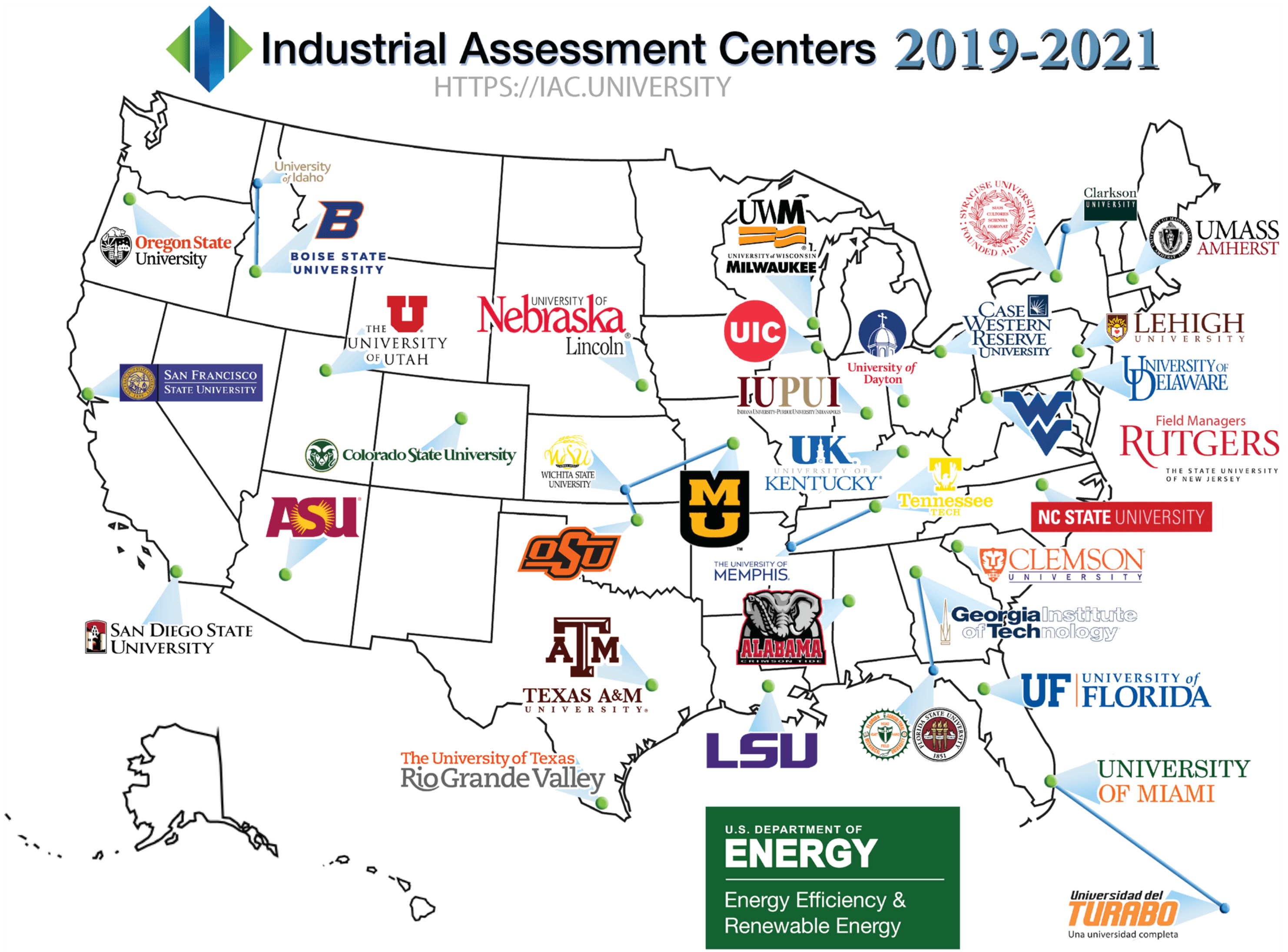
Locations of Existing IACs



IAC@ASU

- The IAC@ASU was first established in 1990 and ran until 2006 (completing 435 assessments). It was re-established in 2016 and has conducted 44 assessments since then.
- In most cases, the team performs the assessment in a single day by working with plant personnel to identify savings opportunities. The team examines utility bills, facilities, equipment, manufacturing processes, and waste streams.
- Within 60 days, an easy-to-read, confidential report is delivered documenting current practices and recommending ways to save money by reducing energy and waste streams and improving the manufacturing processes.

How An Assessment is Conducted

1. Determine eligibility
2. Obtain utility bills
3. Conduct on-site assessment

   Typically 1 day
4. Generate recommendations for the facility
5. Research and analyze recommendations

   Generate simple payback for each recommendation
6. Deliver confidential report within 60 days, outlining recommendations and their paybacks.
7. Follow up 6 to 9 months later on implementation status

Eligibility

- ❑Standard Industrial Code between 2000-3999 (i.e. manufacturing/industrial)
- ❑Gross annual sales less than $100,000,000
- ❑Annual energy bills between $100,000 and $2,500,000
- ❑Fewer than 500 employees on site
- ❑New initiative to have 2 water facilities assessed per year

Average Savings for 2019 Clients

- Average Annual Usage Savings

583,731 kWh

- Average Annual Demand Savings

106 kW

- Average Annual Energy Cost Savings

$66,734

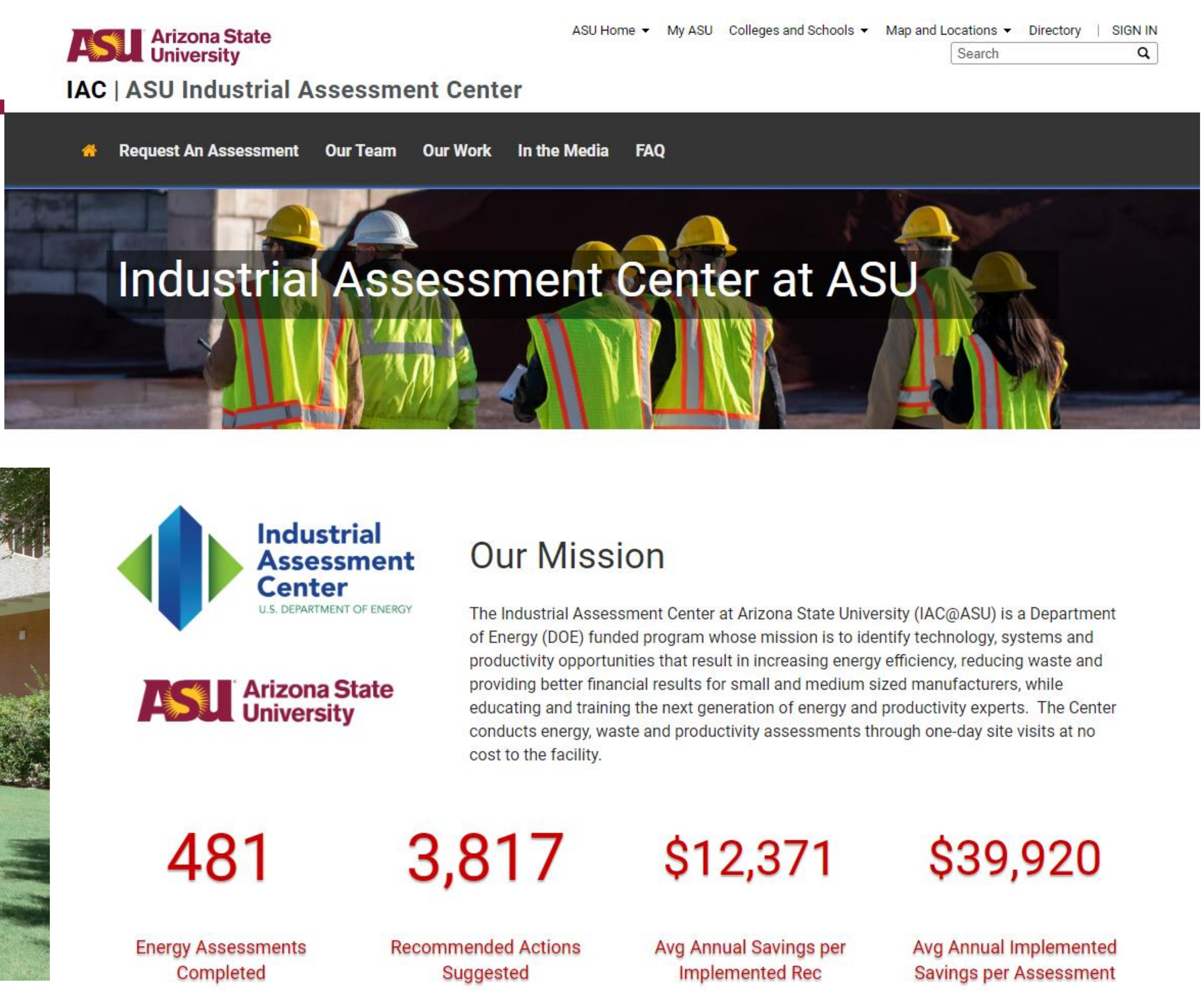
ASU's Top Ten Assessment Recommendations

	ARC	Description	Recc'd	Average Savings	Average Cost	Average Payback	Imp Rate
1	2.7142	UTILIZE HIGHER EFFICIENCY LAMPS AND/OR BALLASTS	602	$4,893	$8,986	2.5	43.9%
2	2.4133	USE MOST EFFICIENT TYPE OF ELECTRIC MOTORS	308	$6,742	$11,599	2.3	53.4%
3	2.4236	ELIMINATE LEAKS IN INERT GAS AND COMPRESSED AIR LINES/ VALVES	243	$6,467	$934	0.4	73.8%
4	2.4239	ELIMINATE OR REDUCE COMPRESSED AIR USAGE	217	$3,844	$611	0.3	42.3%
5	2.7135	INSTALL OCCUPANCY SENSORS	182	$1,190	$2,165	2.6	23.8%
6	2.7232	REPLACE EXISTING HVAC UNIT WITH HIGH EFFICIENCY MODEL	145	$7,190	$12,918	2.3	38.4%
7	2.4111	UTILIZE ENERGY-EFFICIENT BELTS AND OTHER IMPROVED MECHANISMS	136	$2,505	$220	0.1	55.4%
8	2.4146	USE ADJUSTABLE FREQUENCY DRIVE OR MULTIPLE SPEED MOTORS ON EXISTING SYSTEM	132	$15,991	$18,654	2.0	26.9%
9	3.6192	USE A LESS EXPENSIVE METHOD OF WASTE REMOVAL	97	$3,911	$279	0.1	39.3%
10	2.4314	USE SYNTHETIC LUBRICANT	75	$1,715	$1,654	1.3	42.0%

Sorted by number of times recommended

Find Out More:

https://iac.engineering.asu.edu/



Research Topics

- ❑Tools for planning and negotiating for shifting peak demand
- ❑Energy signatures for determining production efficiency
- ❑Development of energy footprints
- ❑Innovative use of technology (PCMs, shading, etc)

Schedule An Assessment

We're always looking for new clients!

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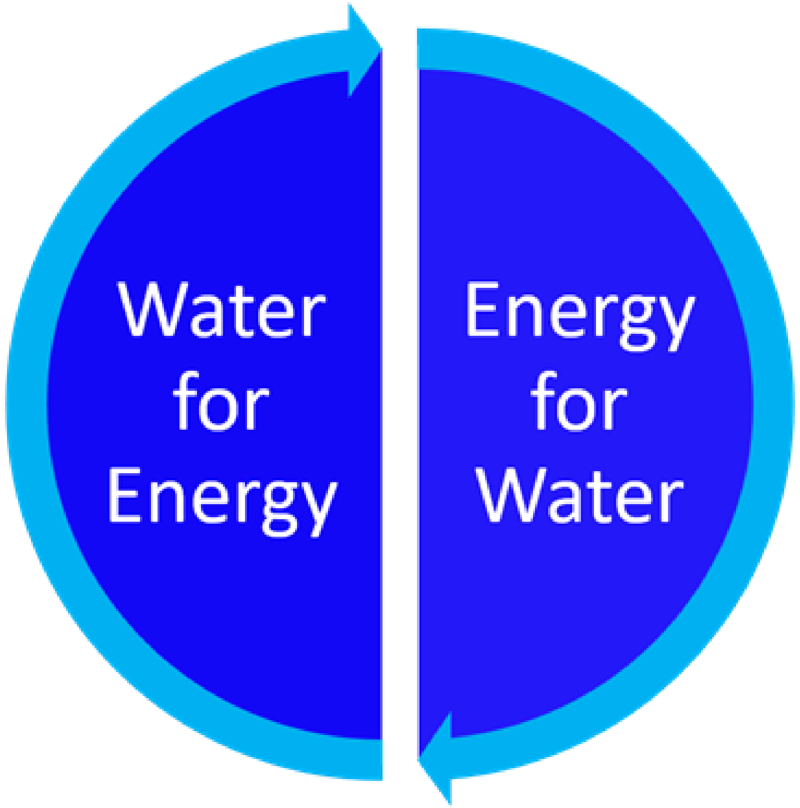
Water Energy Nexus

- Fuel production (Ethanol, hydrogen, biofuel)
- Resource extraction & mining
- Hydropower
- Thermoelectric cooling
- Refining
- Emission control (Carbon capture)



- Pumping for water extraction
- Drinking water treatment / Desalinization
- Drinking water distribution
- Customer end use
- Wastewater treatment

Wastewater Treatment Plants (WWTP)

- WWTPs collectively demand around 2-4% of the U.S. energy consumption, ~$4.7 billion annually (Shen et al. 2015)
- Theoretically municipal wastewater contains 5 to 10 times more chemical and thermal energy than is necessary for its treatment to meet discharge standards (WERF 2011).
- Although only a part of this potential is practically usable, it is possible and feasible for WWTPs to be net energy producers (Frijns et al. 2013)
- Recent legislation and research funds are focusing on WWTPs (Wastewater Efficiency and Treatment Act of 2019)

Y. Shen, et al., Renew. Sustain. Energy Rev. 50 (2015) 346–362.

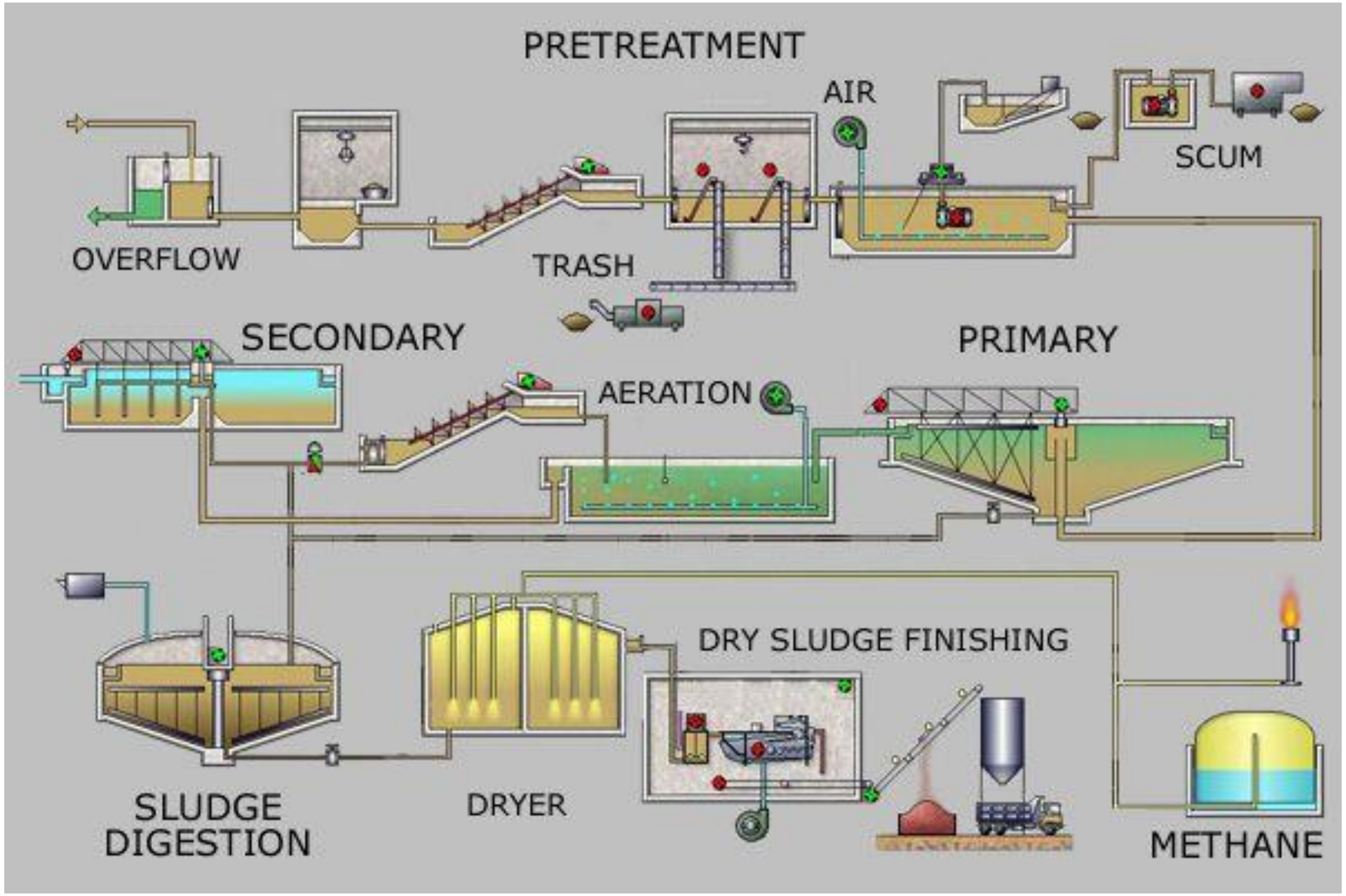
Water Environment Research Foundation (WERF) (2011). Energy Production and Efficiency Research— The Roadmap to Net-Zero Energy. Alexandria, VA.

Frijns et al. (2013). Energy Conversion and Management, 65, 357-363.

Wastewater Treatment Plants (WWTP)

- The general process:

- Despite the fact that 43% of U.S. WWTPs generate biogas with anaerobic digesters, as of 2011, only 3.3% utilize the biogas for electricity production via cogeneration (Goff 2011).



C. Goff, Combined heat and power at wastewater treatment facilities : Market analysis and lessons from the field, in: Northeast Biomass Conf., 2011

Biogas Composition

Species	Concentration
CH_4	60-70%
CO_2	30-40%
N_2	0-1%
O_2	0-1%
H_2O	Saturated
H_2S	50-20,000 ppm
CO	0-1%
NH_3	100 ppm
Siloxane	10 ppm

- The composition of biogas varies with feedstock, environmental conditions, seasonal variations, and other factors.
- Typical composition ranges are shown here.

Siloxane

Major siloxane impurities in biogas.

Table 12
Siloxanes amount in different WWTPs (the location of each plant is also provided together with Reference for original source data) – Part I (to be continued on the next page).

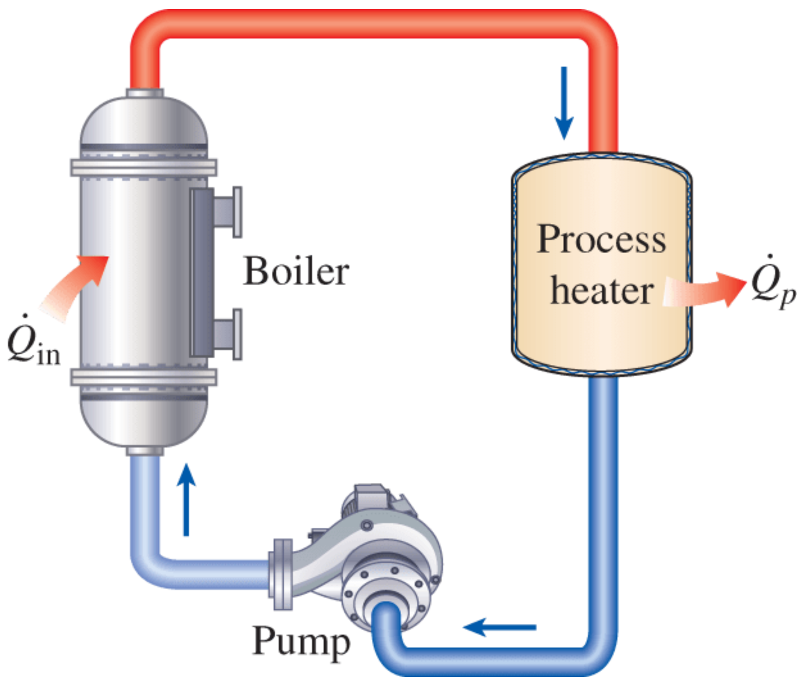
Compound	Chemical formula	M.W. (g/mol)		Finland [89]	Finland [89] (note 1)	Finland [89] (note 2)	Germany [90]	Germany [90]	US [91] (note 3)	Italy (note 4)	Italy (note 4)	Italy (note 4)
Total siloxanes			[mg/m^3]	29.6	2.4	5.5	16.5	6.0	107.4	14.4	10.8	6.2
(D6) Dodecamethylcyclohexasiloxane	$C_{12}H_{36}O_6Si_6$	444.92	[mg/m^3]	n.a.	n.a.	n.a.	n.a.	n.d.	6.99	0.7	n.d.	n.d.
(D5) Decamethylcyclopentasiloxane	$C_{10}H_{30}O_5Si_5$	370.77	[mg/m^3]	27.05	0.90	4.46	9.31	2.78	56.61	11.0	5.50	3.63
(D4) Octamethylcyclotetrasiloxane	$C_8H_{24}O_4Si_4$	296.62	[mg/m^3]	1.21	0.10	0.13	6.69	2.95	32.50	2.5	1.29	0.87
(D3) Hexamethylcyclotrisiloxane	$C_6H_{18}O_3Si_3$	222.46	[mg/m^3]	0.00	0.03	0.06	0.17	0.19	3.27	0.0	0.26	0.36
(L4) Decamethyltetrasiloxane	$C_{10}H_{30}O_3Si_4$	310.69	[mg/m^3]	1.29	1.29	0.51	0.14	0.02	n.a.	n.d.	3.36	1.34
(L3) Octamethyltrisiloxane	$C_8H_{24}O_2Si_3$	236.53	[mg/m^3]	0.03	n.d.	0.2	0.03	0.02	1.93	0.2	0.33	n.d.
(L2) Hexamethyldisiloxane	$C_6H_{18}OSi_2$	162.38	[mg/m^3]	0	0.04	0.09	0.05	0.01	6.14	n.d.	0.07	0.02
(TMS) Trimethylsilanol	$C_3H_{10}OSi$	90.20	[mg/m^3]	n.d.	n.d.	n.d.	0.14	0.07	n.d.	n.d.	n.d.	n.d.
Si tot (*calculated*)	–	–	[mg Si /m^3]	**11.0**	**0.8**	**2.0**	**6.2**	**2.3**	**40.3**	**5.4**	**3.7**	**2.2**

H. Madi, et al., J. Power Sources. 279 (2015) 460–471.

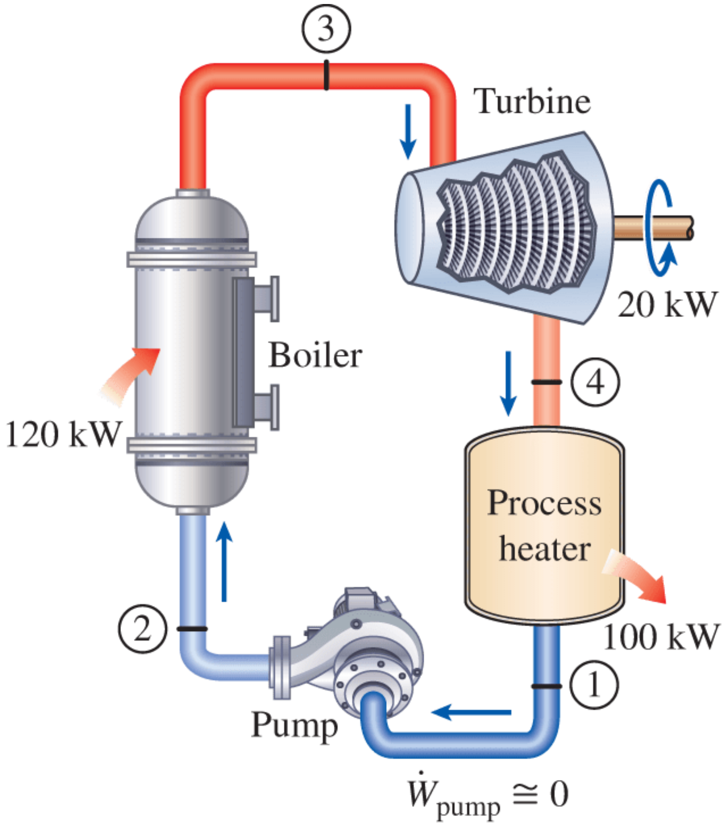
Cogeneration or Combined Heat and Power

- ❑*Def.* Production of more than one useful form of energy from the same energy source.
- ❑Industries that rely on process heat:
  - ❑Chemical
  - ❑Pulp and paper
  - ❑Oil production
  - ❑Refining
  - ❑Steelmaking
  - ❑Textile

Conventional Process Heating



Cogeneration for heating and power generation



Cogeneration or Combined Heat and Power

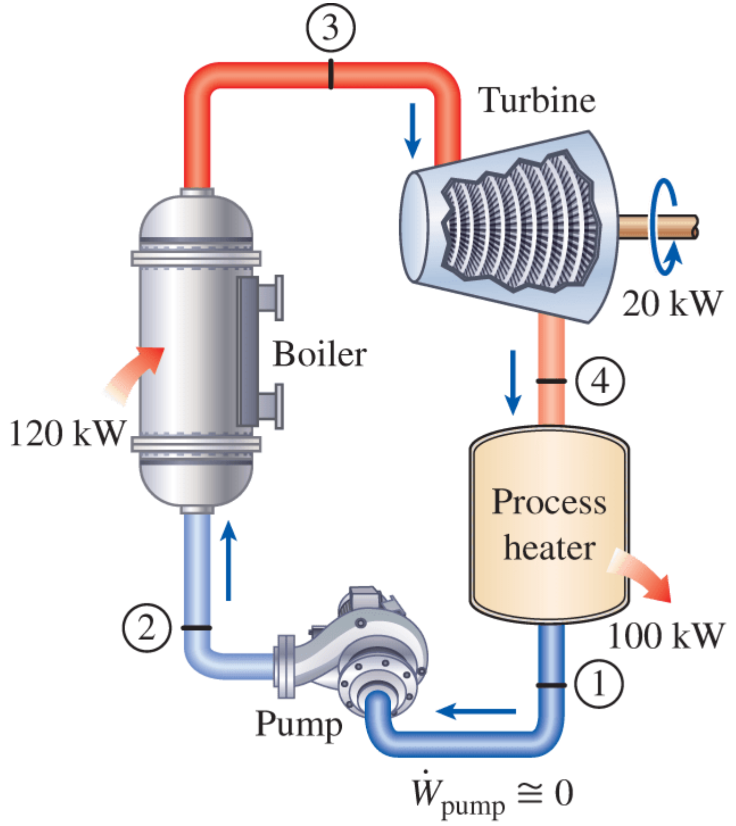
- *Efficiency:*

$$\varepsilon_{el} = \frac{\dot{W}_{el}}{\dot{m}_{fuel} HHV_{fuel}}$$

$$\varepsilon_{th} = \frac{\dot{Q}_{p}}{\dot{m}_{fuel} HHV_{fuel}}$$

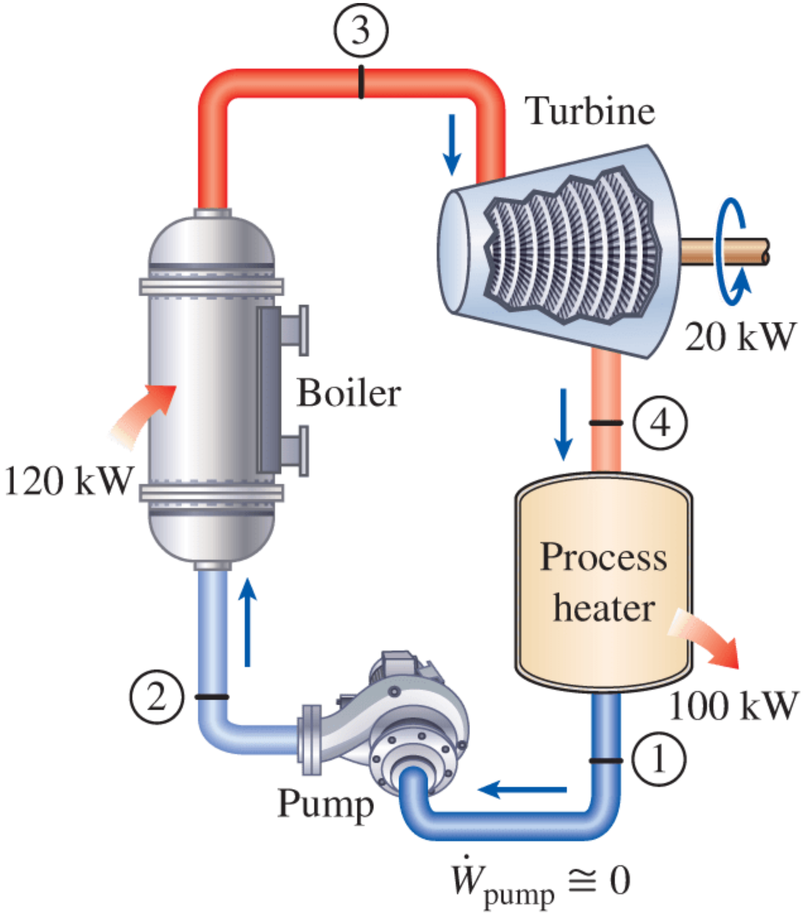
$$\varepsilon_{combined} = \frac{\dot{W}_{el} + \dot{Q}_{p}}{\dot{m}_{fuel} HHV_{fuel}}$$

Cogeneration for heating and power generation

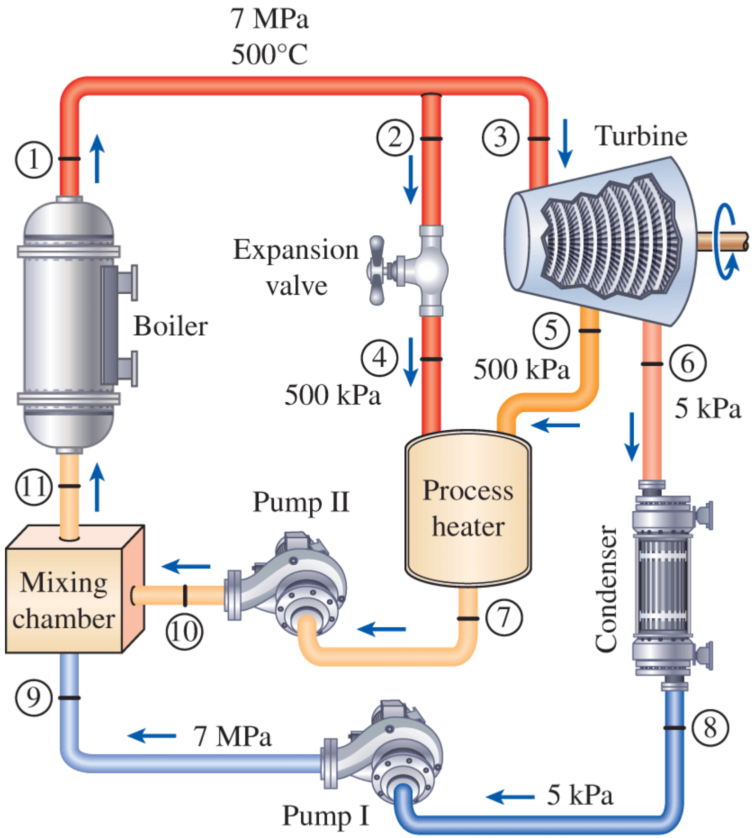


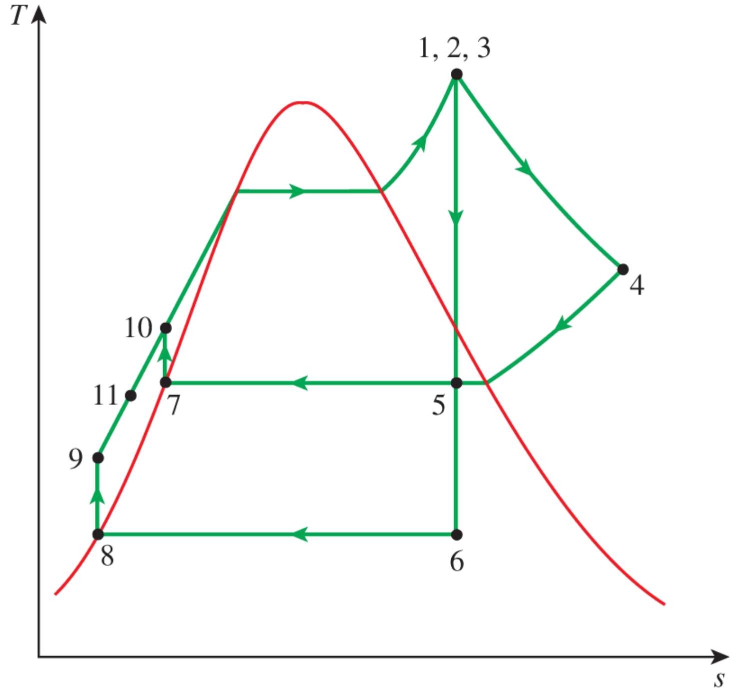
Cogeneration or Combined Heat and Power

Ideal cogeneration



Cogeneration Plant with Adjustable Loads





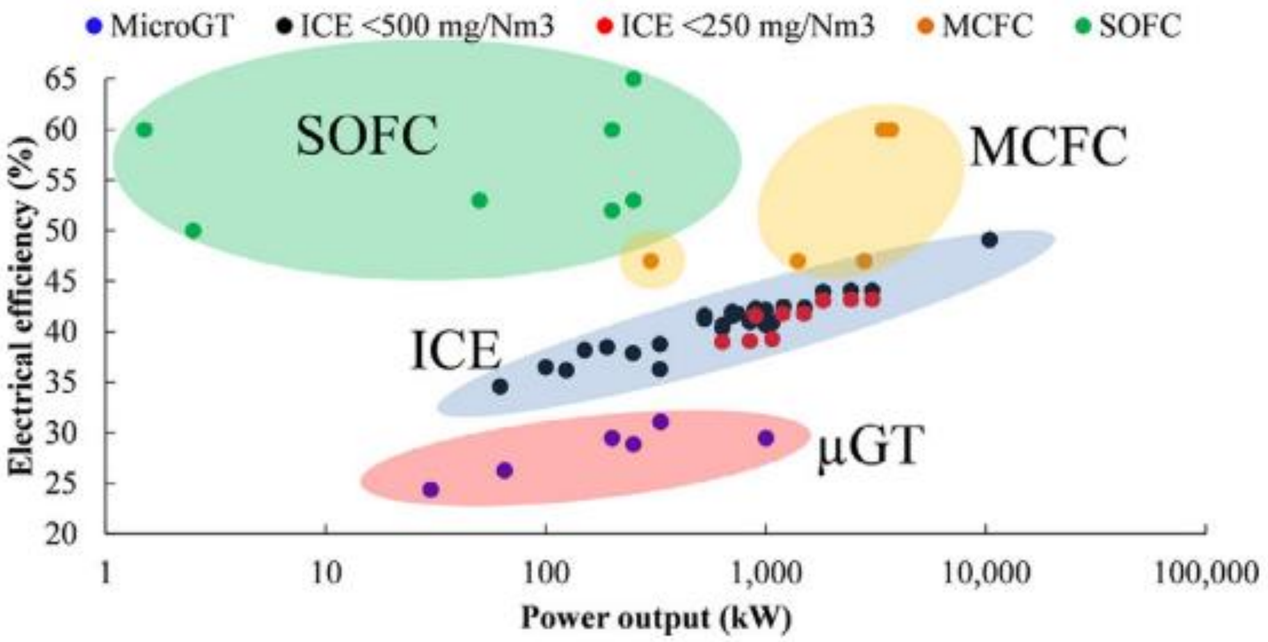
Characteristic	Prime Mover					
	Steam Turbine	Gas Turbine	Micro-turbine	Reciprocating IC Engine	Fuel Cell	Stirling Engine
Size	50 kW to 250 MW	500 kW to 300 MW	30 kW to 330 kW	10 kW to 10 MW	5 kW to 3 MW	< 200 kW
Fuel Preparation	None, biogas fueled boiler for steam	PM filter needed	PM filter needed	PM filter needed	Sulfur, CO, CH_4 can be issues	None
Sensitivity to fuel moisture	N/A	Yes	Yes	Yes	Yes	No
Electric efficiency (HHV)	5-30%	22-36%	22-30%	22-45%	30-63%	5-45%
Overall CHP Efficiency (HHV)	80%	65-71%	64-72%	70-87%	62-75%	NA
Turn-down ratio	Fair, responds within minutes	Good, responds within a minute	Good, responds quickly	Wide range, responds within seconds	Wide Range, slow to respond (minutes)	Wide range, responds within a minute

Characteristic	Prime Mover					
	Steam Turbine	Gas Turbine	Micro-turbine	Reciprocating IC Engine	Fuel Cell	Stirling Engine
Operating issues	High reliability, slow startup, long life	High reliability, requires gas compressor	Fast start-up, requires fuel gas compressor	Fast start-up, noisy	Low durability, low noise	Low noise
Field experience	Extensive	Extensive	Extensive	Extensive	Some	Limited
Commercialization status	Numerous models available	Numerous models available	Limited models available	Numerous models available	Commercial introduct., demo.	Commercial introduct., demo.
Installed cost (as CHP system)	\$350-1,100/kW (without boiler)	\$700-2,000/kW	\$1,100-3,200/kW	\$800-2,900/kW	\$3,000-10,000/kW	\$1,000-10,000/kW
Operations and maintenance (O&M) costs	0.4-1¢/kWh	0.6-1.3¢/kWh	0.8-2¢/kWh	0.8-2.5¢/kWh	1-4.5¢/kWh	1 ¢/kWh

Biogas Cogeneration Overview

Prime Mover	Number of Sites	Capacity (MW)
Reciprocating engine	54	85.8
Microturbine	29	5.2
Fuel cell	13	7.9
Combustion turbine	5	39.9
Steam turbine	2	81.0
Combined cycle	1	28.0
Total	**104**	**247.8**

C. Goff, Combined heat and power at wastewater treatment facilities : Market analysis and lessons from the field, in: Northeast Biomass Conf., 2011.



H. Madi, et al., J. Power Sources. 279 (2015) 460–471.

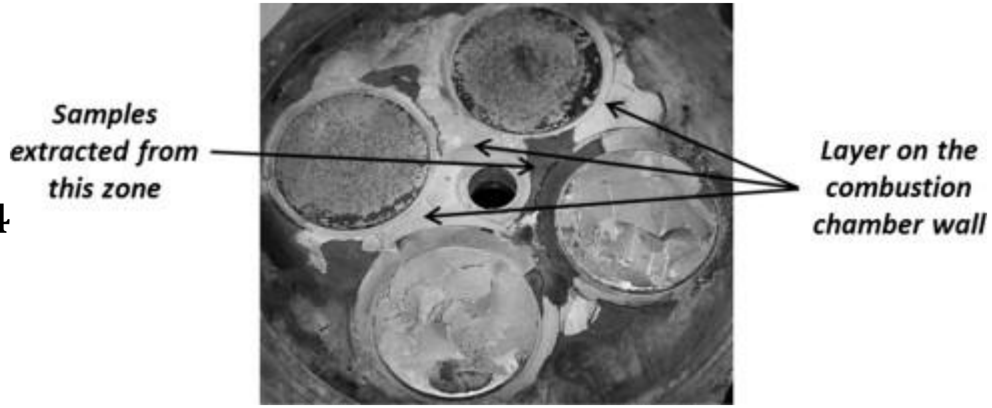
Biogas Reactions in CHP

Combustion of Biogas:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52\,N_2$$

$$H_2S + 1.5O_2 \rightarrow SO_2 + H_2O \qquad SO_3 + H_2O \rightarrow H_2SO_4$$

$$((CH_3)_2SiO)_3 + 12O_2 \rightarrow 3SiO_2 + 6CO_2 + 9H_2O$$



Alvarez-Florez et al., Eng Failure Analysis 50 (2015) 29-38.

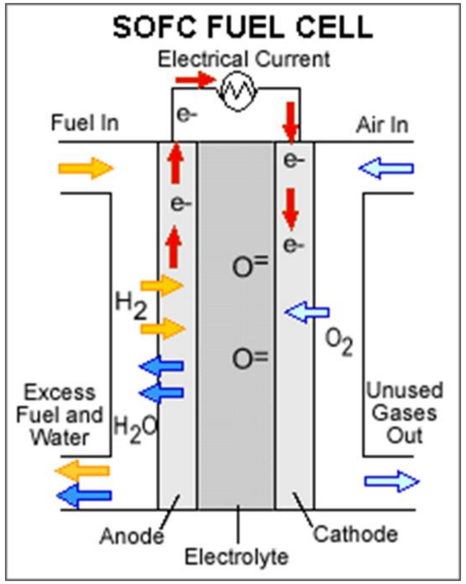
Electrochemical oxidation of Biogas:

$$CH_4 \rightarrow C + 2H_2$$

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

$$C + O^{2-} \rightarrow CO + 2e^-$$

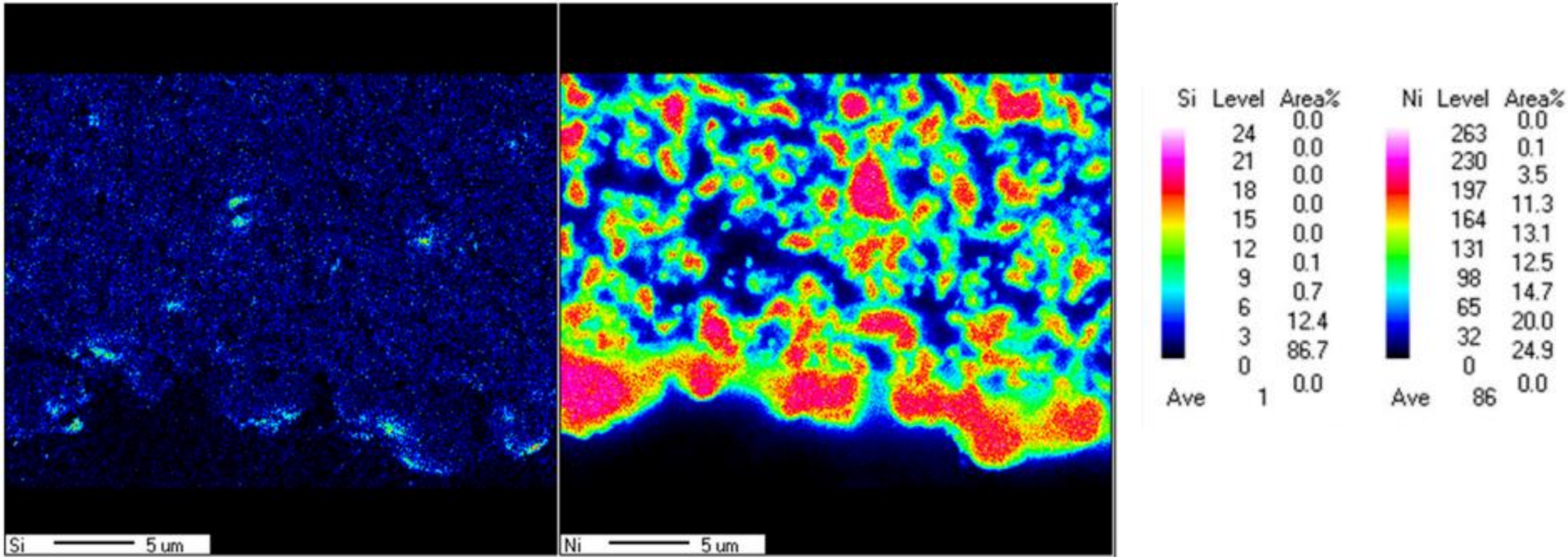
$$CO + O^{2-} \rightarrow CO_2 + 2e^-$$



$$O_2 + 4e^- \rightarrow 2O^{2-}$$

Siloxanes in Fuel Cells

Si and Ni distribution in the anode from EDS.

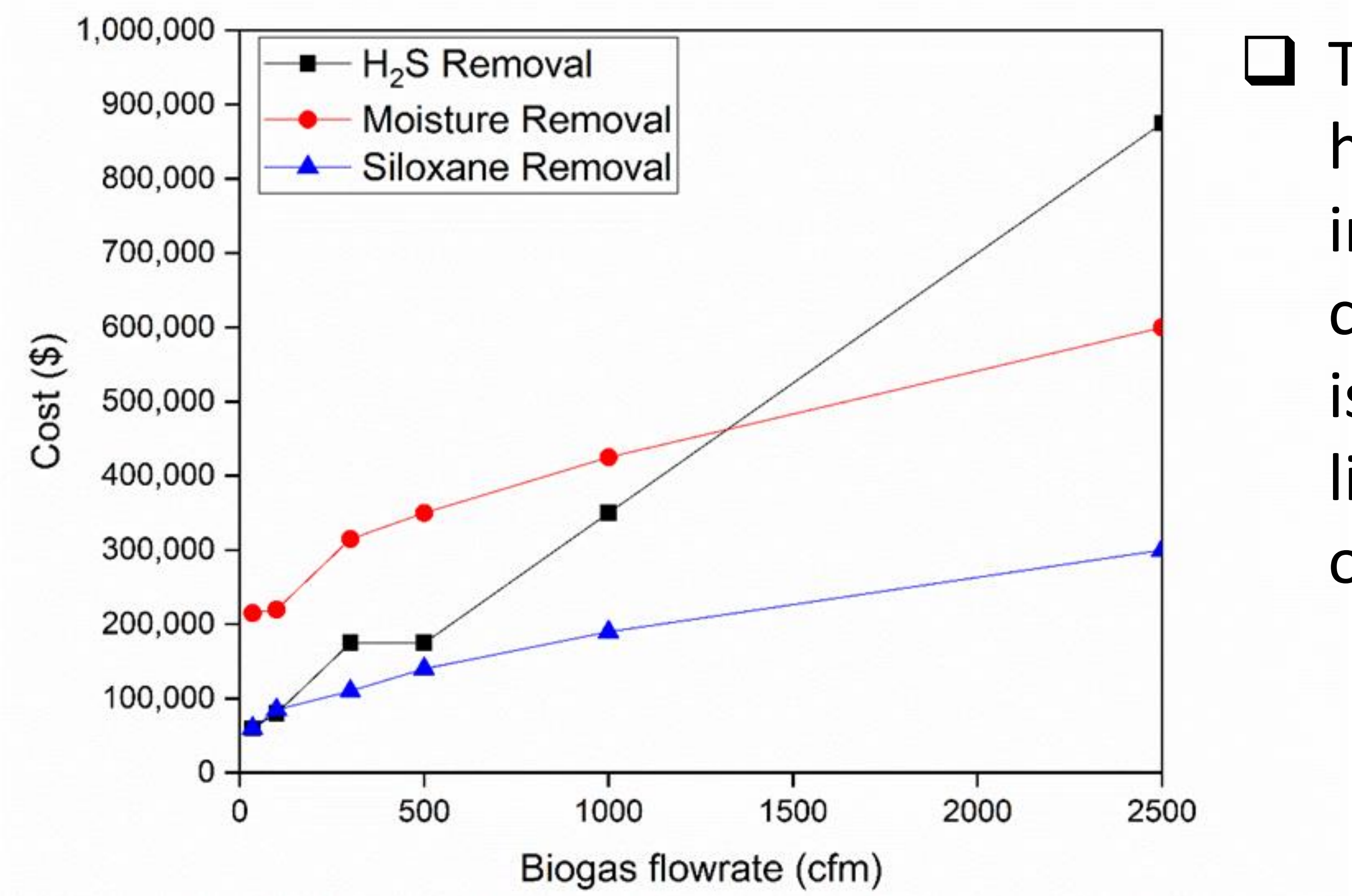


H. Madi, et al., J. Power Sources. 279 (2015) 460–471.

Tolerance to Biogas Impurities

CHP Prime Mover Tolerance to Biogas Contaminants						
Characteristic	Prime Mover					
	Steam Turbine	Gas Turbine	Micro-turbine	Reciprocating IC Engine	Fuel Cell	Stirling Engine
Hydrogen sulfide, H_2S	< 1,000 ppm	< 10,000 ppm	< 10,000 ppm	< 100 ppm	< 1 ppm	< 1,000 ppm
Silicon compounds	< 1 ppm	< 1 ppm	< 1 ppm	<100 ppm	< 1 ppm	< 1 ppm

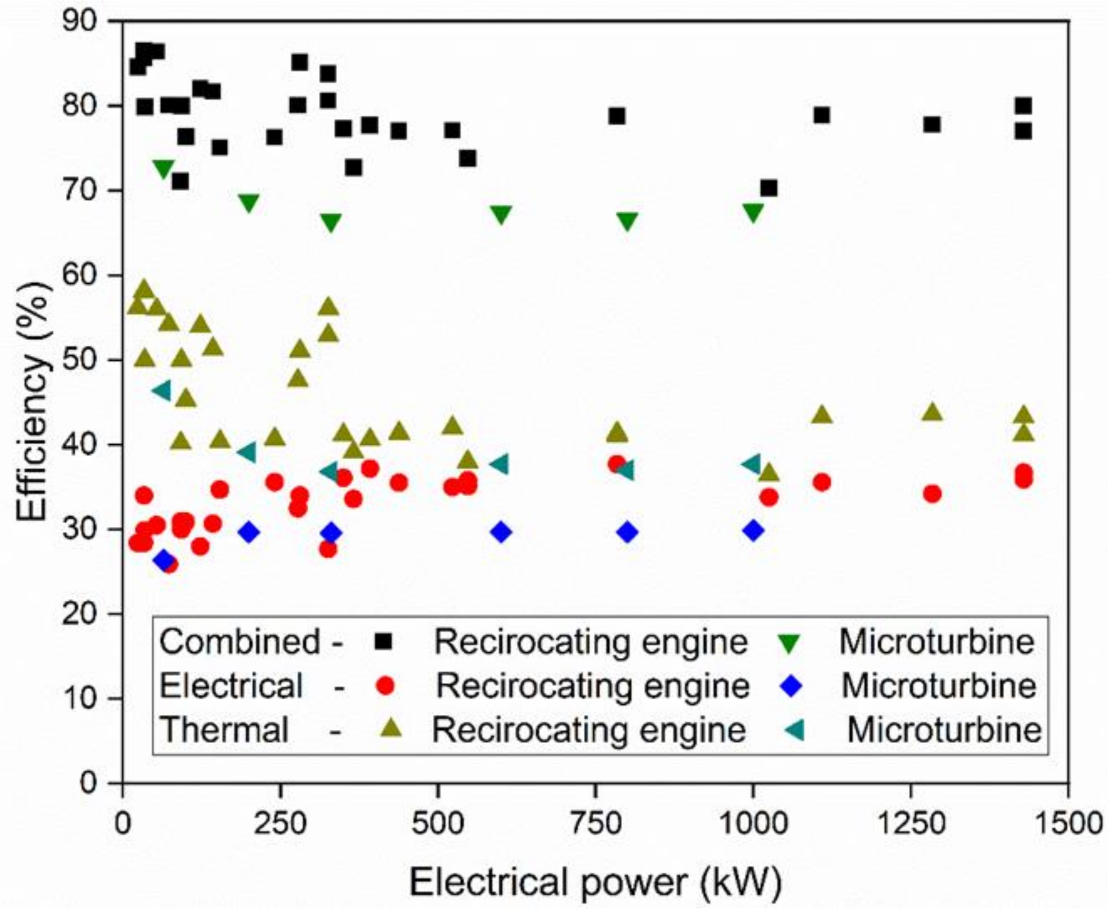
Cost of Impurity removal



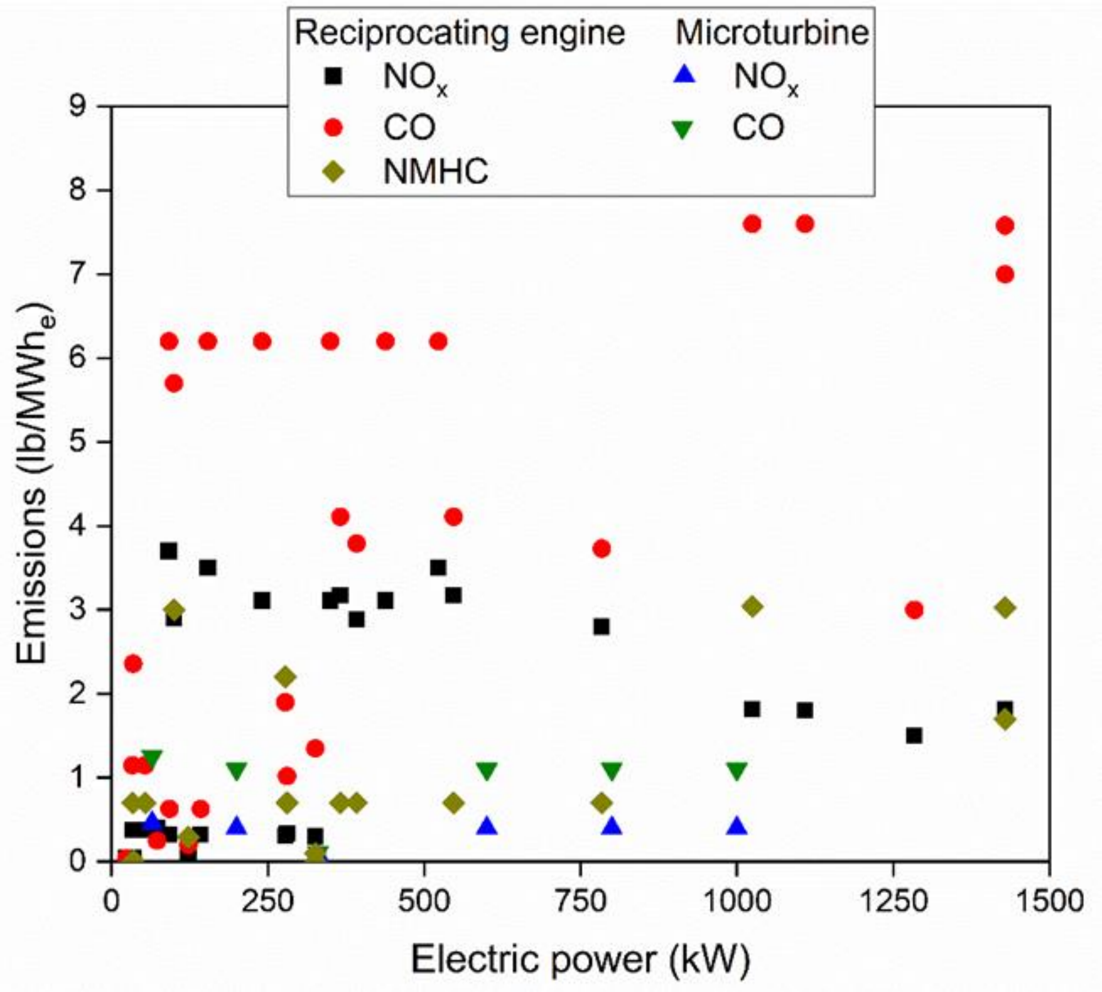
Typical cost of H_2S, water and siloxane removal systems for reciprocating engine CHP.

- The prime mover can handle a small amount of impurities, but if the concentration of impurities is uncontrolled, the CHP lifetime can be reduced to only a few years!

Current Systems (https://chp.ecatalog.lbl.gov/search)



Electrical, thermal and combined efficiency



Emissions

Case Study WWTP – Sizing a CHP System

Inputs				
Utilities	UC	Electric Usage	0.05	\$/kWh
	DC	Electric Demand	15	\$/kW-mo
	NGC	Natural Gas	5	\$/MMBtu
Plant Information	OH	CHP Operating Hours	8,322	hr/yr
	DM	Thermal Demand Met	0.7	(out of 1)
Current Utility Usage	EU	Current Electric Usage	40,000,000	kWh/yr
	NG	Current Natural Gas	25,000	MMBtu/yr
	DG	Digester Gas Produced	100,000	MMBtu/yr
Implementation Costs	CC	Raw Capital Cost	2,500	\$/kW
	OC	Operation Cost	0.02	\$/kWh
Efficiencies	EF_B	Boiler Efficiency	0.80	(out of 1)
	EF_T	Thermal Efficiency	0.40	(out of 1)
	EF_E	Electric Efficiency	0.35	(out of 1)
Constants	C_1	Conversion Constant	293.07	kWh/MMBtu

Case Study WWTP - Calculations

Efficiency Losses (EF_L)
$EF_L = 1 - EF_T - EF_E$
$EF_L = 0.25$

Current Plant Thermal Demand (TD)
$TD = NG \times EF_B$
$TD = 16{,}000\ MMBtu/yr$

Boiler Thermal Load (BTL)
$BTL = TD \times (1 - DM)$
$BTL = 4{,}800\ MMBtu/yr$

CHP Fuel Consumption (CF)
$CF = DM \times TD / EF_L$
$CF = 44{,}800\ MMBtu/yr$

Boiler Fuel Consumption (BF)
$BF = BTL / EF_B$
$BF = 6{,}000\ MMBtu/yr$

CHP Electric Output (EO)
$EO = E_{in} \times EF_E$
$EO = 553\ kW$

CHP Energy Input (E_{in})
$E_{in} = CF \times C_1 / OH$
$E_{in} = 1{,}578\ kW$

Total Fuel Consumption (TF)
$TF = BF + CF$
$TF = 50{,}800\ MMBtu/yr$

Electric Usage Savings (US)
$US = EO \times OH$
$US = 4{,}602{,}066\ kWh/yr$

Natural Gas Savings (NGS)
$NGS = NG - (TF - DG)$*
$NGS = 19{,}200\ MMBtu/yr$

Electric Usage Cost Savings (UCS)
$UCS = US \times UC$
$UCS = \$230{,}103/yr$

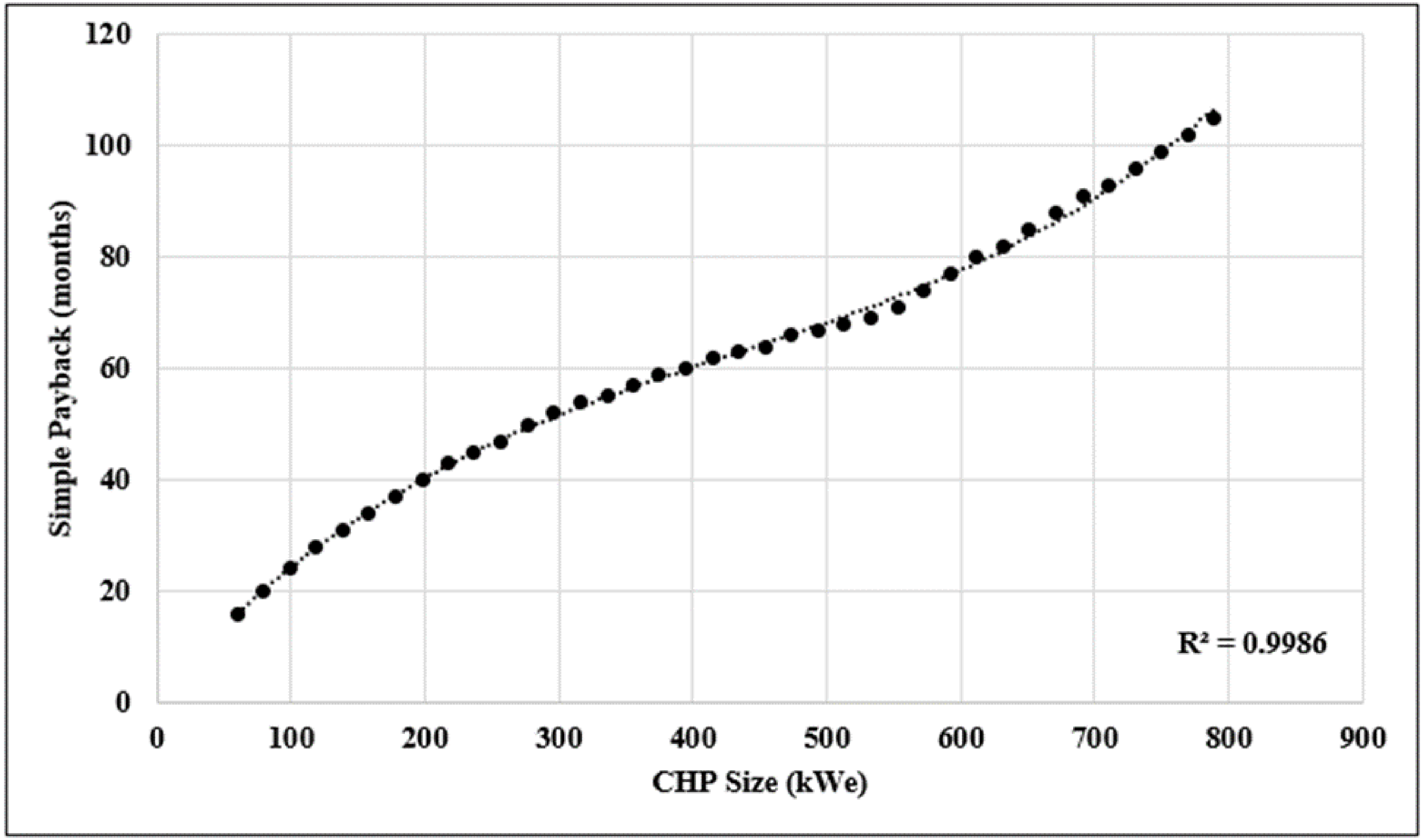
Added Operation Costs (AOC)
$AOC = EO \times OC \times OH$
$AOC = \$92{,}041/yr$

Natural Gas Cost Savings $(NGCS)$
$NGCS = NGS \times NGC$
$NGCS = \$96{,}000/yr$

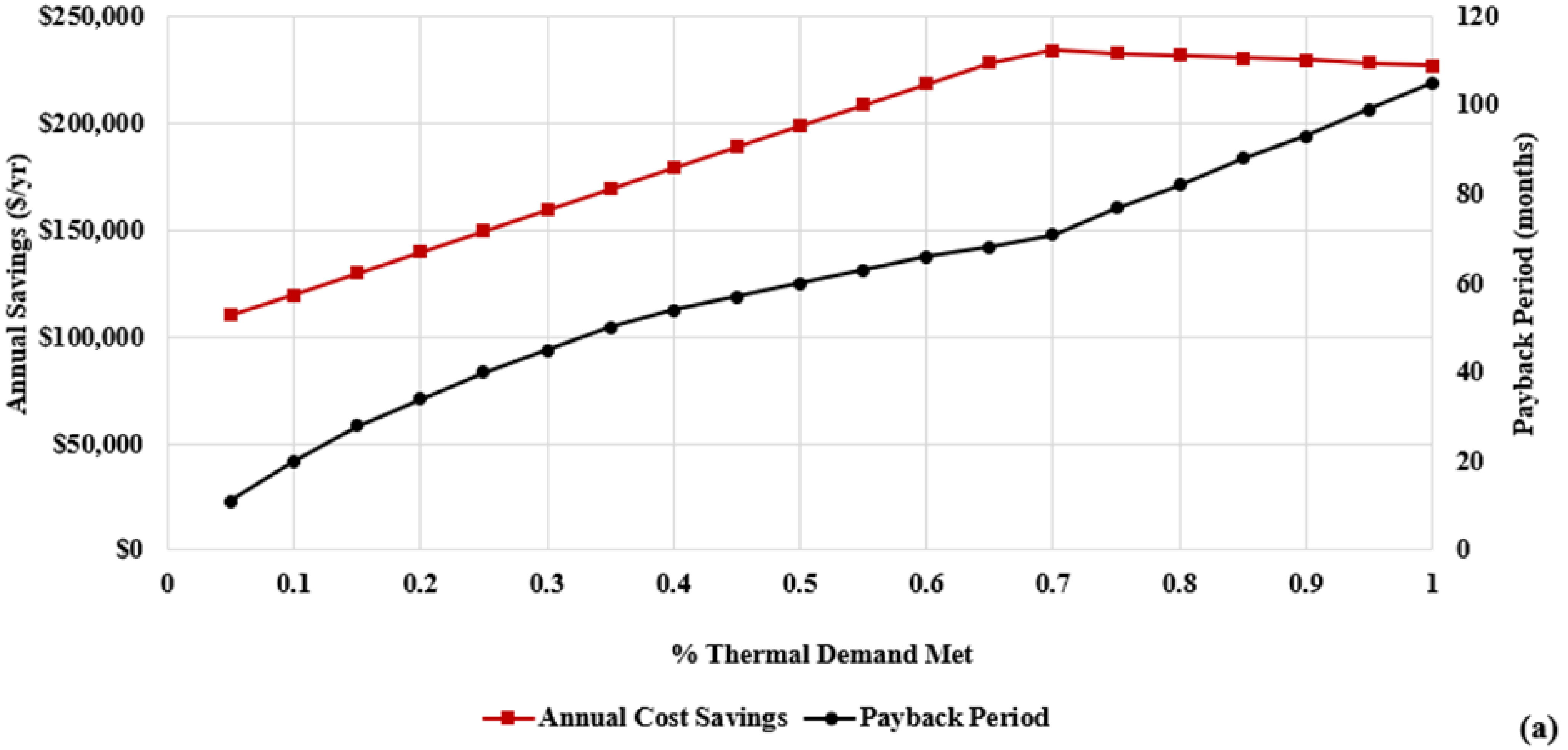
Total Cost Savings (TCS)
$TCS = NGCS + UCS - AOC$
$UCS = \$234{,}062/yr$

*(TF-DG) only utilized if TF is greater or equal to DG; if TF is less than DG, assume TF – DG = 0

Case Study WWTP - Results



Case Study WWTP - Results



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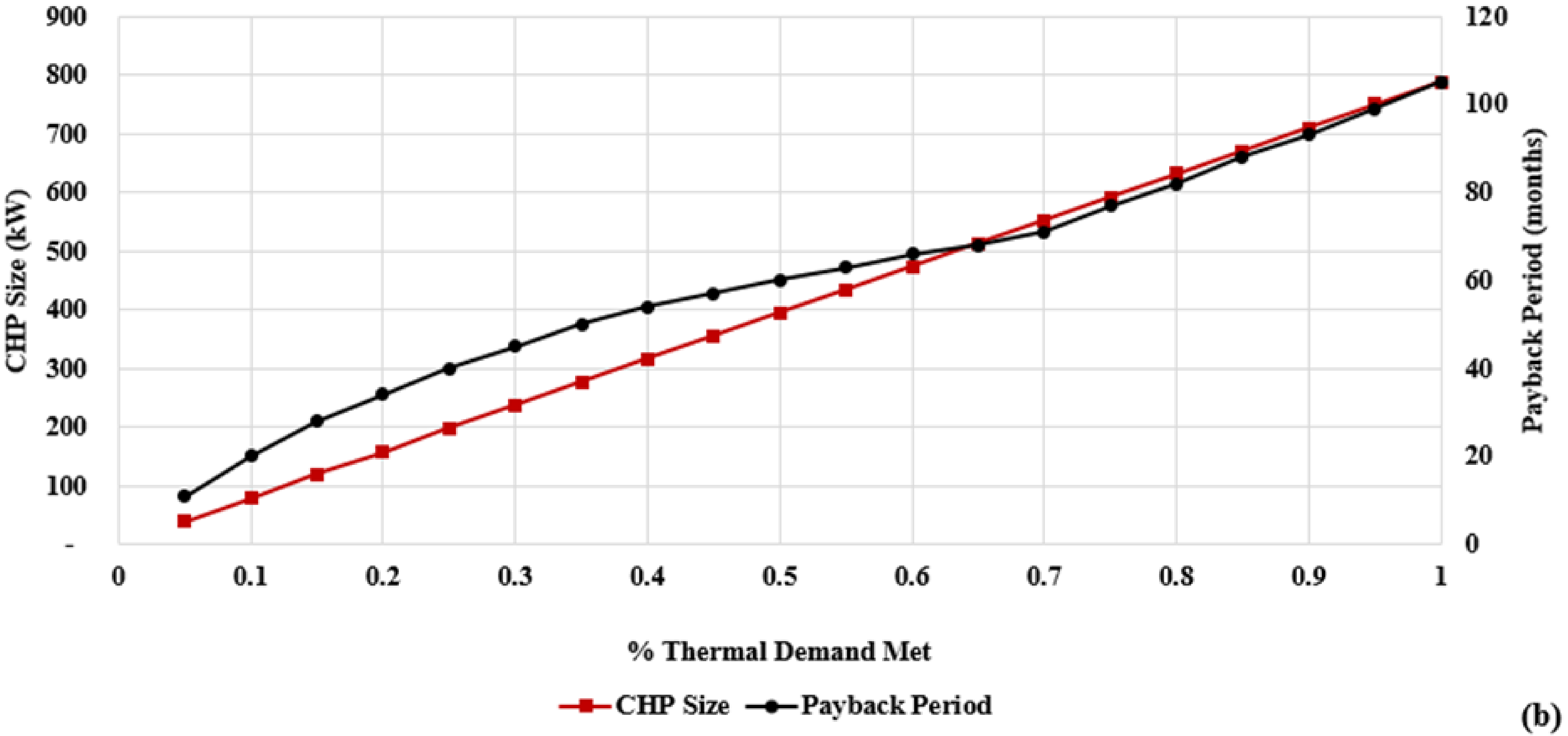

Conclusions

- IAC@ASU helps industrial or municipal WTPs and WWTPs as well as small- and medium-sized manufacturers increase their energy efficiencies and reduce their energy costs by having no-cost technical assessments.
- The Center makes recommendation in various areas, an example of which is presented in this article.
- The tool developed by the Center shows that optimal energy savings and payback period are a balance between the biogas produced and additional natural gas needed.

Acknowledgement

- This material is based upon work supported by the U.S. Department of Energy under award number DE-EE0007721.

Industrial Assessment Center

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Schedule An Assessment

We're always looking for new clients!

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