Advanced Biogas Processes applied in Fuel Cell Systems

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Workshop
Hydrogen and Fuel Cells in a future sustainable Energy-system

31.3.-01.05.2004 Vienna

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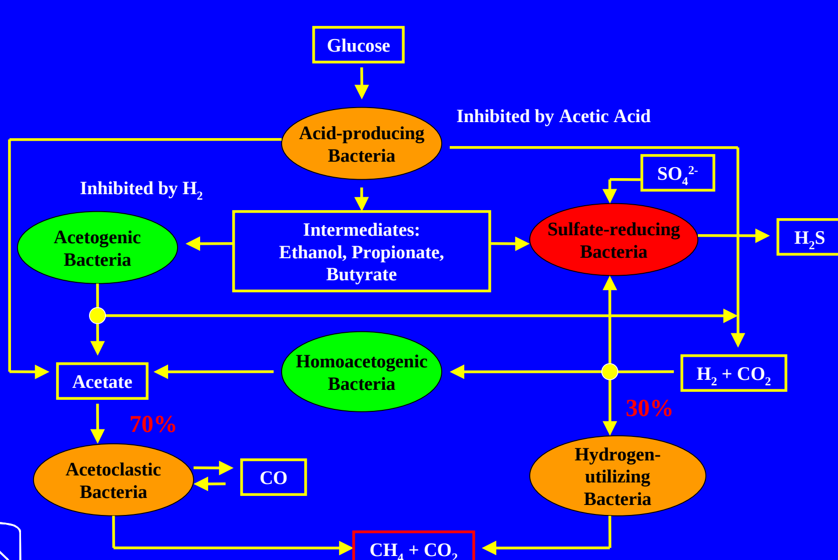
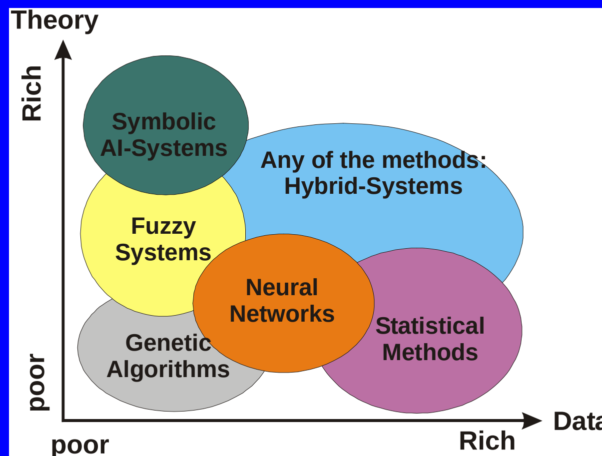
Why Monitoring and Control?

- Proper monitoring and control can prevent the transformation of a minor operational problem into a major disaster.
- As hydraulic- and organic loading rates are pushed upwards in order to reduce the size of the reactor, monitoring and control become more critical to avoid plant failure.
- Instrumental process monitoring and control are small prizes to be paid for higher loading rates, lower alkalinity costs and smaller reactor volumes. Such investments can yield very favorable paybacks.
- Monitoring and control can increase the biogas-yield in AD and improve the waste water treatments plant's overall energy balance.

Black Box Anaerobic Digestion

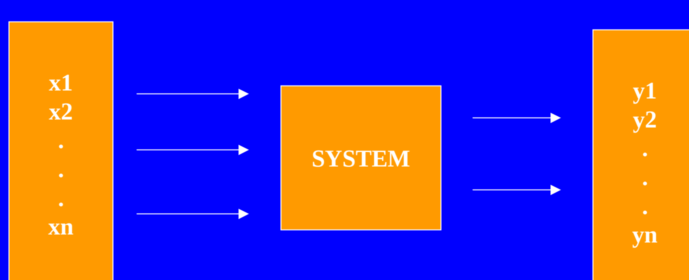


Use of Neural Networks



Neural Networks are

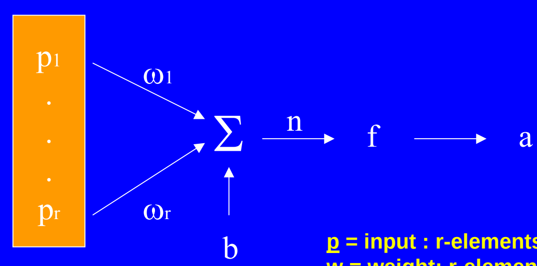
•mathematical models inspired by biological nervous systems.
•composed of simple interconnected elements operating in parallel.
•basically a method for handling multivariate - multiresponse data.



Single-Neuron Model

Vector input

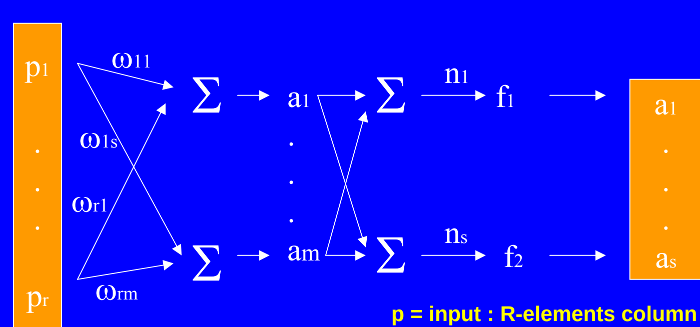
$a = f(\underline{w}\ x\ \underline{p} + b)$



$\underline{p}$ = input : r-elements column vector
w = weight: r-elements row vector
b= bias
n = net input to the transfer function =$\underline{wp}$ + b
f = transfer function
a = output (scalar)

Multi-Neuron Model

Multiple layers of neurons



p = input : R-elements column vector
wij = weights: S x R matrix
b= bias: S-elements column vector
n = W x p + b
f = transfer functions
a = output: S-elements vector

Neuronal Network

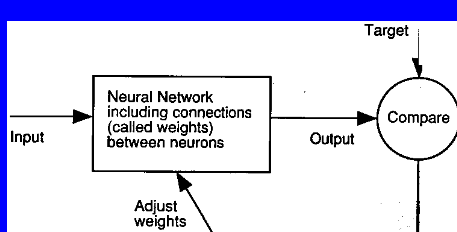
- A neural network consists of several calculator units
- Each unit is called neuron

$$pH_t \xrightarrow{\omega_1} \Sigma, \quad VFA_t \xrightarrow{\omega_2} \Sigma, \quad CSB_t \xrightarrow{\omega_3} \Sigma$$

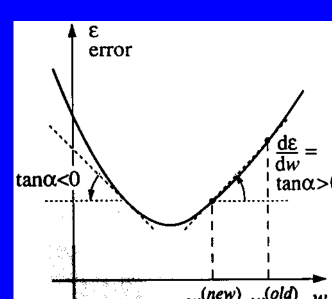
$$\Sigma \longrightarrow f \longrightarrow \text{Biogas}_{t+1}$$

$$\text{Biogas}_{t+1} = f(\omega_1 pH_t + \omega_2 VFA_t + \omega_3 CSB_t)$$

Feed Forward Back-propagation Network

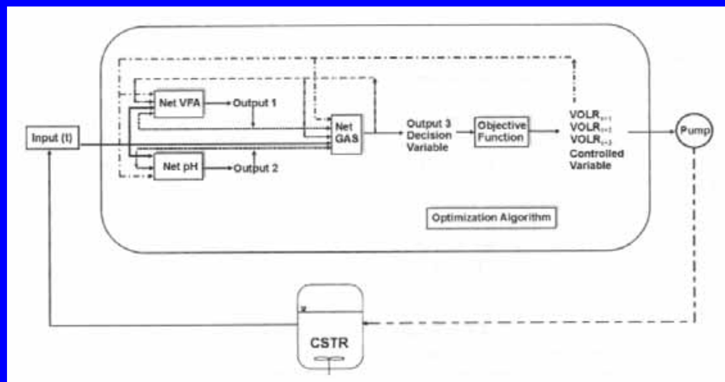


Learning due to adjustment of weights

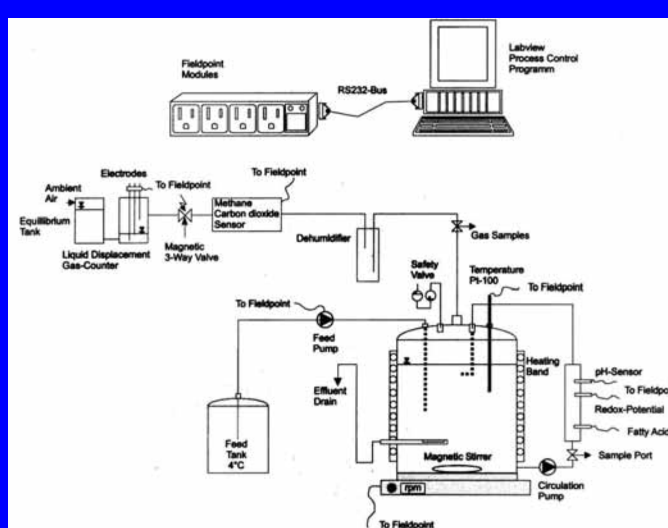


Adjustment of weights to search for a minimum in the error-function

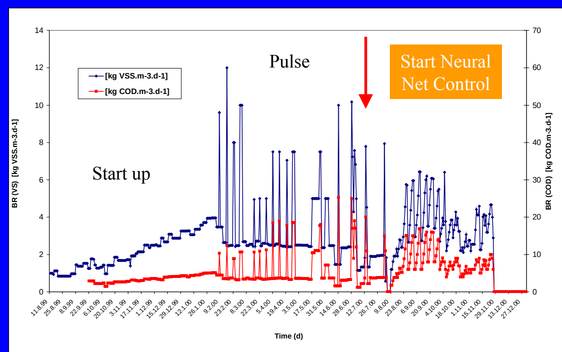
Neural Network-based Decision Support System



Lab-scale anaerobic CSTR

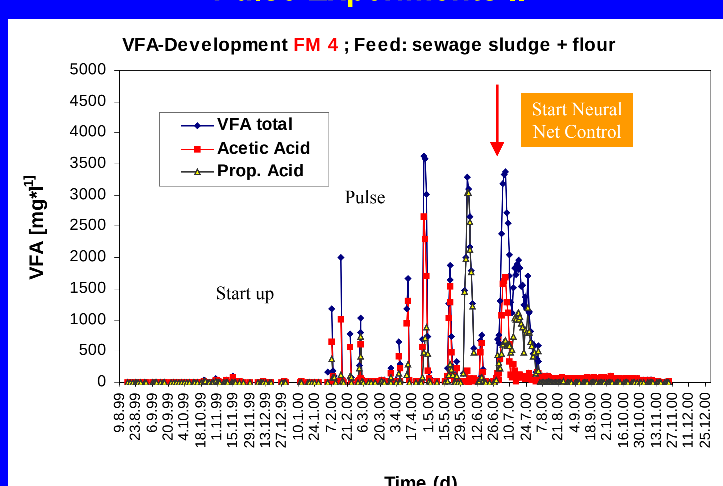


Pulse Experiments I



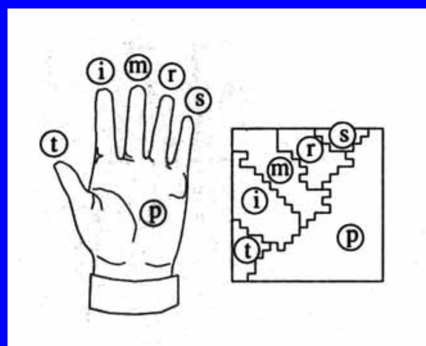
Organic Loading Rate

Pulse Experiments II



Volatile Fatty Acids

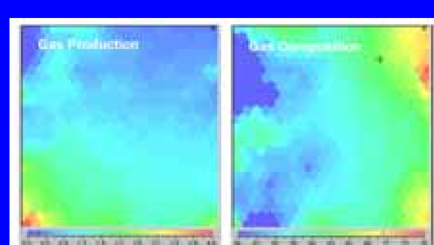
Kohonen SOMs - Self Organizing Maps



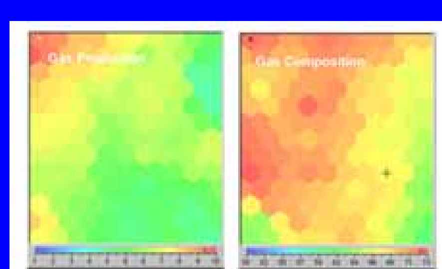
Transformation of n-dimensional data sets into a 2-dimensional map.

Visualization of Operational Space

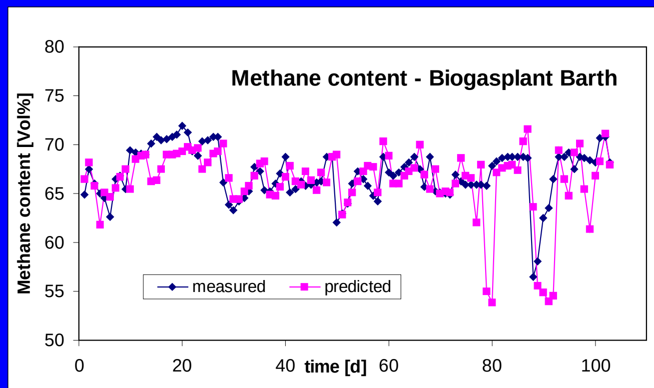
Without NN-control



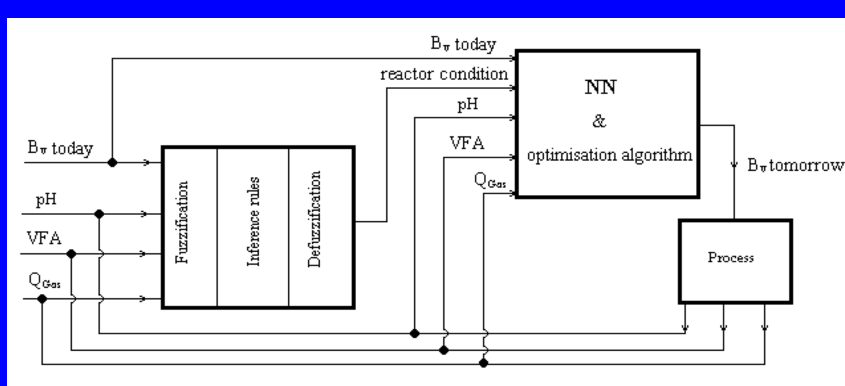
With NN-control



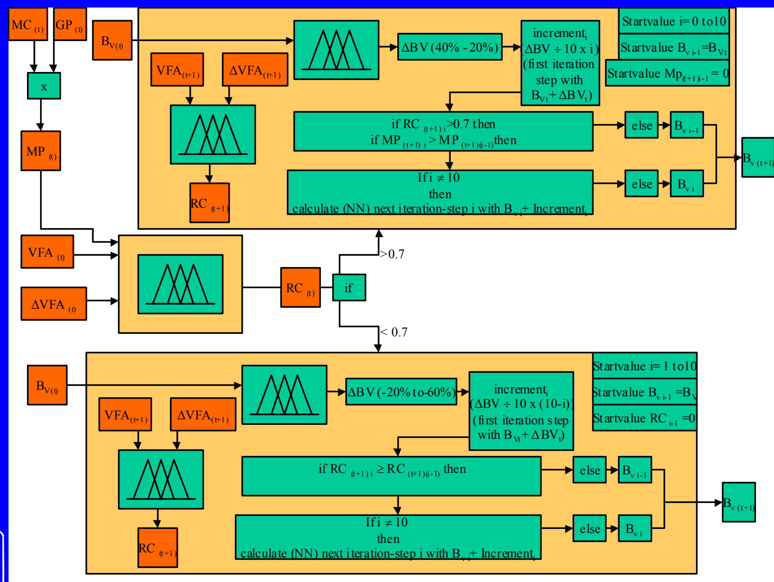
Test of Tool on Biogas-plants



Fuzzy Control - reactor condition parameter

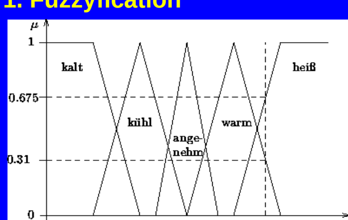


Fuzzy Control - reactor condition parameter



Fuzzy Logic

1. Fuzzyfication



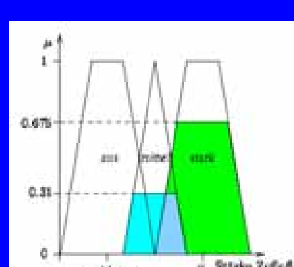
2. Inference-Rules

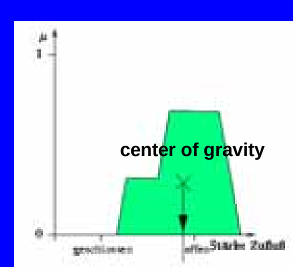
1. *IF temperature = „hot",*
   THEN cold water flow= "high"
   AND warm water flow = "off"

2. *IF temperature = „warm",*
   THEN cold water flow ="medium"
   AND warm water flow = "off"

3. Defuzzyfication

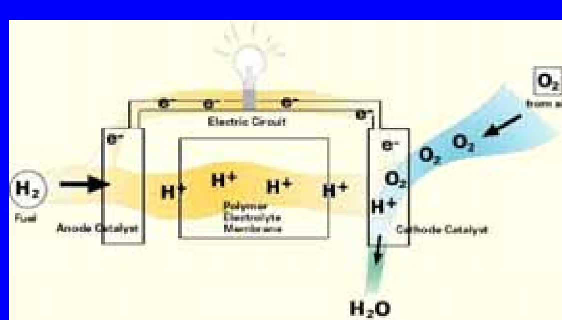
Cold water





The Problem of Trace Gases

Use of Biogas in Fuel Cells



Fuel Cell - Effect of Trace Gases

Fuel cell	PEFC	PAFC	MCFC	SOFC
Operating T. (°C)	70-90	160-210	600-700	800-1000
H2	Fuel	Fuel	Fuel	Fuel
CO2	Dilutent	Dilutent	Re-circulated	Dilutent
CO	Toxic	Toxic	With water shifted to H2	With water shifted to H2
C2-C6		Toxic	Fuel, plugging & coking	Fuel, plugging & coking
Sulfur		Toxic	Toxic (< 1 ppm H2S)	Toxic (1 ppm H2S)
NH3		Toxic	Fuel or inert?	Fuel (< 5000 ppm)
Halogens		Toxic	Toxic (< 0,1-1 ppm)	Toxic (1 ppm)
Alkali metals			Electrolyte loss (1–10 ppm)	

Modeling Sulfate-Reduction by ADM1 Parameters

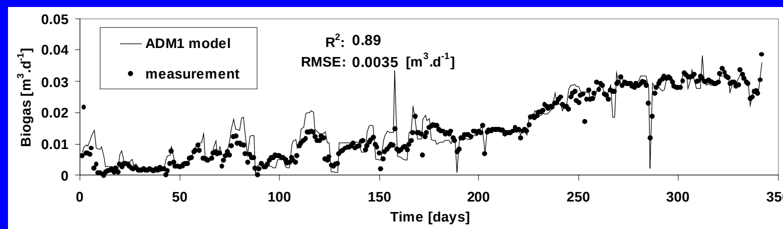
4 types of metabolic reactions (X5-X8)

ρ20 X_5:	$C_3H_7COOH + 0.5\ SO_4^{2-} \rightarrow 2\ CH_3COOH + 0.5\ S^{2-}$ 100% butyrate COD → 80% acetic COD + 20% sulfide COD
ρ21 X_6:	$C_2H_5COOH + 0.75\ SO_4^{2-} \rightarrow CH_3COOH + CO_2 + H_2O + 0.75\ S^{2-}$ 100% propionate COD → 57% acetate COD + 43% sulfide COD
ρ22 X_7:	$CH_3COOH + SO_4^{2-} \rightarrow 2\ CO_2 + 2\ H_2O + S^{2-}$ 100% acetate COD → 100% sulfide COD
ρ23 X_8:	$4\ H_2 + SO_4^{2-} \rightarrow S^{2-} + 4\ H_2O$ 100% hydrogen COD → 100% sulfide COD

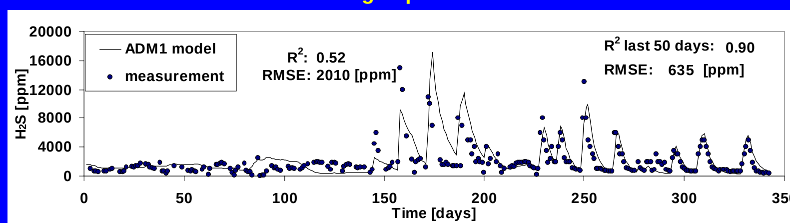
Parameter	Value	Range from literature*
k_{m_ac} ($COD.COD^{-1}.d.^{-1}$)	35	0.14 – 52[1]
K_{S_ac} (kg $COD.m^{-3}$)	0.03	0.011 – 0.93[1]
Y_{X5} ($COD.COD^{-1}$)	0.12	0.0329[2]
Y_{X6} ($COD.COD^{-1}$)	0.12	0.0329[2]
Y_{X7} ($COD.COD^{-1}$)	0.12	0.0342[2]
Y_{X8} ($COD.COD^{-1}$)	0.12	0.0366 $(COD.COD^{-1})^2$ – 13 (g cell mat.mol H_2^{-1})[3]
K_{H_h2s} ($M.bar^{-1}$)	0.04	0.0952[4] Can differ a factor 2 or 3[5]

(1) Batstone et al., 2002; (2) Fedorovich et al., 2003; (3) Badziong and Thauer, 1978; (4) Stumm and Morgan, 1996; (5) Mackay and Shiu, 1981

Modeling Sulfate-Reduction by ADM1

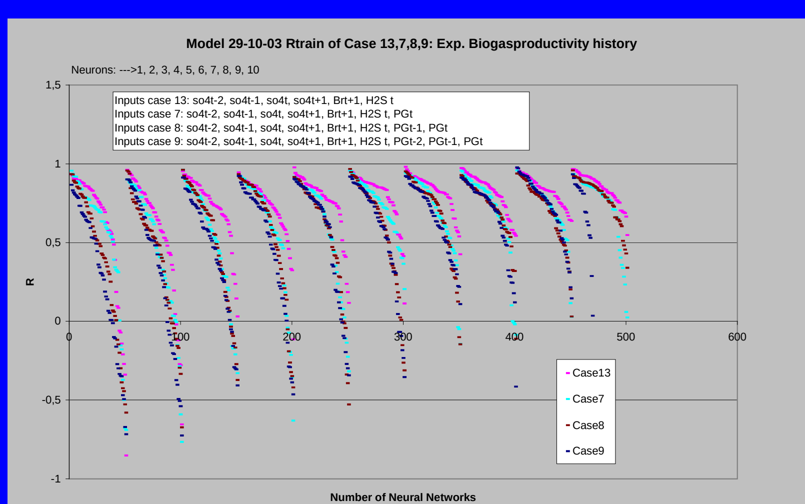


biogas-production



hydrogen sulfide-production

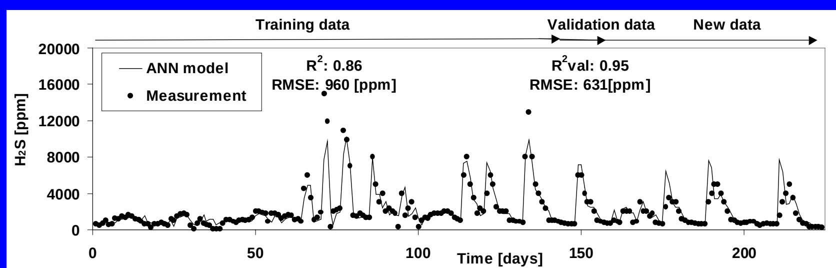
Finding the best Neural Network



Modeling Sulfate-Reduction by Neural Networks

Inputs	Hidden layer	Output
1. Sulfate loading rate t+1[g SO_4-S.m^{-3}.d^{-1}]	Six neurons	1. Hydrogen sulfide t+1 [ppm]
2. Sulfate loading rate t [g SO_4-S.m^{-3}.d^{-1}]		
3. Sulfate loading rate t-1 [g SO_4-S.m^{-3}.d^{-1}]		
4. Sulfate loading rate t-2 [g SO_4-S.m^{-3}.d^{-1}]		
5. Organic loading rate t+1[kg COD.m^{-3}.d^{-1}]		
6. Hydrogen sulfide t [ppm]		

hydrogen sulfide-production



Financial Balance of Monitoring & Control of AD

Basic assumption				
Reactor volume	300 m³			
Investment expenses	200 €·m^{-3}			
Operation expenses	18.000 €	(includes depreciation, insurance, servicing,		wages, energy cost)
Energy content of biogas	6 kWh·m^{-3}			
Electricity output	1.92 kWh$_{el}$·m^{-3}			
Market price electricity	16 Cent·kWh^{-1}			
Revenues				
Monitoring		No	VFA (Lange)	external laboratory
Control		minimal	optimized	Optimized
Biogas yield	m^3·m$^{-3}_{reactor}$·d^{-1}	1.2	2.5	2.5
Biogas yield	m^3·a^{-1}	131.400	273.750	273.750
Energy content	kWh·a^{-1}	788.400	1.642.500	1.642.500
Electricity output	kWh$_{el}$·a^{-1}	252.288	525.600	525.600
Sales revenues	€·a^{-1}	40.366	84.096	84.096
Costs				
Working hours	h·d^{-1}	-	0.6	0.5
Person hours	h·a^{-1}	-	219	182
Wages (15 €·h^{-1})	€·a^{-1}	-	3.285	2.730
Consumables	€·a^{-1}	-	3.281	20.440
Depreciation for lab- equipment	€·a^{-1}	-	1.335	750
Σ Operation expenses	€·a^{-1}	18.000	18.000	18.000
Σ costs per year	€·a^{-1}	18.000	25.900	41.920
Profit & loss account	**€·a^{-1}**	**22.366**	**58.196**	**42.176**

“When you think that everything is under control, you don't drive fast enough.”

Alain Prost

Thank you for your attention.