International Water Association

On the way to an energy producing nutrient removal WWT plant

Presentation at

Tokyo University

July 16, 2015

Prof. Helmut Kroiss, IWA President
Vienna University of Technology

Where I come from

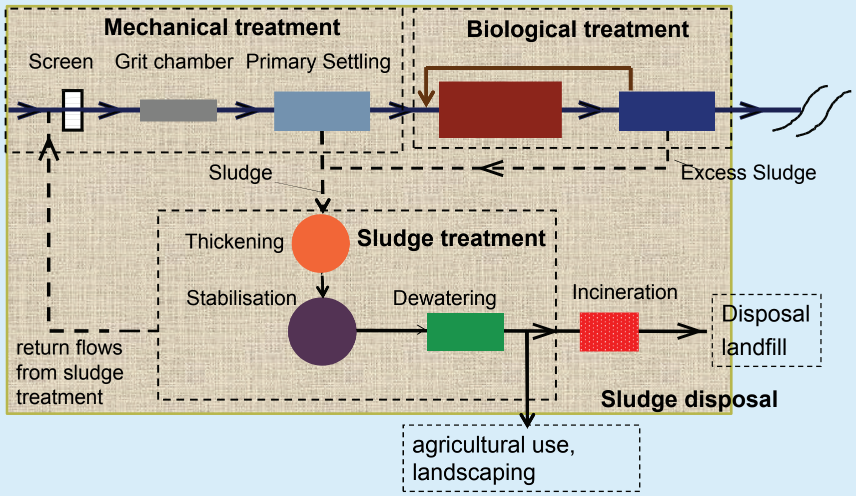
Relevant "primary" power data in kW per inhabitant

Global Solar power	~10,000
Global primary power input	3
EU primary power input	6
Municpal Waste water treatment	<0.02
Waste water pollution	~0.04

Important basics for this presentation

- "Efficient waste water treatment" (AS)
  - ⇨Full nitrification at any time (NH4-N < 5 mg/l)
  - ⇨COD removal >90 % (BOD $_5$ effluent <10 mg/l)
  - ⇨Phosphorus removal > 85%
  - ⇨Nitrogen removal >75%
- Why:
  - ⇨No oxygen removal from receiving water
  - ⇨Most of micro-pollutants are removed
  - ⇨Eutrophication abatement (P and N)
  - ⇨P resource recovery
  - ⇨Minimisation of energy requirement (N)

Conventional waste water treatment plant configuration


Mechanical treatment
Screen
Grit chamber
Primary Settling
Biological treatment
Sludge
Excess Sludge
Thickening
Sludge treatment
Stabilisation
Dewatering
Incineration
Disposal
landfill
return flows
from sludge
treatment
Sludge disposal
agricultural use,
landscaping

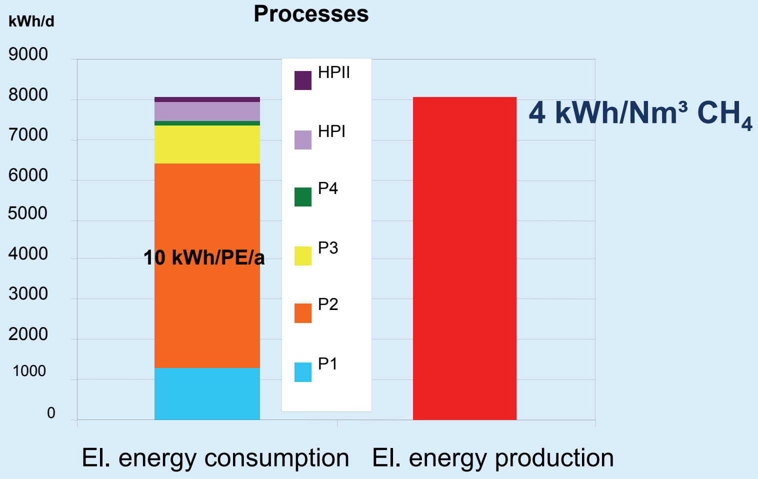
Austrian process benchmarking results

Stefan Lindtner Consultant
Austrian Water and Waste Association
http://www.abwasserbenchmarking.at

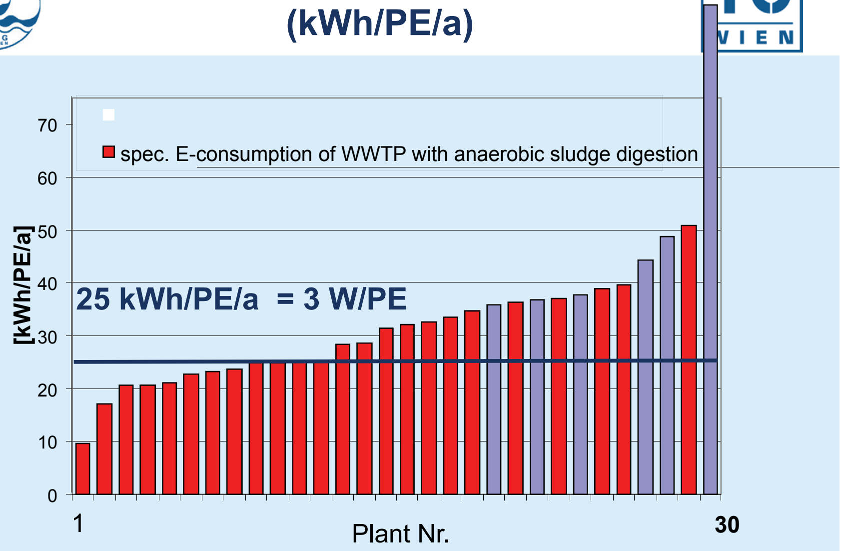
- 4 main processes without influent pumping
  - ⇨ pretreatment (screening, grit)
  - ⇨ mechanical-biological treatment
  - ⇨ sludge thickening, stabilisation
  - ⇨ Sludge dewatering, disposal
- 2 support processes (monitoring, other)
- All costs are related to 1 PE_{COD}
- Data quality assessment by mass balances for COD, P
- Process indicators for energy efficiency

Benchmarking result
1st energy self-sufficient WWTP

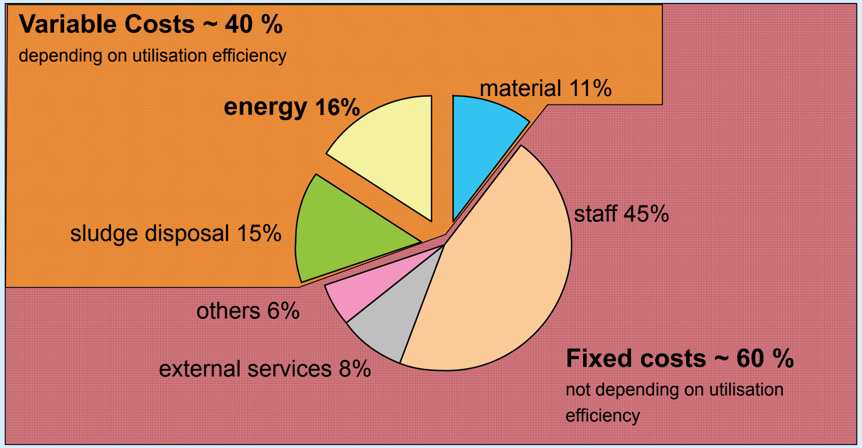
170.000 PE



Electric energy consumption (kWh/PE/a)



Distribution of operational costs



Benchmarking results

- Energy demand of most of the large plants: 20 to 30 kWh/PE/year (~3W/PE)
- Aeration: 60 to 70 %
- Energy costs 15 to 17 % of operating costs
  - ⇨Other cost factors: staff, sludge handling and disposal, monitoring
- Capital costs similar to operating costs
- Total costs 20 to 30 €/PE/a
- Actual energy costs 1.5 to 2 €/PE (1€ = 136 Yen)

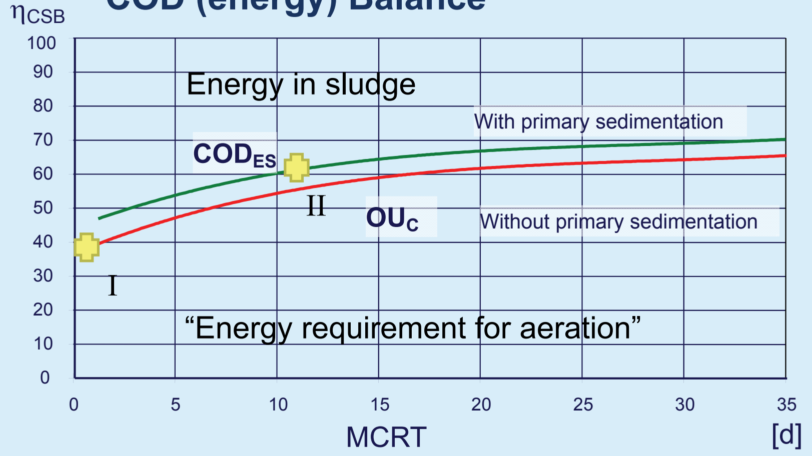
On which scientific background can we rely?

Important basics for this presentation

- COD allows mass and energy balances for organic waste water pollution and sludge treatment processes (1. law if TD)
- **Energy data are related to the yearly mean COD load of raw WW influent after grit removal expressed as**
- **PE = 120 g COD/d (60g BOD_5/d)**

- **1 kg COD corresponds to ~14 MJ (MWs) 120*14/86.4 = 19 W/PE**

Hard facts WWT
COD (energy) Balance



Sum of OU$_C$ und COD$_{ES}$ = COD load removed

Hard facts nitrification, N-removal

- 1 g N removed as N_2 = 1.7 g O_2 (DN, DA) OUDN
- 1 g NO_3-N in effluent = 4.6 g O_2 OUN
- $TN_{in} - TN_{effl} - TN_{sludge} = N_{removed}$

Hard facts sludge digestion

- COD (PS + ES) – COD (digested sludge) [kg/d]= COD of CH_4
- 1 kg COD = 350 Nm³ Methane (CH_4) (Biogas)
- TN (PS+ES) – TN (dewatered sludge) = TN (reject water)

Vienna: EOS-Project

A new process scheme for waste water treatment with 8 years of full scale operational data and 1 year of on site pilot scale investigations

The Vienna Main Treatment Plant

EOS-Project start of operation 2020)

Extension to energy producing operation,
start of full scale operation in 2020

Vienna Main treatment Plant 1980
raw sludge incineration 3 Mio PE

Actual situation

Vienna Main Treatment Plant 2005

Designed for

4 Mio PE (240 t BOD_5/d)

Special 2-stage activated sludge process with primary sedimentation for nutrient removal

raw sludge incineration with ash disposal

Vienna Main treatment Plant 2005
raw sludge incineration (4 Mio PE)

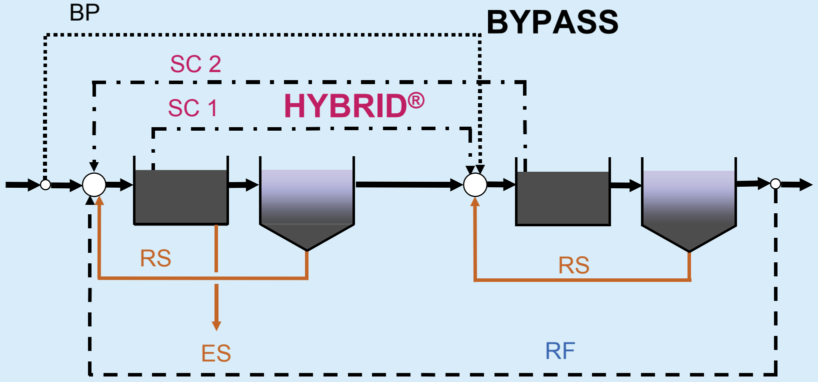
- Specific local situation:
  - ⇨Temperature range from 10 to 23 °C (mean ~15°C)
  - ⇨Combined sewer system
  - ⇨Influent COD 650 mg/l
  - ⇨Max. RW flow 18 m^3/s (design flow)
  - ⇨Max. dry weather flow actually 7 m^3/s
  - ⇨Mean yearly precipitation 550 mm

MTPV 2. stage 2005
Characteristic data 4 Mio PE

- Treatment efficiency requirements: >75%N rem.
  ⇨EU-UWWD Sensitive area, NH_4-N <5 mg/l, TP<1mg/l

	2-stage	1-stage
PST-Volume:	5 l/PE	5 l/PE
Aeration tank volume I:	10 l/PE	130 l/PE
SST-Volume I:	18 l/PE	
Aeration tank volume II:	42 l/PE	
SST-Volume II	51 l/PE	51 l/PE
Total	**126 l/PE**	**186 l/PE**

Process scheme of 2- stage biological treatment developed at TU Vienna



BP	Bypass line	***SC 1***	Sludge circulation line 1	**RS**	Return sludge
RF	Recirculation flow	**SC 2**	Sludge circulation line 2	**ES**	Excess sludge

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Assumptions for energy balance (based on full scale experience)

COD removal primary sedimentation:	30%
COD removal TP	92%
Aeration efficiency	2.0 kg O_2/kWh
COD of digested sludge	30 g/PE_{COD}
N-removal yearly mean	80%
N in sludge disposed	2 g N/PE
Gasmotors el. efficiency	4 kWh/Nm³ CH_4

Case 1: 1-stage ASP with PS + sludge digestion N/COD= 10/120

COD Influent (N-influent 10 g N/EW/d, 80% rem.))	120 g/PE/d
COD Effluent primary sed. (COD-removal PS = 30%)	84 g/PE/d
COD in primary sludge	36 g/PE/d
COD Effluent TP	10 g/PE/d
COD removal in aeration tank: 84 – 10 =	74 g/PE/d
OUC (60% of COD removed)	44g/PE/d
COD excess sludge (40% of COD removed)	30 g/PE/d
COD input digester: 36 + 30 =	66 g/PE/d
COD in digested sludge	30 g/PE/d
COD of digester gas production (CH4) 66 - 30 =	36 g/PE/d
OUN (denitrified N-load 6 g N/PE/d): (10-2-6.0)*4.6	9.2 g/PE/d
OUDN: 6.0*1,7 =	10,2 g/PE/d

Case 2: 2-stage ASP with PS sludge digestion N/COD = 10/120

COD influent (N influent 10 g N/PE/d, 80% rem.)	120 g/PE/d
COD effluent PS (COD removal by PS: 30%)	84 g/PE/d
COD of primary sludge	36 g/PE/d
COD effluent	10 g/PE/d
COD removal aeration tank 84 – 10 =	74 g/PE/d
OUC (40% 1.stage/ 60% 2.Stufe)	38g/PE/d
COD in excess sludge	36 g/PE/d
COD in digester feed: 36 + 36 =	72 g/PE/d
COD in digested sludge (N: 4 g/PE/d)	30 g/PE/d
COD in digester gas: 72 - 30 =	42 g/PE/d
OVN (nitrate in effluent 2g N/PE/d): (10-2-6) * 4,6	9.2 g/PE/d
OVDN: (4+2") * 1,7 =	10.2 g/PE/d

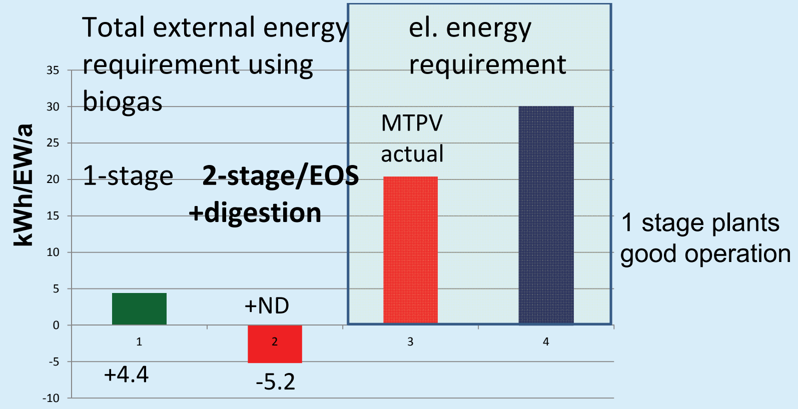
Aerobic denitrification of reject water (Anamox, Demon,….)

Energy balance comparison

	Dim	1-stage η_N= 80%	MTPV/EOS η_N= 75%	HKA actually
"aeration efficiency"	*kgO_2/kWh*	*2,0*	*2,0*	*Raw sludge*
η_{el} gasmotor	*%*	*38*	*38*	*Incinera-tion*
Power for aeration	W/EW	1,6	1,25	2,26 to 2,33
Other power requirements	W/EW	0,80	1,10	
Biogas el. power prod	W/EW	1,9	2,75	-
Total el. power requ.	**W/EW**	**+ 0,5**	**- 0,4**	**2,3**
El. Energy requ.	**kWh/EW/a**	**+ 4,4**	**- 3,5**	**20,4**

EOS Project (2020): MTPV with digestion, 83 % N-removal, reject water nitritation+Deni in AT 1

Energy requirements for nutrient removal plants in kWh/pe/a



DN reject water nitritation and denitritation in 1. stage AS

Energy balance

	Aeration energy		Other energy		Total energy	ηel Gas-motor 38% el. efficiency
	W/PE		W/PE		W/PE	W/PE
1-stage ASP N/COD =8/120	1.6	+	0.7	=	**2.3**	**1.9 W/PE**
2-stage ASP N/COD =8/120	1.2	+	0.9	=	**2.1**	**2.7 W/PE**

Power requirement production

EOS - project

- **Reconstruction of 1. stage PS +AS**
- Sludge Digestion with high solids concentration
- Reject water Nitritation-Denitritation
- Gas motors for electric energy production
- (Drying and Incineration of Digested sludge)
- (Recovery of Phosphorus from Ashes)

The plant remains connected to the public electric grid. Independent operation would markedly increase the investment costs.

Vienna main Treatment plant in 2020

Die Hauptkläranlage Wien im Jahr 2020. © LBS/OPEN Brand Design

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TECHNISCHE
UNIVERSITÄT
WIEN
Vienna University of Technology

Institut für
Wassergüte
Ressourcenmanagement
und Abfallwirtschaft

Project EOS Pilot investigations

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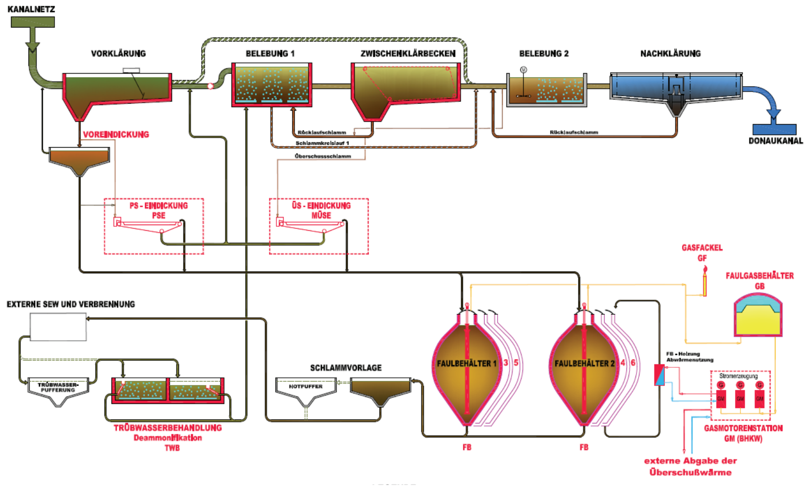
Project EOS: Introduction

2020 process scheme for Main Treatment Plant of Vienna



Projekt EOS: Pilot Investigations

- Questions to be answered
  - Digestion: design basis
    - Thickeing behavioour, polymer requirements
    - COD and oDS-removal, gasproduction, gas composition
    - Operatonal experience
    - Rheology: viscosity, mixing behavious, hydraulic losses
  - Reject water pretreatment: design basis
    - N-removal efficiency with real reject water
    - Process selection
    - Operational experience
- Pilot investigations
  - Pilot plant: Sludge digestor, reject water treatment plant
  - Field investigations: Rheology, hydraulic losses
  - Lab scale experiments: ammonia inhibition of digestion, reject water treatment, rheology

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Project EOS: Pilot Plant

- Digestion:
- Mechanical sludge thickeningl
- Reactor volume 130 m³
- Gas motor: 15 $kW_{electric}$

- Full scale: 70.000 m³

Project EOS: Pilot Plant

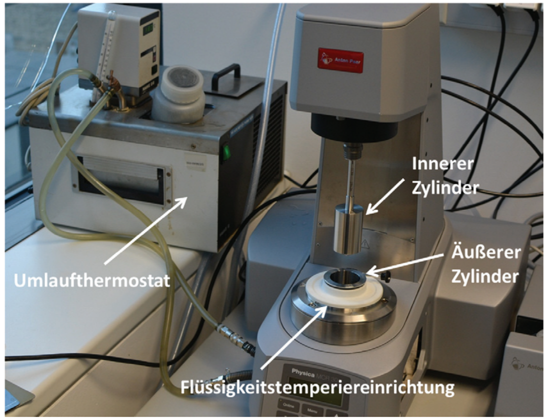
- Reject water treatment (pretreatment)
  - Sludge dewatering with screw press
  - 5 m³ buffer tank
  - 2 reactors 2 m³ each

Project EOS: Lab scale experiments

- Sludge digestion with high NH_3
- 3 Reactors 3 liters each
  - 35 to 40°C
  - Gas production: quality, quantity
  - Ammonia inhibition testing

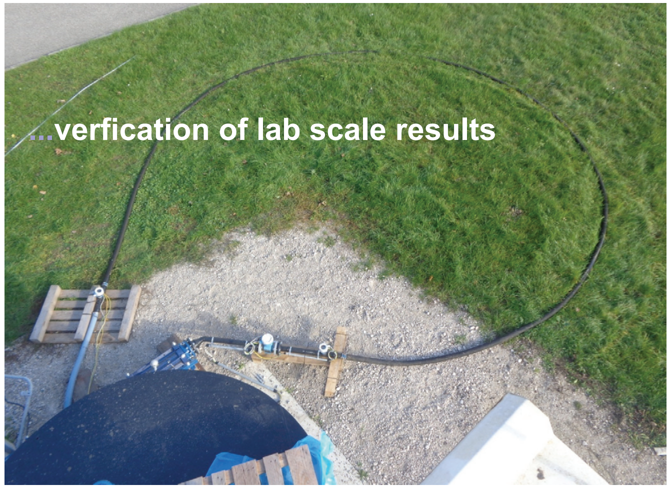
Project EOS: Rheology investigations

- Lab scale experiments:
- Rheological behaviour of:
  - Water
  - Thickened raw sludge
  - Digested sludge



Project EOS: Pilot scale investigations on rheology

- Rheological pipe investigations at pilot plant



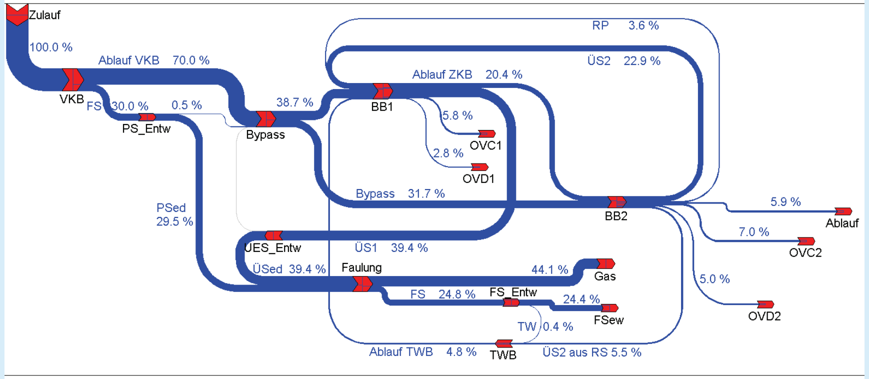
Results sludge digestion

Parameter	Unit	Standard-operation	max. loading	high loading	Limits for digestion:	
					max. loading	High temperature
Ø temperature	°C	38,0	37,9	37,5	37,2	**41,0**
MCRT	d	**24,2**	**19,8**	**17,3**	**11,5**	23,0
pH	-	7,52	7,37	7,38	7,33	7,42
Ø DS $_{\text{Digester}}$	kg/m³	40,65	38,63	43,02	44,73	43,71
Ø NH_4-N	mg/L	1.885	1.819	1.902	1.888	1.927
DS-removal	%	37,2	41,0	37,9	36,1	35,4
oDS removal	%	**50,5**	**52,7**	48,0	48,5	48,2
Ø oDS_{feed}	%	75,2	81,1	78,8	77,5	76,7
Ø oDS_{DS}	%	59,3	65,0	66,0	62,5	61,5
Ø CH_4 content	%	64,6	63,2	67,3	68,3	67,3
COD-removal	%	**59,4**	**59,3**	58,5	52,0	75,1
COD/oDS_{in}	-	1,88	1,82	1,84	1,84	1,88
COD/oDS_{out}	-	1,60	1,60	1,44	1,65	1,60

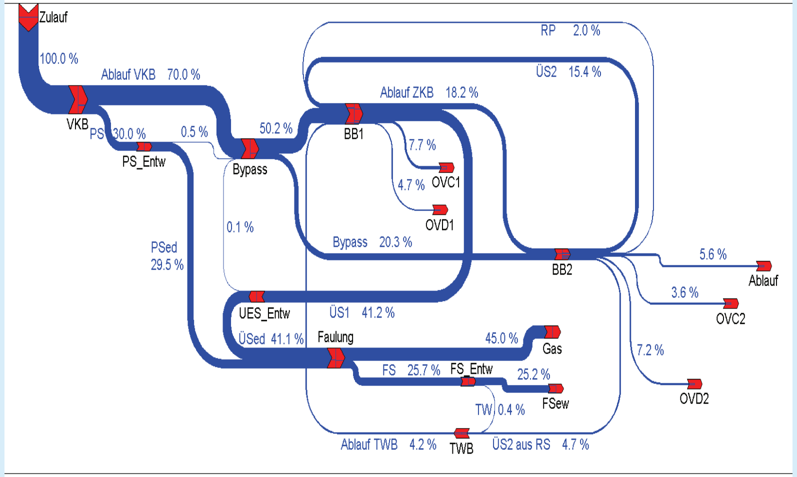
Simulation results for 2020

- **Data basis**: mean daily loading conditions for 365 days (COD, TN, TP influent and effluent, T, DS_{AT}, PS- and ES prod.) from the full scale plant (last 5 years data)
- **Modelling tool:** Site specific linked dynamic model for the 2-stage AS plant, sludge digestion, reject water treatment adapted to the data from full scale operation and pilot investigation data (basis: ASM 1, ADM)
- **Design load simulation:** Multiplication of the actual loading situation with a constant factor to simulate design loading (4 Mio. PE)
- Design Load: 85%ile of daily loadings (COD, TN) over one year

COD Balance with fixed bypass operation, nitritation/denitritation of reject water

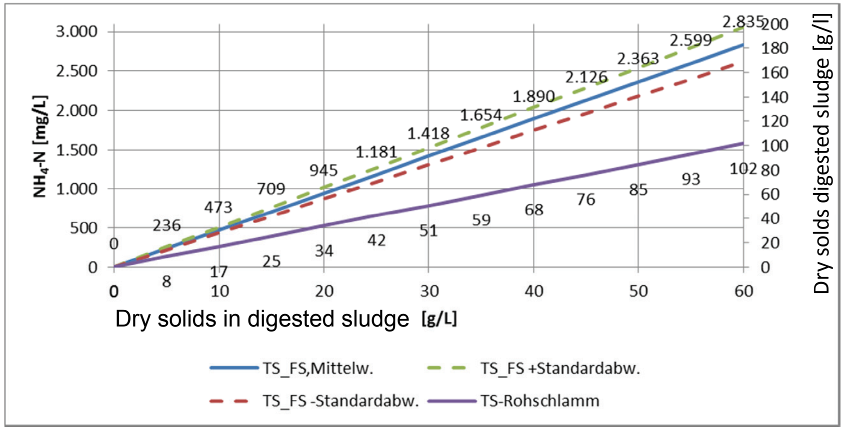


COD Balance for controlled bypass operation, nitritation/denitritation of reject water

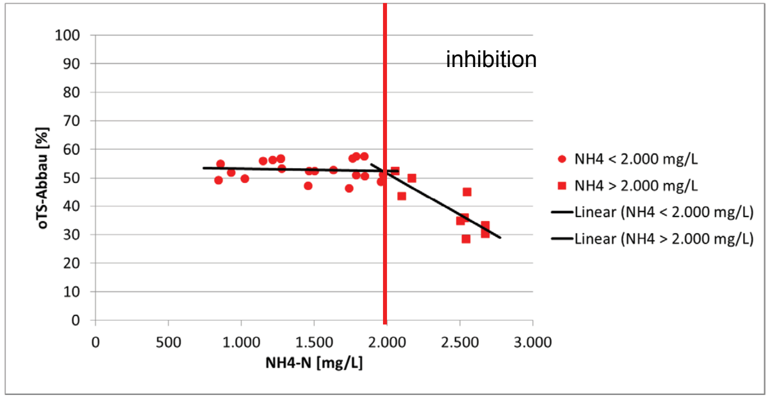


Ammonia inhibition of anaerobic digestion

Relationship: DS_{DS} and NH_4-N in digester versus DS_{DS}



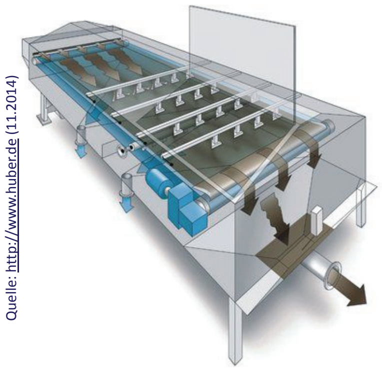
Ammmonia Inhibition of Digestion (ODS removal)



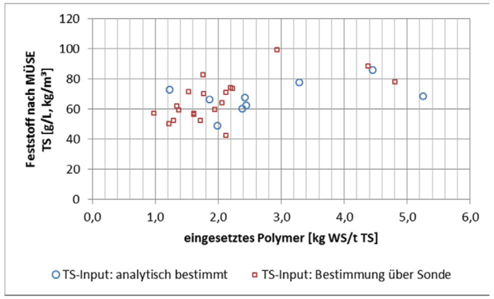
Mechanical thickening

Polymer addition versus $DS_{\text{thickened sludge}}$

- No good correlation possible



Quelle: http://www.huber.de (11.2014)



Digester mixing with gas production

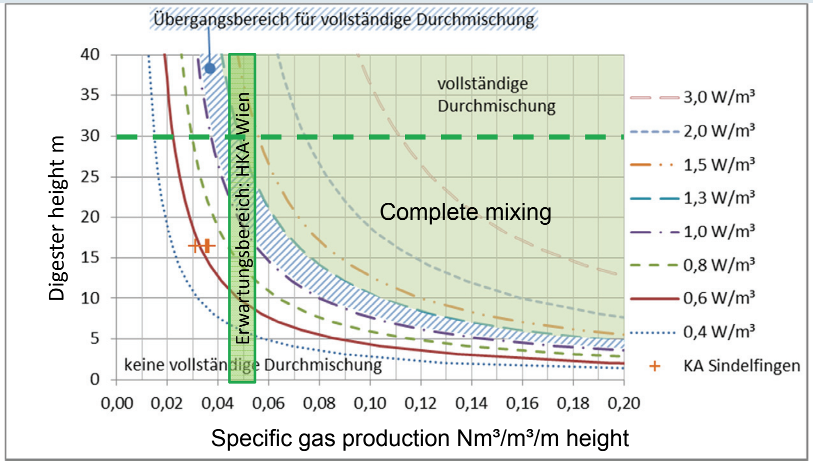
2.7 Wh/Nm³/m depth

Mixing in Digester

Digestion needs complete mixing

- Power requirements for complete mixing:
  - Influencing factors: Mixing system, digester volume and shape, viscosity, inhibitory effects
  - Literature data: Mechanical mixers 2-6 W/m^3
    Gas mixing 5-10 W/m^3
- Mixing by gas production
  - Advantage: no external energy requirement
  - Disadvantage: mechanical mixing equipment necessary for start up and operation
- Goal of investigations: will complete mixing need external energy supply under normal operating conditions

Digester mixing by gas production (only)



Vienna MTP:

Gas production	0,043 $m^3_{gas}/(m^3_{Digester} \cdot h)$…normal operation
	0,055 $m^3_{Gas}/(m^3_{FB} \cdot h)$………design load
Digester height:	30 m

Rheological investigations

Rheology results

- All sludges
  - Viscosity higher than water
  - Non-Newtonian behavior
- Calculation of hydraulic losses:
  - Mathematical models for non-newtonian liquids are existing but need parameters from experimental investigations
  - Influencing parameters: DS, Temp., type of sludge (PS/ES/DS, static/flowing, Polymer addition, etc.
- Goal for design purposes:
  - Method for the determination of friction losses in pipes for different sludges and conditions:

Rheology results

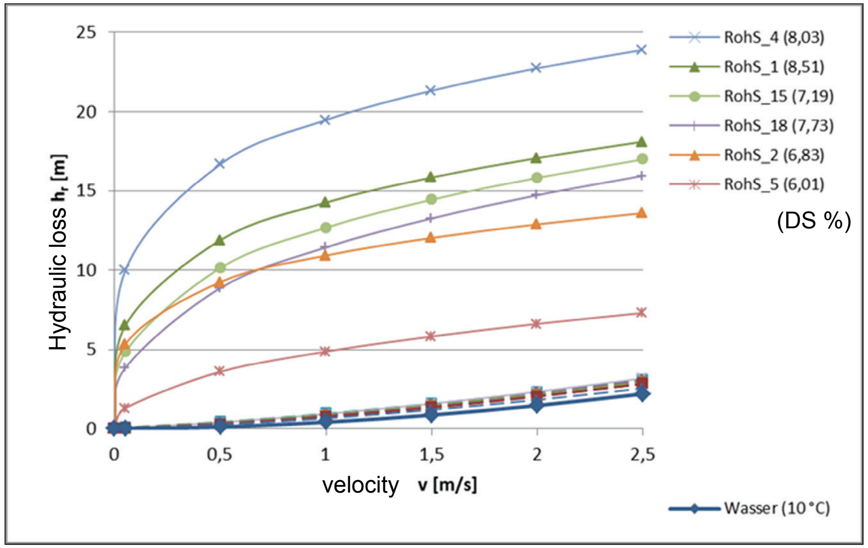
Findings:

- Hydraulic losses: thickened raw sludge>> digested sludge> water
- Raw sludge has strong non-newtoninan behaviour
- Digested sludge similar to water
- DS concentration has dominating effect
- Quality of sludge (mixing of different sludges and seasonal effects) has great influence and cannot directly be transferred from one plant to another
- But estimation possible

Example:

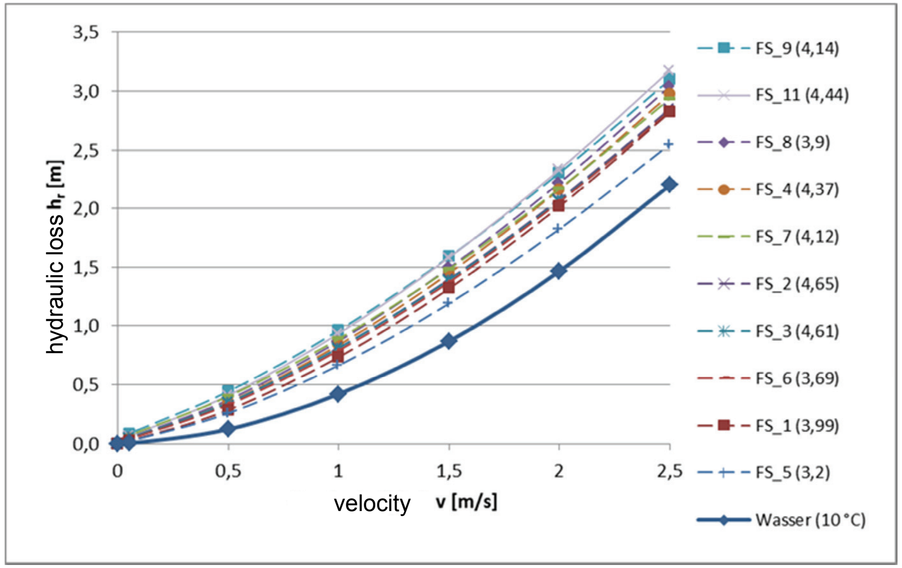
Pipe diameter 0,2 m, length 100m
head loss versus velocity

Rheology example (raw sludge)



Marcus Reichel Thesis 2015

Rheology example (digested sludge)



Marcus Reicher Thesis 2015

Treatment of reject water from sludge dewatering

Nitrogen removal oxygen requirement

- Oxidation of 1 g of NH_4-N to N_2 needs 1.7 g of O_2 irrespective of process used (deammonification or denitrification, denitritation)
- If oxygen uptake for carbon removal is the limiting factor for denitrification, nitrate effluent will increase
- 1 g of NO_3-N in the effluent needs additional energy for aeration of 2.9 g of oxygen

Side stream nitritation /main stream denitritation in 1-stage ASP evaluation

- Ammonia concentration inhibitory for nitritation (NOB)
- Ammonia oxidisers (AOB) have higher growth rate at temperatures > 30°C than nitrite oxidisers (NOB)
- MCRT (2-5d) for stable operatio much less than for deammonification in side stream
- no solids removal before nitritation necessary
- Very low sensibility to operational conditions, fast start up

- As nitritation (AOB) reduces pH **alkalinity addition** (lime) will be necessary to achieve >50% N conversion to nitrite (goal ~80%)

Deammonification evaluation

- Optimum ratio NO_2-N/NH_4-N = 1,32 difficult to achieve
- Anammox bacteria have a very low growth rate (sludge retention and solids removal from RW necessary,)
- Buffer tank for RW necessary
- Higher sensitivity and cost for control equipment
- If biocoenosis is affected slow recovery (low growth rate)
- Sludge transport for start up for a 2 mio PE plant not possible
- Process more sensitive as compared to nitritation denitritation (minimisation of nitrate production)
- If problems occur rapid reaction necessary (nitrate!)
- Higher personal costs for control and operation

Nitritation in Pilot plant

- Test program
  - Adaptation of AS to nitritation by continuous increase of loading
  - Simulated steady state process (intermittend feeding)
  - Variation of sludge age (1,5 to 4 days)
  - Variation of temperature (32 to 45 °C)
  - Different control strategies for aeration (DO concentration and/or pH)
  - Only aerobic or intermittend aeration
  - Testing of probes (pH, T, NH_4-N, NO_3-N, O_2)
  - Foam development at RW treatment

Nitritation in der Versuchsanlage

- Comparison SBR versus continuous flow
- Maximum conversion to nitrite by increasing pH by addition af alkalinity, economic evaluation
- RW-treatment at temperatures< 30 °C
- Minimum sludge age
- Shock load behaviour
- Influence of suspended solids (digested sludge) on nitratation process

- …

Nitritation results from pilot plant

- Nitritation is a very stable process (much less senitive than deammonificaiton)
- No nitrate production even at high sludge age
- ratio NO_2-N/NH_4-N without pH control at 1,10 to 1,15
- Slow changes of temperature do not affect the process
- Sudden temperature changes cause adaptation problems
- Stable operation at temperatures from 32 to 45 °C
- Stable operation at sludge ages from 1,5 to 4 d
- Foam development (h~15cm) normal

→ Stable process under varying loading and temperature conditions as in reality

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Consequences for EOS project

- Decision is made to use nitritation in side stream and denitritation in 1. step ASP
- Both processes SBR and continuous flow will be possible (sludge age is equal to hydraulic detention (in SBR mode sludge age can be higher than hydraulic detention time)
- Chemical addition (lime) for pH control will be installed in order to control the nitritation efficiency (80% conversion of ammonia to nitrite probably the economic optimum)
- COD will not become limiting for denitritation in 1. step ASP even at 40% bypass ⇨ 85% N-removal from RW
- The nitritation volume can also be used for controlled discharge of nitrite to 1. step ASP in order to minimise aeration peaks for OU_C during the day

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Conclusions

- Design and energy calculations as well as modelling can be based on sound theoretical background if enough full scale and pilot scale experience is available
- Process selection, efficient aeration and gas conversion are decisive for achieving energy “neutral” nutrient removal WWTP
- Life cycle analysis indicates that anaerobic digestion with gas-motors for energy recovery have nearly the same greenhouse gas emission (CO_2, N_2O, CH_4) as aerobic sludge stabilisation process. The differences mainly result from the necessary assumptions or selection of literature data *(Parravicini 2014)*

Many thanks for your attention