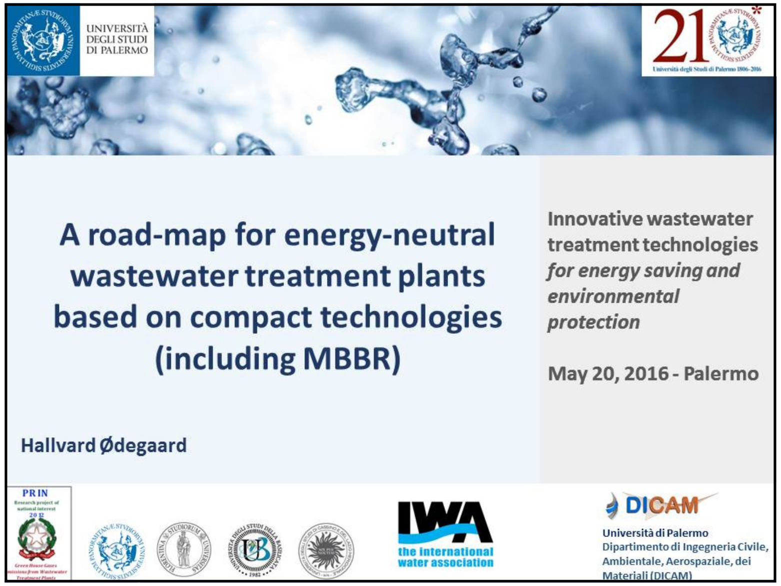

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A road-map for energy-neutral wastewater treatment plants based on compact technologies (including MBBR)

Innovative wastewater treatment technologies ***for energy saving and environmental protection***

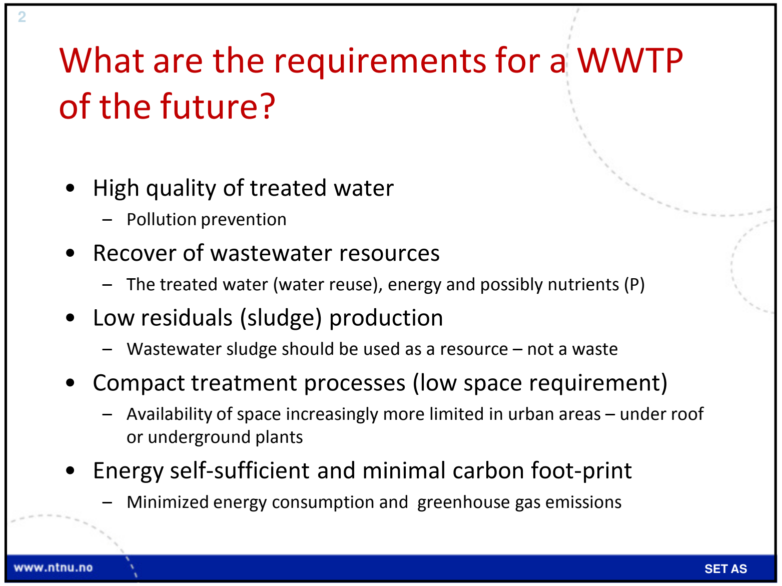
May 20, 2016 - Palermo

Hallvard Ødegaard

PRIN Research project of national interest 2012 Green House Gases emissions from Wastewater Treatment Plants

IWA the international water association

DICAM
Università di Palermo
Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali (DICAM)



What are the requirements for a WWTP of the future?

- High quality of treated water
  - Pollution prevention
- Recover of wastewater resources
  - The treated water (water reuse), energy and possibly nutrients (P)
- Low residuals (sludge) production
  - Wastewater sludge should be used as a resource – not a waste
- Compact treatment processes (low space requirement)
  - Availability of space increasingly more limited in urban areas – under roof or underground plants
- Energy self-sufficient and minimal carbon foot-print
  - Minimized energy consumption and greenhouse gas emissions

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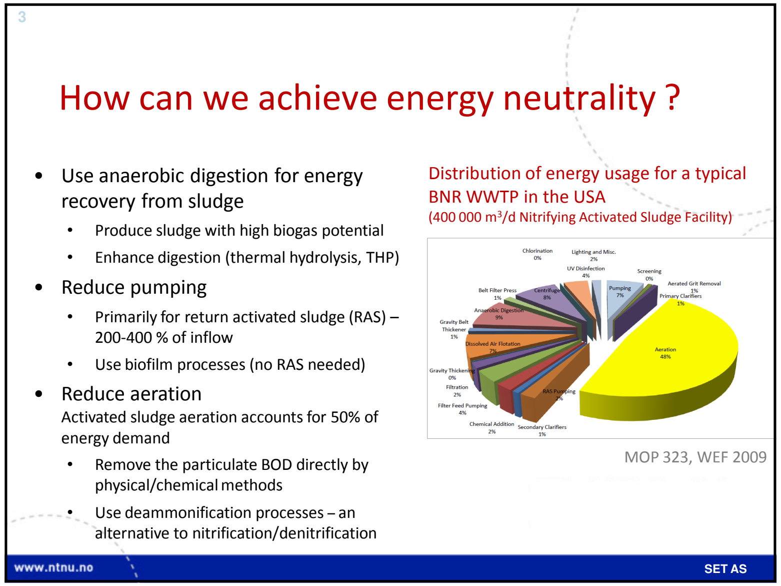
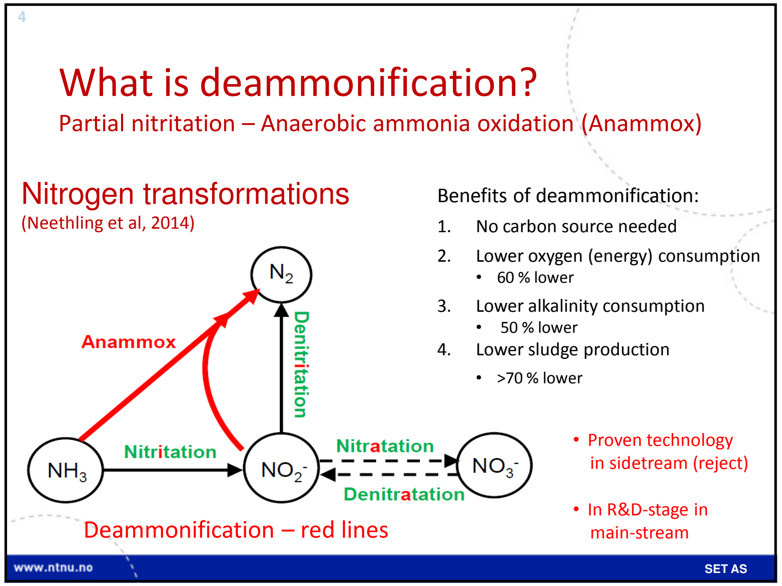


How can we achieve energy neutrality ?

- Use anaerobic digestion for energy recovery from sludge
  - Produce sludge with high biogas potential
  - Enhance digestion (thermal hydrolysis, THP)
- Reduce pumping
  - Primarily for return activated sludge (RAS) – 200-400 % of inflow
  - Use biofilm processes (no RAS needed)
- Reduce aeration
  Activated sludge aeration accounts for 50% of energy demand
  - Remove the particulate BOD directly by physical/chemical methods
  - Use deammonification processes – an alternative to nitrification/denitrification

Distribution of energy usage for a typical BNR WWTP in the USA
(400 000 m^3/d Nitrifying Activated Sludge Facility)

MOP 323, WEF 2009



What is deammonification?

Partial nitritation – Anaerobic ammonia oxidation (Anammox)

Nitrogen transformations
(Neethling et al, 2014)

Deammonification – red lines

Benefits of deammonification:

1. No carbon source needed
2. Lower oxygen (energy) consumption
   - 60 % lower
3. Lower alkalinity consumption
   - 50 % lower
4. Lower sludge production
   - >70 % lower

- Proven technology in sidetream (reject)
- In R&D-stage in main-stream

My discussion

I will discuss compact process technologies that may be used to meet the requirements we set for the WWTP of the future - by the use of two example flow diagrams :

1. One based on well known compact technologies that are in use today
   - Nitrification/denitrification for N-removal and deammonification in side-stream
2. The other based on emerging technologies, particularly
   - Deammonification for N-removal in the mainstream as well as the side-stream

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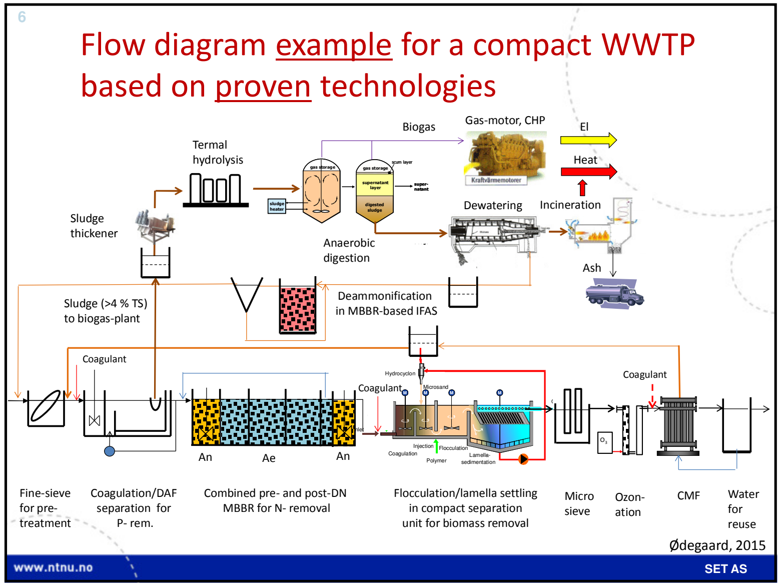
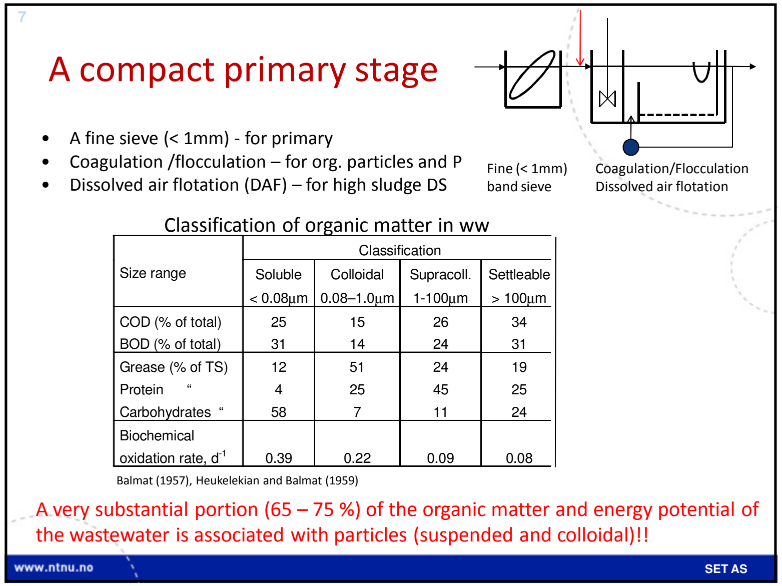


Flow diagram example for a compact WWTP based on proven technologies

Ødegaard, 2015



A compact primary stage

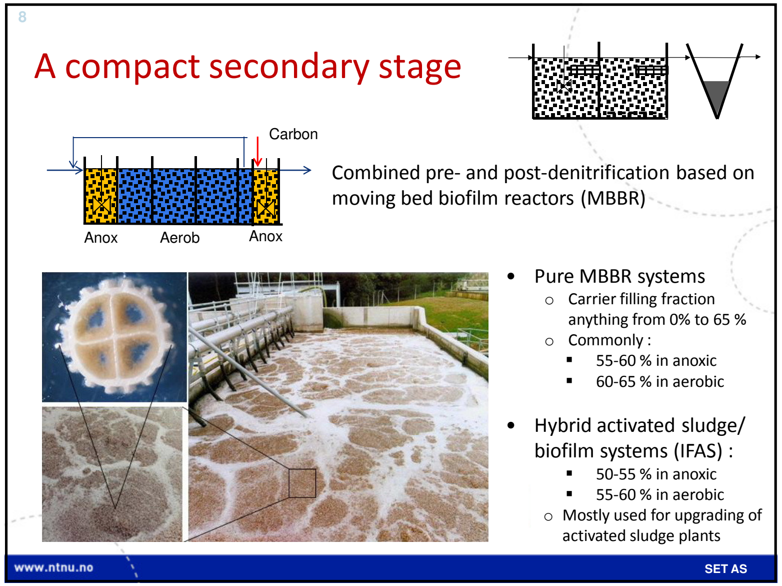
- A fine sieve (< 1mm) - for primary
- Coagulation /flocculation – for org. particles and P
- Dissolved air flotation (DAF) – for high sludge DS

Classification of organic matter in ww

Size range	Classification			
	Soluble < 0.08µm	Colloidal 0.08–1.0µm	Supracoll. 1-100µm	Settleable > 100µm
COD (% of total)	25	15	26	34
BOD (% of total)	31	14	24	31
Grease (% of TS)	12	51	24	19
Protein “	4	25	45	25
Carbohydrates “	58	7	11	24
Biochemical oxidation rate, d^{-1}	0.39	0.22	0.09	0.08

Balmat (1957), Heukelekian and Balmat (1959)

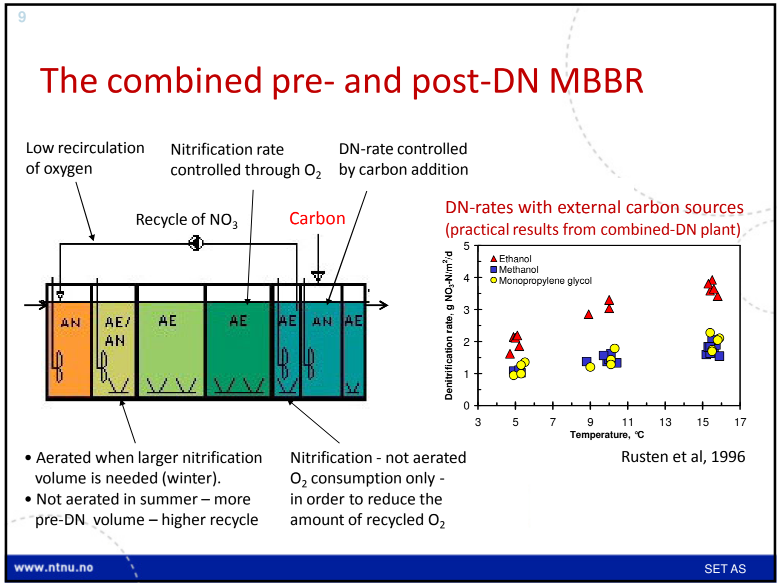
A very substantial portion (65 – 75 %) of the organic matter and energy potential of the wastewater is associated with particles (suspended and colloidal)!!



A compact secondary stage

Combined pre- and post-denitrification based on moving bed biofilm reactors (MBBR)

- Pure MBBR systems
  - Carrier filling fraction anything from 0% to 65 %
  - Commonly :
    - 55-60 % in anoxic
    - 60-65 % in aerobic
- Hybrid activated sludge/ biofilm systems (IFAS) :
  - 50-55 % in anoxic
  - 55-60 % in aerobic
  - Mostly used for upgrading of activated sludge plants



The combined pre- and post-DN MBBR

Low recirculation of oxygen

Nitrification rate controlled through O_2

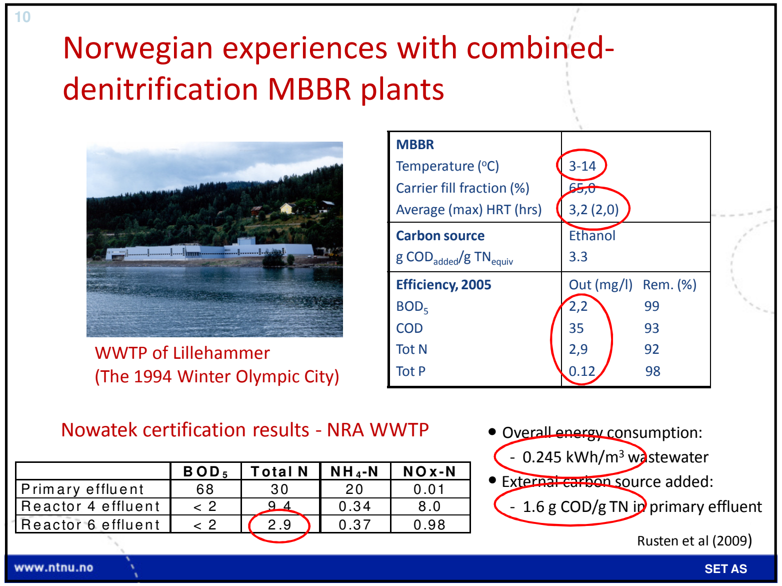
DN-rate controlled by carbon addition

DN-rates with external carbon sources (practical results from combined-DN plant)

- Aerated when larger nitrification volume is needed (winter).
- Not aerated in summer – more pre-DN volume – higher recycle

Nitrification - not aerated O_2 consumption only - in order to reduce the amount of recycled O_2

Rusten et al, 1996



Norwegian experiences with combined-denitrification MBBR plants

WWTP of Lillehammer (The 1994 Winter Olympic City)

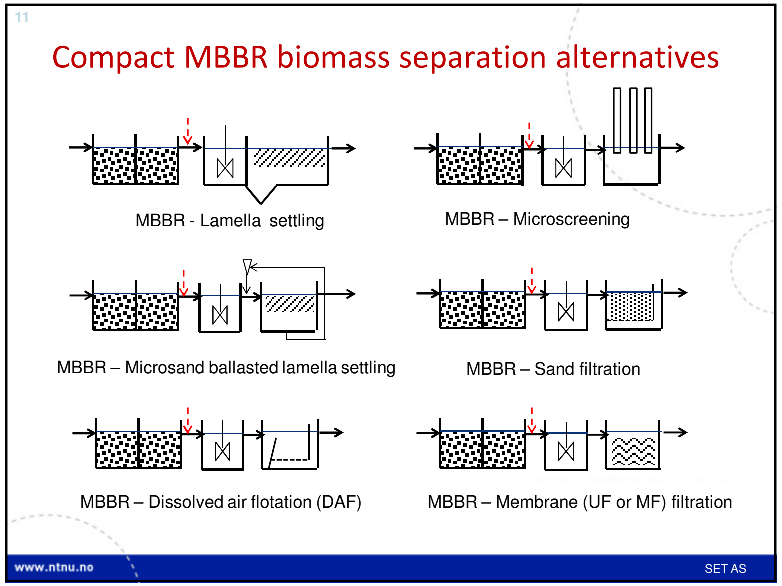
MBBR		
Temperature (°C)	3-14	
Carrier fill fraction (%)	65,0	
Average (max) HRT (hrs)	3,2 (2,0)	
Carbon source	Ethanol	
g COD_{added}/g TN_{equiv}	3.3	
Efficiency, 2005	Out (mg/l)	Rem. (%)
BOD_5	2,2	99
COD	35	93
Tot N	2,9	92
Tot P	0.12	98

Nowatek certification results - NRA WWTP

	BOD_5	Total N	NH_4-N	NOx-N
Primary effluent	68	30	20	0.01
Reactor 4 effluent	< 2	9.4	0.34	8.0
Reactor 6 effluent	< 2	2.9	0.37	0.98

- Overall energy consumption:
  - 0.245 kWh/m³ wastewater
- External carbon source added:
  - 1.6 g COD/g TN in primary effluent

Rusten et al (2009)



Compact MBBR biomass separation alternatives

MBBR - Lamella settling

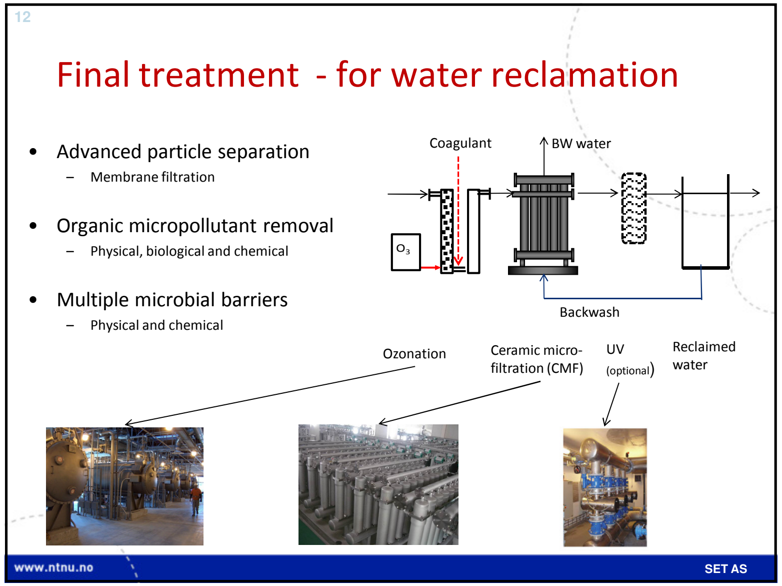
MBBR – Microscreening

MBBR – Microsand ballasted lamella settling

MBBR – Sand filtration

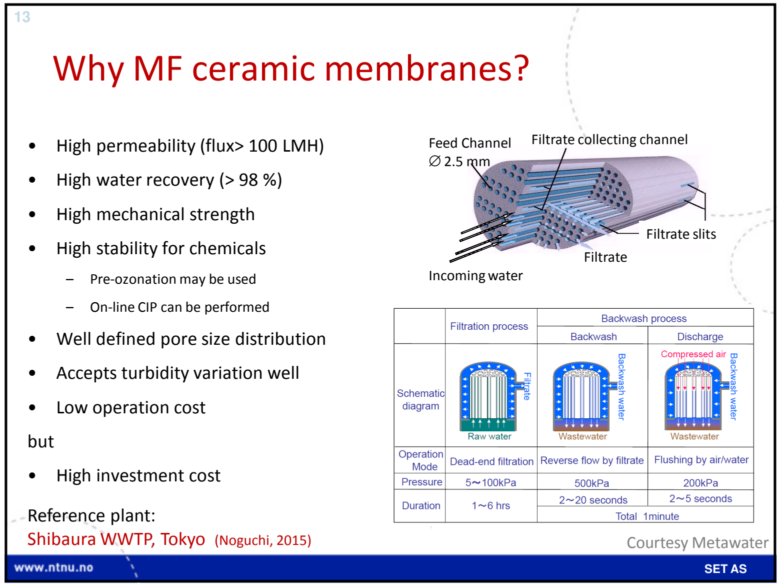
MBBR – Dissolved air flotation (DAF)

MBBR – Membrane (UF or MF) filtration



Final treatment - for water reclamation

- Advanced particle separation
  - Membrane filtration
- Organic micropollutant removal
  - Physical, biological and chemical
- Multiple microbial barriers
  - Physical and chemical



Why MF ceramic membranes?

- High permeability (flux> 100 LMH)
- High water recovery (> 98 %)
- High mechanical strength
- High stability for chemicals
  - Pre-ozonation may be used
  - On-line CIP can be performed
- Well defined pore size distribution
- Accepts turbidity variation well
- Low operation cost

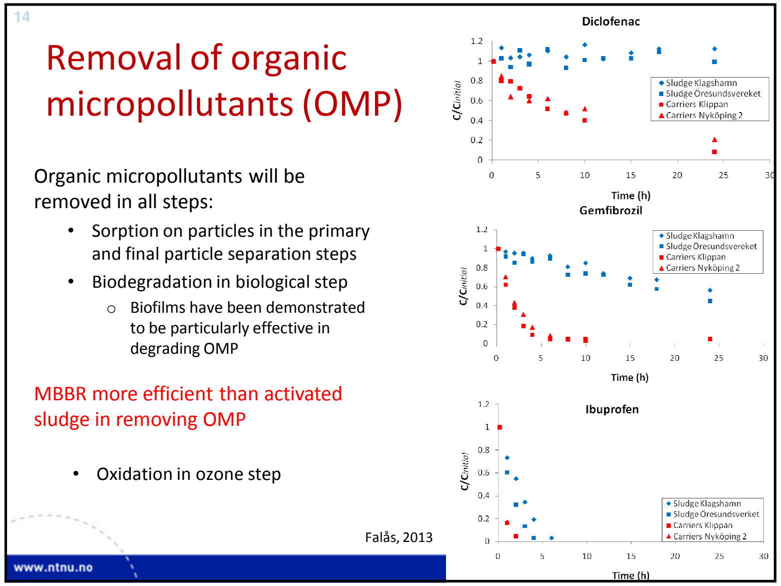
but

- High investment cost

Reference plant:
Shibaura WWTP, Tokyo (Noguchi, 2015)

	Filtration process	Backwash process	
		Backwash	Discharge
Schematic diagram	Filtrate Raw water	Backwash water Wastewater	Compressed air Backwash water Wastewater
Operation Mode	Dead-end filtration	Reverse flow by filtrate	Flushing by air/water
Pressure	5～100kPa	500kPa	200kPa
Duration	1～6 hrs	2～20 seconds	2～5 seconds
		Total 1minute	

Courtesy Metawater



Removal of organic micropollutants (OMP)

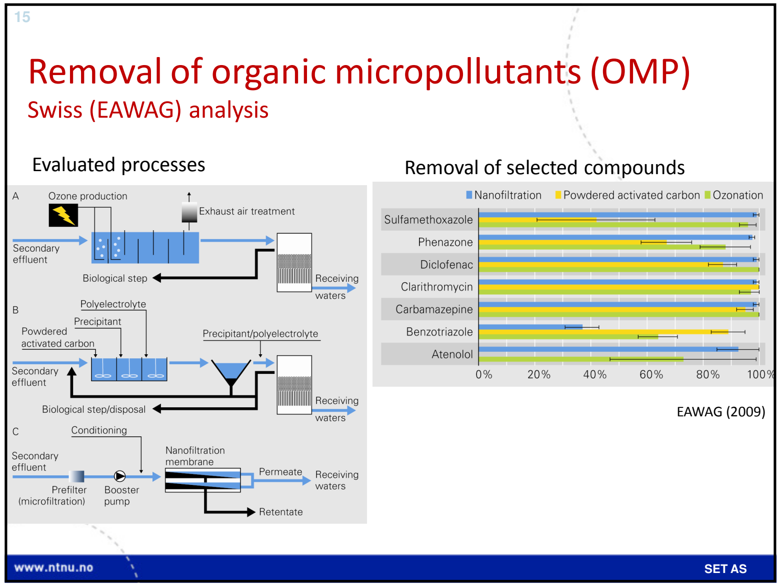
Organic micropollutants will be removed in all steps:

- Sorption on particles in the primary and final particle separation steps
- Biodegradation in biological step
  - Biofilms have been demonstrated to be particularly effective in degrading OMP

MBBR more efficient than activated sludge in removing OMP

- Oxidation in ozone step

Falås, 2013



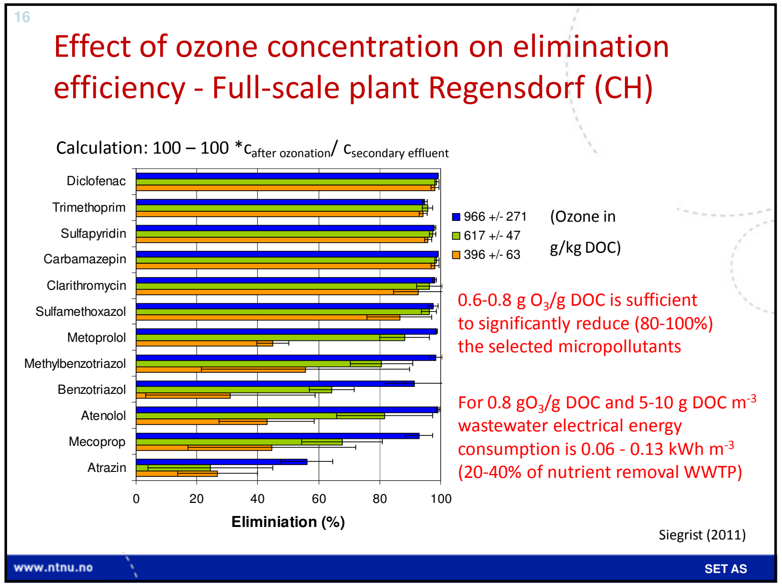
Removal of organic micropollutants (OMP)

Swiss (EAWAG) analysis

Evaluated processes

Removal of selected compounds

EAWAG (2009)



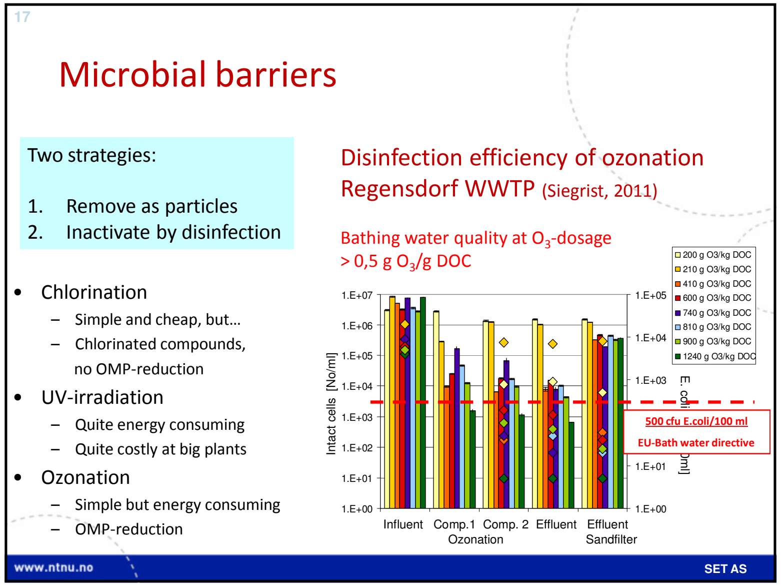
Effect of ozone concentration on elimination efficiency - Full-scale plant Regensdorf (CH)

Calculation: 100 – 100 *$c_{after\ ozonation}$/ $c_{secondary\ effluent}$

0.6-0.8 g O_3/g DOC is sufficient to significantly reduce (80-100%) the selected micropollutants

For 0.8 gO_3/g DOC and 5-10 g DOC m^{-3} wastewater electrical energy consumption is 0.06 - 0.13 kWh m^{-3} (20-40% of nutrient removal WWTP)

Siegrist (2011)



Microbial barriers

Two strategies:

1. Remove as particles
2. Inactivate by disinfection

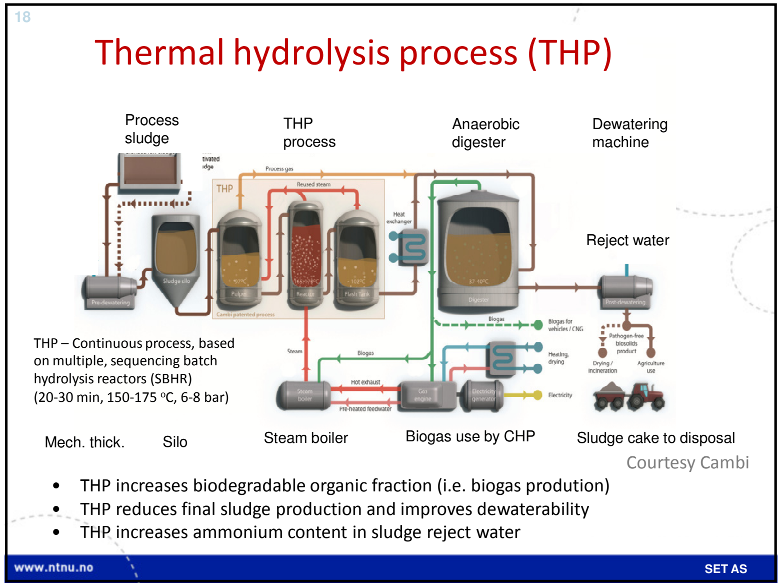
- Chlorination
  - Simple and cheap, but…
  - Chlorinated compounds, no OMP-reduction
- UV-irradiation
  - Quite energy consuming
  - Quite costly at big plants
- Ozonation
  - Simple but energy consuming
  - OMP-reduction

Disinfection efficiency of ozonation Regensdorf WWTP (Siegrist, 2011)

Bathing water quality at O_3-dosage > 0,5 g O_3/g DOC

500 cfu E.coli/100 ml

EU-Bath water directive

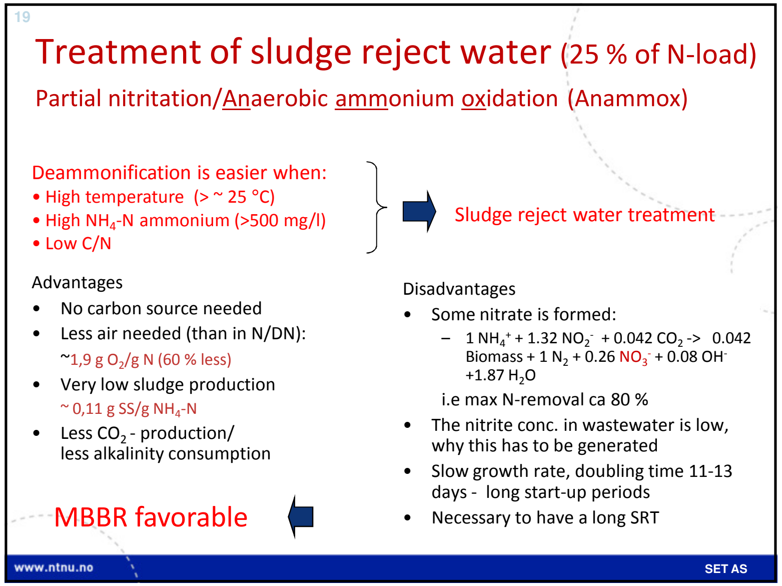


Thermal hydrolysis process (THP)

THP – Continuous process, based on multiple, sequencing batch hydrolysis reactors (SBHR) (20-30 min, 150-175 ºC, 6-8 bar)

Courtesy Cambi

- THP increases biodegradable organic fraction (i.e. biogas prodution)
- THP reduces final sludge production and improves dewaterability
- THP increases ammonium content in sludge reject water



Treatment of sludge reject water (25 % of N-load)

Partial nitritation/Anaerobic ammonium oxidation (Anammox)

Deamonification is easier when:
- High temperature (> ~ 25 °C)
- High NH_4-N ammonium (>500 mg/l)
- Low C/N

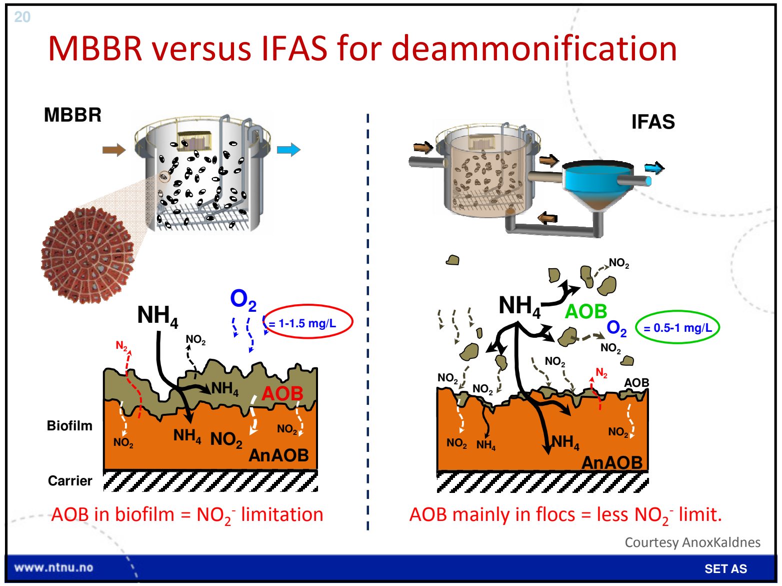
Sludge reject water treatment

Advantages
- No carbon source needed
- Less air needed (than in N/DN):
  ~1,9 g O_2/g N (60 % less)
- Very low sludge production
  ~ 0,11 g SS/g NH_4-N
- Less CO_2 - production/
  less alkalinity consumption

MBBR favorable

Disadvantages
- Some nitrate is formed:
  - $1\ NH_4^+ + 1.32\ NO_2^- + 0.042\ CO_2 \rightarrow 0.042\ \text{Biomass} + 1\ N_2 + 0.26\ NO_3^- + 0.08\ OH^- + 1.87\ H_2O$

  i.e max N-removal ca 80 %
- The nitrite conc. in wastewater is low, why this has to be generated
- Slow growth rate, doubling time 11-13 days - long start-up periods
- Necessary to have a long SRT

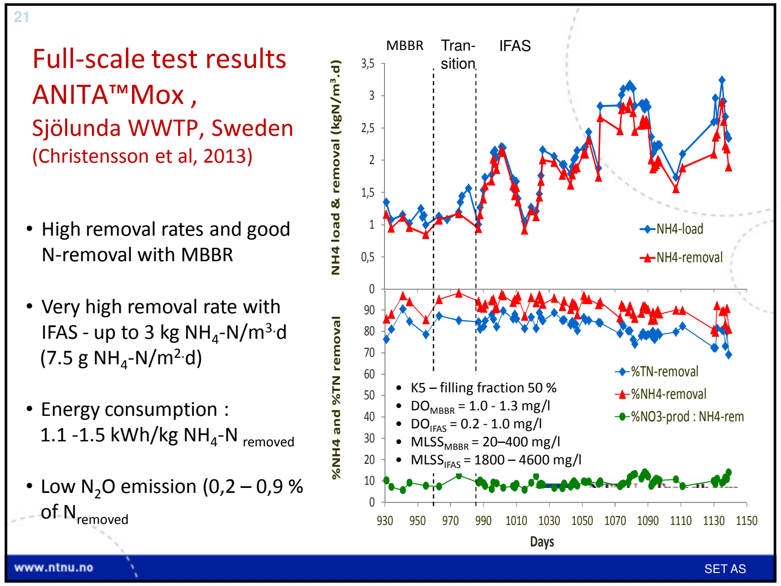


MBBR versus IFAS for deammonification

AOB in biofilm = NO_2^- limitation

AOB mainly in flocs = less NO_2^- limit.

Courtesy AnoxKaldnes



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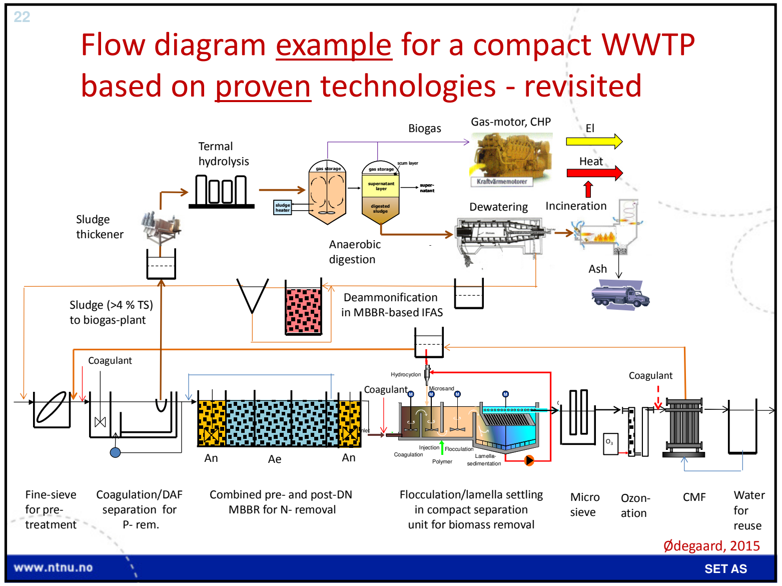
Full-scale test results ANITA™Mox , Sjölunda WWTP, Sweden (Christensson et al, 2013)

- High removal rates and good N-removal with MBBR
- Very high removal rate with IFAS - up to 3 kg NH_4-N/m³·d (7.5 g NH_4-N/m²·d)
- Energy consumption : 1.1 -1.5 kWh/kg NH_4-$N_{removed}$
- Low N_2O emission (0,2 – 0,9 % of $N_{removed}$

- K5 – filling fraction 50 %
- DO_{MBBR} = 1.0 - 1.3 mg/l
- DO_{IFAS} = 0.2 - 1.0 mg/l
- $MLSS_{MBBR}$ = 20–400 mg/l
- $MLSS_{IFAS}$ = 1800 – 4600 mg/l



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Flow diagram example for a compact WWTP based on proven technologies - revisited

Fine-sieve for pre-treatment

Coagulation/DAF separation for P- rem.

Combined pre- and post-DN MBBR for N- removal

Flocculation/lamella settling in compact separation unit for biomass removal

Micro sieve

Ozon-ation

CMF

Water for reuse

Ødegaard, 2015

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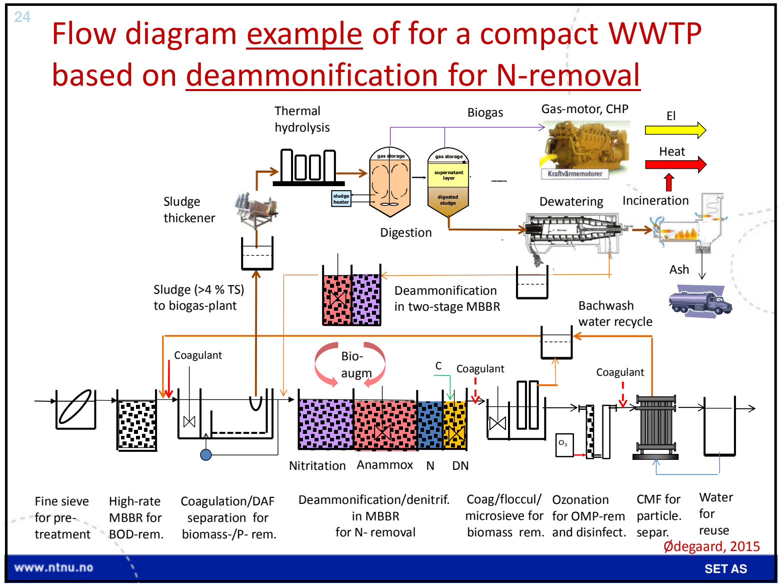
However -
the big leap forward will come
if we can also implement
deammonification in the main-stream !



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Flow diagram example of for a compact WWTP based on deammonification for N-removal

Fine sieve for pre-treatment

High-rate MBBR for BOD-rem.

Coagulation/DAF separation for biomass-/P- rem.

Deammonification/denitrif. in MBBR for N- removal

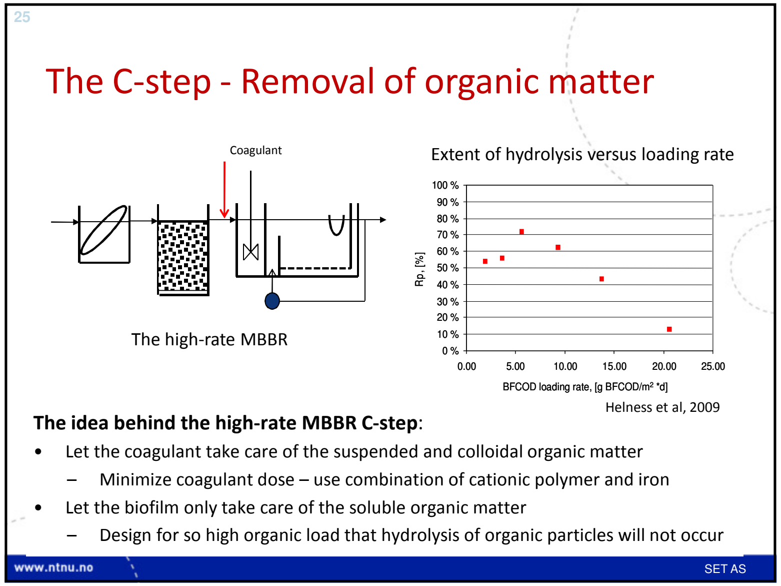
Coag/floccul/ microsieve for biomass rem.

Ozonation for OMP-rem and disinfect.

CMF for particle. separ.

Water for reuse

Ødegaard, 2015



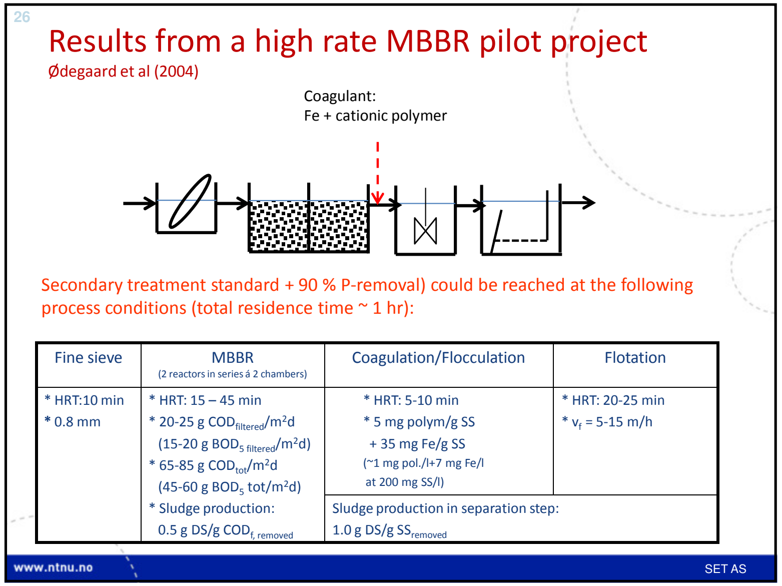
The C-step - Removal of organic matter

The high-rate MBBR

Helness et al, 2009

The idea behind the high-rate MBBR C-step:

- Let the coagulant take care of the suspended and colloidal organic matter
  - Minimize coagulant dose – use combination of cationic polymer and iron
- Let the biofilm only take care of the soluble organic matter
  - Design for so high organic load that hydrolysis of organic particles will not occur



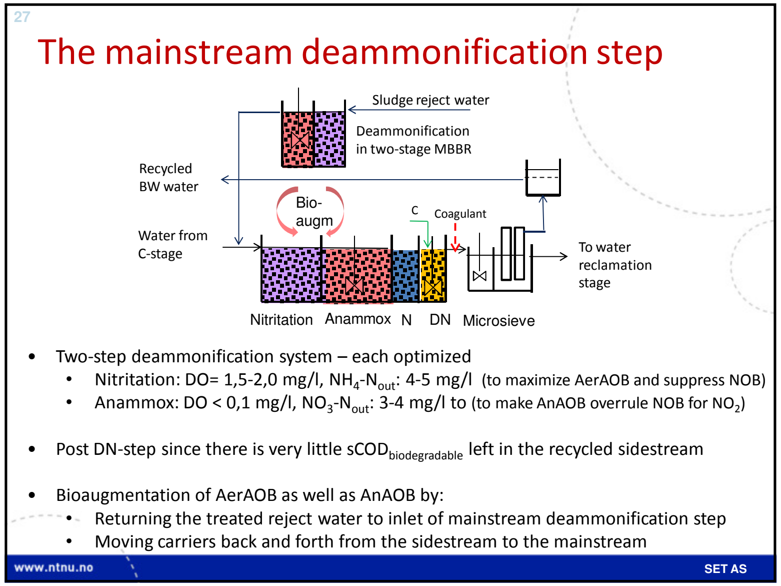
Results from a high rate MBBR pilot project

Ødegaard et al (2004)

Coagulant:
Fe + cationic polymer

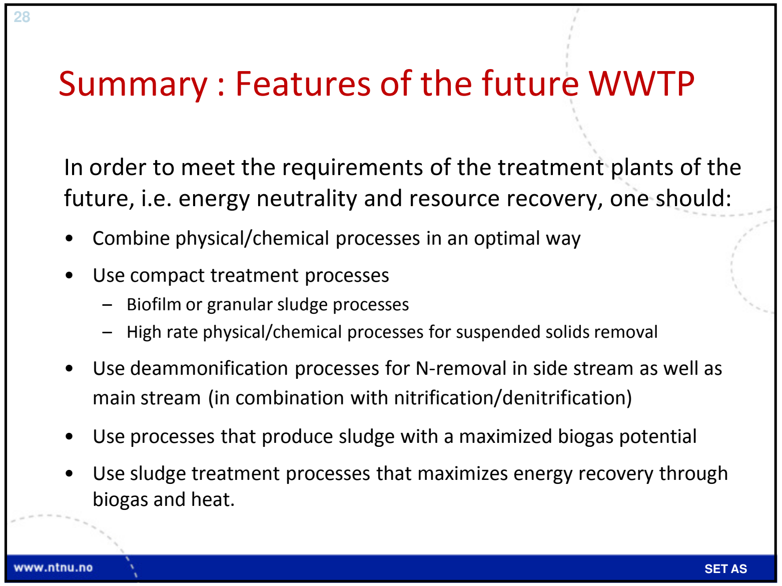
Secondary treatment standard + 90 % P-removal) could be reached at the following process conditions (total residence time ~ 1 hr):

Fine sieve	MBBR (2 reactors in series á 2 chambers)	Coagulation/Flocculation	Flotation
* HRT:10 min * 0.8 mm	* HRT: 15 – 45 min * 20-25 g $COD_{filtered}/m^2d$ (15-20 g $BOD_{5\ filtered}/m^2d$) * 65-85 g COD_{tot}/m^2d (45-60 g BOD_5 tot/m²d) * Sludge production: 0.5 g DS/g $COD_{f,\ removed}$	* HRT: 5-10 min * 5 mg polym/g SS + 35 mg Fe/g SS (~1 mg pol./l+7 mg Fe/l at 200 mg SS/l)	* HRT: 20-25 min * v_f = 5-15 m/h
		Sludge production in separation step: 1.0 g DS/g $SS_{removed}$	



The mainstream deammonification step

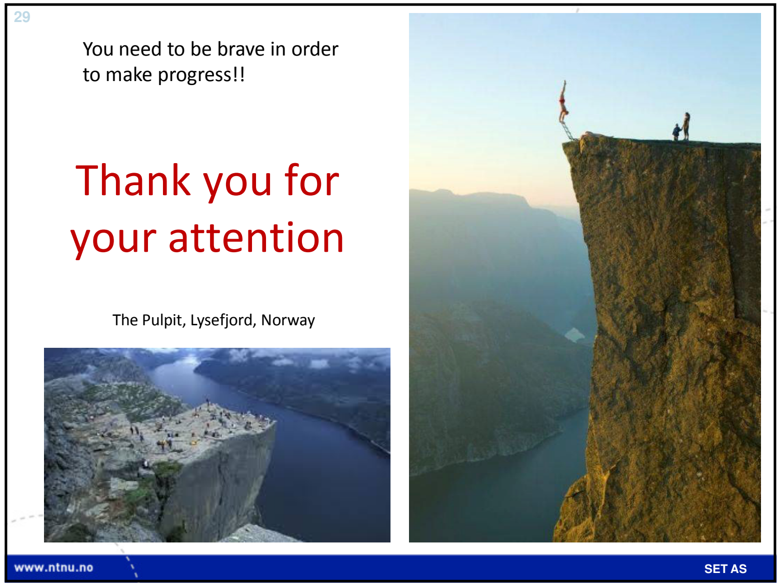
- Two-step deammonification system – each optimized
  - Nitritation: DO= 1,5-2,0 mg/l, NH_4-N_{out}: 4-5 mg/l (to maximize AerAOB and suppress NOB)
  - Anammox: DO < 0,1 mg/l, NO_3-N_{out}: 3-4 mg/l to (to make AnAOB overrule NOB for NO_2)
- Post DN-step since there is very little $sCOD_{biodegradable}$ left in the recycled sidestream
- Bioaugmentation of AerAOB as well as AnAOB by:
  - Returning the treated reject water to inlet of mainstream deammonification step
  - Moving carriers back and forth from the sidestream to the mainstream



Summary : Features of the future WWTP

In order to meet the requirements of the treatment plants of the future, i.e. energy neutrality and resource recovery, one should:

- Combine physical/chemical processes in an optimal way
- Use compact treatment processes
  - Biofilm or granular sludge processes
  - High rate physical/chemical processes for suspended solids removal
- Use deammonification processes for N-removal in side stream as well as main stream (in combination with nitrification/denitrification)
- Use processes that produce sludge with a maximized biogas potential
- Use sludge treatment processes that maximizes energy recovery through biogas and heat.



You need to be brave in order to make progress!!

Thank you for your attention

The Pulpit, Lysefjord, Norway