Forward with Wastewater

Forward osmosis for recovery of valuables and clean water from municipal wastewater

Project 20014

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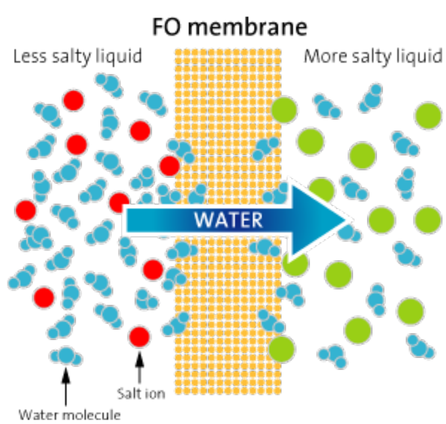

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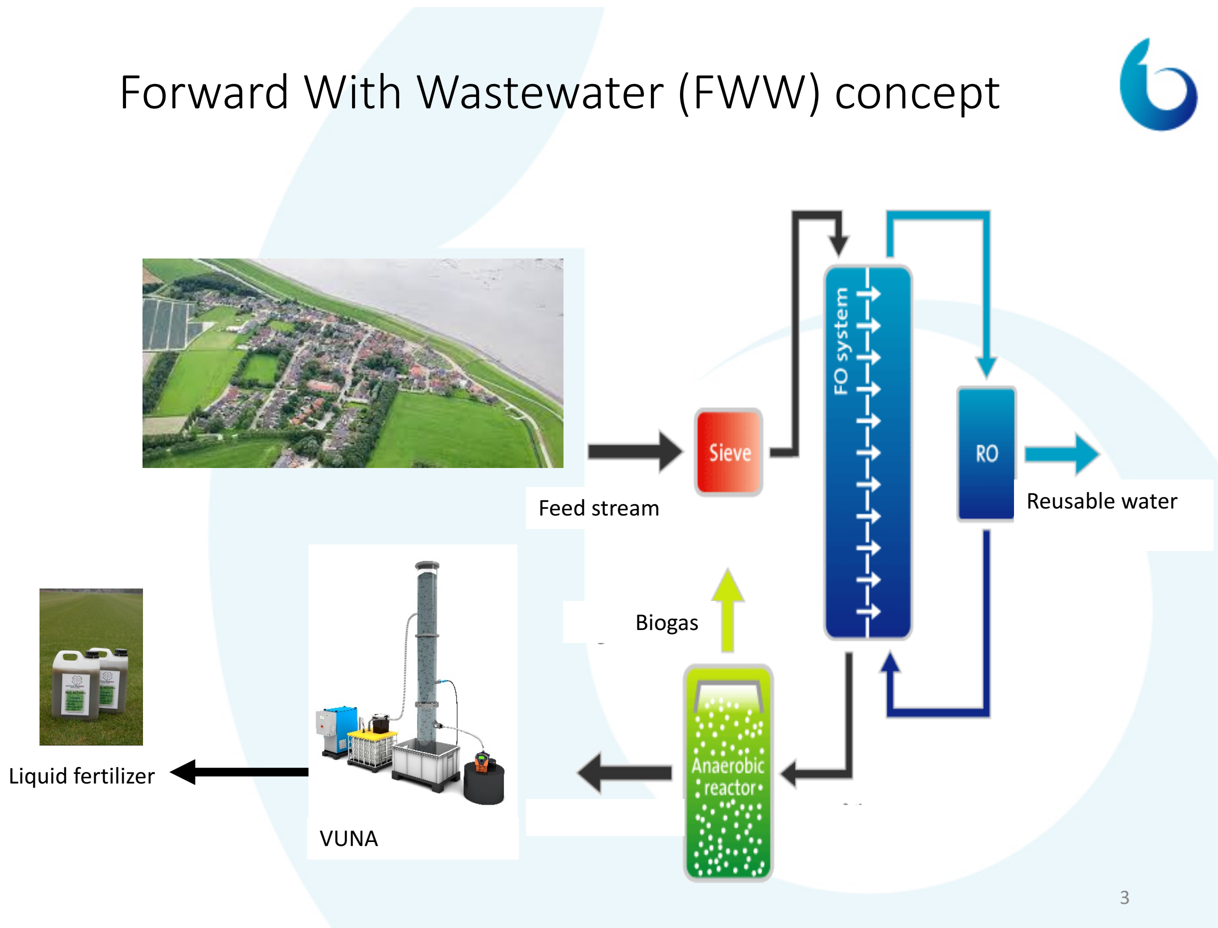
Content

1. Samenvatting

In deze studie is een nieuw concept voor afvalwaterzuivering onderzocht: het "Forward With Wastewater" (FWW)-concept. In dit concept wordt ruw afvalwater direct gescheiden door middel van membraanfiltratie in schoon water en een kleine concentraatstroom. Het schone water kan direct geloosd of hergebruikt worden, bijvoorbeeld als industriewater. Het concentraat wordt verder opgewerkt tot een vloeibare meststof. Het FWW principe staat in onderstaande figuur schematisch weergegeven.



Centraal in dit concept staat de toepassing van de Forward Osmose membraantechnologie (FO), die zich onderscheid van klassieke membraanscheiding door een veel minder grote gevoeligheid voor vervuiling.

In dit onderzoek zijn drie business case onderzocht:

- Zuivering van het afvalwater van dierenpark Wildlands in Emmen

- Zuivering van het afvalwater op het Waddeneiland Terschelling
- Zuivering van het afvalwater op de locatie van de bestaande rioolwaterzuivering de "Scheve Klap"

Voor het FWW concept zijn de volgende processtappen doorgerekend:

- Voorbehandeling door middel van een fijnzeef en ontwatering van het afgezeefde materiaal;
- Concentratie van het voorgezeefde afvalwater met een factor 40;
- Lozing van het geproduceerde effluent;
- Anaerobe behandeling van het concentraat, waarbij het biogas omgezet wordt in stoom;
- Behandeling van het anaerobe concentraat met behulp van de VUNA technologie voor de productie van vloeibare kunstmest. De VUNA technologie bestaat uit:
    - Partiele nitrificatie;
    - Actief kool adsorbtie voor organische microverontreinigingen;
    - Sterilisatie en indamping (met gebruik van stoom uit de biogasopwekking);
- Opslag vloeibare kunstmeststof (6,3w%N en 1w%P).

Op basis van de business cases kunnen de volgende conclusies worden getrokken:

- Door middel van het FWW concept kunnen schoon water, vloeibare kunstmest en droge biomassa (60w%) uit afvalwater gewonnen worden;
- Het FWW concept kan een economisch en duurzaam alternatief zijn voor klassieke waterzuivering;
- De economische haalbaarheid hangt onder meer sterk af van de prijs voor het vloeibare mestproduct en de verdunning van het afvalwater door regenwater of lekwater in het riool;
- De footprint van het FWW concept is kleiner dan het klassieke zuiveringsproces;
- Vanuit een energieoogpunt is het FWW concept meer duurzaam dan het klassieke zuiveringsproces, mits het water niet te verdund raakt door extern water (drainage water, regenwater, etc)..

Het FWW proces lijkt een interessant alternatief voor de zuivering van afvalwater. De duurzaamheid is groot, waarbij zoveel mogelijk waardevolle stoffen worden hergebruikt (zoals N en P) en schadelijke stoffen worden verwijderd (zoals microverontreinigingen en pathogenen). Ook de economische haalbaarheid lijkt interessant, één en ander afhankelijk van de opbrengsten van de teruggewonnen stoffen en de specifiek situatie.

Vanuit technologisch oogpunt zijn er nog diverse vragen. Het TRL niveau van deze technologie bedraagt nu 3 tot 4. In een volgende stap zullen duurtesten naar de FO technologie gedaan moeten worden en nader onderzoek naar de concentraat behandeling, waardoor het TRL niveau stijgt naar 5 tot 6. De eeste stap zal een grootschaliger pilot onderzoek moeten vormen om de technologische hiaten beter in kaart te brengen. In een laatste stap kan dan een kleinere demonstratie unit gerealiseerd worden, waardoor het TRL niveaus op 7 tot 9 komt.

2. Introduction

In this study a new concept for wastewater treatment will be examined. In this concept, domestic wastewater will be separated by means of Forward Osmosis in a highly concentrated part and clean water. The highly concentrated part can be upgraded by the VUNA technology, which is developed at the EAWAG. This concept is called Forward With Wastewater (FWW)

In this case study three cases will be examined for the treatment of wastewater with the FWW concept:

- Treatment of domestic wastewater at the location “De Scheve Klap” in the province of Groningen
- Treatment of domestic wastewater at the zoo “Wildlands” in Emmen
- Treatment of domestic wastewater at the Wadden island Terschelling.

The following treatments steps will be taken into account:

- Pre-treatment by micro-sieves for the removal of particular matter
- Forward Osmosis /Reverse Osmosis for the concentration of the raw wastewater water and production of clean effluent
- Anaerobic treatment of the concentrate for biogas production
- Final treatment of the concentrate by the VUNA technology (partial nitrification, activated carbon adsorption and distiller) to produce a liquid fertilizer and the final removal of micro-pollutants and pathogens.

The cases will be examined on:

- Financial aspects
- Energy aspects
- Sustainability

Finally, an evaluation of the FWW concept will be made in relation to classical wastewater treatment, where the system will be compared on aspects like feed flows, reliability, sustainably, applicability, etc. Recommendations for further research and lacks in knowledge will be identified.

3. General technology description

3.1 General

A growing population, increasing water demands and impairment, escalating energy use and the depletion of raw materials, such as phosphorous, over the past decades (and likely to continue in the near future) have stimulated the exploration of alternative water and energy sources. Wastewater can be an interesting source for the reclamation and recovery of water, energy and raw materials. Domestic wastewater contains potential energy due to the content of organics and valuable nutrients such as ammonium and phosphorous. Due to the presence of organic micropollutants, i.e. endocrine disrupting compounds, pharmaceuticals, pesticides, etc., in wastewater treated conventionally there is an increasing demand for sophisticated technologies to remove such pollutants. In the cases where the treated water will be reused, the removal of these micropollutants is of high importance.

In the Netherlands many initiatives have been started to explore this potential in the so called “Energiefabriek” and “Grondstoffenfabriek” initiatives. Although these initiatives made a big step forward, most of the COD and nitrogen is still converted in CO_2, N_2, water, and biomass and most of the phosphate is bound to the sludge ending up in the final sludge disposal.

Another trend is the decentralized treatment of wastewater in order to recover nutrients and biogas. Although very promising, this approach’s draw-back is that most households don’t have the infrastructure for decentralized treatment as they are connected to a central sewer systems combined with water flushing.

The reuse of water and recovery of energy and valuable materials from municipal wastewater faces several problems. A main problem is that the concentration of many components (organics, nutrients) is too low to recover them efficiently. In Table 1 the desired concentration for efficient recovery is shown together with typical concentrations in domestic wastewater.

Table 1: Composition of domestic wastewater and the desired concentrations for recovery of valuable components

	Domestic wastewater	Minimal concentration required for recovery	Desired concentration factor
COD	600 mg/l	5000 mg/l	8
NH_4-N	50 mg/l	500 mg/l	10
P	10 mg/l	100 mg/l	10

An option to concentrate wastewater and produce reusable water is via membrane filtration. The application of direct membrane filtration on raw wastewater can be very interesting:

- the increased concentration of components makes recovery of nutrients and biogas possible;
- the direct production of clean, reusable water is possible, especially when tight membranes such as reverse osmosis (RO) are used;
- the concentrated wastewater contains micropollutants in high concentrations and in a relatively small volume, making the removal of these micropollutants more effective;
- the total treatment system will have a smaller footprint than conventional systems.

Applying conventional membrane filtration processes such as RO, nanofiltration (NF), ultrafiltration (UF) or microfiltration (MF) might lead to severe membrane fouling due to the pressurized processes involved. This is especially true when using these pressure-driven membrane filtration methods on raw wastewater.

An interesting alternative membrane system for concentrating wastewater, while simultaneously producing water for reuse, is forward osmosis (FO). FO uses the osmotic pressure difference across a semipermeable dense membrane to extract clean water and to concentrate impaired feed streams (see Figure 1).

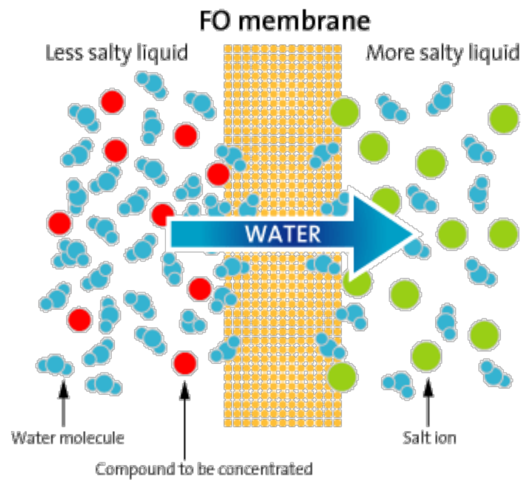


Figure 1: Principle of Forward Osmosis

Unlike the pressure-driven membrane processes, FO requires minimal energy input, mainly for liquid recirculation. Yet, an energy input would be needed if the draw solution (high osmotic solution) is to be regenerated, for reuse in the process, or for water recovery. The main advantage of FO over pressure-driven membrane processes includes low fouling tendency and minimal pre-treatment requirement of the feed water, reduced cake layer formation, which simplifies membrane cleaning, and low-pressure operation which simplifies the design and equipment used and reduces the energy input.

Due to these characteristics FO can be used to treat many types of complex feed steams, such as complex industrial streams, wastewater from oil and gas well fracturing, landfill leachate, brine, and municipal wastewater.

In this article the background of FO is presented including membrane and module configurations as well as the options for draw solution recovery. A new concept for wastewater treatment will be discussed and finally a business case for industrial wastewater treatment will be presented.

3.2 BACKGROUND OF FORWARD OSMOSIS

3.2.1 Mass transport

Although FO is a relatively simple process, mass transport through FO membranes is complex and depends on many parameters including membrane type, structure, orientation, temperature, and composition of the feed and draw solution, hydraulics, etc. FO mass transport models, especially for wastewater applications, are limited. Most models neglect fouling phenomena, mainly because of the complexity and variability of wastewater. The classical solution-diffusion model coupled with diffusion convection is generally used to explain solute and water transport behaviour in semipermeable membranes. The water flux (J_w) (m/s) across the membrane is a function of the osmotic pressure of the draw solution π_{DS} and feed solution π_{FS}:

$$J_w = K_m ln\left(\frac{A\pi_{DS} + B}{A\pi_{FS} + J_w + B}\right)$$

In this formula K_m is the mass transfer coefficient, A the pure water permeability constant and B the solute permeability constant. The non-linear behaviour of this equation is mainly due to internal concentration polarisation

(ICP). ICP is the dilution of the draw solute in the support layer due to the flux of clean water through the membrane into the support layer. ICP is considered a major problem in FO, reducing the water flux and increasing the reverse solute flux.

Another important parameter is the membrane structure parameter S. The membrane structure parameter (S) is an intrinsic membrane parameter used to determine the degree of internal concentration polarization (ICP) in the porous support structure of forward osmosis (FO) membranes, and is crucial in evaluation of FO membrane performance. The membrane structure parameter is inversely related to the mass transfer through the membrane:

$$K_m = \frac{D}{S}$$

in which D is the solute diffusion coefficient. S is given by the product of the support layer thickness (l) and tortuosity (τ) and is inversely proportional to the porosity (ε).

$$S = \frac{\tau . l}{\varepsilon}$$

Essentially, thinner, more porous and less tortuous support layers will have smaller S values and produce higher water fluxes. To obtain a high water flux in FO the membranes should possess high water permeability. The salt permeability B depends on the intrinsic properties of the dense top-layer. This parameter needs to be low enough to suppress the reverse salt flux through the support layer. Despite high rejections, forward and reverse solute diffusion are significant in FO. Forward diffusion occurs when solutes move from the feed (wastewater) into the draw solution side, while reverse diffusion (solute leakage) occurs from the draw side into the feed. B is solute dependent and should be minimized to avoid solute leakage, as this decreases Δπ, impacts draw solute costs and may contaminate the feed concentrate. In Figure 2 difference between a traditional RO membrane and a membrane optimized for FO are shown.

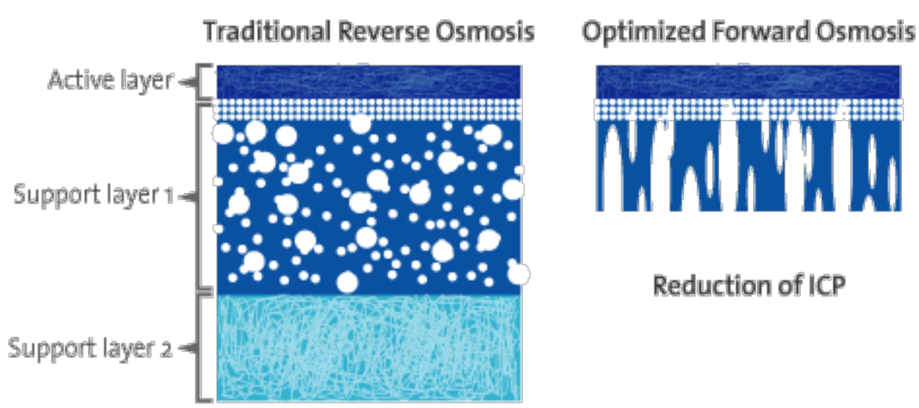


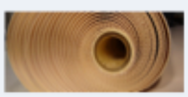
Figure 2 Traditional RO membrane vs optimized FO membrane

3.2.2 Membranes, process conditions and modules for FO

Generally, any dense, non-porous, selectively permeable membrane material could be used for FO. The desired characteristics of membranes for FO are: dense active layer for high solute rejection and thin membrane with minimum porosity of the support layer for low ICP (leading to higher water flux). Membranes are mainly characterized by A, which should be high, B which should be as low as possible and S which should be small. The most promising FO membranes nowadays are the thin film composite (TFC) membranes, which are typically more water permeable and with low solute permeability values.

Membrane module configuration implies the packing of a membrane into a module for maximizing the surface to volume area (see Table 2). This also reduces the external concentration polarisation which is causing particle deposition by sufficient cross flow. The different modules’ configurations are (i) plate-and-frame, (ii) spiral-wound and (iii) tubular. Plate-and-frame and spiral-wound modules are currently most widely used in RO and FO applications. The use of tubular membranes (tubes or hollow fibres) has a limited application in RO as well as in FO. For continuously operated FO processes tubular membranes could be more practical for several reasons. Tubular membranes are self-supported. This means they can support higher hydraulic pressures without deformation and they can be easily packed in bundles directly inside a holding vessel. Tubular membranes may have an ultrathin support layer, which results in reduced ICP and enhanced performance. Furthermore, the packing density can be relatively high and these modules allow liquids to flow freely on both sides of the membrane, a flow pattern necessary for FO.

Table 2: Module configurations for FO

Module type		Advantages	Disadvantages
Plate and Frame		Easy construction	Often low density 100 -300 m^2/m^3 Flow control Complex to produce in big volumes
Spiral wound		Well kown from RO High density 600 m^2/m^3	Control of membrane blocking Pre-treatment
Hollow fiber		High density up to 1600 m^2/m^3	Control of membrane blocking
Tubular		High density 800 m^2/m^3 Industrial applicatoin Fouling control	No commercial modules yet

3.2.3 Draw solute and draw solute recovery

The concentrated solution on the permeate side of the membrane is the source for the driving force in the FO process. In most tests and applications NaCl has been used as the draw solute due to its high solubility, low cost and high osmotic potential. An effective draw solution for wastewater concentration should induce a high water flux on the one hand, but also have a low reverse solute leakage. Many types of draw solutions have been tested, such as inorganic substances (salts), zwitterionic substances, highly charged compounds (EDTA), thermolytic solutes (ammonium bicarbonate) and even engineered draw solutions (magnetic nanoparticles).

An important criterion in the application of FO is the selection of a suitable process for reconcentrating the draw solution after it has been diluted in the FO process. When NaCl is used as a draw solute reconcentration is often done by RO. For other draw solutes other types of reconcentration can be applied, for example, NF when highly charged compounds are used. When waste heat is available membrane distillation (MD) can be a very promising method for draw solute recovery. The principle of FO combined with draw solute recovery is presented in Figure 3.

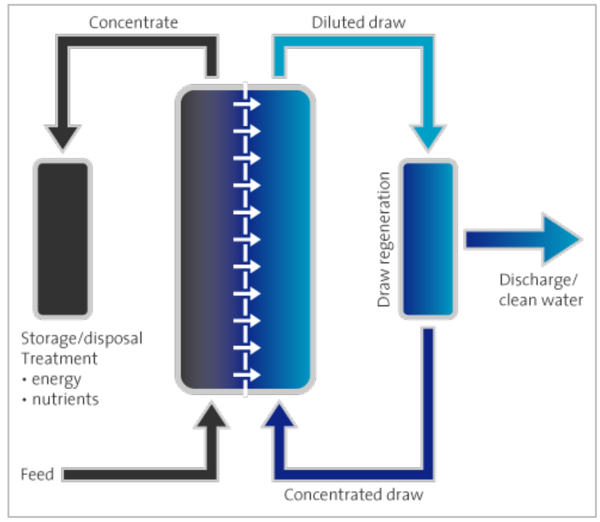


Figure 3: FO with draw solute recovery system

3.3 THE NEW WASTEWATER TREATMENT CONCEPT

FO with an effective draw solute recovery system can lead to a new concept for wastewater treatment. For the application of FO for wastewater treatment several aspects must be taken into account: (i) recovery rate in relation to wastewater composition, (ii) energy aspects, (iii) foulants and scalents in the wastewater and (iv) organic micropollutants.

The composition of the wastewater determines the recovery rate of the FO-system. The less concentrated the wastewater, the higher the recovery rate needed to achieve concentrations high enough for the recovery processes, like anaerobic treatment or ammonia stripping. As can been seen from Table 3 for domestic wastewater a recovery rate of 90% would be preferable. The recovery rate might be limited due to fouling of the membranes and can determine the method of pre-treatment.

In the sustainable wastewater treatment concept energy consumption is an important aspect. Energy demand of FO/RO for average wastewater are assumed to be 2 kWh/m^3 and for RO only 1.5 kWh/m^3 for water reclamation from the treated water after aerobic treatment. Energy production from anaerobic digestion is about 1.5 kWh/kg COD. The energy use for oxidation of COD in a classical wastewater treatment plant amounts to 0.5 kWh/kg COD. From this data the energy balance can be calculated for different COD concentrations:

Table 3: Energy balance for the FO process for wastewater treatment

COD concentration (mg/l)	Energy for FO (kWh/kg COD)	Energy from biogas (kWh/kg COD)	Avoided energy for aeration (kWh/kg COD)	Avoided energy for RO (kWh/kg COD)	Net energy production (kWh/kg COD)
250	8	1.5	0.5	6	0
500	4	1.5	0.5	3	1
1000	2	1.5	0.5	1.5	1.5

2000	1	1.5	0.5	0.75	2.25

From Table 3 it can be seen that a COD concentration above 250 mg/l can give a positive energy balance compared to a classical aerobic treatment in combination with RO for water recovery.

FO membranes are generally at a lower risk of membrane fouling due to the lack of hydraulic pressure. Major foulants in wastewater are microorganisms, organic matter and inorganic matter. Fouling due to inorganic matter may be of great importance when treating wastewater with FO, especially at high recoveries, due to precipitation and therefore possible scaling. Module design can effect fouling, for example, cross flow velocity, can be controlled in specific module designs, which affects fouling in different way. Tubular membranes could be beneficial to control fouling and prevent blocking of membranes.

When FO is used for water reuse, rejection of organic micro pollutants is of great importance. This rejection depends on the type of compounds (e.g. molecular size, polarity, and charge, i.e. ionic or neutral), type of membrane (hydrophobicity, molecular weight cut-off) and fouling of the membrane. Limited research with respect to the rejection of micropollutants with FO has been done, but in most cases a removal of >90% is found in FO.

This new concept for wastewater treatment consists of several unit-operations as shown in Figure 4:

- Pre-treatment
- FO-unit
- Draw solute recovery
- Concentrate treatment

3.3.1 Pre-treatment

In many cases a pre-treatment will be necessary before entering the FO-unit. The pre-treatment depends on the type of membrane configuration in the FO-unit. Modules with a very limited space between the membranes, like spiral wound modules or hollow-fibre modules will need pre-treatment with a finer mesh size than for example tubular FO-membranes. The pre-treatment will be in most cases a sieve-like drum screen, which can be operated with mesh sizes down to 50 µm.

3.3.2 FO-unit

To use FO for wastewater treatment (in the case of water reuse), recovery of biogas and nutrients, and effectively treat the remaining concentrate, the membranes should have several characteristics. First of all, the treatment of raw wastewater has a very high fouling tendency. Wastewater contains many particles and is different over time and location thus undefined in its composition. Membrane configurations where process conditions, such as flow velocity over the membrane, osmotic backwash options, and cleaning possibilities can be controlled easily are of great importance. Developments on the membrane modules have been quite limited up to now. A new interesting candidate for this type of FO application is found in tubular FO membranes.

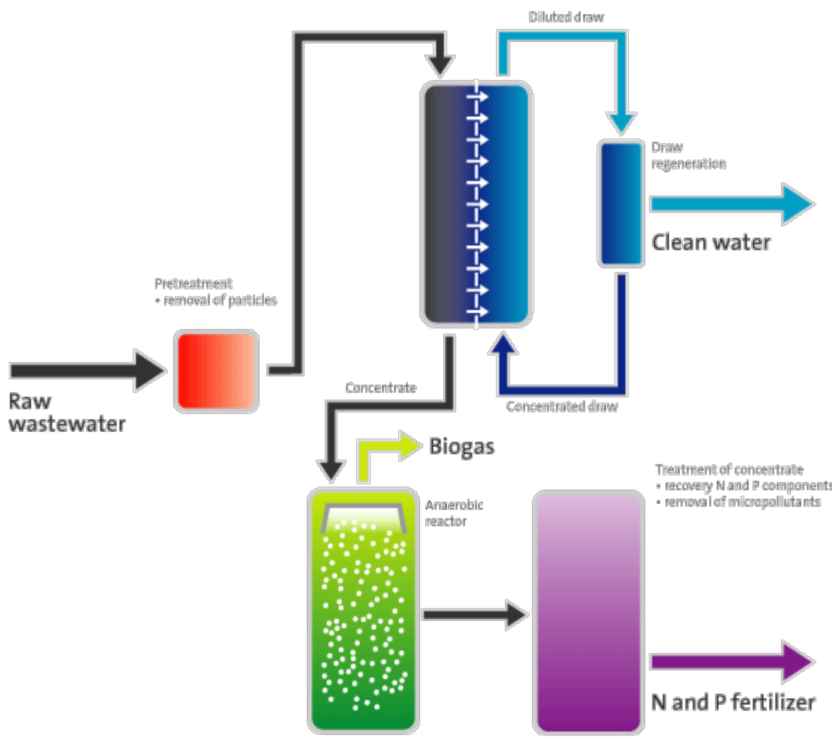


Figure 4: The new wastewater concept based on FO

Furthermore, the membrane itself should feature specific characteristics. First of all, the rejection of bulk and trace organics as well as nutrients should be very high, required by the reuse water standards. Draw solute leakage (known as reverse solute flux) should be limited, but is dependent on the costs for the draw solute and the effect on the quality of the concentrate, which might be less critical.

3.3.3 Draw solute recovery

For the draw solute recovery several technologies are available. In the case of wastewater treatment, the draw recovery should produce clean water that can be reused, preferably as drinking or high quality process water, and the system should be as energy efficient as possible. An option is to use RO in combination with energy recovery (the increase in hydraulic pressure in the diluted draw can be used as feed pressure in the RO). When waste heat is available (e.g. waste heat from the CHP when biogas from the concentrate is converted into electricity) alternative technologies, for example, membrane distillation can be used.

3.3.4 Concentrate treatment

Next to clean water a concentrate is produced in the FO process. The composition and concentration of the concentrate is dependent on the nature of the feed wastewater and recovery rate of the FO system. In Table 1 the typical concentration of domestic wastewater is shown and the composition of the concentrate when a 90% recovery rate of the FO system is applied (concentration factor 10).

Several technologies are applicable for the recovery of valuable materials and removal of unwanted components, (i) anaerobic treatment, (ii) nutrient removal and (iii) removal of micropollutants/final treatment.

3.3.4.1 Anaerobic treatment

For the production of biogas from bulk organics anaerobic treatment can be applied. High rate anaerobic reactors are available for the treatment of concentrated wastewater. COD-loadings can go up to 15 kg COD/m^3.d with a removal of up to 80%. The produced methane can be converted into electricity and heat.

3.3.4.2 Nutrient removal/recovery

In domestic wastewater treatment, nutrient removal has received a lot of attention in recent decades due to problems with eutrophication of surface water and coastal sea. Nowadays nitrogen is removed biologically by the nitrification/denitrification process converting ammonium into nitrogen gas which is released into the atmosphere. Phosphorous is normally precipitated by iron or aluminum salts. The precipitated phosphate finally ends up in the sludge. When the sludge is incinerated, which is increasingly practiced nowadays, the phosphate ends up in the ash.

From the concentrate nitrogen can be recovered by air-stripping or membrane stripping where ammonia-sulphate as a fertilizer can be produced. Phosphate can be precipitated by magnesium or calcium forming a solid fertilizer as struvite or calcium phosphate.

3.3.4.3 Removal of organic micropollutants/final treatment

After removal of the organics for biogas and nutrients for recycling, the final concentrate might contain residual COD, micropollutants and an elevated salt concentration due to the concentration process. Several post treatment technologies are available to remove these residual components:

- Aerobic treatment (MBR)
- Activated carbon filtration
- Ozonation
- Evaporation, crystallization or distillation

The technological choice strongly depends on the actual composition of the concentrate and local discharge possibilities.

3.3.4.4 VUNA concept

The most interesting option for treating the concentrate might be the so called VUNA concept.

The VUNA technology is developed at EAWAG, Switzerland for the treatment of urine converting it into a fertilizer. The VUNA technology contains the following process steps (see Figure 5):

- Nitrificatoin
- Activated carbon filtration
- Distillation

Figure 5: Scheme of the VUNA reactor together with all necessary components

The first step in the VUNA technology is a nitrification reactor. Here the malodourous liquid with high concentrations of ammonia (NH_3) is converted partially in NO_3 and heterotrophic bacteria remove the remaining bio-degradable substances. Temperature and pH are the essential parameters in the process control.
The results from the nitrification process are in line with those from research reports on biological wastewater treatment, a reasonable share of pharmaceuticals is eliminated, but effluent concentrations remain considerable and some compounds are hardly effected. An additional treatment can ensure that sufficient low pharmaceutical concentrations are achieved. For example, the adsorption to PAC is the lack of by-products.

The final step in the VUNA concept is distillation in order to minimize the cake volume and to have a pathogens-free product. State of the art distillers with vapour compression are used with 90% energy recovery. The final product is a liquid fertilizer.

The liquid fertilizer from the VUNA technology has been intensively tested. The plant growth study demonstrated that under specific growing conditions, the liquid VUNA fertilizer performed just as well as reference commercial fertilizers.

3.4 The FWW concept

Based on the above analysis a basic concept is developed for the treatment of wastewater with the new Forward Osmosis concept (Forward with Wastewater: FWW).

The FWW consist of the following process steps:

- Screen/micro-sieve
    - **Screenings as raw material for board production**
- FO-RO/FO-HBRO
    - **Final effluent (reuse, heat recovery)**
        - Concentrate treatment
            - Anaerobic treatment
            - VUNA reactor
    - **Fertilizer**

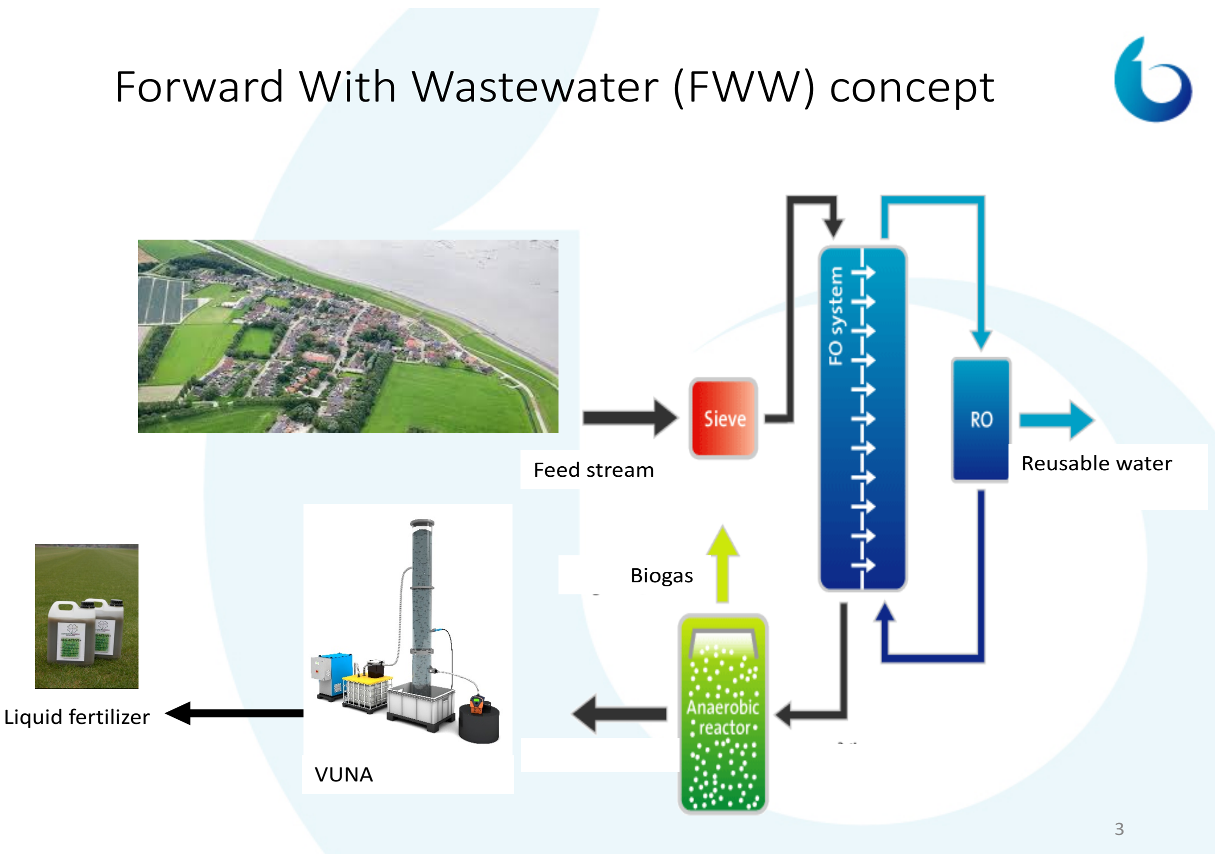


Figure 6: Forward with wastewater (FWW) concept

4. Scale up calculations

The FWW concept will consist of the following treatment steps:

Pre-treatment

The pre-treatment will be performed by a fine sieve (drum sieve) with a mesh of 200 µm. The following design parameters have been taken into account:

- Suspended solids removal 50%
- COD removal 35%
- N-Kj removal 2%
- P-tot removal 1%

The final disposal of the sieved fraction can be:

- Used as raw material for board production
- Digestion
- Incineration
- Disposal as sludge

In this study it is assumed that the sludge will be dewatered with a screw press up to 60w% and disposed of as waste sludge. The costs for disposal are set on € 60,-/ton.

FO and draw solution recovery

The forward osmosis step for concentrating the filtrate from the fine sieve is split in two sections in order to optimize the energy consumption.

FO-step 1

- FO-flux 10l/m^2.h
- Draw solution 0,5 M
- Reverse salt flux 0,2 g/l
- Draw solution recovery Brackish Water RO (BWRO)
- BWRO-flux 25 l/m^2.h
- Specific energy consumption 0,31 kWh/m^3 permeate

FO-step 2

- FO-flux 3 $l/m^2.h$
- Draw solution 1 M
- Reverse salt flux 0,2 g/l
- Draw solution recovery Sea Water RO (SWRO)
- SWRO-flux 25 $l/m^2.h$
- Specific energy consumption 2,13 kWh/m^3 permeate

General

- Reverse salt flux (RFS) 0,2 g/l
- Concentration factor 40 -

For the calculations a NaCl solution has been chosen as a draw solution. Other draw solutions can also be applied, such as KNO_3 in order to improve the quality of the final fertilizer. For this reasons the costs for adding salt due to RSF has been neglected.

It is assumed that due to the FO-RO treatment retention of the main components are around 99,8 %. Due to the high quality of the treated water it can be reused as industrial water or for irrigation. The price for this water is set at € $0,00/m^3$.

Anaerobic treatment

For the anaerobic reactor the following design parameters were taken into account:

- COD-load 3 kg $COD/m^3.d$
- COD-conversion 75%
- Biogas treatment boiler for distiller VUNA
- Boiler efficiency 90%

The produced steam from the boiler is used for the distiller in the VUNA. Calculations show that the energy production from the biogas and the energy consumption from the distiller are matching.

VUNA -reactor

- Nitrification reactor packed bed
    - Retention time 2 days
    - NH_4-N conversion 50%
    - COD conversion 30%
    - Energy consumption 0,91 kWh/m^3
- Distiller
    - Cf 20 -

- Energy consumption 50 kWh/m^3 (distillate thermal)

- Fertilizer product
    - N 6,3%
    - P 1,0%
    - COD 3,3%

For the fertilizer product a profit of € 0,50/kg is taken into account.

5. Business cases

VWNWW has defined three cases in the northern provinces of the Netherlands to assess the FWW concept.

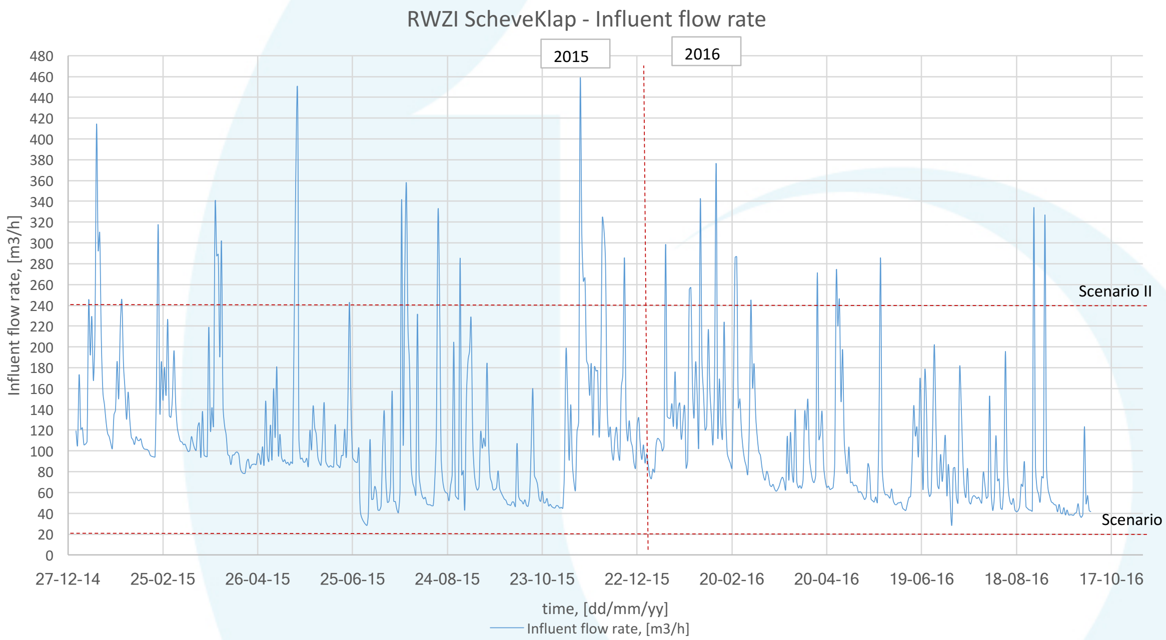
5.1 WWTP "De Scheve Klap"

WWTP "De Scheve Klap " is a small carrousel type which is currently under study. Options are to redirect the wastewater to a bigger plant or to optimize the current system.

5.1.1 Feed stream analysis

In the figure below the feed flow to the wastewater treatment is presented for the year 2015 and 2016. The feed flow of WWTP is strongly influenced by rainwater and probably also by leakage of ground water in the sewer system (high flows in the winter). As the FWW is a membrane based treatment technology relatively high and varying flows are not favourable.

Inflow design capacity



Scenario I

- Qdesign = 20 m3/h
- The rest of the flow is treated by the existing system
- No buffer tank

Scenario II

- Qdesign = 240 m3/h
- All ww is treated by the proposed concept
- Buffer tank volume = 6,576 m3
- HRT = 3 days

Figure 7: Annual influent flow rate – RWZI Scheveklap

For the calculations of the FWW concept two scenarios are examined:

- Scenario I: design flow of 20 m^3/h , the rest is treated by the existing system
- Scenario II: design flow 240 m^3/h and a buffer tank of 6.576 m^3

5.1.2 Dimensioning

In the tables below the dimensioning of the FWW for the Scheve Klap are presented for the mentioned scenarios, including a cost analysis and comparison with the current system

Proposed FWW concept	Scenario I	Scenario II	
Inflow capacity	**20**	**240**	**m3/h**
Average annual feed flow	**20**	**78**	**m3/h**
Population equivalent	**3,000**	**7,500**	**p.e.**
Reducing inflow peaks			
Buffer tank volume	0	6,576	m3
HRT	0	3	days
Sieve			
Cake (60 wt%)	0.11	0.44	ton/d
Energy consumption	0.09	0.36	kW
FO-BWRO/FO-SWRO (CF=40)			
FO membrane surface area	2066.19	8,058.13	m2
# FO membrane elements	135	1,756	qty
RO membrane surface area	761	3,041.29	m2
# RO membrane elements	22	266	qty
Permeate production	467.89	1,824.78	m3/d
Total energy consumption	6.84	38.89	kW
Anaerobic reactor			
Volume anaerobic reactor	42.62	166.23	m3
Biogas production	33.57	130.91	Nm3/d
Energy production	10.47	40.83	kW
VUNA			
Volume nitrification reactor	23.99	93.58	m3
Energy consumption Nitrif. Reactor	0.44	1.71	kW
Distillate production	11.40	44.45	m3/d
Energy consumption Distiller	23.74	92.60	kW
Total energy consumption	24.18	94.31	kW
Product			
Flow	0.60	2.34	m3/d
N	3.14	3.14	wt%
P	0.71	0.71	wt%

Proposed FWW concept		Scenario I		Scenario II	
Inflow capacity		**20**		**240**	**m3/h**
Average annual feed flow		**20**		**78**	**m3/h**
Population equivalent		**3,000**		**7,500**	**p.e.**
Investment	€	858,383.91	€	9,454,197.26	
Cake disposal	€	2,444.04	€	9,531.76	
Electrical energy	€	18,673.18	€	72,825.40	
Membrane costs	€	36,841.43	€	143,681.59	
Personell	€	25,000.00	€	50,000.00	
Maintenance	€	21,459.60	€	236,354.93	
Interest	€	25,751.52	€	283,625.92	
Depreciation	€	60,086.87	€	661,793.81	
Income fertilizer	€	109,474.54	€	426,950.71	
Total costs	**€**	**80,782.10**	**€**	**1,030,862.69**	
Costs per capita	**€**	**26.93**	**€**	**137.45**	

	Current treatment system			Scenario I	Scenario II	Units
Inflow capacity				**20**	**240**	**m3/h**
Average annual feed flow		**78**		**20**	**78**	**m3/h**
Population equivalent		**7,500**		**3,000**	**7,500**	**p.e.**
Sludge production	fraction		fraction			
Sludge volume		2818		40.73	158.86	tonnes/year
Water content	97%	2740	60%	24.44	95.32	tonnes water/year
Dry matter	3%	78	40%	9.78	63.55	tonnes/year
Energy consumption						
Aeration energy consumption	66%	115,707	2%	3,839	14,971	kWh
Total energy consumption		175,514		208,294	812,348	kWh
Product						
Fertilizer production		0		218.95	853.90	m3/year
Clean water production		0		174,940	682,267	m3/year

5.1.3 Conclusion

Replacing WWT “De Scheve Klap” by the FWW system the sewer system should be renovated, so that the sewage is not diluted by rain water or leakage water. In such a case the FWW system would be more economic than a classical wastewater treatment system. Costs for renovating the sewer system have not been taken into account in the comparison.

5.2 FWW on the Wadden island Terschelling

Terschelling wants to become a self-sufficient sustainable island. By producing a fertilizer form wastewater and reducing sludge production FWW can be an attractive option. Interesting about the Terschelling option is that sea water can be used as a draw solution, what will lead to an energy saving for the treatment. Drawback of this way of treatment is that the effluent cannot be reused.

5.2.1 Feed stream analysis

In figure 8 the feed flow of the WWTP Terschelling is shown. The feed flow of WWTP is strongly influenced by rainwater and season variations.

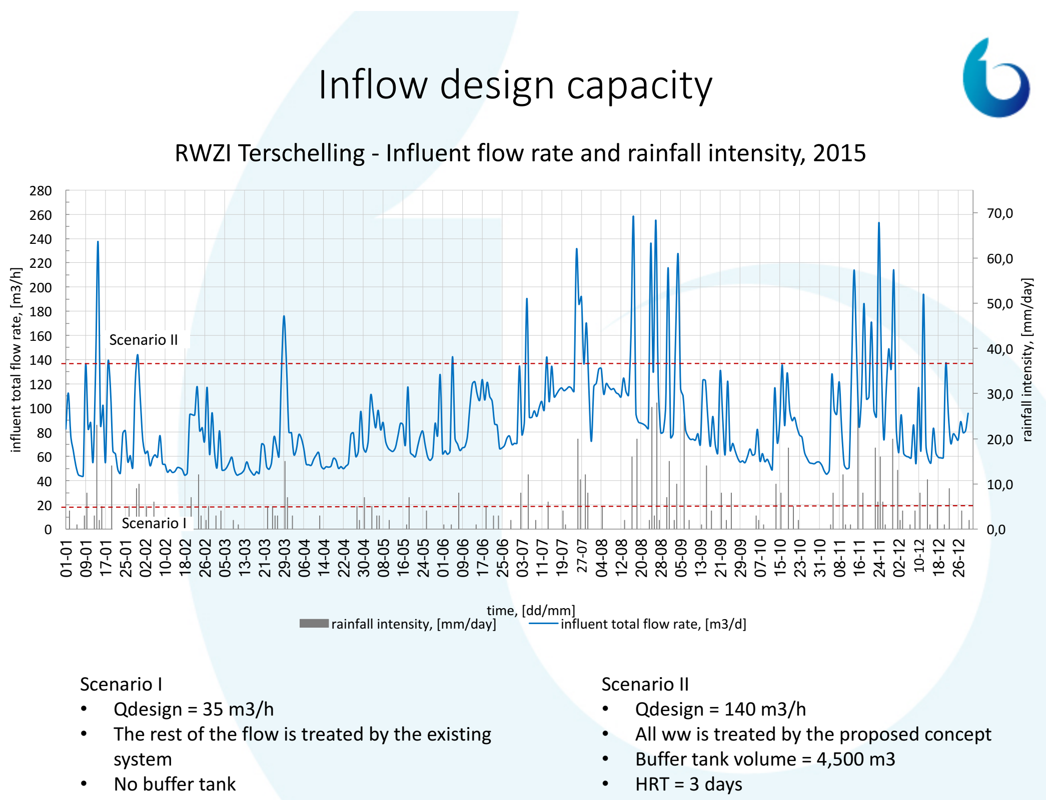


Figure 8: Annual inflow rate and rainfall intensity – RWZI Terschelling

For the calculations of the FWW concept two scenarios are examined:

- Scenario I: design flow of 35 m^3/h , the rest is treated by the existing system
- Scenario II: design flow 140 m^3/h and a buffer tank of 4.500 m^3

5.2.2 Dimensioning

In the tables below the dimensioning of the FWW for the Terschelling case are presented for the mentioned scenarios, including a cost analysis and comparison with the current system.

Proposed FWW concept	**Scenario I**	**Scenario II**	
Inflow capacity	**35**	**140**	**m3/h**
Average feed flow	**35**	**80.54**	**m3/h**
Population equivalent	**4,908**	**11,293**	**p.e.**
Reducing inflow peaks			
Buffer tank volume	-	4,500	m3
HRT	-	3	days
Sieve			
Cake (60 wt%)	0.31	0.54	ton/d
Energy consumption	0.26	0.45	kW
FO-Sea water/FO-SWRO			
FO membrane surface area	3615.32	19871.4	m2
# FO membrane elements	236	1299	qty
SWRO membrane surface area	34.34	137.4	m2
# SWRO membrane elements	1	3	qty
Permeate production	20.99	48.31	m3/d
Total energy consumption	10.84	23.4	kW
Anaerobic reactor			
Volume anaerobic reactor	110.26	253.7	m3
Biogas production	86.83	199.8	Nm3/d
Energy production	28.18	64.8	kW
VUNA			
Volume nitrification reactor	41.98	96.6	m3
Nitrif. reactor energy consumption	1.08	2.5	kW
Distillate production	19.94	45.9	m3/d
Distiller energy consumption	41.55	95.6	kW
Product			
Flow	1.05	2.4	m3/d
N	4.36	4.36	wt%
P	0.65	0.65	wt%

Proposed FWW concept	Scenario I	Scenario II	
Inflow capacity	**35**	**140**	**m3/h**
Feed flow	**35**	**80.54**	**m3/h**
Population equivalent	**4,908**	**11,293**	**p.e.**
Investment	€ 1,472,816.35	€ 5,285,791.02	
Cake disposal	€ 6,861.49	€ 11,747.97	
Electrical energy	€ 19,938.06	€ 95,777.34	
Membrane costs	€ 54,487.33	€ 172,052.20	
Personell	€ 25,000.00	€ 50,000.00	
Maintenance	€ 36,820.41	€ 132,144.78	
Interest	€ 44,184.49	€ 158,573.73	
Depreciation	€ 103,097.14	€ 370,005.37	
Income fertilizer	€ 191,553.53	€ 440,834.13	
Total costs	**€ 98,835.39**	**€ 549,467.26**	
Costs per capita	**€ 20.14**	**€ 48.65**	

Current treatment system				Scenario I	Scenario II	Units
Inflow capacity		**470**		**35**	**140**	**m3/h**
Average feed flow		**80.54**		**35**	**80.54**	**m3/h**
Population equivalent				**4,908**	**11,293**	**p.e.**
Sludge production	fraction		fraction			
Sludge volume		5200		114.36	195.80	tonnes/year
Water content	96%	4992	60%	68.61	117.48	tonnes water/year
Dry matter	4%	208	40%	27.45	78.32	tonnes/year
Energy consumption						
Aeration energy consumption	71%	330,243	4%	9,446	21,736	kWh
Total energy consumption		462,600		223,821	500,067	kWh
Product						
Fertilizer production		-		383.11	881.67	m3/year
Clean water production		-		14,941	34,385	m3/year

5.2.3 Conclusion

The business cases for Terschelling are more interesting than the “Scheve Klap”. This is mainly due to the use of “free” seawater as a draw solution. Also in this case a mixed sewer system with rain water is making the business case less attractive.

5.3 FWW at the Zoo "Wildlands" in Emmen

At the "Wildlands" Zoo in Emmen the domestic wastewater together with the concentrate of several filters (UF, drum sieves) is currently treated by a so called living machine. The living machine is a more or less conventional activated sludge treatment plant, which is partly integrated in the park. The advantage of applying the FWW concept is a smaller unit, where a fertilizer is produced, which can be applied directly in the park.

5.3.1 Feed stream analysis

The feed stream to the "living machine" is shown in figure 9. Next to domestic wastewater also reject of the UF is mixed with this feed. This is a relatively large clean water flow.

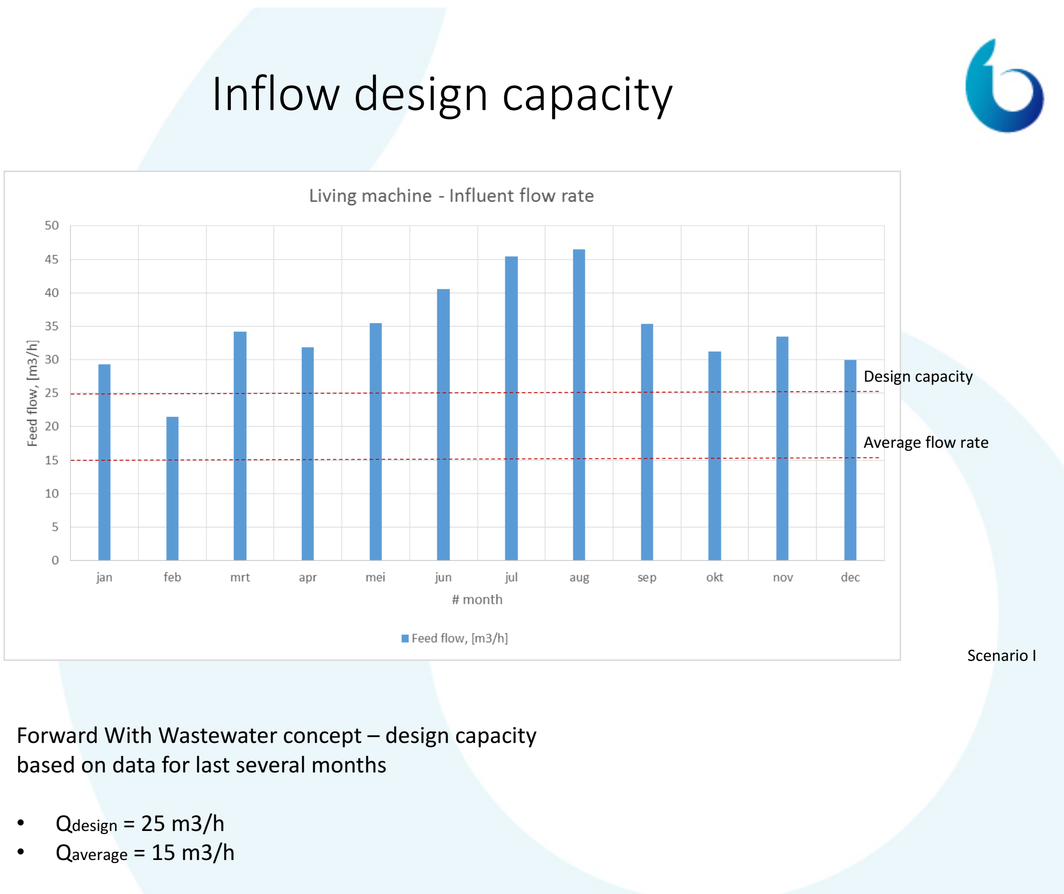


Figure 9: Annual influent flow rate for the 'Living machine' – Zoo Wildlands in Emmen

For the calculations of the FWW concept two scenarios are examined:

- Scenario I: design flow of 25 m^3/h (15 m^3/h average) including back wash water UF
- Scenario II: design flow 12,5 m^3/h (7,5 m^3/h average) excluding back wash water UF

5.3.2 Dimensioning

In the tables below the dimensioning of the FWW for the “Wild Land Zoo” case are presented for the mentioned scenarios, including a cost analysis and comparison with the current system. For the Wild Lands case the price for the fertilizer had been set on euro 0,05/kg due to the lower concentration of produced fertilizer.

	Scenario I	Scenario II	
Desing capacity	**25**	**12,5**	**m3/h**
Average inflow rate	**15**	**7,5**	**m3/h**
Amount of visitors	**1.700.000**	**1.700.000**	**persons**
Sieve			
Cake (60 wt%)	0,04	0,04	ton/d
Energy consumption	0,03	0,03	kW
FO-BWRO/FO-SWRO (CF=40)			
FO membrane surface area	2583,18	1291,51	m2
# FO membrane elements	169	84	qty
RO membrane surface area	975	487	m2
# RO membrane elements	26	13	qty
Permeate production	350,97	7,31	m3/d
Total energy consumption	5,13	3,74	kW
Anaerobic reactor			
Volume anaerobic reactor	11,34	7,73	m3
Biogas production	6,07	6,11	Nm3/d
Energy production	0,69	1,50	kW
VUNA			
Volume nitrification reactor	30,00	15,00	m3
Energy consumption Nitrif. Reactor	0,12	0,12	kW
Distillate production	4,50	2,25	m3/d
Energy consumption Distiller	9,37	4,69	kW
Total energy consumption	9,49	4,80	kW
Product			
Flow	4,50	2,25	m3/d
N	0,12	0,24	wt%
P	0,02	0,05	wt%

		Scenario I			
Inflow capacity		**25**		**12,5**	**m3/h**
Average annual feed flow		**15**		**7,5**	**m3/h**
Amount of visitors		**1.700.000**		**1.700.000**	**persons**
Investment	€	994.316,34	€	549.783,25	
Cake disposal	€	784,02	€	784,02	
Electrical energy	€	12.835,83	€	5.554,66	
Membrane costs	€	27.634,75	€	13.816,00	
Personell	€	25.000,00	€	25.000,00	
Maintenance	€	15.943,60	€	9.346,54	
Interest	€	19.132,32	€	11.215,85	
Depreciation	€	44.642,08	€	26.170,32	
Income fertilizer	€	82.116,83	€	41.054,33	
Total costs	**€**	**63.855,77**	**€**	**50.833,06**	
Costs per capita	**€**	**0,04**	**€**	**0,03**	

Current treatment system				Scenario I	Scenario II	Units
Desing capacity				**25**	**12,5**	**m3/h**
Average inflow rate		**15**		**15**		**m3/h**
Amount of visitors		**1.700.000**		**1.700.000**		**persons**
Sludge production	fraction		fraction			
Sludge volume		2920		13,07	13,07	m3/year
Water content	-	-	60%	7,84	7,84	tonnes water/year
Dry matter	-	-	40%	3,14	5,23	tonnes/year
Product						
Fertilizer production		0		1.642	821	m3/year
Energy consumption						
Living machine	100.000	kWh	pre-treatment + FO	20.860	10.560	kWh
UF	5000	kWh	RO	44.926	22.461	kWh
UV	2600	kWh	VUNA	77.095	28.959	kWh
Total energy consumption	107.600	kWh	Total energy consumption	142.882	61.980	kWh

5.3.3 Conclusion

The costs for treatment of the domestic wastewater at Wildlands with the FWW concept are very low per visitor. It also offers the opportunity to reuse the wastewater and produce fertilizer for the park at the same time.

6. Sensitivity analyses

6.1 Feed flow

The feed flow has a strong impact on the feasibility of the FWW concept. This is due to the fact the costs of FO and RO are directly related to the flow, as well in energy consumption as investment.

As can be seen from all three cases peaks in feed flow are present:

- Leakage of ground water in the sewer system (Scheve Klap)
- Rain water peaks (Scheve Klap and Terschelling)
- UF-back wash water (Wild lands)

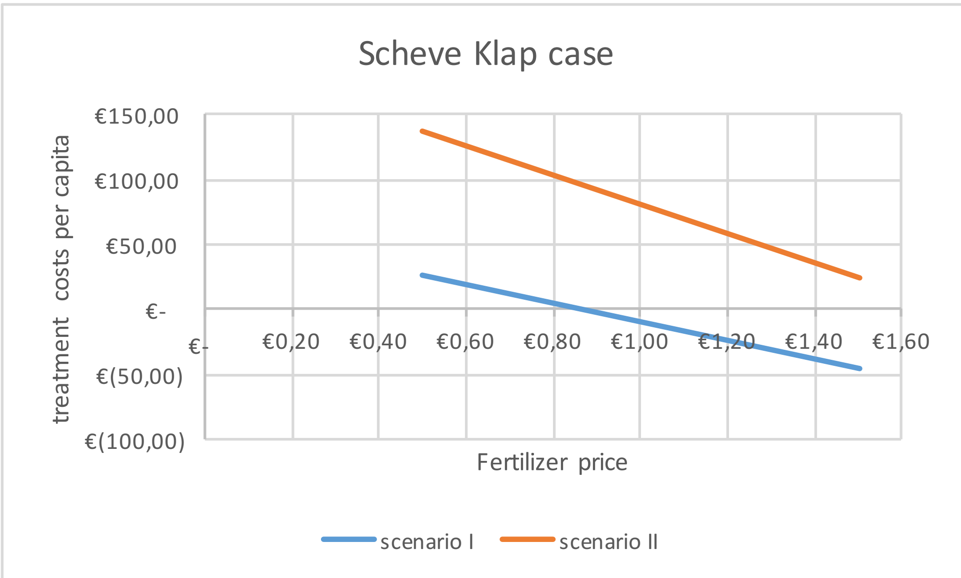
In the current situation business cases are only acceptable when there is no additional dilution of the wastewater. This is the case where there is a new sewer system without rainwater and leaking of ground water. In those cases a flow close to dry water flow of 150 l/ per person per day can be taken into account.

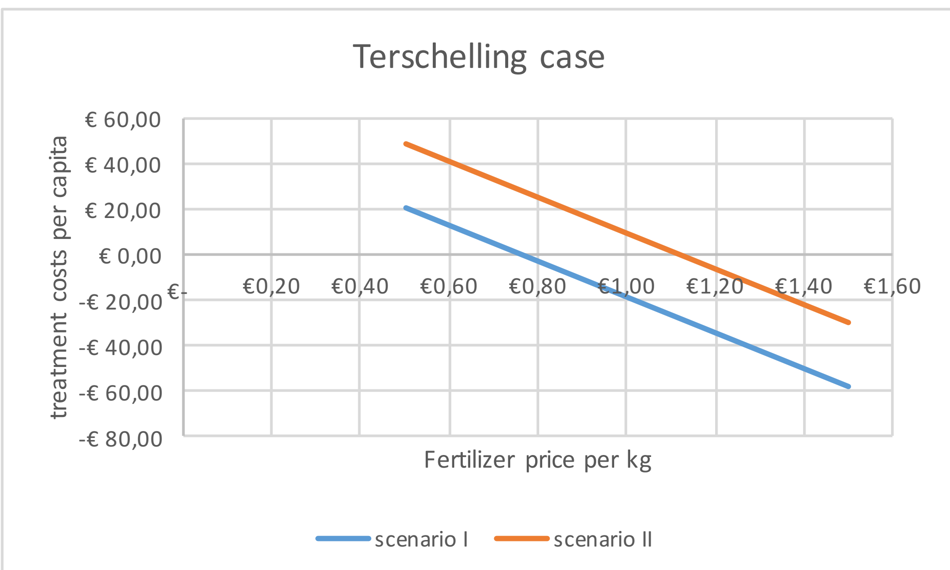
6.2 Income of fertilizer product

The composition of the fertilizer product is very close to the commercially sold liquid fertilizer products. The fertilizer product produced from the VUNA installation in Switzerland is certified for usage in domestic applications, like gardening, golf courses, etc.

The commercial prices for these products ranges from € 5 – to € 15,-./kg. Based on experiences of the EAWAG the raw price for the unpacked fertilizer should be in the range of € 0,50 to € 1,50,-/kg. For the Wildlands case the fertilizer price is set between € 0,05 and 0,15 per kg due to a more diluted fertilizer product.

The effect of the price of the fertilizer on the p.e. price for the different cases is shown in figure 10 below.


Scheve Klap case
€150,00
€100,00
€50,00
€-
€(50,00)
€(100,00)
treatment costs per capita
€-
€0,20
€0,40
€0,60
€0,80
€1,00
€1,20
€1,40
€1,60
Fertilizer price
scenario I
scenario II


Terschelling case
€ 60,00
€ 40,00
€ 20,00
€ 0,00
-€ 20,00
-€ 40,00
-€ 60,00
-€ 80,00
treatment costs per capita
€-
€0,20
€0,40
€0,60
€0,80
€1,00
€1,20
€1,40
€1,60
Fertilizer price per kg
scenario I
scenario II

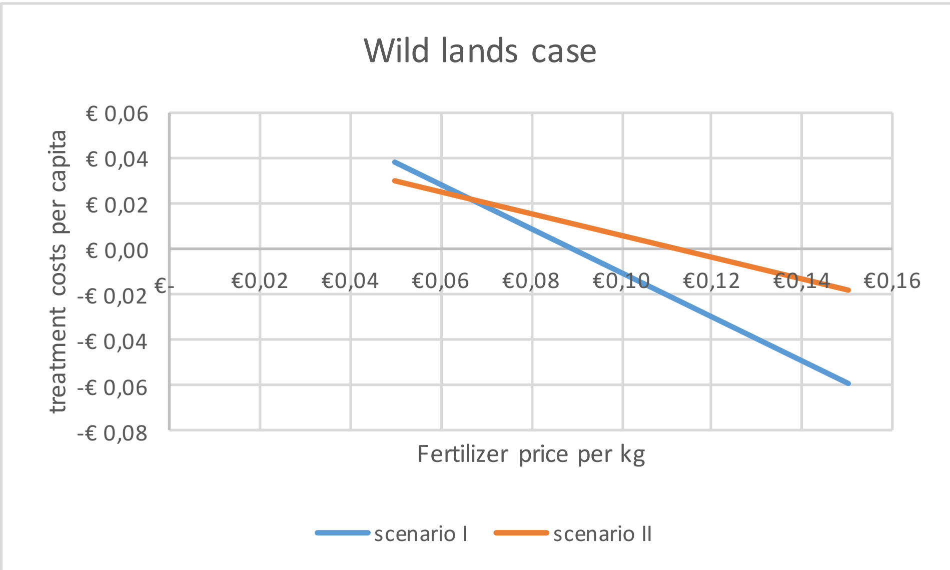
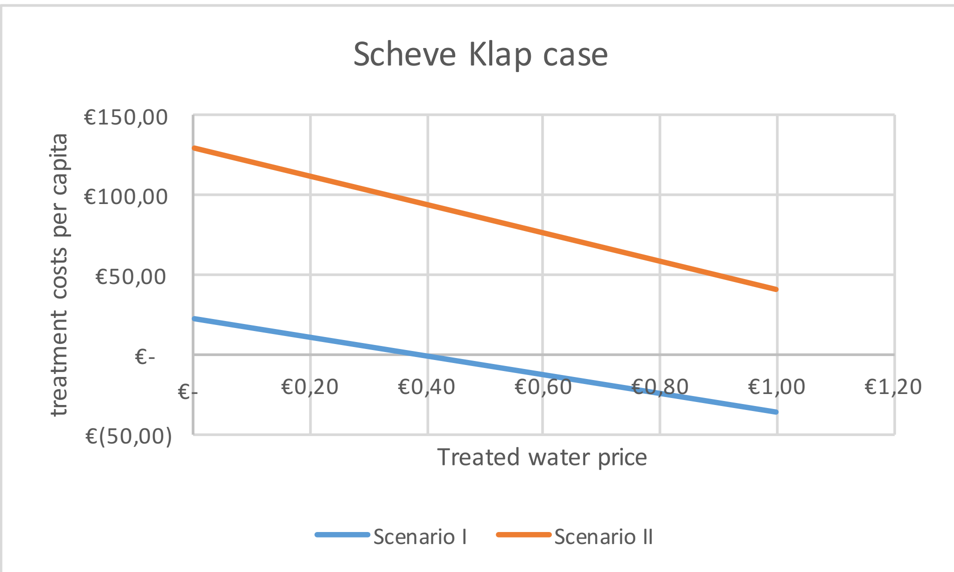


Figure 10: Correlation between fertilizer prices and the size of the FWW plant

Effluent price

In the base case an effluent price of € 0,- has been taken into account. However, the effluent quality of FWW plant is with extremely good quality, which will open options for effluent reuse. The sensitivity of the pe price connected with the effluent prices in the range of €0,- to €1,00 is shown in figure 11. For the Terschelling case this cannot be calculated as the effluent is discharged to the sea as diluted se water.



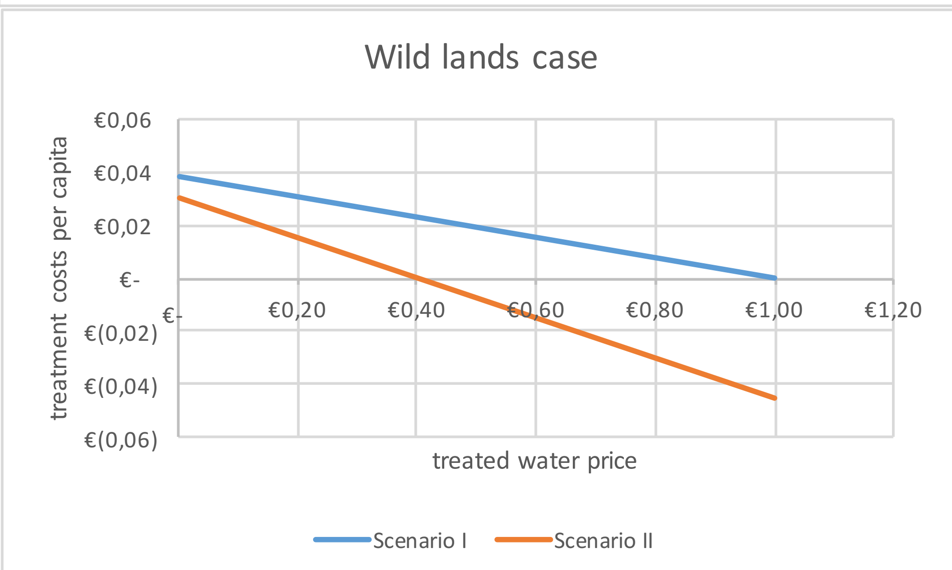
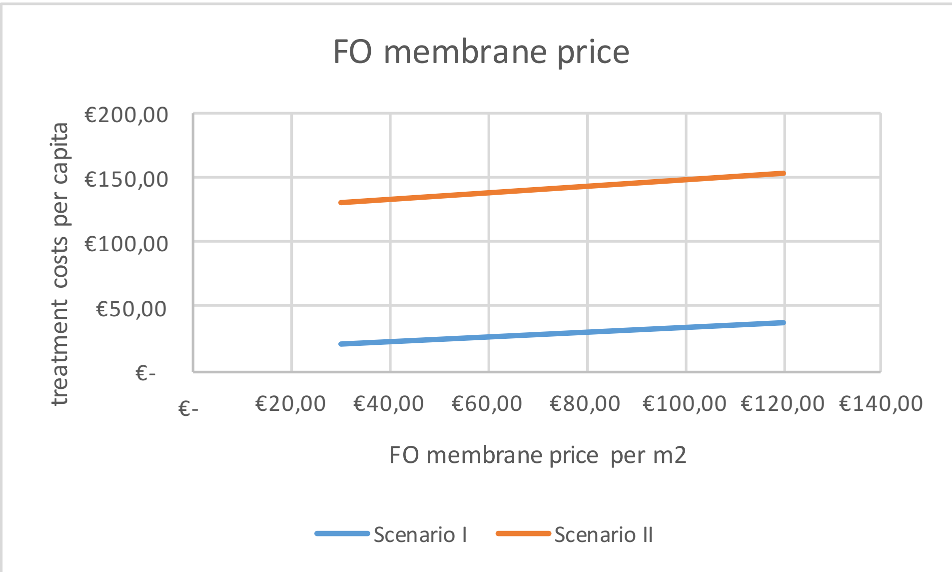
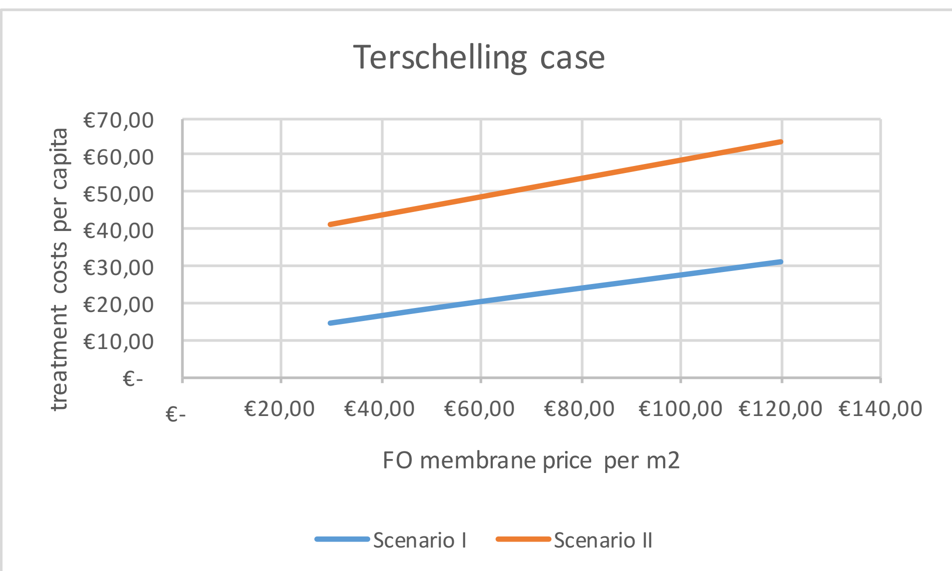


Figure 11: Permeate prices in relation with prices per population equivalent

FO-membrane price

Forward Osmosis is a fast developing technology. The current membrane module price is around € 120,-/m^2. The last few years a fast decrease in the price can been observed. It is expected that in the future the FO price will be close to the RO price (€ 25,- to € 30,-/m^2). In figure 12 the effect of the FO membrane price on the pe price is shown.





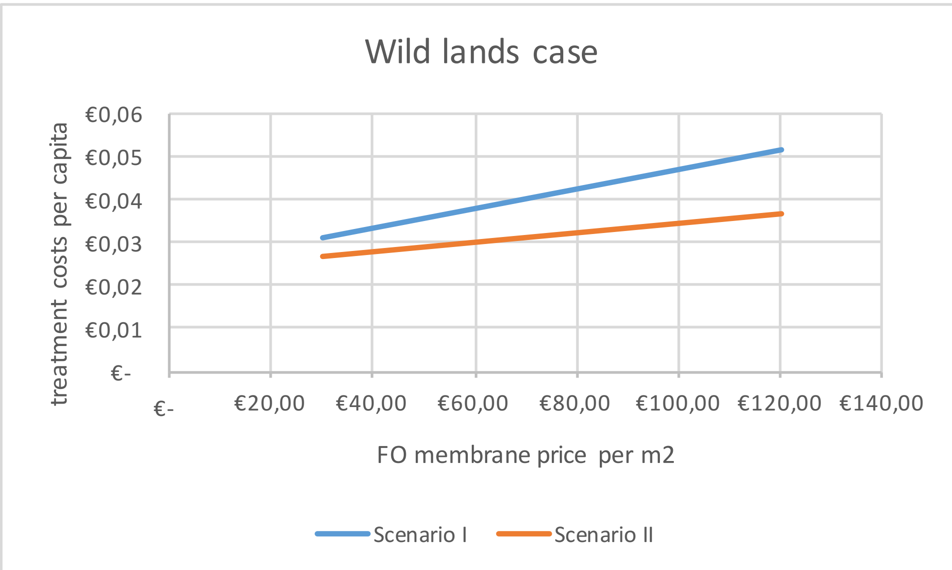


Figure 12: Correlation between FO membrane prices and prices per population equivalent

7. Comparison with classical treatment

7.1 Introduction

It is quite difficult to make a straight comparison between the FWW-concept and classical wastewater treatment processes since the FWW-concept is focused on recycling all the valuables from wastewater, including nutrients and the primary goal of classical wastewater treatment is focused on producing dischargeable water.

Below, the comparison between FWW and classical treatment is made on several specific aspects, such as energy requirements, sustainability and environmental aspects, space requirements, and costs.

7.2 Energy requirements

In the FWW process the following energy sources can be distinguished:

- Electrical energy for the FWW process: - 215 MJ/pe
- Energy consumption for the distiller process: covered by the energy from the biogas
- Potential energy production from sludge cake: + 150 to +200 MJ/pe
- Energy savings Haber-Bosch (from product): + 52 MJ/pe

From the energy balance it can be concluded that the energy balance for the FWW process is close to neutral with a total energy consumption of – 37 to + 7 MJ/pe. This means that the FWW concept is energy neutral to energy producing, which is better than the achievement of current WWTPs. Developing the plant in a way to utilize all the produced energy will increase the capital and exploitation costs, but will drastically reduce the energy consumption. It is possible that the FWW plant becomes an energy producer which compared to the conventional WWTP is a considerable advantage.

7.3 Sustainability & environmental aspects

- No discharge of micro-pollutants
- Recovery of effluent
- Recovery of nutrients
- Energy neutral

Sustainability is one criterion that has many indicators. In the case of a WWTP most important to look at are: quality of effluent, possible reusability, energy consumption, chemical use, sludge production.

The quality of the effluent is one of the most important characteristics of a WWTP. In the case of the FWW plant, due to the membrane treatment all the pollutants, including hard to treat micro-pollutants, are retained by the membrane. This means, that there is no need for special post-treatment to prevent mirco-pollutants' discharge into the environment. At the same time, the produced permeate is of high quality and is suitable for reuse.

Another important aspect of the FWW plant, which increases its sustainability level is the fact that the concentrate, produced via the membrane technologies, is converted to fertiliser. Unlike current WWTPs where nutrients such as

N and P are lost during the process of treatment, in the FWW plant, these nutrients are recovered. Additionally, conventional treatment not only removes the nutrients, but also produces greenhouse gasses such as CO_2, N_2, whereas in the FWW plant, no greenhouse gas emissions are released.

Finally, because the wastewater influent is pre-concentrated to a factor of 40, the size of the bioreactor is drastically reduced. This affects the footprint of the plant, but most importantly, it significantly affects the energy consumption. Due to higher concentration of the wastewater, the treatment is performed by anaerobic bioreactor, which does not require energy for aeration and at the same time produces bio gas that can be reused at the plant. Naturally, the effluent flow of the anaerobic bioreactor has a reduced volume of a factor 40 due to the FO, which leads to smaller VUNA installation and even smaller final treatment step – distiller. The decrease in size leads to concomitant decrease of energy consumption.

7.4 Space requirements

Rough estimations were made on the FWW plant space requirements for a 10.000 p.e. plant. Considering the size of each treatment technology, spaces chemicals’ storage, maintenance, roads, etc. the total area required amounts to 1500m².

A classical WTTP of 10.000 p.e. has an space requirement of around 5.000 – 10.000 m^2 depending on the set up and the actual type of treatment (activated sludge, oxidation ditch, etc.). In general, it can be stated that the space requirements for the FWW process are equal or smaller than a classical treatment process.

7.5 Costs

Current costs for large scale classical WWTP are around € 50,- per pe.

From this study it is shown that the costs for the FWW concept can vary between minus € 50,- to plus € 150,- per varying on several factors, like:

- Dilution of the wastewater by rain water or other dilution water
- Price for the fertilizer
- Availability of a cheap (free) draw solution
- Price for the effluent (reuse)
- Development of the FO-membrane price

In general, the price for the treatment unit should be established case by case.

8. Conclusions & recommendations

This study consisted of tests with the FO-RO system to concentrate raw waste water and calculated three business cases:

- Wastewater treatment “De Scheve Klap”
- Wastewater treatment at Terschelling
- Wastewater treatment at the zoo “Wildlands” in Emmen

Based on the results from the three business cases the following conclusions can be drawn:

- By applying the FWW concept, it is possible to achieve direct production of clean reusable water, liquid fertilizer and dry biomass (60w%) originating from domestic wastewater
- There is no discharge of micro-pollutants, also energy neutrality can be reached, which makes the FWW concept an economic and sustainable alternative to the conventional wastewater treatment
- The economic viability varies considerably depending on the price for liquid fertilizer, the dilution of wastewater by rainwater or groundwater infiltration and the abundance of a saltwater source
- The proposed treatment system has a smaller footprint than the conventional systems
- From an energy perspective, the FWW concept proved to be more sustainable than the conventional treatment systems, when wastewater is not diluted (rainwater, groundwater infiltration)

Further research needs to be done:

- Feasibility study on the application of the FWW concept for treatment of source separated domestic wastewater (decentralized sanitation) for newly built residential buildings and wastewater transported by pipe-in-pipe solutions for existing buildings
- Experimental tests for the FO technology for rising the Technology Readiness Level (TRL) from 5 to 6 for more clear identification on the technological gaps
- As a final step a demonstration unit should be developed, which will increase the TRL from 7 to 9

The FWW process seems an interesting alternative for the treatment of domestic wastewater. The sustainability level is very promising, as far as possible valuable materials are reused (such as N and P) and harmful substances are removed (such as micro-pollutants and pathogens). The economic feasibility seems interesting; however, all this depends on the quality of the recovered material and the specific situation.