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A techno-economic analysis of membrane-based advanced treatment processes for the reuse of municipal wastewater

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ABSTRACT

The objective of this paper is to compare, under Dutch market conditions, the energy consumption and net costs of membrane-based advanced treatment processes for three water reuse types (i.e. potable, industrial, agricultural reuse). The water source is municipal wastewater treatment plant effluent. Results indicate that the application of reverse osmosis is needed to reclaim high quality water for industrial and potable reuse but not for irrigation water which offers significant energy savings but may not lead automatically to lower net costs. While a reclamation process for industrial reuse is economically most promising, irrigation water reclamation processes are not cost effective due to low water prices. Moreover, process operational expenditures may exceed capital expenditures which is important for tender procedures. A significant cost factor is waste management that may exceed energy costs. Water recovery rates could be significantly enhanced through the integration of a softener/biostabilizer unit prior to reverse osmosis. Moreover, the energy consumption of wastewater reclamation processes could be supplied on-site with solar energy. The possibility of designing a 'fit for multi-purpose' reclamation process is discussed briefly. This comparative analysis allows for better informed decision making about which reuse type is preferably targeted in a municipal wastewater reuse project from a process design perspective.

Key words: cost-benefit analysis, process innovation and optimization, sustainability, techno-economic assessment, water-energy nexus, water reuse

HIGHLIGHTS

- Water prices determine the economic feasibility of water reuse.
- Brine treatment costs exceed energy costs in processes that apply reverse osmosis.
- Operational expenditures of reuse processes are higher than capital expenditures.
- A softener/biostabilizer unit as reverse osmosis pre-treatment may significantly improve the recovery rate, energy consumption and cost effectiveness of water reclamation processes.

INTRODUCTION

Humans consume water across the globe for domestic consumption, industrial manufacturing purposes and agriculture. While the industrial sector, and especially the power generation industry, is in many western countries the largest consumer of abstracted freshwater, agriculture is responsible for the highest water abstraction rates in other countries (Blackhurst *et al.* 2010; Ranade & Bhandari 2014). Water scarcity is the geographic and temporal mismatch between freshwater demand and availability and is expected to be increased due to climate change, increasing population, improving living standards, changing consumption patterns, water pollution, and expansion of irrigated agriculture (Paranychianakis *et al.* 2015; Mekonnen & Hoekstra 2016; WWAP 2017). The reclamation of water from municipal wastewater treatment plant (WWTP) effluents has been widely recognized as a practical alleviation of regional water scarcity (Trussel 2012; Lazarova *et al.* 2013; Eslamian

2016; Fatta-Kassinos *et al.* 2016) and is therefore promoted politically by the European Commission (European Commission 2018).

Several technologies have been proposed to reclaim water from municipal wastewater, such as advanced oxidation (Oturan & Aaron 2014), pollutant adsorption technology (ALOthman & Wabaidur 2019), activated carbon (Luukkonen *et al.* 2019) or constructed wetlands (Vymazal 2010). Membrane-based technologies have attracted special attention because membranes act as a physical barrier for a wide range of contaminants including contaminants of emerging concerns (CECs) (Fatta-Kassinos *et al.* 2016). Especially, ultrafiltration (UF) and reverse osmosis (RO) have been successfully applied in full scale WWTP effluent reclamation processes (Shang *et al.* 2011; Helmecke *et al.* 2020). Another advantage of membrane processes is that they can flexibly be scaled up with different unit operations and membrane types to add treatment capacity if necessary (Quist-Jensen *et al.* 2015). Various full-scale studies have demonstrated that membrane-based advanced treatment processes (MATP) can be designed to reclaim WWTP effluents for all three water usage types: (i) (in)direct potable reuse for domestic consumption (Ortuño *et al.* 2012; Chalmers & Patel 2013; Van Houtte & Verbauwhede 2013), (ii) demineralised process water for industrial reuse (Majamaa *et al.* 2010; Shang *et al.* 2011) and (iii) irrigation water for agricultural reuse (Hamoda *et al.* 2015).

Despite the proven applicability and advantages, two main bottlenecks have been repeatedly identified in scientific literature that need to become optimized to make membrane driven wastewater reuse even more feasible. Those are the high energy consumption due to required operational pressure and high process operational and investment costs (Verstraete *et al.* 2009; Yangali Quintanilla 2010; Batstone *et al.* 2015; Eslamian 2016; Helmecke *et al.* 2020). Little is known about the generic differences in energy consumption and costs of MATPs that reclaim WWTP effluents for different reuse types.

This is because a generic comparison between existing case studies that reclaim wastewater for the three reuse types is difficult due to different unit operations applied in each case study, differing feed water compositions, and different methods to calculate energy consumption and process costs. Therefore, it is difficult to state from an energy and cost perspective which reuse type should be preferably targeted by a wastewater reuse project and why. To provide decision guidance from a reclamation process performance perspective and enable a fair comparison, a common reference has to be defined. The WWTP effluent quality, the applied unit operations and the process assessment methodology should be consistent. Only then can a valid comparison of MATP performances for different reuse types be carried out (Raffin *et al.* 2013).

It is unquestionable that the energy consumption and process net costs of MATPs depend on the targeted reuse type because it defines the required water quality and consequently the process design. This also implies that each MATP has different water recovery rates and therefore, revealing the different energy consumption and costs of each reuse type requires a comparison of results based on m^3 reclaimed water. In addition, market prices for reclaimed water may differ significantly (e.g. potable water is usually more expensive than irrigation water) and a fair net cost comparison needs to take this into account.

The primary goal of this study is to estimate and compare the net costs and the energy consumption of MATPs that reclaim wastewater for industrial, potable, and agricultural use. This is achieved by theoretically designing and modelling four different MATPs that are all based on the same core process (Figure 1). The reclamation of WWTP effluents to alleviate water scarcity can conflict with other sustainability related goals of water utilities. For example, due to a high energy consumption and brine production of MATPs, their environmental footprint including CO_2 emissions has been criticized (Daigger 2008; Delacamera *et al.* 2016). The sustainability of an MATP is defined in this study by its energy consumption, water recovery rate, and costs. Regarding the water-energy nexus we argue that due to renewable energy conversion technologies energy is a less critical resource compared to water, which should therefore be prioritised. The second goal of this study is therefore to present two different process optimisation possibilities that further improve the sustainability of MATPs. One possibility is the integration of renewable energy technologies (i.e. solar energy and biogas). The area of photovoltaic modules required to run the modelled MATPs solely on solar energy is calculated assuming Dutch climate conditions. Another possible renewable energy integration system investigated is the recovery of electricity from the chemical oxygen demand (COD) contained in municipal wastewater via anaerobic digestion (Rulkens 2008).

The second process optimisation possibility studied is the integration of a softener/biostabilizer RO pre-treatment to increase the RO recovery rate. Practical experiences from full scale UF-RO reclamation processes report severe biofouling potential in RO which leads to extensive membrane cleaning (Majamaa *et al.* 2010). Although the UF is successful in total suspended solids (TSS) removal, its capability to provide high-quality RO feed water is limited as it does not remove pollutants responsible for scaling, organic and bio fouling. Designing an RO pre-treatment that is more robust to variable feed water qualities would improve RO recovery rates, energy consumption and brine production (Slagt & Henkel 2019).

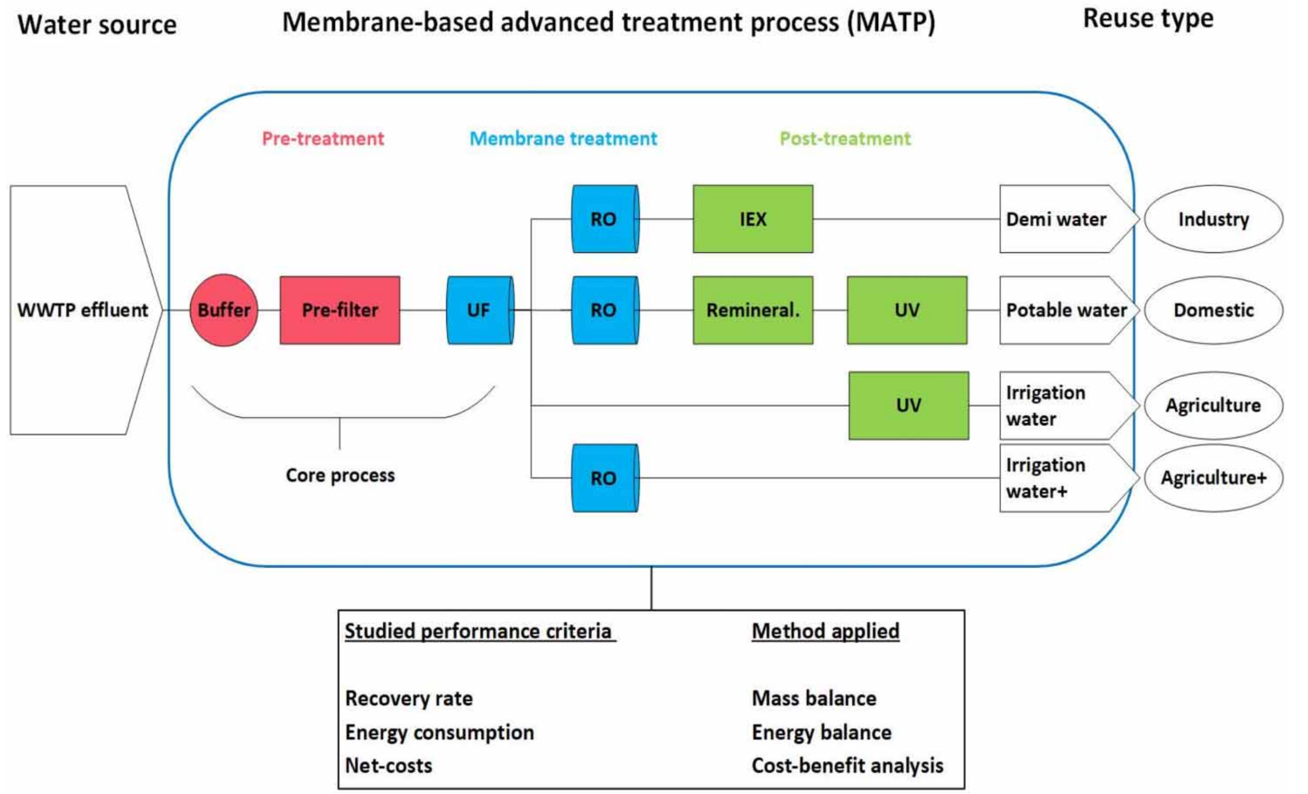

Figure 1 | Scope and concept of the study with system boundaries in blue rectangle. Four individual MATP designs have been modelled. Irrigation water is reclaimed by two processes where 'irrigation water+' indicates the higher water quality obtained compared to 'irrigation water'.

Since this study is based on the idea that a fair comparison of MATPs for different reuse types requires a consistency in unit operations applied in each process model, it also shows what changes are needed to design a 'fit for multi-purpose' instead of a fit for single-purpose MATP. Therefore, in the outlook the possibility of designing a fit for multi-purpose MATP that can reclaim wastewater for different reuse types and cope with temporarily changing water demand patterns (e.g. from agriculture) is presented.

Several studies have investigated techno-economic performance and/or the energy consumption of particular water reclamation technologies or process designs (Pearce 2008; Kajenthira *et al.* 2012; Mendret *et al.* 2019; Koutsou *et al.* 2020). However, to the best of the authors' knowledge this is the first study to generically compare different reuse types and associated MATP process designs in the performance criteria of energy consumption and net costs. Beyond that, the introduction of new technical process optimization possibilities is urgent to reduce the trade-off between: (i) the sustainability goal of decreasing water scarcity; and (ii) carbon footprint reduction and cost effectiveness. The results allow better informed decisions to be made in water reuse projects because knowing in which range the differences in energy consumption and net costs lie helps to decide which reuse type is preferable over another.

METHODOLOGY

In the following section the modelled membrane-based advanced treatment processes are described including the rationale for process design choices. Studied MATPs are shown in Figure 1 while important process parameters and assumptions of each operational unit are presented in Table 2. More detailed information of operational parameters can be found in the Supplementary information.

All studied MATPs are modelled with a fixed feed flow of 100 $m^3 h^{-1}$, which represents a small WWTP and provides a generic scalable number. Each MATP is based on the same core process design including a buffer tank, a pre-filtration step and an ultrafiltration unit. Depending on the specific water quality requirements of a reuse type, the core process is extended by reverse osmosis, ion-exchange, remineralisation and/or ultraviolet light treatment (Figure 1). All materials and process units applied in this study are commercially available technologies ready for full scale application. In total, three performance criteria have been investigated for each MATP: (i) recovery rates, (ii) energy consumption and (iii) net costs.

One of the most important variables for the performance (e.g. energy consumption) of reclamation processes is the WWTP effluent quality. To obtain generically comparable results, a 'standard' WWTP effluent quality was defined that meets the Dutch legal effluent quality standards (Table 1) (Shang *et al.* 2011). A sensitivity analysis was conducted at the end of the study to reveal the impact of possible effluent quality fluctuations (±20%) on the measured performance criteria.

Mass and energy balances (MEBs) are conducted to estimate the recovery rates and energy requirements of designed processes using different modelling tools. The 'DuPont Water Solutions Water Application Value Engine' (WAVE) software is used for integrated modelling of the UF, RO, and ion exchange mixed bed (IEX). It uses harmonized data for all products and processes and provides complete mass and energy flows (DuPont).

The impact of fouling and the required chemical cleaning-in-place (CIP) in the RO are added using an in-house calculation method (Jafari *et al.* 2021). This means that both economical and operational impacts of fouling are calculated based on plant performance data (e.g. pressure drop, permeability and CIP events) using non-empirical cost models as explained in detail by Jafari *et al.* (2021). This way, the energy consumption and costs caused by RO fouling have been taken into account through operational downtime, chemical use and CIP heat requirements. To model the unit operations that are not available in the WAVE software (i.e. pre-filtration, remineralisation (remin.), ultraviolet light (UV)), performance data from full-scale installations described in scientific articles and/or estimated in consultation with technology providers were used. Table 2 summarizes the major process parameters applied in the models unit operations. More detailed model metrics can be found in the Supplementary information.

Modelled MATPs and process design choices

Prior to the core process, a buffer tank functions to balance out hydraulic load variations during day/night or seasons (Figure 1) (Majamaa *et al.* 2010). The following pre-filter (100 μm) protects the downstream UF from larger suspended solids. This combination of unit operations has been applied in various full scale WWTP effluent reclamation processes (Van Houtte & Verbauwhede 2013; Hamoda *et al.* 2015). Instead of UF, microfiltration (MF) membranes have been applied for wastewater reclamation in the Netherlands (Shang *et al.* 2011) but UF has distinct advantages. First, it gives process designers more flexibility to choose a suitable membrane for a given feed quality as UF pore sizes have a wider range between 0.1 and 0.001 μm (Rao 2013). Second, in contrast to microfiltration, UF membranes also remove soluble organic particles, including coliform bacteria, more effectively and therefore may produce a permeate quality that lies closer to the legal standards for irrigation water (Oron *et al.* 2006). Sand filtration has also been discussed as an alternative unit operation to UF but the removal efficiency of suspended solids may vary greatly and the effluent still contains colloidal matter which can cause

Table 1 | Modelled WWTP effluent quality (Shang *et al.* 2011)

Parameter	Value
Na^{+} (ppm)	311
Cl^{-} (ppm)	463
Mg^{2+} (ppm)	31
HCO_3^{-} (ppm)	325
SO_4^{2-} (ppm)	96.5
Ca^{2+} (ppm)	83
SDI 15	5
TSS (ppm)	6
Turbidity (NTU)	4
Conductivity (μS/cm)	2,187
pH (15 °C)	7.5

Table 2 | General process parameters shown for each unit operation applied in the model

Pre-filter	
Pore size (μm)	100
Ultrafiltration	
Applied pressure (bar)	2.3
Operation mode	Constant flux
Total number of elements	28
Elements type	DOW™UF SFP-2880
Design flux (LMH)	50
Cleaning protocol:	
Forward flush	With UF feed water
Backward flush interval (h)	1
Backward flush with UF permeate (min)	3.8
CEB water with UF permeate (min)	16.1
CEB water interval (h)	12
CIP cleaning interval (h)	30
CIP water with UF permeate (min)	312.8
Reverse osmosis	
Configuration	Double stages (2:1)
Total number of elements	90
Element type	FilmTec™ ECO-PRO 400
RO average flux (LMH)	22.5
Antiscalant (mg/L)	3.5
RO feed flow rate (m^3/h)	94.2
RO recovery (%)	80
Cleaning protocol:	
CIP frequency (events/yr)	40
CIP duration (h)	8
CIP step 1 acid cleaning (HCL)	4 hours at pH 2
CIP step 2 alkaline cleaning (NaOH)	4 hours at pH 12
Rinsing after each step	demineralized water
Ion-exchange (mixed-bed)	
Vessel type	Amberpack™ Sandwich
SAC (internal regeneration)	AmberLite™ HPR1200 H
SBC (internal regeneration)	AmberLite™ HPR4200 Cl
Linear velocity (m/h)	38
Design flow rate (m^3/h)	75
Design run time (h)	48
Regeneration time (h)	4.5
SAC volume (m^3)	2.2
SBA volume (m^3)	4.5
Regeneration (SAC) (HCl g/L)	80
Regeneration (SBA) (NaOH g/L)	80
Regeneration temperature (°C)	15

(*Continued*)

Table 2 | Continued

Pre-filter	
Remineralisation	
Total hardness achieved (mmol/L) (Ca+Mg)	>1
Type of remineralisation process	Lime saturator
Ultraviolet light disinfection	
Assumed UV dosage (mJ/cm^2)	80
Assumed log removal	4
Lifetime of lamps (h)	12,000
Energy consumed per lamp (W)	100
Softener/biostabilizer	
Vessel type	Amberpack™ Sandwich
SAC (internal regeneration)	AmberLite™ HPR1100 Na
SBC (internal regeneration)	AmberLite™ HPR4580 Cl
Internal bed area (m^3)	4.4
Linear velocity (m/h)	23
Design flow rate (m^3/h)	100 (SAC); 94 (SBA)
Design run time (h)	10 (SAC); 10 (SBA)
Regeneration time (h)	1.71 (SAC); 3.46 (SBA)
SAC volume (m^3)	8.3
SBA volume (m^3)	5.3
Regeneration temperature (°C)	15
Regeneration solution	RO brine

problems in the RO (Verstraete *et al.* 2009). However, in this study the UF unit is modelled with full redundancy of equipment to ensure a steady operation despite the operational downtime during membrane cleaning.

Figure 1 illustrates the process extension for demi water reclamation. Due to industrial water applications at high temperatures together with internal water evaporation processes, industrial process water should have a low hardness and a low salt concentration (Rietveld *et al.* 2011). In the past two decades, RO in combination with ion-exchange mixed bed (IEX) has become the standard process to treat water for industrial applications to a quality that prevents scale formation and/or corrosion in equipment, like for example high pressure steam systems. The IEX resins are regenerated using hydrochloric acid and sodium hydroxide. To ensure a steady operation during resin regeneration the IEX unit is applied with full redundancy of equipment. Moreover, an open tank degasification unit is applied prior to the mixed-bed IEX to remove 70% of CO_2 from the RO permeate.

Removal of pathogens and toxic pollutants is paramount in reclamation of potable water to avoid potential health risks. Related to this, safeguarding the membrane integrity is very important (Trussel 2012). Generally speaking, and dependent on the membrane type, RO is expected to reach a log removal value (LRV) of 6 while UF reaches an LRV of 4 (Warsinger *et al.* 2018). Recent studies even suggest that RO membranes can reach an LRVs of >7 for different natural viruses (Hornstra *et al.* 2019). However, due to its modular design, a full-scale membrane installation contains a large number of O-ring seals, interconnectors, glue lines and other potential locations which could be vulnerable for integrity breaching (Pype *et al.* 2016). Consequently, the modelled MATP for potable reuse includes a final UV disinfection step to reach an additional LRV of 4 (Pype *et al.* 2016).

Moreover, WWTP effluents still contain a wide range of unregulated inorganic and organic CECs (Helmecke *et al.* 2020). It has been stated that assessing only pathogen indicators is therefore not safe in the case of potable reuse (Wang *et al.* 2015) and that post-treatment with advanced oxidation or adsorption process for CEC removal have to be applied (Stefanakis 2016). For example, the incomplete removal of certain chemicals has been reported, e.g. for boron or di-butyl phthalate (DBP)

(Trussel 2012). The removal of CECs may become a requirement in the future due to changing legislations and additional quality indicators (Hendry & Benidickson 2017). Nevertheless, the modelled process for potable reuse does not include a final advanced oxidation process because it is not clear which CECs could be primarily subject to new legislation nor which advanced oxidation process is most suitable to be applied.

To ensure that no sand particles or other debris enter the RO system in the case of potential UF system leakages or due to other unforeseen problems, it is common practice to install cartridge filters before an RO (Farhat *et al.* 2020). Since the UF permeate is still biologically active, cartridge filter costs cannot be neglected. Therefore, the model includes cartridge filters as an integral part of the RO system without labelling them as a separate filtration step.

The permeate of the RO unit is not directly potable due its low alkalinity and must be remineralised with hardening components (Ca^{2+} and Mg^{2+}). The model follows the remineralisation process described by El Azhar *et al.* 2012, to reach a total hardness higher than 1 mmol/L required to meet Dutch potable water quality legislation (Beyer *et al.* 2014). Considering the low solubility of lime in water this process applies a lime saturation tank and a mixer that feeds an adequate amount of lime saturated water into the RO permeate (El Azhar *et al.* 2012). Remineralisation of water after reverse osmosis can improve drinking water quality significantly and even allows the adjustment of total dissolved solid contents to empirically confirmed concentrations that provide users with the most favourable taste intensity (Vingerhoeds *et al.* 2016).

The discussion whether to apply UF or UF-RO for irrigation water reclamation from municipal wastewater is controversial due to the trade-offs between process costs and microbial and chemical safety (Helmecke *et al.* 2020). The EU guidelines on water quality for irrigation water from municipal wastewater (Table 3) differentiate between four water qualities depending on the targeted crop, its intended use and the irrigation method applied (European Commission 2018):

- Quality A allows direct contact of the reclaimed water with the edible part of the crop;
- Quality B is not allowed to have direct contact with the edible parts of the crop but is suitable for food crops that are processed before consumption and for crops used as feed;
- Quality C is only allowed when drip irrigation is applied to crops mentioned in quality B;
- Quality D only allows to irrigate crops for industrial use, energy and seeded crops.

Reaching the highest quality for safe direct contact of the reclaimed water with the edible part of the crop requires the following LRVs to be reached by any wastewater reclamation process: *E. coli* $\geq$5; total coliphages $\geq$6; *clostridium perfringens* $\geq$5 (European Commission 2018). Since UF alone can be expected to not consistently reach these LRVs (Warsinger *et al.* 2018), one may evaluate the use of UF permeate for irrigation as too risky. Although several studies suggest that UF alone can successfully remove bacteria and nematode eggs from effluents (Gómez *et al.* 2006; Sabater Prieto *et al.* 2012), in practice, UF membranes operated at reuse facilities did not always achieve complete bacterial rejection (Warsinger *et al.* 2018). Therefore, it is recommended to integrate a subsequent disinfection step which is usually achieved with UV light treatment. This may be especially valid for greenhouse irrigation where the risk of aerosolisation of pathogens is given (European Commission 2018).

Due to these uncertainties regarding UF, RO has been claimed to be the better option because it is a total barrier for pathogens and also salts and CECs are rejected at a high rate (Warsinger *et al.* 2018). Irrigating crops with lower quality water may require fresh water to be added to prevent salt accumulation in the soil causing significant yield losses (Quist-Jensen *et al.*

Table 3 | Recommendation of the European Commission to implement water quality standards for irrigation water reclaimed from municipal WWTPs (European Commission 2018)

	A (≤)	B (≤)	C (≤)	D (≤)
E. coli (cfu/100 mL)	10	100	1,000	10,000
BOD5 (mg/L)	10	25		
TSS (mg/L)	10	35		
Turbidity (ntu)	5	–		
Legionella spp. (cfu/L)	1,000 (greenhouse use)			
Intestinal nematodes (eggs/L)	1 (feed and pasture)			

2015). An additional argument in favour of RO integration is potentially higher crop yields achieved with RO permeate compared to UF permeate (Oron *et al.* 2006).

Considering these controversial results, two different processes are modelled for agricultural reuse. One consists of UF-UV treatment and reclaims irrigation water while the other uses UF-RO treatment, which is referred to as 'irrigation water+' in this study. The plus sign indicates that it may easily meet quality standards for a wide range of other applications outside of the agricultural sector since RO can reach an LRV of >7 and removes most CECs (Hornstra *et al.* 2019).

Economic analysis

To estimate the economic performance of each MATP, cost-benefit analyses (CBA) have been conducted calculating their net present value (NPV). The procedure has been described in the field of wastewater resource recovery elsewhere in greater detail (Kehrein *et al.* 2020) and makes use of Equation (1):

$$NPV = \sum_{t=0}^{n} \frac{NB_0}{(1+i)^0} + \frac{NB_1}{(1+i)^1} + \ldots + \frac{NB_n}{(1+i)^n} \tag{1}$$

where the net present value (NPV) at time t, calculated for a time horizon of n years, is the sum of discounted annual net benefits (NB) assuming a discount rate i (Kehrein *et al.* 2020).

A discount rate of 5% has been applied in the CBA which accounts for the opportunity cost of time by discounting future costs and benefits because of the profit that could be earned in alternative investments (European Commission 2015). All net benefits have been discounted along a 20-year time horizon which represents the life time of the reclamation process. Cost factors as well as water prices assumed in the CBA are representative for the Netherlands in the year 2020. Electricity costs are assumed to be 0.1 € per kWh which represents an average price for non-household electricity consumers below 2,000 MWh yr^{-1} in the Netherlands (CBS Statline 2020).

As shown in Equations (2)–(4) and Figure 2, the CBA includes revenues from water sales of either demi water ($€_{demi}$), potable water ($€_{potable}$), irrigation water ($€_{irrigation}$), irrigation water+ ($€_{irrigation+}$) as the only benefits. Costs include operational expenditures (opex) for energy ($€_{energy}$), input of chemicals ($€_{chem}$), waste disposal costs ($€_{waste}$), equipment replacements ($€_{replace}$) and labour for process operation ($€_{labour}$). Labour requirements and costs are estimated based on personal communication with sector specific companies and are typical for the Netherlands to operate a process of similar size. For the calculation of capital expenditures (capex), only costs related to the purchase of process equipment and its installation ($€_{equip\ \&\ install}$) are considered. The equipment purchase prices of each unit operation have been estimated in close consultation with existing technology providers to obtain realistic 'plug and play' prices of each unit operation. Real prices are more accurate because prices of individual unit operations vary considerably in literature studies and at online market places. However, other possible capex factors, e.g. land acquisition, planning, and construction of buildings, are excluded from the capex calculations. The reason is that those cost factors are highly case dependent or depend heavily on economy of scale:

$$€_{OPEX} = €_{energy} + €_{chem} + €_{waste} + €_{replace} + €_{labour} \tag{2}$$

$$€_{CAPEX} = €_{equip\,\&\,install} \tag{3}$$

$$€_{\mathrm{Revenues}} = €_{demi} + €_{potable} + €_{irrigation} + €_{irrigation+} \tag{4}$$

The water prices applied in the CBA represent Dutch gross market values and have been corrected for 9% value-added tax to obtain net prices (Table 4).

Gross potable water prices have been estimated to be 0.93 €/m^3, which is the price charged in 2020 to households by the water company 'Evides Waterbedrijf N.V.' that serves over two million inhabitants in South-West Netherlands (Evides 2020). Gross demi water prices paid by industries may depend on different factors, e.g. the delivered water quality (e.g. demineralised) and especially on the purchased volume. The modelled flow rate of 100 $m^3\ h^{-1}$ WWTP effluent leading to a typical recovery rate of 70–80% demi water represents a relatively small water quantity in an industrial context. Considering this low purchase volume, a gross price of 1.1 €/m^3 was assumed for demi water which may be lower (≈1 €/m^3) when purchased on a large industrial scale (>1,000 $m^3\ h^{-1}$). Irrigation water+ has been accounted for with a gross price of 0.6 €/m^3, which is paid by

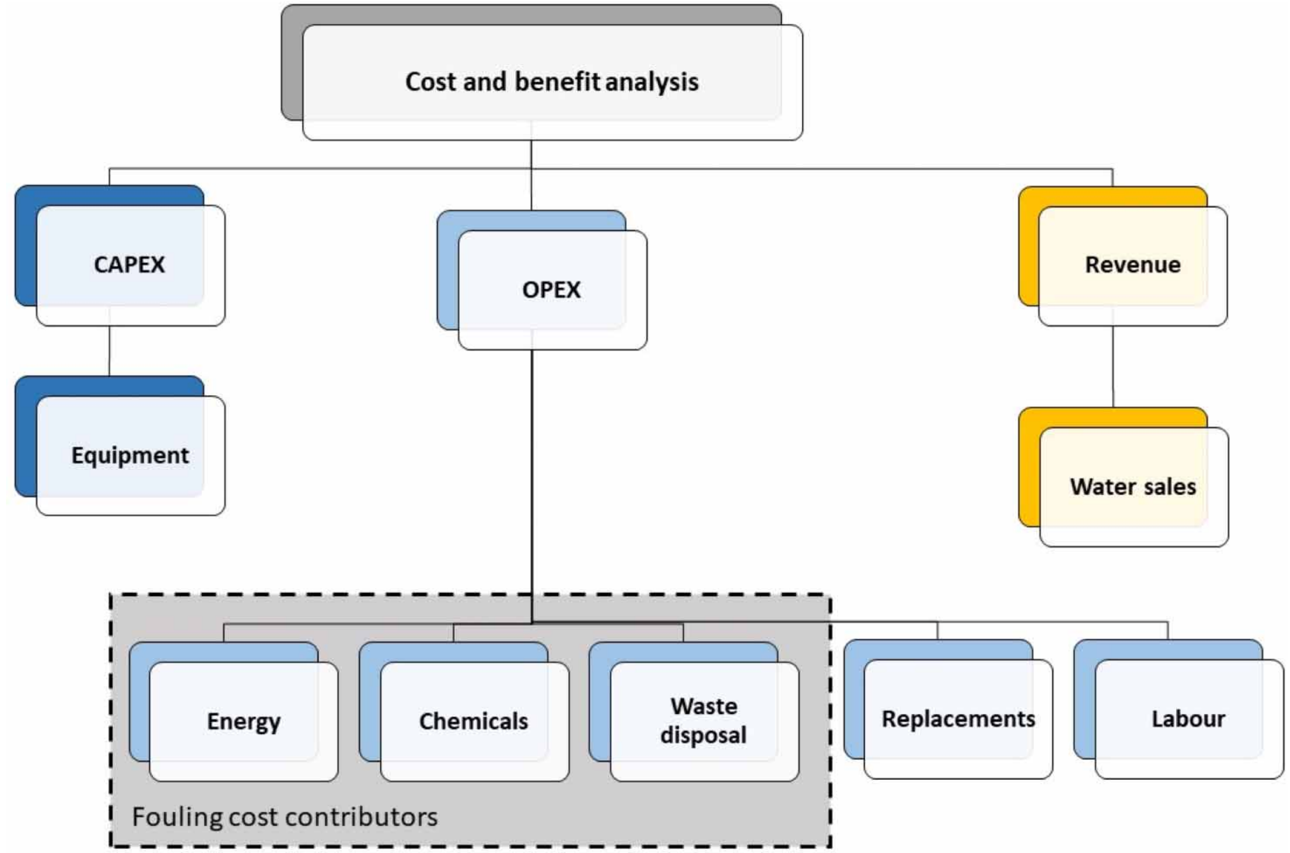

Figure 2 | Cost factors (capex, opex) and benefits (revenues) included in the CBA calculations.

Table 4 | Assumed market prices (€/m^3) for reclaimed water for different reuse types

Water prices	Gross price	Net price (excl. 9% VAT)
Demi water	1.10	1.00
Drinking water	0.93	0.85
Irrigation water	0.19	0.17
Irrigation water+	0.60	0.55

fruit growers in the Dutch region Zuid-Beveland for potable water to irrigate fruit trees (STOWA 2019). The lower quality irrigation water is estimated to cost 0.19 €/m^3 which is the fee that farmers pay for the allowance to pump and use groundwater in the Dutch region of Brabant (STOWA 2019). These low prices for irrigation water have also been confirmed by studies from other European countries that have shown that farmers may perceive reclaimed municipal wastewater as of minor quality and therefore have a low willingness to pay if alternative water sources are available (Quist-Jensen *et al.* 2015).

Moreover, it is assumed that all water prices remain constant over the 20-year time horizon applied in the CBA. The residual value of each reclamation process has been calculated by using the NPV of cash flows occurring for an additional five years after the computed time horizon is over. Costs of finance are not considered in the CBA.

Process optimisation and integration for more sustainability

As stated above, this study also aims to explore the potential to further improve the sustainability of MATPs by: (i) modelling a process optimisation approach that increases RO recovery rates; and (ii) by integrating renewable energy sources into MATPs.

Although the UF is successful in TSS removal, its capability to provide a high-quality RO feed water is limited as it does not remove pollutants responsible for scaling, organic and bio fouling. Applying an RO pre-treatment that is more robust to variable feed water qualities than only UF would improve RO recovery rates, energy consumption and brine production. Consequently, an optimized process design for demi water reclamation is modelled and compared to the initially modelled standard process. It integrates a softener and a biostabilizer unit prior to the RO to maximize process recovery rates. The applied ion exchangers target the specific problem species that can influence RO performance.

First, a pre-softening unit is integrated that removes multivalent cations (Ca^{2+}, Mg^{2+}, Fe^{2+}) which lowers the RO's scaling potential and therefore may improve membrane performance (Salvador Cob *et al.* 2015; Hijnen *et al.* 2016). This can be achieved by exchanging those ions with monovalent ions (Na^{+}) under slightly acidic conditions. Second, to decrease the biofouling potential of the RO feed even further an anion exchange step is integrated that also removes fractions of TOC including organic contaminants from the RO feed, e.g. humic acids. In addition, it removes multivalent anions (e.g. PO_4^{3-} and SO_4^{2-}) from the RO feed which provides a bio-stabilizing effect (Slagt & Henkel 2019). Such a combined cation/anion exchange unit prior to the RO, named here softener/biostabilizer, allows an increase in RO recovery to significantly higher values (>90%) due to negligible risk of scaling and low biofouling potential due to phosphate limitation (known as biofouling control strategy) (Vrouwenvelder *et al.* 2010; Slagt & Henkel 2019). Therefore, 50% less CIP events have been modelled for the optimized demi water MATP design.

Water reclamation is generally referred to as an energy intensive process leading to an increased carbon footprint of WWTPs (Eslamian 2016). To better understand how renewable energy sources can lower the carbon footprint the photovoltaic (PV) net energy that can be generated in the city of Delft (The Netherlands) has been calculated using the 'Photovoltaic Geographical Information System' database and calculator provided by the European Commission's Joint Research Centre (European Commission 2020). Assumed parameters are shown in Table 5. It is estimated how much PV area is needed to operate studied MATPs, which is an important number to show if PV installations can be integrated on-site of a WWTP.

The second renewable energy integration system investigated is the recovery of electricity from the chemical oxygen demand (COD) contained in the WWTP influent via anaerobic digestion (Rulkens 2008). The obtained methane is assumed to be converted into electricity in a combined heat and power unit to be then consumed by the MATP. Table 6 shows the realistic assumptions made in the calculations of electricity recoverable from the anaerobic sludge digestion route.

Table 5 | Parameters applied to calculate required PV area to operate MATPs with solar energy

Database used for calculation	**PVGIS-SARAH**
1 kWp PV capacity (m^2)	10
PV technology	Crystalline silicon
Yearly in-plane irradiation (kWh/m^2)	1,263
Total loss (%)	–18.85
Yearly PV energy production (kWh)	1,025

Table 6 | Assumptions made to estimate the electricity recovery from municipal wastewater

Parameter	**Assumption**	**Reference**
Influent COD concentration (mg/L)	750	Henze & Comeau (2008)
Flow rate (m^2/h)	100	Own assumption
Energy content COD (kJ/g)	17.8	Heidrich *et al.* (2011)
Primary COD capture (%)	60	Wan *et al.* (2016)
COD into secondary sludge (%)	40	Winkler *et al.* (2013)
COD converted into biogas (%)	50	Khiewwijit *et al.* (2016)
Methane content biogas (%)	65	Frijns *et al.* (2013)
Electrical efficiency (%)	40	Verstraete & Vlaeminck (2011)

RESULTS AND DISCUSSION

In the following section the energy consumption and net costs are presented and discussed for all studied MATPs. More detailed process design information can be found in the Supplementary information. The results show the recovery rates for each reuse type taking an upstream perspective in the process designs that all consider 100 $m^3 h^{-1}$ WWTP effluent as a feed (Figure 3). The recovery rate is highly dependent on the RO unit which has 19% loss as brine leading to an overall process recovery rate of ca. 75% for demi, potable, and irrigation water+ reclamation. Applying no RO but only UF followed by UV light disinfection would lead to a significantly higher recovery rate above 90%. The reclamation of quality irrigation water therefore provides advantages due to less brine production and more water actually reused.

The model predicts that UF easily meets the turbidity and TSS requirements of all EU guidelines on water quality for irrigation water from municipal wastewater (Table 3) (European Commission 2018). However, as explained in the Methodology section above, it is questionable if microbial standards can be reached reliably (Warsinger *et al.* 2018). However, the significantly lower overall process recovery rate associated with RO integration could be a valid argument to design processes for irrigation water reclamation only with UF to decrease process costs.

The operation of a WWTP in Europe has been estimated to require ca. 0.45–0.6 kWh/m^3 (Solon *et al.* 2019) and can account for a significant share of the total energy consumption of a small municipality (Berger *et al.* 2013). The energy consumption of MATPs covers in literature also a broad range of 0.7–2.3 kWh/m^3 reclaimed water depending on the system boundaries of the respective study (Quist-Jensen *et al.* 2015). The study at hand confirms previous results that the energy consumption of an MATP is largely determined by the integration of RO. Figure 4 shows the absolute energy consumption of MATPs defined as the kWh required to treat 100 m^3 WWTP effluent. In absolute numbers, the treatment of 93.7 $m^3 h^{-1}$ UF permeate with RO requires ca. 43 kWh, which is significantly higher than all other operational units. The specific energy consumption of each MATP (Table 7) reveals the energy required per 1 m^3 of reclaimed water and allows a fair comparison between modelled MATPs. Reclamation of irrigation water with UF and subsequent UV disinfection consumes much less energy compared to the other processes because of the absence of RO and the higher recovery rate of the process. The energy consumption of UV disinfection shows that despite the fact that the larger UF permeate stream for irrigation water reclamation requires more UV lamps than the smaller and cleaner RO permeate stream for potable water reclamation, both UV units have similar specific energy consumption.

The European water framework directive expects that urban water systems are managed in an economically self-sustained way. This requires that costs are covered by the system itself through pricing of reclaimed water and service fees for wastewater treatment (Castillo *et al.* 2017). Therefore, the economic performance of MATPs is critical for successful water reuse. To assess this a CBA has been conducted revealing the specific costs per m^3 reclaimed water and the NPVs of modelled MATPs. More detailed cost information can be found in the Supplementary information. Figure 5 shows that the opex

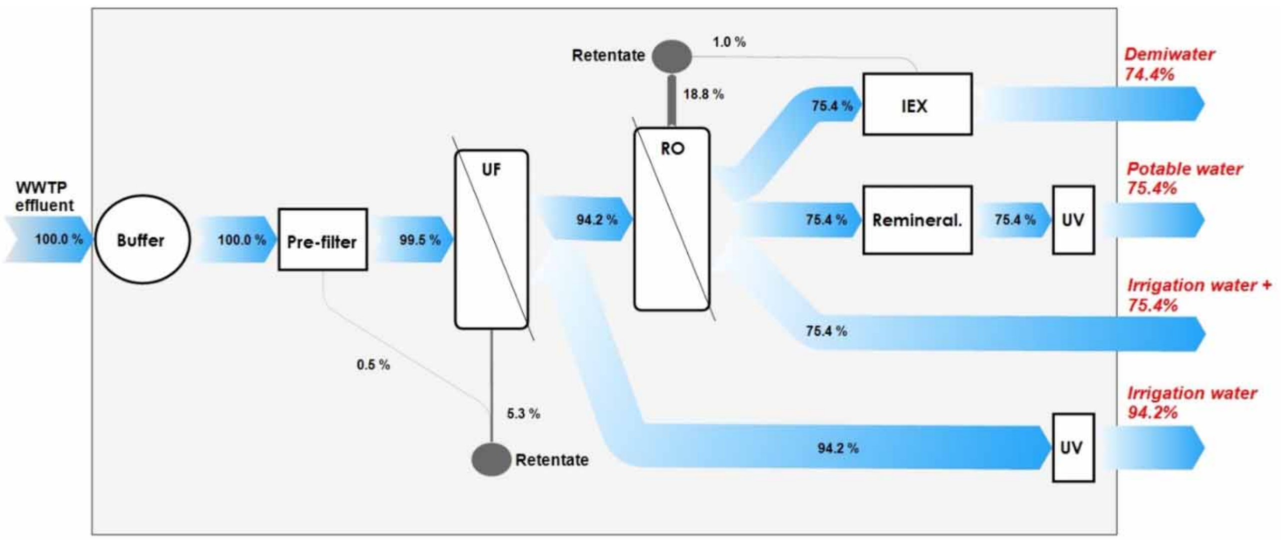

Figure 3 | Modelled process designs showing water flows in %. Final recovery rates are highlighted in red.

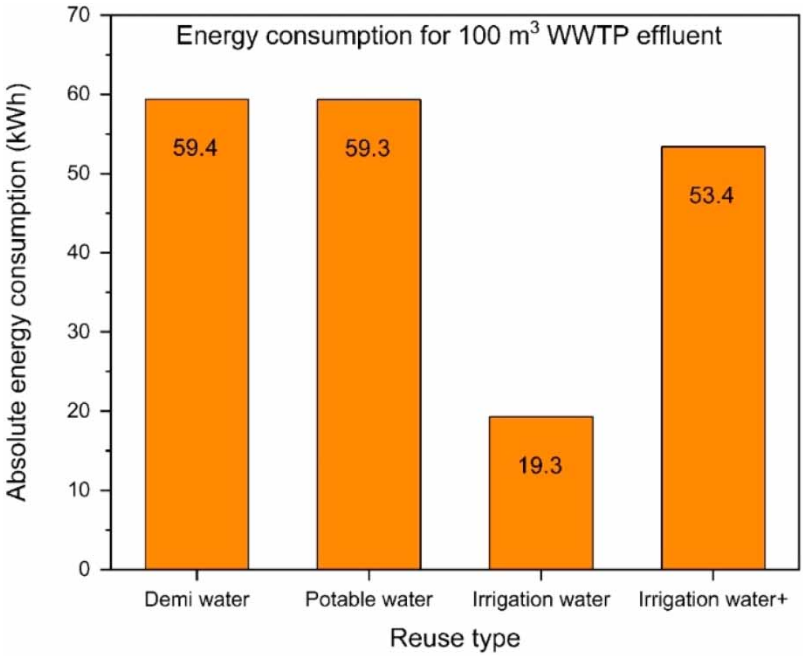

Figure 4 | Absolute energy in kWh required to treat 100 m^3 WWTP effluent with modelled MATPs.

Table 7 | Energy requirements of modelled unit operations shown as specific energy in kwh per m^3 reclaimed water

	Demi water	Potable water	Irrigation water	Irrigation water+
Pre-filter	0.003	0.003	0.002	0.003
UF	0.15	0.14	0.11	0.14
RO	0.60	0.59	–	0.59
IEX	0.08	–	–	–
Remin.	–	0.002	–	–
UV	–	0.08	0.09	–
Total	0.83	0.82	0.20	0.74

per m^3 reclaimed water are far higher than the capex needed for initial process equipment and installation. The difference is due to the fact that capex occurs only once at the beginning of the assumed 20-year lifetime while opex are due constantly. Therefore, it is arguably more important to design MATPs with the goal to optimize its operation and to safe opex rather than saving capex. This is especially important to consider in tender procedures where decisions are usually capex driven. Nevertheless, it should be noted again that other potential capex factors, e.g. land acquisition or buildings, have been excluded in this study due to highly site specific variations. The inclusion of those cost factors would increase capex further but are unlikely to exceed opex. Table 8 reveals that the RO, UF determine the operational costs of MATPs to the largest extent compared to other unit operations and that labour costs are the second largest opex factor after RO. To show how to possibly design a more cost-effective process, an optimized process for demi water reclamation that decreases total opex by increasing RO recovery rates is presented below. When RO is applied the highest operational cost factor of MATPs is waste management which refers to the discharge or additional treatment of RO brines (Table 9) followed by labour costs. If irrigation water is reclaimed without RO, labour costs represent the highest opex factor.

The discounting of future cash flows reveals that both process costs and water prices determine the economic feasibility of MATPs significantly. Demi water reclamation is the most economically attractive reuse type showing a positive NPV of

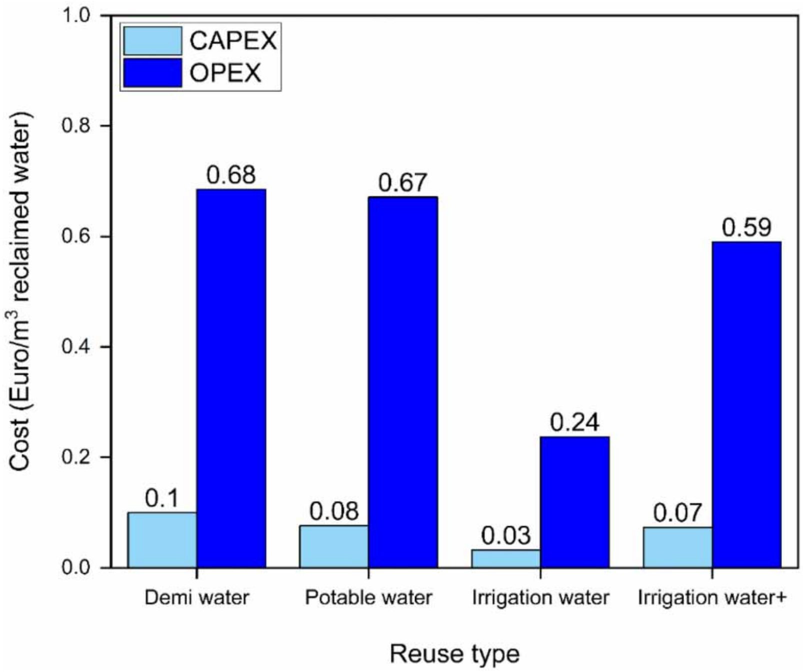

Figure 5 | Total capex and total opex in € per m^3 reclaimed water. All values are undiscounted.

Table 8 | Overview of capex and opex of each unit operation applied in each MATP (€ct per m^3 reclaimed water per year)

	Demi water		**Potable water**		**Irrigation water**		**Irrigation water+**	
	Capex	**Opex**	**Capex**	**Opex**	**Capex**	**Opex**	**Capex**	**Opex**
Buffer	0.7	–	0.7	–	0.5	–	0.7	–
Pre–filter	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
UF	3.2	10.6	3.2	10.6	2.5	8.1	3.2	10.5
RO	3.4	32.9	3.4	32.9	–	–	3.4	32.5
IEX	2.5	8.9	–	–	–	–	–	–
Remin.	–	–	0.1	4.1	–	–	–	–
UV	–	–	0.2	3.6	0.2	3.5	–	–
Labour	–	15.9	–	15.7	–	12.1	–	15.7

All values are undiscounted. Capex consists only of initial process equipment and installation costs.

Table 9 | Opex factor distribution (%) in total opex for modelled MATPs based on opex per m^3 reclaimed water

	Demi (%)	**Potable (%)**	**Irrigation (%)**	**Irrigation+ (%)**
Energy	12	14	10	13
Chemicals	11	7	2	4
Waste	42	44	21	47
Replacement	11	10	10	10
Labour	23	25	57	26

1.3 Mil € (Figure 6). This is due to the relatively high price of demi water (Table 4). A lower price becomes realistic for very large-scale industrial clients that purchase much higher quantities (>1,000 $m^3 h^{-1}$) than the 100 $m^3 h^{-1}$ assumed in this study which would lower the NPV. In contrast to demi water, it may be very difficult to develop an economically viable business case for irrigation water reclamation. Given the low prices for irrigation water, it is not even economically attractive to forego the RO unit and only apply UF in combination with UV disinfection which implies relatively low opex and capex but still shows a highly negative NPV of ca. –1.2 Mil €. To generate a positive NPV a net price for low quality irrigation water of a minimum 0.3 € per m^3 needs to be applied. At first glance it seems surprising that the irrigation water+ (UF-RO) shows a similar negative NPV as the irrigation water (UF-UV) as process costs are higher and recovery rates lower. However, the significantly large price difference of 0.38 €/m^3 between irrigation water and irrigation water+ leads to an equal NPV. This shows that from an economic perspective the application of RO for irrigation water reclamation is as feasible as the application of UF-UV if the difference in water quality is also reflected in the water prices.

When it comes to potable water reclamation, process costs may be covered by the revenues from water sales as a positive NPV is achieved. However, it is important to state that a positive NPV does not suggest an automatic profit can be earned with the reclamation of wastewater but only that the main process costs can be covered by the projected revenues. The positive net benefits can be used for covering cost factors which are excluded in this study, e.g. construction and non-process related cost factors that occur in water reuse projects like water distribution costs (Pearce 2008). Whether an overall solid business case can be developed for a reuse project therefore depends strongly on site specific cost factors, e.g. distance to customers, land purchase costs and/or right of way costs. Nevertheless, this study shows that the highest probability to operate a municipal wastewater reuse scheme in an economically feasible way is the reclamation of demi water for industrial purposes.

The presence of multivalent ions in the feed water of RO systems contributes significantly to scaling and biofouling on the membrane surface which results in limited RO system recovery (Hilal & Wright 2018). To increase the RO recovery rate a softener/biostabilizer can be integrated to pre-treat the RO feed (Slagt & Henkel 2019). We applied this concept to the initially modelled MATP for demi water reclamation to compare both process performances in recovery rates, energy consumption and net costs. Since the obtained RO brine is due to the installation of softener/biostabilizer, free of any risk of biofouling and scaling, it can be used for UF cleaning. Moreover, due to the absence of both multivalent cations and anions the brine is chemically suitable for the regeneration of the ion exchange resins of the softener/biostabilizer unit (Vanoppen *et al.* 2016). This has the advantage that no fresh water has to be subtracted from the process for these purposes

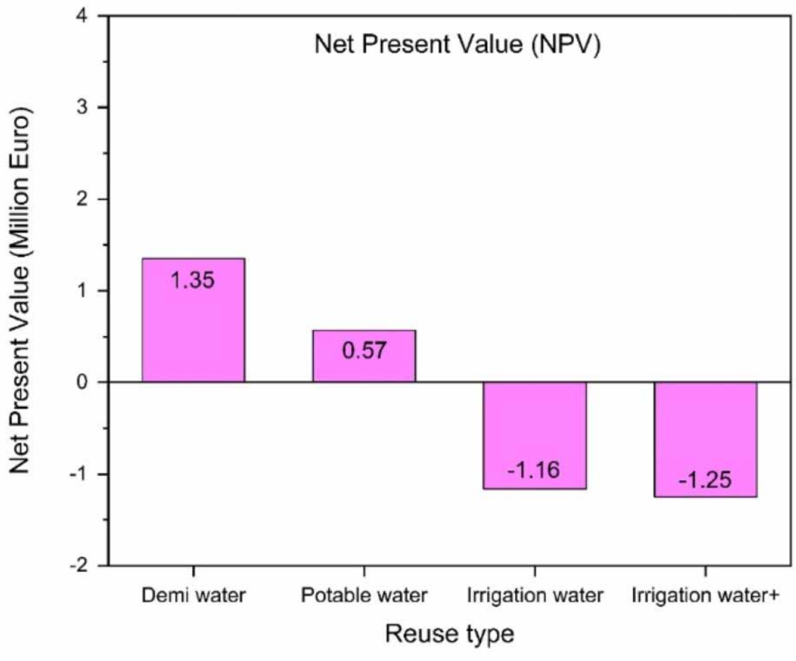

Figure 6 | Net present value (€) of modelled MATPs.

and also the process's chemical consumption is lower (chemicals are often used in the IEX regeneration) (Slagt & Henkel 2019). For the presented optimized process an addition of only 2.2 g NaCl L^{-1} brine is enough to obtain a useful resin regeneration solution which saves costs. However, since the number of operational units is increasing, the process complexation does too. Nevertheless, all applied technologies are mature and often used solutions that are in this concept only operated in a different manner than is usually the case.

The comparison of recovery rates of the initially modelled demi water process (Figure 3) and the optimized process (Figure 7) shows that the overall recovery rate increases from 74.4 to 87.3%. As discussed above, this is mainly due to negligible scaling and biofouling potential of the RO feed which allows for elevated RO recovery rate from 80 to 95%. Moreover, a lower number of CIP events are required for RO in the optimized process (due to lower fouling) leading to a lowered operational down-time of the plant which contributes to a higher process recovery rate too.

The overall performance improvement of the optimized process compared to the initially modelled demi water process is shown in Figure 8. The energy consumption of the RO is lowered due to less scaling and biofouling and since RO is the most energy intensive unit the energy consumption per reclaimed m^3 of demi water of the optimized process is decreased by 11%. The comparison of the CBAs of both process designs reveals that absolute capex (equipment and installation cost) for the optimized process are 31% higher than for the standard process. This is not only due to the softener/biostabilizer unit but also due to an overall higher requirement of RO modules.

On the contrary, the optimized process requires lower opex per m^3 reclaimed demi water due to its higher recovery rate. Especially, the significantly lower brine generation leads to brine management cost savings. In addition, the higher salt concentration of the brine would facilitate the extraction of solids to comply with zero liquid discharge policies. After discounting future cash flows the final NPV per m^3 reclaimed water is 30% higher for the optimized process. This shows that the initially higher capex are easily offset by the decreased opex. Thus, a potential economic advantage has been revealed in this study by integration of a softener/biostabilizer as an RO pre-treatment. The decreased opex is a positive argument for the optimized process from an operator's point of view (opex oriented) while a technology supplier (capex oriented) may be deterred by the high capex at first but should consider the full economic performance over time. This should especially be considered for tender procedures in public water reuse projects.

The results presented in Table 10 reveal how much photovoltaic (PV) area is required under Dutch climate conditions to operate each MATP with solar energy. For demi water reclamation a PV area of ca. 5,000 m^2 would be required which represents 70% of the size of a football field. This shows that it is realistic to operate MATPs on solar energy as probably only relatively little extra space than the plant itself is required. However, the calculations are based on the assumption that the PV system is connected to the grid. If an off-grid system is applied, energy storage facilities are necessary which implies that additional energy conversion losses have to be considered and the required PV area would increase.

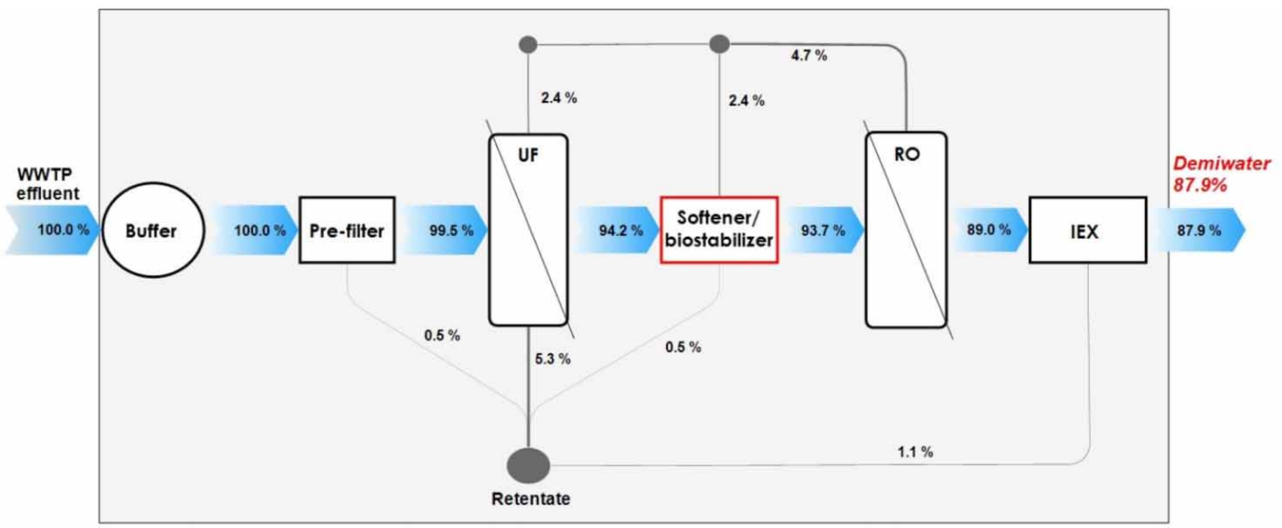

Figure 7 | Optimized process design for demi water reclamation showing water flows in %. Final recovery rate in red.

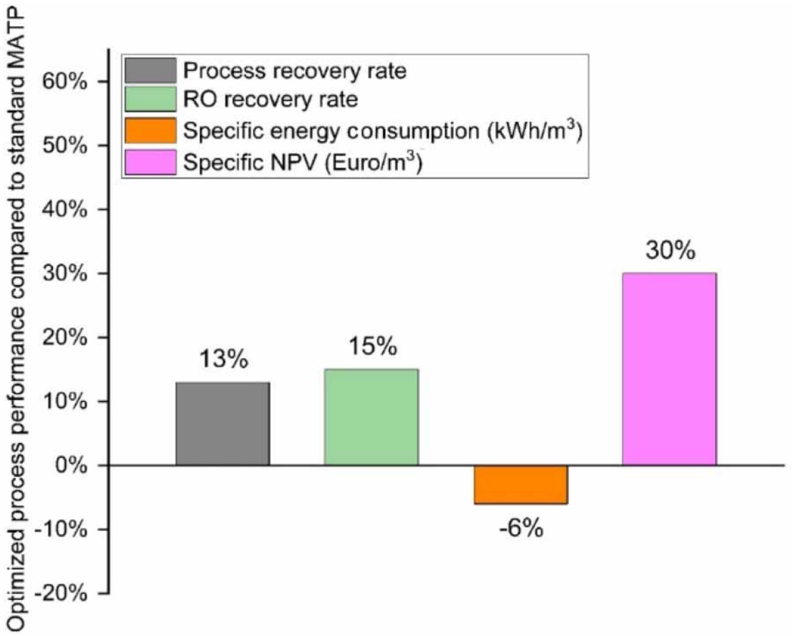

Figure 8 | Performance of the optimized process design for demi water reclamation compared to the performance of the standard process for demi water reclamation shown in %. 'Specific' refers to results are based on m^3 reclaimed water.

Table 10 | Photovoltaic module area required to operate modelled MATPs (flow rate: 100 $m^3\ h^{-1}$) on solar energy in the city of Delft (The Netherlands)

MATP	PV area required (m^2)	PV area required (m^2/m^3 reclaimed)
Demi water	5,077	0.0081
Potable water	5,072	0.0080
Irrigation water	1,647	0.0020
Irrigation water+	4,564	0.0072
Optimized demi	5,728	0.0076

In addition to solar energy, the energy that can be recovered in a WWTP from COD via the anaerobic digestion and combined heat and power biogas combustion was estimated (Frijns *et al.* 2013). The question arises as to how much energy could come from anaerobic sludge digestion to offset the energy consumption of the MATP and achieve a good overall energy balance of both the WWTP and MATP. The realistic assumptions presented in Table 6 lead to only 2.6×10^{-5} kWh electricity that could be recovered from the 100 m^3 raw wastewater entering the WWTP. This is a negligible amount of electricity compared to the absolute electricity required to operate an MATP, as shown in Figure 4. This estimation excludes a similar amount of heat energy that is additionally recoverable from the biogas combustion process. It should also be mentioned that if a WWTP is designed to recover not only chemical energy but additionally also the heat energy from the effluent via heat exchangers, the total WWTP energy recovery could be significantly further increased (Hao *et al.* 2019).

The results of this study may be sensitive to the WWTP effluent quality assumed in the model (Table 1). Therefore, a sensitivity analysis was conducted for the demi water reclamation MATP (Figure 9). The impact of the effluent quality was tested by changing the concentrations of selected ions (Na^+, Cl^-, Mg^{2+}, Ca^{2+}), TSS and turbidity by $\pm$20% of the initially modelled values. Total organic carbon (TOC) is not considered although it is possible that effluent TOC concentrations impact membrane fouling and thus would impact the process energy consumption. Since the distinct correlation of TOC composition and membrane permeability is not clear (Kennedy *et al.* 2008) and there is a lack of operational data about the impacts of other changing effluent quality parameters and membrane fouling, fouling costs are assumed to be linearly correlated to the effluent quality.

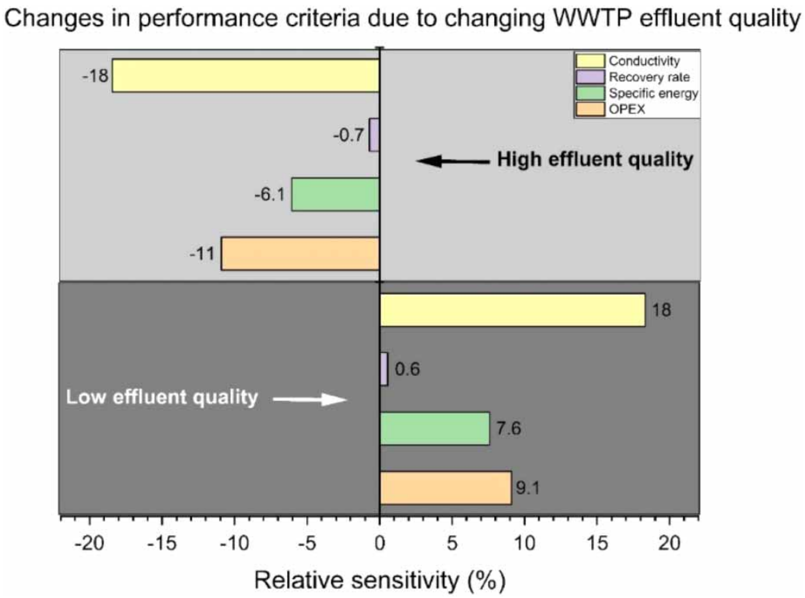

Figure 9 | Sensitivity of WWTP effluent quality changes measured in Na^+, Cl^-, Mg^{2+}, Ca^{2+}, TSS, turbidity. High WWTP effluent quality represents 20% lower concentrations compared to the initially modelled WWTP effluent quality while low WWTP effluent quality represents 20% higher concentrations. Results are shown in % change.

However, the results in Figure 9 show that changing ion concentrations would change the conductivity of the effluent by ±18% leading to opex changes of ca. ±10%. While labour costs have been assumed to not be affected by WWTP effluent quality changes, the other opex factors (i.e. energy, chemical reagents, brine management, and equipment replacements) have been included in the sensitivity analysis. The specific process energy consumption increases by 8% if effluent qualities decrease by 20%. In contrast to this, no significant changes in recovery rates occur due to changing WWTP effluent qualities.

OUTLOOK AND FUTURE RESEARCH

Most studies in the field of WWTP effluent reclamation investigate potable or agricultural reuse possibilities but the results of this study suggest that industrial reuse is economically most attractive and therefore deserves more attention in future research. A process design approach that aims to improve RO performance is needed. RO pre-treatment steps, such as lime softening, coagulation and flocculation, could be more effective than only UF. They can better eliminate substances leading to scaling, organic and bio fouling. It is therefore important to understand how those formerly applied technologies worked and to challenge the current standardized approach of applying for example UF-RO-IEX subsequently for demi water reclamation. It is necessary to find new ways to integrate these three key technologies in the most efficient and effective way to improve robustness and recovery rates of RO systems (Slagt & Henkel 2019). This study indicates that the integration of a softener/biostabilizer could be very promising to improve the performance of RO driven water reuse and therefore this concept should be investigated further.

The choice to design a MATP for a certain reuse type depends on the specific demands for reclaimed water (Garcia & Pargament 2015). The demand for a certain water quality can underlie high temporal variations (Wang *et al.* 2015). For example, a major difficulty for agricultural reuse is that a varying demand of irrigation water throughout a year or vegetation period meets a relatively steady supply potential as WWTP effluent quantities are relatively steady. It could be increasingly necessary in the future to supply high loads of irrigation water in short drought periods that threaten harvest losses in summer due to increasing heat wave events (Buras *et al.* 2020). Therefore, it is necessary to study the usefulness of designing a 'fit for multi-purpose' MATP that can be adjusted flexibly to changing water demand patterns and reclaim different water qualities. Since this study is based on the idea that a fair comparison of MATPs for different reuse types requires a consistency in chosen unit operations in each process model, it also shows how many changes are needed to design a fit for multi-purpose instead of a fit for single-purpose MATP.

From Figure 3 it becomes obvious that, if a demi or potable water reclamation process is already installed at a WWTP, it may be relatively simple to react on such a temporary urgent demand. Either RO or UF permeate (or both) needs to be abstracted from the process to supply irrigation water. If UF permeate is used, only a stand-by UV disinfection unit is required to treat it further to meet irrigation water quality regulations (Table 3). The RO permeate instead has the advantage of being suitable to satisfy several non-potable applications with varying temporal demand patterns at once. Examples are firefighting, dust control or fish farm basin refilling (Garcia & Pargament 2015). Also, the supply of additional water to river banks or other natural habitats that may fall dry in drought periods and lose their ecosystem services (Cazurra 2008) can be achieved with the irrigation water+. Other possible applications include landscaping or urban irrigation (Wang *et al.* 2015), vehicle washing, recreational activities and street cleaning (Meneses *et al.* 2010). A fit for multi-purpose MATP design that could reclaim water of different qualities to supply it to various usage types and switch flexibly between them if necessary would require that all unit operations studied in this paper are installed which implies higher initial capex. Another bottleneck to overcome would be the cost-effective distribution of reclaimed water to its users, possibly requiring costly infrastructure. Since WWTPs are usually located at the lowest point of a catchment area to use gravity flow, uphill pumping or transportation of reclaimed water is often necessary to reach the demand location (Lee *et al.* 2013). Nevertheless, a fit for multi-purpose concept could be a solution to ensure that wastewater is not only fully reused in a water stressed city or region, but also that it is available at times and places where needed most and with the required quality.

CONCLUSIONS

This study contributes to better informed decision making in water reuse projects in the Netherlands revealing differences in recovery rates, energy consumption and costs of MATPs designed for different reuse types (industrial, potable, agricultural) under Dutch conditions. The main findings are:

- Demi water for industrial purposes seems the most economically attractive reuse type in the Netherlands while the price for irrigation water is too low to reclaim it cost effectively. However, this estimation needs further study and can probably only be addressed accounting for additional site specific cost factors, e.g. water transport costs to users;
- High quality irrigation water (UF-RO) can reach a similar net present value as low quality irrigation water (UF-UV) if the difference in water quality is also reflected in the water price;
- In literature, high energy costs are often stated as the major bottleneck for water reclamation processes but when RO is applied waste management may be a considerably higher opex cost factor as brine disposal costs can be high. Therefore, processes decreasing brine generation (as presented in the optimized demi water reclamation process) need further research attention. Also, the integration of salt and water recovery technologies from brines seem economically interesting due to their disposal cost reduction potential;
- MATP process costs are mainly determined by opex instead of capex and therefore processes with higher capex may be even more cost effective over a 20-year process lifetime (important for tender procedures);
- The integration of a softener/biostabilizer prior to RO may significantly improve a process's recovery rate, energy consumption and net present value. In addition, it offers brine reduction potential as an environmentally important impact;
- Electricity recovery via anaerobic sludge digestion is not a solution for renewable energy integration to run MATPs because recoverable energy quantities are very small compared to the required energy. Solar energy integration seems feasible for flow rates of 100 $m^3\ h^{-1}$ in the Netherlands considering the required solar panel area.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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