Economic evaluation of different treatment options for water reuse in industrial parks using modular cost functions

Jens Hilbig, Birte Boysen, Philipp Wolfsdorf and Karl-Ulrich Rudolph

ABSTRACT

Industrial parks (IPs) play a significant role in the context of economic growth as well as urban and regional development strategies. They rely on the availability of factors of production and an enabling environment, which also includes the legal framework and economic conditions. The availability of water is essential for the operation and expansion of IPs. Sustainable, efficient and reliable water supply is crucial for IPs and the companies located in the IPs. Reusing wastewater to reduce the amount of drinking or process water necessary for production requires economically viable treatment processes. From an economic point of view, it is important to compare the costs of different treatment trains and to ensure that technical solutions generate an economic benefit for the operators of the IPs. Based on data from municipal wastewater treatment, the authors derive cost functions for individual treatment processes and develop tools for a modular economic assessment of water reuse in IPs.

Key words | calculation model, cost functions, economic evaluation, industrial wastewater treatment, water reuse

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HIGHLIGHTS

- Comparison of costs of different wastewater treatment trains.
- Based on municipal wastewater treatment, a meta-analysis has been conducted to derive cost functions of different treatment technologies.
- Development of a calculation model that can serve as a strategic decision-making tool.
- The objective is a sustainable and economically feasible treatment and recycling of wastewater streams in industrial parks.

INTRODUCTION

Industrial parks (IPs) play a significant role in the context of economic growth and urban and regional development strategies. They rely on the availability of factors of production and an enabling environment, which also includes the legal framework and economic conditions. The availability of water is essential for the operation and expansion of IPs. The concentration of industrial production, on one hand, a major challenge with regard to increasing water demand, (regional) water shortages and other environmental impacts. In northern and western China, for example, economic development is limited by water shortages that are conflicting

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with the establishment or expansion of industrial production sites (Bauer *et al.* 2019). On the other hand, IPs open up a wide range of options for saving resources, energy and costs.

Water reuse in IPs is an important measure to reduce the water demand of IPs and to mitigate the depletion of available freshwater resources in the catchments around the industrial areas. The implementation of sustainable reuse concepts is essential to overcome possible future water shortages that would cause huge problems for industries, economies and societies. Based on studies of several IPs in Germany, China and Vietnam, a sustainable water reuse concept for IPs is being developed under the frameworks of the joint research project Water Reuse in Industrial Parks (WaReIp). The main goal of the WaReIp project is to increase water reuse for general infrastructure purposes, in-plant reuse and reuse within specific production processes is not considered.

Sustainable, efficient and reliable water supply is crucial for IPs and the companies located in the IPs. Reusing wastewater to reduce the necessary amount of drinking or process water requires economically viable treatment processes. The pollution of industrial wastewater is often more complex compared with municipal wastewater and requires a more elaborate treatment. Wastewater treatment plants (WWTPs) in IPs often provide several treatment trains for different wastewater inputs. Nonetheless, if sophisticated treatment technologies are already in place (for example, in order to comply with discharge qualities), it sometimes requires only minor adjustments to make the water suitable for infrastructure reuse purposes (Rudolph *et al.* 2014; Zaffaronia *et al.* 2016). Closing the water circuit within IPs (Rudolph 2011) should be considered before tapping new external water resources.

From an economic point of view, it is important to compare the costs of different treatment trains and to ensure that technical solutions generate an economic benefit for the operators of IPs, not limited to a specific kind or size. This will create an incentive to invest in innovative wastewater treatment concepts and technologies. Furthermore, the economic evaluation of different treatment options for water reuse described in this paper is part of a multi-criteria analysis consisting of economic, environmental, technical and other criteria that is conducted under the WaReIp project (Wasser Abwasser Technik 2020).

Among others, a method is being developed to support the decision-making process of industrial users in order to identify and select measures, processes or changes of use for industrial water, wastewater and water reuse. The objective is a sustainable and economically feasible treatment and recycling of wastewater streams in IPs by reducing the demand from natural resources and providing reuse water for several infrastructure purposes, for example sanitation (toilet flushing), irrigation and street cleaning. Within WaReIp, an infrastructure reuse factor of up to 25% has been calculated, which is defined as reuse-flows from the central WWTP (Bauer *et al.* 2019).

The economic benefit of WaReIp depends both on the costs of the existing water supply and wastewater treatment systems and on external factors. These factors, such as legal requirements, effluent standards, water shortages or demand-related behaviour, are important additional drivers of water reuse. In contrast, water reuse systems tend to be more expensive than 'traditional' water supply systems if the price of the existing water supply is subsidised or not calculated on a full cost recovery basis. To compare the cost of the entire water cycle of IPs, the required investment and annual costs of water treatment plants can be calculated based on the cost functions.

The objective of this paper is to show an approach of how to estimate the cost of wastewater treatment in an IP with municipal investment cost functions and a developed MS-based calculation model.

Using cost functions for possible reuse projects has been done before for municipal wastewater. For example in a project funded by the European Union and the Italian Ministry of Education, Universities and Scientific Research (Sipala *et al.* 2003), the costs of different municipal wastewater treatment and reuse scenarios were investigated. With the help of an online tool, non-experts can also explore different reuse options, the legal framework, process combinations and the associated costs. The cost functions for individual procedures and procedure combinations are based on Italian and international literature research. Functions are given for primary, secondary treatment, filtration, nitrification/denitrification and filtration, nitrification/denitrification plus phosphate decomposition and filtration, coagulation flocculation, carbon adsorption as well as reverse osmosis (see Table 1). They are specified for WWTPs either smaller

Table 1 | Cost functions of individual treatment technologies (Sipala *et al.* 2003)

Treatment alternatives	$X < 30{,}000$ p.e.	$X > 30{,}000$ p.e.
Primary treatment	$Y = 0.317–9 \times 10^{-6} \times X$	$Y = 0.132–5 \times 10^{-7} \times X$
Secondary treatment	$Y = 0.474–7 \times 10^{-6} \times X$	$Y = 0.309–4 \times 10^{-7} \times X$
Filtration	$Y = 0.507–7 \times 10^{-6} \times X$	$Y = 0.342–4 \times 10^{-7} \times X$
Nitrification/denitrification + filtration	$Y = 0.559–8 \times 10^{-6} \times X$	$Y = 0.369–5 \times 10^{-7} \times X$
Nitrification/denitrification + phosphate removal + filtration	$Y = 0.602–8 \times 10^{-6} \times X$	$Y = 0.393–5 \times 10^{-7} \times X$
Coagulation–flocculation	$Y = 0.939–2 \times 10^{-5} \times X$	$Y = 0.471–5 \times 10^{-7} \times X$
Carbon adsorption	$Y = 1.132–1 \times 10^{-5} \times X$	$Y = 0.730–5 \times 10^{-7} \times X$
Reverse osmosis	$Y = 1.503–2 \times 10^{-5} \times X$	$Y = 0.907–5 \times 10^{-7} \times X$

Y indicates the unit cost in €/m^3.
X indicates the number of population equivalent (p.e.).
For $X < 1{,}000$ p.e., a constant cost is assumed equal to that obtained for 1,000 p.e.
For $X > 200{,}000$ p.e., a constant cost is assumed equal to that obtained for 200,000 p.e.

or larger than 30,000 inhabitants. However, no distinction is made between investments and operating costs. The specific total costs may also serve to validate the calculated combined data of investment and operational expenditures but are not used for the average WaReIp cost functions.

Another example of the use of cost functions when differentiation between investment and operational expenditure is not needed, the results of the Spanish project NOVEDAR-Consolider can be adduced (Hernandez-Sancho *et al.* 2011). Within the project in 2010, cost data from 341 WWTPs were evaluated. Depending on the treatment technology, the cost functions can include not only the capacity but also the age of the treatment plant, the degradation rate of settleable solids, chemical oxygen demand (COD), biological oxygen demand (BOD), nitrogen and phosphorus, as shown in Table 2. Cost functions for a total of seven treatment stages are given: extended aeration (EA); activated sludge without nutrient removal (AS); activated sludge with nutrient removal (NR); bacterial beds (BB); peat beds (PB); biodisk (BD) and tertiary treatment (TT) (Hernandez-Sancho *et al.* 2011). The Spanish cost functions are not used to derive the calculated cost functions but for the purpose of the WaReIp project, and they can be used for verification if the corresponding degradation rates are known.

In this publication, cost functions are further examined and broken down in order to adjust them for industry and country-specific circumstances in the next step.

METHODICAL APPROACH

Industrial wastewater treatment requires industry-specific technical process stages, for example pre-flotation in the

Table 2 | Cost functions of individual treatment technologies (according to Hernandez-Sancho *et al.* (2011))

Technology	Cost functions	R^2
EA (extended aeration)	$C = 169.4844\ V^{04540} e^{(0.0009A+06086SS)}$	0.6133
AS (activated Sludge without nutrient removal)	$C = 2.1165\ V^{07128} e^{(0.0174A+1.5122SS+0.0372BOD)}$	0.6849
NR (activated Sludge with nutrient removal)	$C = 2.518 V^{07153} e^{(0.518+1455COD+0258N+0243P)}$	0.7301
BB (bacterial beds)	$C = 17.3617\ V^{0.5771} e^{(0.1006A+0.6932COD)}$	0.9862
PB (peat beds)	$C = 1{,}510.8400\ V^{0.2596} e^{(0.0171SS)}$	0.5240
BD (biodisk)	$C = 28.9522\ V^{0.4493} e^{(2.3771SS)}$	0.8058
TT (tertiary treatment)	$C = 3.7732\ ^{V0.7223} e^{(0.6721COD+0.0.1958N+0.7603P)}$	0.9029

food industry. In Germany, requirements for 55 different branches are given in the wastewater ordinance (Abwasserverordnung 2020). Furthermore, industrial WWTPs are often enclosed and automated and therefore vary from municipal WWTPs. The ideal treatment process depends not only on the source of wastewater but on the reuse purposes as well. Wherever the reuse water is produced for agricultural purpose nutrients (phosphorous and nitrogen) are valuable and there is no advantage in removing them before reuse. When the reuse water is purposed, for example, for electronic production processes or potable reuse nutrients have to be removed. To cover as many possibilities as possible, a broad spectrum of treatment processes is required. However, a literature review showed that most of the data and cost functions published for treatment options are based on municipal wastewater treatment. Interviews with companies and IP operators in Germany, China and Vietnam led to similar results: either detailed data on individual treatment steps are not collected in IPs or companies are quite reluctant to publish process details and cost functions, as they are concerned to disclose commercially sensitive information.

To bypass this problem, data of municipal wastewater treatment have been collected in a meta-analysis using several sources. The data collected date back to the 1990s and include different studies, research projects, technical guidelines or public reference data mainly from Germany. The data have been converted into Euros to a common reference year (2017) taking into account inflation rates as well as exchange rates for data from other countries than Germany. By this, an average cost function is derived for each different treatment processes. Despite the limitation of the underlying data (e.g. long observation period, different size of treatment plants in the individual studies and heterogeneous study design and number of plants evaluated), the resulting cost functions provide sufficient information for further use. Under the WaReIp project, the cost functions are used to show general trends and allow for a comparison of different treatment steps as well as a model calculation of capital (CAPEX) and operational expenditure (OPEX)) as well as annual costs and costs per cubic metre of different treatment trains. This calculation is conducted in a specially developed MS office calculation model to allow transparency and easy adaptability. Unlike the described cost functions within the WaReIp project, municipal CAPEX and OPEX data are collected and calculated separately in an approach to adapt input parameters individually according to industry- or country-specific conditions and then calculate the cost per cubic metre or annual cost accordingly.

DERIVATION OF COST FUNCTIONS

By setting up cost functions for individual treatment steps, possible process chains and reuse of partially treated wastewater within the IP can be economically evaluated in a modular fashion and with varying volumes. In the following paragraphs, some of the cost functions incorporated are described.

Cost functions and data for individual process steps are available for municipal sewage treatment plants from various sources (Bohn 1993; Türk *et al.* 2013; Horstmeyer *et al.* 2014). The cost functions of treatment technologies published in several different studies include the usual process steps for municipal WWTPs: screen, grit chamber, primary and secondary clarification, phosphate precipitation/flocculation, activated sludge process, UV disinfection, ozonation, sludge thickening, mechanical sludge dewatering and digestion/stabilisation.

Publications explaining the cost functions of several treatment stages mostly date back to a time when sewage treatment plants were increasingly built in Germany, such as Bohn (1993), Schoenenberg (1996) as well as Günthert & Reicherter (2001). These publications use data from existing WWTPs as examples to derive cost functions. Some of these functions are divided into civil works and mechanical equipment. The derived functions are generally linear or degressive. Economies of scale are clearly identifiable, as can be seen in Figure 1 showing investments of activated sludge.

The Hessisches Ministerium für Umwelt, ländlichen Raum und Verbraucherschutz (Hessian Ministry for the Environment, Rural Areas and Consumer Protection) has published cost functions which are to be used as reference values for the investment of new WWTPs (Hessisches Ministerium für Umwelt ländlichen Raum und Verbraucherschutz 2006). In the published graphs, economies of scale are apparent with limitations as shown in Figure 2.

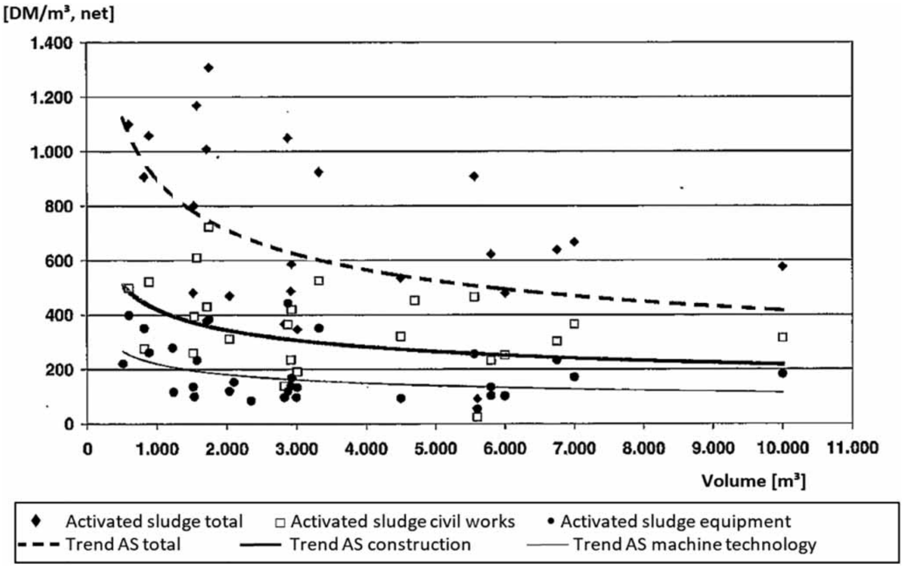

Figure 1 | Cost functions investment of activated sludge (Günthert & Reicherter 2001).

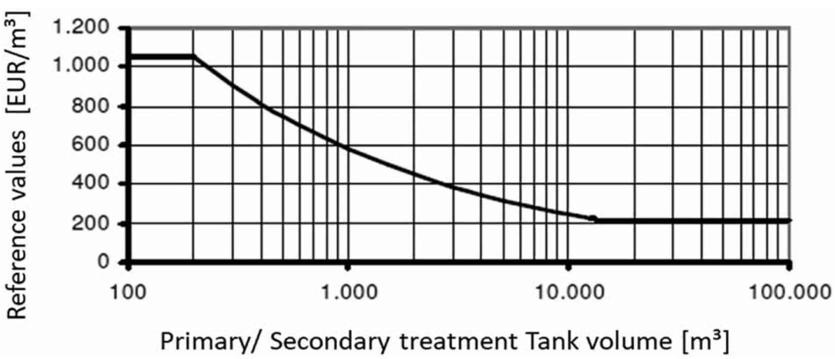

Figure 2 | Cost function primary/secondary treatment tanks (Hessisches Ministerium für Umwelt ländlichen Raum und Verbraucherschutz 2006).

Horstmeyer *et al.* (2014) set out various cost functions of individual treatment steps. However, due to a partial lack of data basis or too wide a spread, it is not possible to calculate the costs for all treatment steps. Not only the cost functions determined by Horstmeyer *et al.* but also the data points are included in the underlying database of this study and used to develop cost functions.

In its study 'Micropollutants from municipal wastewater', the Swiss Federal Office for the Environment refers to data from Hunziker-Betatch from a previous study in 2008 (Hunziker-Betatech 2008; Abegglen & Siegrist 2012). The cost analysis includes the investment and operating costs for two different dosages for ozonation and activated carbon adsorption at six sites in Switzerland (Hunziker-Betatech 2008). The specific extension costs of UV systems are described by Müller *et al.* (2009). A cost function can be derived from the examples given.

In the study 'Economic benefit of upgrading municipal wastewater treatment plants to eliminate organic trace substances, pharmaceuticals, industrial chemicals, bacteriologically relevant germs and viruses' by Türk *et al.* (2013), operating and investment costs of activated carbon treatment and ozonation are compared. The cost functions of the investment are based on constructed plants. The investments consist of civil works, equipment, electronic instrumentation and control (E/I&C) and additional costs

(Türk *et al.* 2013). Some of these treatment plants are also part of the data basis of Hunziker-Betatech (2008), and the dual use of the data in the cost functions slightly influences the arithmetic mean.

Metzger *et al.* (2014) evaluate in their study extensions of WWTPs by adsorption stages from Baden-Württemberg. For the six plants considered, the capital costs and operating costs are given with further subdivisions. A study commissioned by the German Federal Environment Agency on an area-wide coverage of the fourth treatment stage in Germany shows the total costs for ozonation and treatment with activated carbon. Among others, data from Hunziker-Betatech (2008) and Metzger *et al.* (2014) are used (Hillenbrand *et al.* 2015, 2016).

Palmowski & Pinnekamp (2018) use the costs of adding activated carbon to an existing filter with data published by Bornemann *et al.* (2015) to derive a cost function for the investment of silos and dosing stations. In a study by Helmreich *et al.* (2017), the costs of phosphate precipitation are analysed in relation to the size of the WWTP. For municipal WWTPs between 1,000 and 25,000 inhabitants, a distinction is made between investments, precipitant costs, costs for sludge disposal and costs for labour and maintenance. The specific costs for additional phosphorus removed are also given (Helmreich *et al.* 2017). As a result of the recent discourse on the fourth treatment stage and the resulting additional costs, there are more and more publications on the possible process steps of ozonation, activated carbon and disinfection with UV (Hillenbrand *et al.* 2016; Jekel *et al.* 2016; Palmowski & Pinnekamp 2018).

For other treatment processes like Membrane Bioreactors, a sufficient database from Germany is not given. Pinnekamp (2007), for example, published an invest cost function for German MBR based on six plants. The availability of International data is better (DeCarolis *et al.* 2004, 2007). To avoid the issue of different cost levels from different countries as much as possible, it is refrained from combining and publishing this data. As described above, there is no sufficient data from industrial WWTPs for the individual process steps. Therefore, the published municipal data and internal IEEM data from former projects are used. To cover a broad spectrum of possible process chains, a rather large number of process steps is used: screen, grit chamber, primary and secondary clarification, phosphate precipitation/flocculation, anaerobic reactors, activated sludge, UV disinfection, ozonation, activated carbon adsorption, sludge thickening, mechanical sludge dewatering, digestion/stabilisation, sandfiltration and chlorination.

In order to be able to compare the above-described cost functions of different references, the functions must be converted to one price level and one unit. Cost data from other countries are converted (via price index of the respective country) to a 2017 level and then converted into Euros. The data are mostly based on German WWTPs with exceptions, for example, from Hunziker-Betatech (2008) and the data for chlorination (US EPA 1999; Das 2002). For compatibility, the results are converted to €/m^3/d and €/m^3. The average daily runtime of machines was used from Schoenenberg (1996), and it was assumed that the treatment plant runs 365 days a year. As most of the functions were given as net costs, it is assumed when no information of the value-added tax (VAT) is available those are net as well.

By calculating the arithmetic function of the individual cost functions from literature and introducing a trend line, an average cost function (potential (average)) of the municipal WWTPs can be derived for individual process steps as shown in Figure 3. This also covers treatment sizes that are not considered in all of the underlying publications of the database. Despite the limitations of the underlying database, it is possible to determine cost functions that allow for an estimation of the costs for individual treatment processes.

The determination of an average net cost function is carried out for the possible treatment technologies listed in Table 3.

Cost functions for investment are as far as available from the literature and useful broken down to civil works, equipment and if available E/I&C (see Figure 4) to later calculate depreciations and adapt the sections separately to country-specific conditions. In case a specific breakdown is not available, a percentage allocation is made.

OPEX is calculated separately. There are a large number of publications on operational costs for individual treatment technologies, such as activated carbon adsorption or ozonation (Hunziker-Betatech 2008; Türk *et al.* 2013; Metzger *et al.* 2014). For other process steps, the operating costs can be estimated individually via publications on energy, consumable and labour demand as well as maintenance requirements.

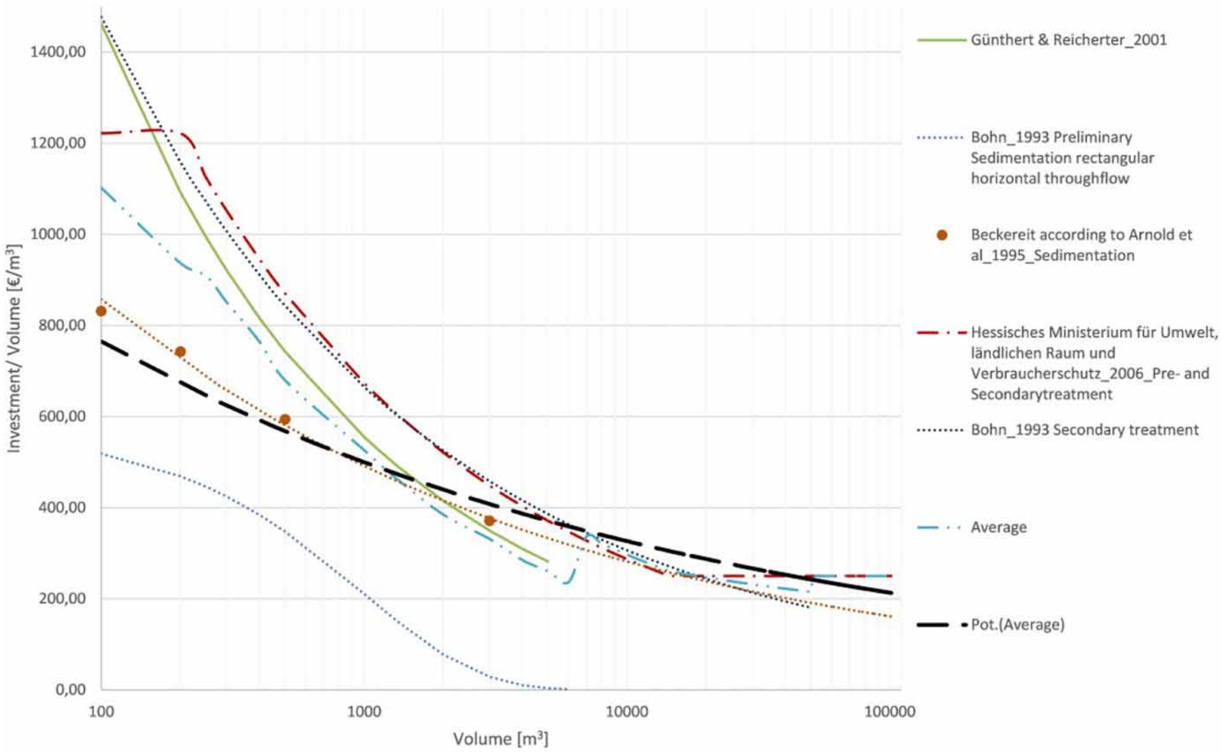

Figure 3 | Determined cost functions primary/secondary treatment.

Table 3 | Determined cost functions

Process	x	y	Average cost function investment	Range for x
Screen	m^3/d	€/m^3/d	$y = 680.78x^{-0.297}$	100–50,000
Grit chamber	m^3/d	€/m^3/d	$y = 2215.1x^{-0.392}$	100–20,000
Pre-/secondary treatment	m^3	€/m^3	$y = 1791.5x^{-0.185}$	100–100,000
Activated sludge	m^3	€/m^3	$y = 1682.7x^{-0.148}$	100–70,000
Phosphate precipitation/flocculation	m^3	€/m^3	$y = 11.950x^{-0.574}$	800–20,000
UV disinfection	m^3/d	€/m^3/d	$y = 1209.2x^{-0.328}$	100–100,000
Ozonation	m^3/d	€/m^3/d	$y = 348.02x^{-0.069}$	100–100,000
Activated carbon adsorption	m^3/d	€/m^3/d	$y = 29.458x^{-0.533}$	700–100,000
Sandfiltration	m^3/d	€/m^3/d	$y = 2045.3x^{-0.273}$	3,000–100,000
Chlorination	m^3/d	€/m^3/d	$y = 3.416x^{-0.422}$	3,000–100,000
Digestion/stabilisation	m^3	€/m^3	$y = 8192.8x^{-0.322}$	400–50,000
Sludge thickening	m^3	€/m^3	$y = 2220.8x^{-0.226}$	10–10,000
Mechanical sludge dewatering	m^3/d	€/m^3/d	$y = 39.745x^{-0.155}$	30–14,000

The energy demand of individual process steps depending on the size of the plant is also frequently discussed, and energy-intensive processes are the focus of these publications (Schoenenberg 1996; Bolle & Pinnekamp 2011). The energy demand is often described as a linear function depending on the volume of wastewater.

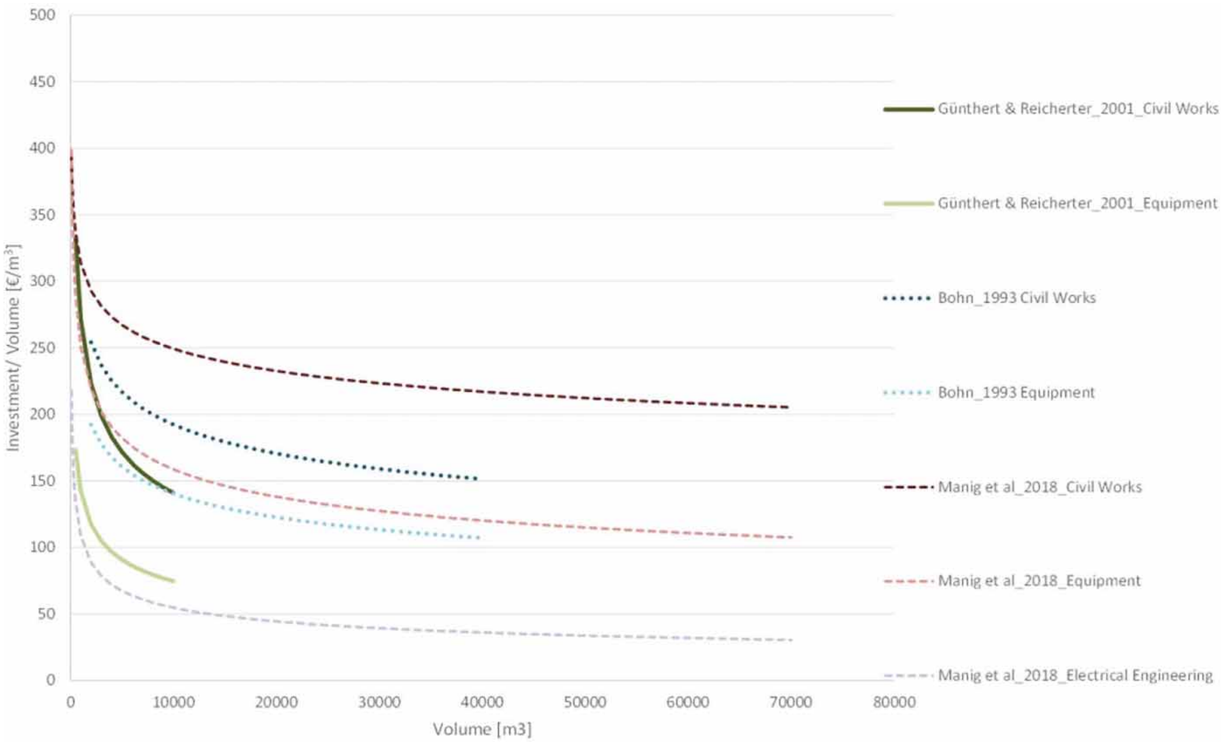

Figure 4 | Literature examples of the breakdown of the activated sludge cost function.

In the leaflet 'DWA M-271' published by the German Association for Water, Wastewater and Waste nomograms of the labour requirements in relation to the size of the plant are given, for example, the biological treatment in Figure 5 (DWA 2017). These can be multiplied by an hourly wage definition of the labour costs. In this case, the wage should not only include one person but an engineer (e.g. 15%), a foreman (e.g. 25%) and technical staff (e.g. 60%).

The average cost of maintenance is presented, for example, for activated carbon and ozonation in Hunziker-Betatech (2008) and Türk *et al.* (2013). In cases where no further information regarding maintenance is available percentages of the investment cost can be used for civil works 0.5%, for equipment 2.5% and E/I&C 1% (Jekel *et al.* 2016). The operational expenses like energy and consumable demand are based on the input data from the module library developed under the WaReIp project and therefore no overall operating expenses cost functions are assembled.

The provided data or customised data can be entered into the calculation model to estimate overall OPEX, annual and cost per cubic metre.

CALCULATION MODEL

In the next step, the derived cost functions and the OPEX data are incorporated into a specifically developed MS Excel-based calculation model that can serve as a strategic decision-making tool when weighing potential water reuse investment alternatives for IPs. Therefore, the model can calculate up to three different investment alternatives in parallel and compare the resultant costs per cubic metre of produced reuse water over time in order to support the decision-making process.

Guidelines and descriptions of how to calculate the cost of water treatment are widely available (EPA 2014; Ruiz-Rosa *et al.* 2016; Papapetrou *et al.* 2017). MS Excel has been chosen as a widespread and easy accessible tool. The developed calculation model in MS Excel is therefore ideal since input data, as well as formulas, can be altered.

Considering the available data basis for the derived cost functions, the model provides the best results for IPs for various sizes. With the derivation of cost functions from multiple sources with different sizes, an enlarged range

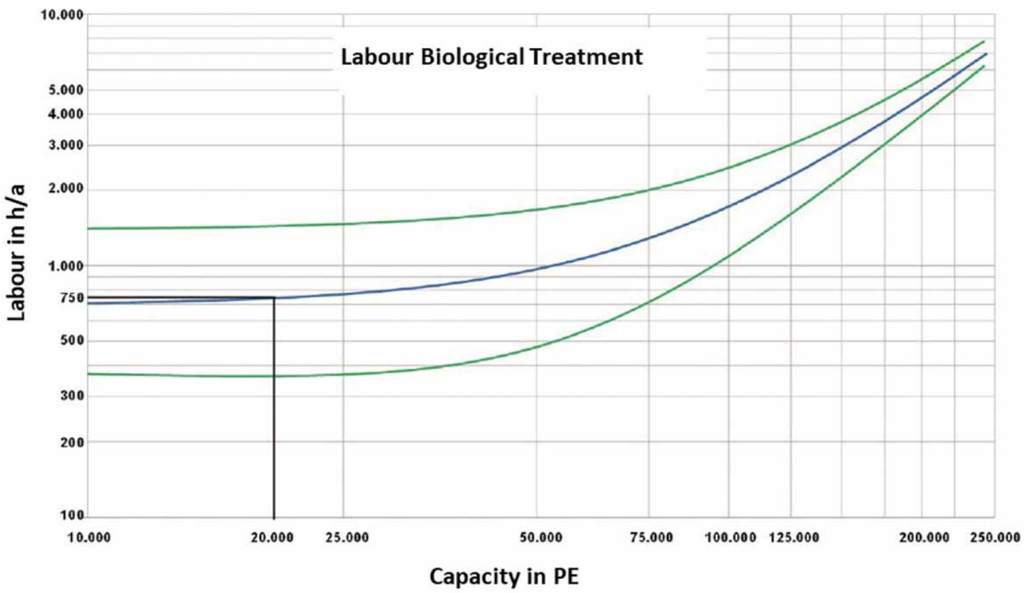

Figure 5 | Nomogram of labour requirements for biological treatment (based on DWA M-271).

can be covered. For example, primary/secondary treatment from 100 m^3 tanks up to 100,000 m^3.

The model was designed in a modular way to allow comparability of different compositions of the technologies and process chains, including sand filtration, UV disinfection, chlorination, and the required distribution network. The main modules are basic set-up, investment expenditures and operative expenditures. The basic set-up module allows definition of several variables that are valid for all three investment alternatives throughout the model, e.g. inflation rate, used currency, VAT rate or operative days per year of the plant. Furthermore, for each investment alternative individually, design capacities, as well as inflow and outflow volumes of each process step, are defined here.

The investment module includes the derived cost functions for investment costs in order to calculate investment amounts and depreciation. Investments are calculated separately for each process step and the required distribution network. For further comparability and more accurate depreciation periods, each technology is (where applicable) separated into investment expenditures for general costs/fees/reserves, environmental works, civil works, equipment and E/I&C. Necessary reinvestments depending on the depreciation periods are automatically taken into account by underlying formulas.

The operating expenditure module similarly differentiates between the processes and distribution network on the one hand and between labour, maintenance, energy and consumable expenditures on the other hand. Where available, the derived cost functions for operative expenditures are included; otherwise, alternative calculations have been applied (e.g. maintenance as a percentage of investment costs). Default values and prices can be used or individually adjusted and therefore calculated with current and specific prices.

The focus of the calculation model is to determine both the total costs and the costs per m^3 of reuse water per scenario and to make them comparable in order to support the decision-making process from an economic point of view. Due to the modular structure, each individual module can also be compared with each other and its influence on the overall cost can be assessed. The model can either be used with the initially derived cost functions, be adapted to a particular company or industry needs or be transferred to meet the conditions of a specific country and industry.

Alternatively, the model can also be used to analyse sensitivities for one investment scenario by comparing it with itself under slightly altered assumptions. In addition, it can theoretically be used as a standalone tool for project calculation, if actual data for all aspects of investment are available and the cost functions are not needed.

CONCLUSION AND OUTLOOK

A literature review, as well as interviews with companies and IP operators in Germany, China and Vietnam, led to the result that either detailed data on individual treatment steps are not collected in IPs or companies are quite reluctant to publish process details and costs. With the approach of using average municipal investment cost functions and divided data on operational expenses and adapting them to industry and country requirements, estimations of industrial wastewater treatment are possible. In a first step, cost functions and costs from municipal plants were collected in a meta-analysis. The cost functions are used to show general trends and allow for a comparison of different treatment steps as well as a model calculation of CAPEX and OPEX as well as annual cost and cost per cubic metre in the developed calculation model.

The cost functions and the calculation model are subject to certain limitations. First, the accuracy of the calculation model's results is dependent on the quality of the derived cost functions. The cost functions as described date back to the 1990s and are not comprehensive, especially with the focus on processes used in the industrial sector. Additional data on similar applicable projects are desirable to further improve the cost functions, as data are from studies with heterogeneous designs and vital information like the inclusion of VAT is often missing. By including data from the United States of America and Switzerland, the cost level is not limited to Germany. Additionally, the model required a generalist approach in design and neglects detailed customisation options for individual calculations in favour of comparability between investment alternatives and transferability of the model to similar conditions. The determined investment cost functions can be used for rough estimates and first impressions of possible investments but need to be adapted to industry and country specifics. Furthermore, the cost degression in the investment is clearly visible. With the ability to adapt the modular calculation model to specific requirements, it is broadly applicable, for example, by IP planners or operators.

To validate the database and model outputs, further expert interviews are currently ongoing. The main objective is to transfer the data from municipal WWTPs to IP requirements and to assess the transferability to other countries, e.g. water-scarce regions. It is recognisable that investments tend to be higher in industrial WWTPs compared with municipal plants due to a high degree of specialisation and automation. The investment in automation technology may be even higher when the WWTP is connected to the existing control and monitoring system of the IP. On the other hand, labour requirements tend to be lower, but salaries tend to be higher compared with municipal WWTPs. A plausible explanation besides the automation is a more efficiently operated plant in IPs.

At this point, the methodology including the cost functions and the calculation model is tested to evaluate the WaReIp Model Industrial Park Reuse Plant which is described in Boysen *et al.* (2020). For this purpose, the German cost functions need to be transferred to Chinese conditions and circumstances, to match the Model IP that is located in China. To achieve this, a data query was started and the first inputs for the Chinese model were incorporated. First results show that, for the majority of the indicators, the installation of the water reuse plant seems to be beneficial for all examined reuse options. From an economic point of view, reuse options with larger volumes of water treated will be preferred since the more water is treated, the cost per cubic metre of reuse water is reduced due to the economies of scale.

Even in cases where water reuse is compared with 'traditional' water supply systems not favourable from purely an economic point of view, it can provide a viable and efficient option to increase water availability for IPs, especially in water-scarce regions. The most promising strategy is to use reuse water for applications that require low water qualities and little additional treatment efforts, e.g. some infrastructural reuse applications (Bauer *et al.* 2019).

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DATA AVAILABILITY STATEMENT

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

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