RENEWABLE ENERGY SUPPLY FOR WASTE WATER TREATMENT PLANT AERATION: A TECHNO-ECONOMIC ANALYSIS OF DIFFERENT TECHNOLOGY OPTIONS

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ABSTRACT

This paper investigates the introduction of renewable electricity (RE) supply in waste water treatment plants (WWTP) aeration. WWTPs are significant energy consumers, constituting 1% of global electricity consumption. In Germany, WWTPs electricity demand was 3.4 TWh in 2017, corresponding to 0.75% of national electricity demand in that year. 50-90% of WWTPs electricity demand results from the aeration of the biological treatment, causing high operational costs. Conventionally, grid-supplied electricity powers blowers to blow air into the biological treatment to satisfy oxygen (O_2) demand. This study advocates for a transition to RE supply to cover the energy demand within the aeration process.

The present contribution examines three technology routes (TR) to introduce RE supply in WWTPs aeration. Each TR consists of RE supply by wind turbines and PV. RE is used either directly in the aeration blowers or indirectly via different energy conversion and storage options, provided by an electrical energy storage in TR 1, by an air compressor and storage in TR 2 and by an O_2 storage with O_2 produced as a byproduct in water electrolysis in TR 3. A case study is conducted on the example of a large-scale WWTP in Germany with an annual O_2 demand of 10.6 million kg, resulting in 5.3 GWh/a of electricity demand for the conventional aeration processes, incurring energy costs of 1.38 million EUR/a. The techno-economic analysis employs linear optimization to minimize the system's total annual costs (TAC) under a predefined RE share constraint between 0% and 100%.

The analysis reveals a substantial economic potential of introducing RE supply in WWTPs aeration. RE supply shares close to 80% are realized without using a storage, coming with a reduction in TAC of up to 50% for the considered economic parameters, if RE is supplied without additional charges. Considering additional charges, the potential TAC reduction diminishes to 17%. RE shares of up to 100% requires storage installation, reducing economic efficiency. At 100% RE supply, TAC increase by 41% in TR 1 using electrical energy storage and by 167% in TR 2 using compressed air storage, compared to TAC without RE supply. The economic efficiency of TR 3 depends on the revenues from hydrogen sales. If the revenues cover hydrogen production costs, TR 3 is the most economical, yielding TAC reductions of up to 65% even at RE shares of up to 100%.

1 INTRODUCTION

The subject of this paper is the investigation of introducing renewable electricity (RE) supply in waste water treatment plants (WWTP) aeration. WWTPs are significant electricity consumers, responsible for around 1% of global electricity consumption (IEA, 2016). In Germany, WWTPs electricity demand was 3.4 TWh in 2017, which corresponds to 0.75% of national electricity demand in the respective year. Furthermore, WWTPs are the largest energy consumer at the municipal level and account for 30-50% of municipalities' energy expenditures. With electricity price rises by 65% in the past ten years, further increases are expected. Therefore, introducing RE supply in WWTPs is motivated by ecological reasons and by the urge to reduce WWTPs energy expenditures (Fricke, 2009; Niederste-Hollenberg *et al*., 2021; Daschner, 2022; DPA, 2022; BDEW, 2023;Umweltbundesamt, 2024).

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The focus of the present study lies on the aeration of the biological treatment, as it is the largest consumer in WWTPs, accounting for 50-90% of total electricity demand. Conventionally, blowers (e.g., turbo compressors) supply the biological treatment tanks with air. Therein, the oxygen (O_2) is used to remove organic substances, particularly carbon and nitrogen compounds by microbiological degradation (Skouteris *et al*., 2020; Fricke, 2009; Gu *et al*., 2023; Metcalf & Eddy, Inc, 2014).

Many WWTPs already cover some of their energy demand by employing combined heat and power units fed by digester gas. If a combined heat and power unit is in place, its production typically covers 20% to 65% of WWTPs electricity demand. The combined heat and power unit is geared towards continuous operation to supply heat for the sludge digestion (Schmitt *et al*., 2017). This option is not analyzed within the present study since the focus lies on the dynamic demand of the aeration and the necessity to implement storages. However, to reduce WWTPs grid electricity purchase, the introduction of RE supply using wind turbines and photovoltaics (PV) is an option. RE can be produced and supplied by onsite RE plants (or direct connection to offsite plants) and offsite RE plants with transmission through the public electricity grid, e.g. via a power purchase agreement (PPA). In recent years, the purchase of RE by means of PPAs has become an increasingly popular option for companies and for municipalities. RE supply is associated with reduced energy expenditures due to low levelized cost of electricity (LCOE) and, in the case of onsite production, avoidance of additional charges (grid transmission fees, taxes, and levies). However, a high share of RE comes with a need for energy storage, as the fluctuating dynamics RE supply and electricity demand limit the direct coverage. In order to store surplus RE during periods of high availability for utilization during low availability, electrical energy storage is an option (Chen *et al*., 2021; Daw *et al*., 2012; Kelly *et al*., 2012; Myszograj *et al*., 2021; Niederste-Hollenberg *et al*., 2021; Stanitsas and Kirytopoulos, 2023).

Besides electrical energy storage to balance electricity demand and supply at WWTPs, current literature discussed further technology routes. The research project *arrive* investigates two storage concepts: The first includes the production, storage, and utilization of compressed air. The other one operates a water electrolysis for the production of hydrogen (H_2) and O_2 by water electrolysis. The O_2 can be stored and used to substitute the air of conventional aeration processes to reduce the energy demand of the blower. The results indicate that both concepts can contribute to flexibility in supply and demand but are not economically feasible (Schmitt *et al*., 2017). Various studies focus on the latter concept using O_2 from water electrolysis in the biological treatment, three of which are outlined below.

Donald and Love (2023) analyzed the O_2 production by PV and grid electricity powered water electrolysis to cover the O_2 demand of a small-scale WWTP during a 24-hour period. Within this process, O_2 is seen as a byproduct, while H_2 is the main value product. The results show the viability of the process, but an economic assessment considering capital and operating expenditures is not performed. This is done in a study by Hönig *et al.* (2023) which investigates the economics of H_2 production by water electrolysis, while using O_2 in the WWTP. Again, the water electrolysis is powered by grid electricity and PV. It is shown that utilizing O_2 improves the economic efficiency of H_2 produced by water electrolysis. A techno-economic assessment carried out by Ramirez *et al.* (2023) also analyzed the economics and the dimensions of the electrolyzer in the described setting. Operation of the water electrolysis follows a predefined cycle with a one-day period based on the availability of RE, which is used together with conventional grid electricity, to power the water electrolysis. H_2 is produced at atmospheric pressure and sold to a nearby industry. O_2 is pressurized by a compressor and stored in a storage tank. The results show that the O_2 demand of a small-scale WWTP with an installed capacity of 80,000 population equivalents is covered for more than 99% of the investigated period. However, the investigated net costs of O_2 production by the water electrolysis are higher than reference costs of industrial O_2 in the reference year 2020, but, within favorable market conditions, a competitiveness is projected for 2030 (Ramirez *et al*., 2023).

Even though previous studies addressed the described technology routes, a comprehensive and comparative techno-economic evaluation of all these concepts within a uniform modeling framework is missing. Further, with a focus on RE supply by means of PV, previous research lacks to address RE

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supply from wind power, also considering offsite RE production and supply, e.g. via PPAs. Further, the daily and seasonal dynamics of the fluctuating RE production are not sufficiently taken into account.

Therefore, the present paper investigates the introduction of RE supply for WWTPs aeration, considering a dynamic generation by wind turbines and PV. It covers three technology routes (TR), including electrical energy storage, compressed air storage and water electrolysis with oxygen storage and a subsequent direct usage of oxygen in the aeration process. They are compared using a cost optimal design for varying RE shares. The analyzed cases include onside as well as offsite RE production and three scenarios for the economic parameters and RE availability (optimistic, reference, and pessimistic).

The paper is structured as follows: Section 2 presents the general study design with the investigated TRs, the optimization model equations, and the input data sets for the conducted case study. In Section 3, the results are discussed, and in Section 4, the main findings are summarized.

2 METHODS

In the first part of this section, the analyzed TRs are introduced. After that, the optimization model equations are outlined in the second part, and the conducted case study with the underlying data sets is presented in the third part.

2.1 Analyzed technology routes

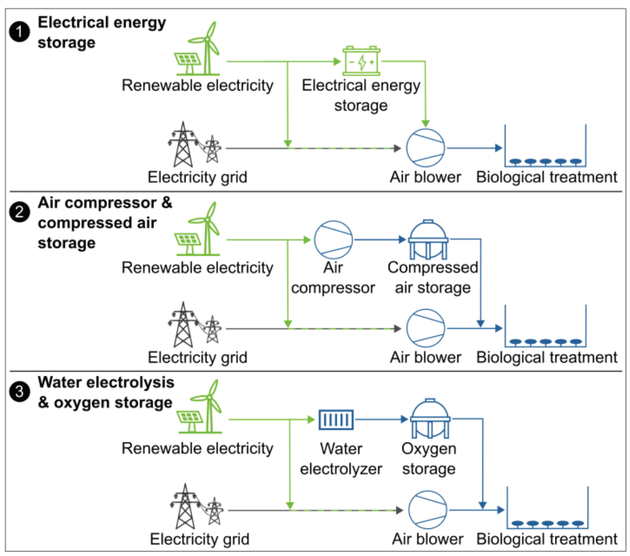

Figure 1: Technology routes for renewable electricity supply of waste water treatment plant aeration of biological treatment: (1) Electrical energy storage; (2) Air compressor and compressed air storage; (3) Water electrolysis and oxygen storage

The investigated TRs are shown in Figure 1. Each TR comprises the RE generation and supply by PV and wind turbines, grid electricity supply, a blower for conventional aeration, and the O_2 demand of biological treatment. In each TR, grid electricity supply for the blower is substituted either by direct supply of RE to the blowers or by indirect supply via the following TRs. In TR 1, an electrical energy storage is used to balance the fluctuations in demand and RE supply. The discharged power is used within the existing air blower. In TR 2, an air compressor uses surplus RE to feed a compressed air storage tank. It is discharged in times of low RE generation. Alternatively, in TR 3, O_2 is produced by water electrolysis and either fed directly in the biological treatment in an adapted aeration process or it can be stored in a storage tank, and used during times of low RE supply. The TR components are solely powered by RE.

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2.2 Optimization model equations

Within the study, the design as well as the dispatch of the components are optimized. The formulation of the optimization problem is based on Brandt *et al.* (2023) and was extended in this study by additional components and constraints. In the following, the basic structure of the model with the essential equations is introduced, and the main extensions of the model added in this analysis are described.
The objective of the optimization is to minimize the total annual costs (TAC) C_{TAC}.

$$C_{\mathrm{TAC}} = \sum_{i=1}^{n} (C_{\mathrm{CAPEX},i} + C_{\mathrm{OPEX},i}) + C_{\mathrm{Grid}} \tag{1}$$

It consists of the annualized acquisition cost $C_{\mathrm{CAPEX},i}$ and the operational cost $C_{\mathrm{OPEX},i}$ for each component i, as well as the cost for power purchase from grid C_{Grid}. In TR 3 the revenue from the sale of the H_2 produced is deducted from the TAC in the objective function. The annualized acquisition costs of each component are calculated by multiplying the nominal power $P_{\mathrm{nom},i}$ by the specific capital cost $C_{\mathrm{CAPEX},i}$ and the annuity factor A_i.

$$C_{\mathrm{CAPEX},i} = P_{\mathrm{nom},i} \cdot c_{\mathrm{CAPEX},i} \cdot A_i \tag{2}$$

The annuity factor is calculated based on the interest rate $r_{\mathrm{WACC},i}$ and the depreciation time $t_{\mathrm{dep},i}$ of the respective component.

$$A_i = \frac{r_{\mathrm{WACC},i} \cdot (1 + r_{\mathrm{WACC},i})^{t_{\mathrm{dep},i}}}{(1 + r_{\mathrm{WACC},i})^{t_{\mathrm{dep},i}} - 1} \tag{3}$$

The annual operational cost of each component results from the nominal power $P_{\mathrm{nom},i}$, the specific capital cost $c_{\mathrm{CAPEX},i}$ and the operational cost factor $f_{\mathrm{OPEX},i}$.

$$C_{\mathrm{OPEX},i} = P_{\mathrm{nom},i} \cdot c_{\mathrm{CAPEX},i} \cdot f_{\mathrm{OPEX},i} \tag{4}$$

The total cost for power purchase from the grid C_{Grid} is calculated by multiplying the sum of purchased power $P_{\mathrm{Grid},t}$ for all time steps t with the time step length Δt and the grid electricity purchase price p_{Grid}.

$$C_{\mathrm{Grid}} = \sum_{t=1}^{T} P_{\mathrm{Grid},t} \cdot \Delta t \cdot p_{\mathrm{Grid}} \tag{5}$$

The optimization comprises both the design and the operation variables of all components. The following equations are the equality constraints that define the system's operation.

$$P_{\mathrm{Grid},t} + P_{\mathrm{PV},t} + P_{\mathrm{Wind},t} - P_{\mathrm{blower},t} = 0 \qquad \forall t \in \{1, 2, 3, \dots, T\} \tag{6}$$

$$\dot{m}_{\mathrm{blower},t} \cdot \eta_{\mathrm{OTE,air}} - \dot{m}_{\mathrm{demand},t} = 0 \qquad \forall t \in \{1, 2, 3, \dots, T\} \tag{7}$$

Equation 6 describes the power balance of all power producers and consumers, while equation (7) describes the O_2 mass balance. Both balance equations must be extended depending on the considered TR. In TR 1, the power balance contains the power $P_{\mathrm{ES},t}$ of the electrical energy storage. In TR 2, air compressor power $P_{\mathrm{Comp},t}$, and in TR 3, water electrolysis power $P_{\mathrm{WE},t}$ is added to the power balance. The O_2 mass balance is extended by $\dot{m}_{\mathrm{ST},t}$ either via compressed air tank (TR 2) or pure O_2 tank and by direct O_2 supply from the water electrolysis $\dot{m}_{\mathrm{WE},t}$ (TR 3). The oxygen transfer efficiency (OTE) η_{OTE} is further discussed in Section 2.3.1.

$$E_{\mathrm{ES},t} - E_{\mathrm{ES},t-1} + \begin{cases} -P_{\mathrm{ES_{in}},t} \cdot \eta_{\mathrm{ES}} \\ \dfrac{P_{\mathrm{ES_{out}},t}}{\eta_{\mathrm{ES}}} \end{cases} \cdot \Delta t = 0 \qquad \forall t \in \{2, 3, \dots, T\} \tag{8}$$

The energy balance of the electrical energy storage is shown in equation (8) with the stored energy $E_{\mathrm{ES},t}$, the charge and discharge power $P_{\mathrm{ES},t}$ and efficiency η_{ES}. The compressed air and O_2 storage balance equations are defined correspondingly. The conversion of power to mass flow is described by the component's specific energy demand ϵ_i (see Table 2), as shown in equation (9) for water electrolysis. It is defined correspondingly for the blower and air compressor. Further, a linearized efficiency curve is used to model the load-dependent specific energy demand ϵ_{WE} (Brandt *et al.*, 2023).

$$P_{\mathrm{WE},t} - \dot{m}_{\mathrm{WE},t} \cdot \epsilon_{\mathrm{WE}} = 0 \qquad \forall t \in \{1, 2, 3, \dots, T\} \tag{9}$$

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Inequality constraints are defined to connect the operation and design of all components, as can be seen in equation (10) on the example of the water electrolysis.

$$P_{\mathrm{WE},t} - P_{\mathrm{nom,WE}} \leq 0 \qquad \forall t \in \{1,2,3,\dots,T\} \tag{10}$$

Within the optimization model, the RE share γ is set as an equality constraint to examine RE shares between 0% and 100% for each TR. γ is calculated by the quotient of actual grid electricity purchased by the necessary grid electricity supply, if no RE would be supplied (equation (11)).

$$1 - \frac{E_{\mathrm{Grid},T}}{E_{\mathrm{Grid,ref}}} - \gamma = 0 \tag{11}$$

The optimization problem, including the objective function and constraints, is linear. It covers a period of one year in hourly resolution. The optimization model was implemented in Matlab and solved via Gurobi.

2.3 Case study

2.3.1 Oxygen demand of waste water treatment plants biological treatment

In the present study, the O_2 demand of biological treatment of a large-scale WWTP in Germany with a size of about 500,000 population equivalents is covered. The annual O_2 demand cumulates to 10.6 million kg. The daily fluctuation within the O_2 demand is between 500 kg/h and 2,000 kg/h. Figure 2 (a) shows the corresponding annual O_2 demand time series. The data was determined by calculations based on measurements of waste water composition and volume flow, carried out by the Institute of Sanitary Engineering and Waste Management at Leibniz University Hannover.

The actual O_2 feed mass flow that must be blown into the biological treatment tank is much higher than biological treatments O_2 demand due to the OTE. The OTE indicates the ratio of O_2 blown into the biological treatment tank to the O_2 transferred and dissolved into the waste water (AquaEnviro, 2022). OTE for O_2 from the air can be considered lower than the OTE for pure O_2, which is mainly due to the 4.7 times higher partial pressure of pure O_2 (Skouteris *et al*., 2020). Therefore, OTE for O_2 from the air is assumed to be 0.2 and OTE for pure O_2 from electrolysis is assumed to be 0.5 in this study (Donald and Love, 2023). Furthermore, OTE is assumed as constant, independent of the waste water characteristics.

2.3.2 Renewable energy availability

This study considers RE generation by onshore wind turbines and PV. The availability of both options is displayed by time series in hourly resolution and expressed as a power factor between 0 and 1 for an annual period (see Figure 2 b) and (c)). Both time series are generated based on data provided by the open-source tool Renewable.ninja for the year 2019 (Pfenninger and Staffell, 2016). The default settings are used to generate the PV power factor time series. The power factor of wind power is calculated using the power curve of the wind turbine model *Enercon E-160 EP5* and wind speed data from the MERRA 2 dataset (Staffell and Pfenninger, 2016; ENERCON GmbH, 2022). The case study investigates three locations for RE production in Germany to address location-specific differences in availabilities displayed as FLH (see Table 1)

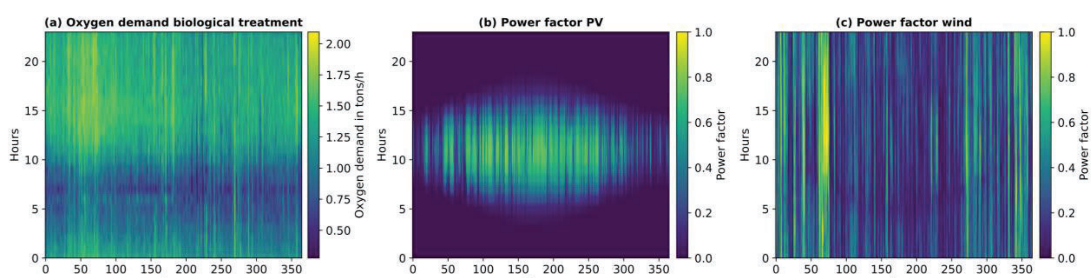

Figure 2: Input data time series for (a) O_2 demand of WWTP biological treatment in kg/h, (b) power factor for PV generation and (c) power factor for wind turbine

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Table 1: Full load hours of the considered RE locations in Germany

	weak wind, strong PV	Reference scenario (good wind, good PV)	strong wind, weak PV
PV generation	1,338	1,268	1,166
Wind generation	1,845	2,460	2,970

Table 2: Techno-economic parameters of system components

Component	Parameter	Reference value	Value range	Unit	Literature reference
Photovoltaic utility-scale	CAPEX	921	[600, 1242]	EUR/kW	[1, 2, 3]
	OPEX fix	13.3	-	EUR/(kW · a)	[1]
	Depreciation time	30	-	a	[1]
	Interest rate	5	-	%	[2]
Wind turbine onshore	CAPEX	1779.5	[1212, 2347]	EUR/kW	[2, 3]
	OPEX fix	20		EUR/(kW · a)	[1]
	Depreciation time	25		a	[1]
	Interest rate	5		%	[2]
Air blower	Spec. energy consumption (@0.8bar pressure increase)	0.1		kWh/kgO_2	[4, 5]*
Electric energy storage	CAPEX	581.5	[463, 700]	EUR/kWh	[1, 6]
	OPEX fix	9.3		EUR/(kW · a)	[1, 7]
	Depreciation time	15		a	[1]
	Interest rate	5		%	[1]*
	Round trip efficiency	86		%	[7]
Air compressor	CAPEX	482.5	[415, 550]	EUR/kW	[8, 9]
	OPEX fix	4		EUR/(kW · a)	[7]*
	Depreciation time	15		a	[2]*
	Interest rate	5		%	[2]*
	Spec. energy consumption (@50bar output pressure)	0.94		kWh/kgO_2	[5]*
Air/O2 storage tank	CAPEX	1950	[1700, 2200]	EUR/m^3	[10]*
	OPEX fix	39		$EUR/(m^3 \cdot a)$	[2]*
	Depreciation time	25		a	[2]*
	Interest rate	5		%	[2]*
Electrolyzer	CAPEX	1297	[804, 1790]	EUR/kW	[2]
	OPEX fix	20.2		EUR/(kW · a)	[2]
	Depreciation time	20		a	[11, 12]
	Interest rate	7		%	[2]
	Specific energy demand at nominal power	52.5		kWh/H_2	[2]
	Specific water consumption	14		kgH_2O/kgH_2	[2]
	Water cost	3.74		EUR/m^3H_2O	[13]

[1] (Kost *et al*., 2021); [2] (Brandt *et al*., 2023); [3] (NREL, 2023); [4] (Frey, 2020); [5] (Bell *et al*., 2014); [6] (Mongird *et al*., 2019); [7] (Schmidt *et al*., 2019); [8] (Zakeri and Syri, 2015); [9] (Madlener and Latz, 2013); [10] (Gretzschel *et al*., 2020); [11] (IEA, 2020); [12] (IRENA, 2020); [13] (Simoes *et al*., 2021);
*own calculation/assumption according to …

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2.3.3 Techno-economic parameters

Besides the described time series, further parameters define the case study and affect strongly the results. Those are first the parameters describing the electricity prices and second the technical and economical parameters describing the considered components (see Table 2). The prices for conventional grid electricity supply are set to a constant value of 260 EUR/MWh (BDEW, 2023; Daschner, 2022). Two RE supply cases are considered. First, no additional charges apply, as would be the case with onsite RE production or direct connection. Second, RE transmission via the public grid is considered, as would be the case in a PPA with offsite RE production. In that case, additional charges (taxes, grid fees, levies) of 120.2 EUR/MWh are added to each unit of RE supplied (Bundesnetzagentur, 2023, 2024). For the CAPEX of all components, a pessimistic and an optimistic scenario are considered.

The mean of both is the reference scenario. Assuming an isentropic process, the specific energy demand for the blower and the air compressor is calculated by the quotient of the enthalpy difference of air at output and input pressure and the isentropic efficiency (Baehr, 2000; Bell *et al*., 2014). The isentropic efficiency is 80% (Gardner Denver, Inc., 2020; van Elburg, 2014). The pressure difference that the air blower has to overcome for aeration due to the tank depth and pressure losses is assumed to be 0.8 bar (Frey, 2020). In TR 2, the output pressure of the compressor required to fill the compressed air storage tank is assumed to be 50 bar (Schmitt *et al*., 2017). In the compressed air tank, higher pressures are assumed compared to the pure O_2 storage tank in TR 3 (30 bar) in order to reduce the necessary storage volume. The output pressure of the water electrolysis is 30 bar. Therefore, no additional compression of the O_2 in TR 3 is required.

3 RESULTS AND DISCUSSION

This section presents the results of the case study. It is structured in three parts. First, optimized TAC for all TRs in the reference scenario are discussed. After that, the same analysis is done for the optimistic and pessimistic parameter scenarios and lastly, the impact of different grid electricity and RE supply costs are examined.

3.1.1 Case study results in the reference scenario

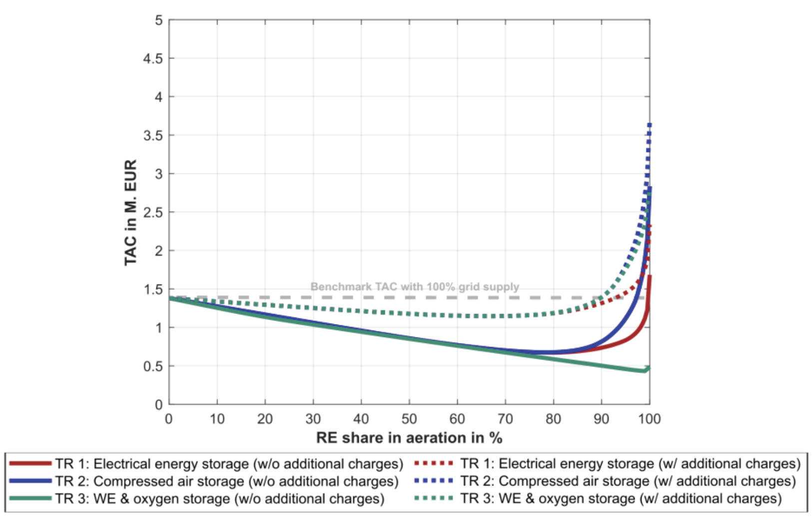

Figure 3: Optimized TAC of each TR in the reference scenario with and without additional charges for RE shares between 0% and 100%. In TR 3, H_2 revenues are deducted from TAC.

Figure 3 shows the TAC for the analyzed TRs in the reference scenario for predefined RE shares between 0% and 100%. It is differentiated between RE supply without additional charges (solid lines) and with additional charges (dashed lines). In the reference scenario, the resulting LCOE are

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57 EUR/MWh for PV and 60 EUR/MWh for wind power. If additional charges (taxes, grid fees, levies) are considered, 120.2 EUR/MWh are added to the LCOE. At a RE share of 0%, no RE is supplied, reflecting the conventional aeration with 100% grid supply, which is referred to as the benchmark TAC in the following and indicated by the dashed grey line in Figure 3. It corresponds to TAC of 1.38 million EUR/a. An increasing share of RE, up to around 80%, yields decreasing TAC. This is due to the lower cost of RE supply compared to grid electricity. At RE shares above 80%, the TAC of all TRs except TR 3 (without additional charges) start to increase to end up above the benchmark TAC.

The reasons behind the cost development for each respective TR is displayed in a cost breakdown in Figure 4. Each subplot displays the cost breakdown of the TAC for one TR without (Figure 4 (a) to (c)) or with additional charges (Figure 4 (d) to (e)). The cost increase in TR 1 and 2 at high RE shares is due to the fluctuations in RE supply. To cover high RE shares, RE must also be supplied at times of low availability. Therefore, wind turbine and PV capacities must be oversized, which leads to excess production at times of high RE availability and an increase in RE supply costs (indicated by the green areas in Figure 4). TAC increase drastically when the RE share is close to 100%, as a storage must be installed to shift excess RE supply to times of low RE availability, which comes with additional costs. Electrical energy storage is installed at RE shares around 80% in TR 1, and a compressed air storage tank in TR 2 is installed at RE shares around 90% (indicated by the dark blue areas in Figure 4). At those high RE shares, TR 1 with an electrical energy storage is more economical than TR 2. This is due to the high specific energy demand of the compressor compared to the specific energy demand of the air blower and the additional acquisition costs for compressed air storage tank.

In TR 3, H_2 production costs consist of the annualized acquisition costs for the water electrolyzer and the costs for an increased RE supply to feed the water electrolyzer. However, the sale of H_2 generates an additional revenue that is deducted from the TAC. The result of the analysis therefore depends heavily on the assumed H_2 sales price. The H_2 price is set to 4.6 EUR/kg, which corresponds to the H_2 production costs in the reference scenario without additional charges for RE supply. Therefore, O_2 is a free byproduct reducing aerations electricity demand making TR 3 is the most economical.

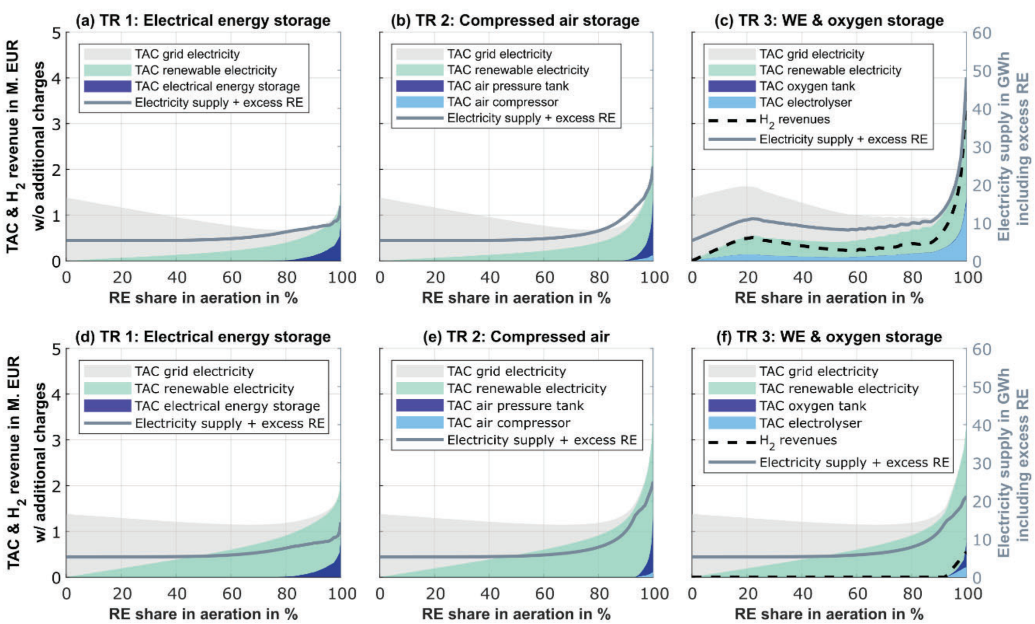

Figure 4: Optimized TAC, H_2 revenues and electricity supply in the reference scenario, for TRs without (a-c) and with (d-f) additional charges over RE share, TAC breakdown shows costs for grid electricity supply, RE supply, and TR components.

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3.1.2 Results in the optimistic and pessimistic scenario

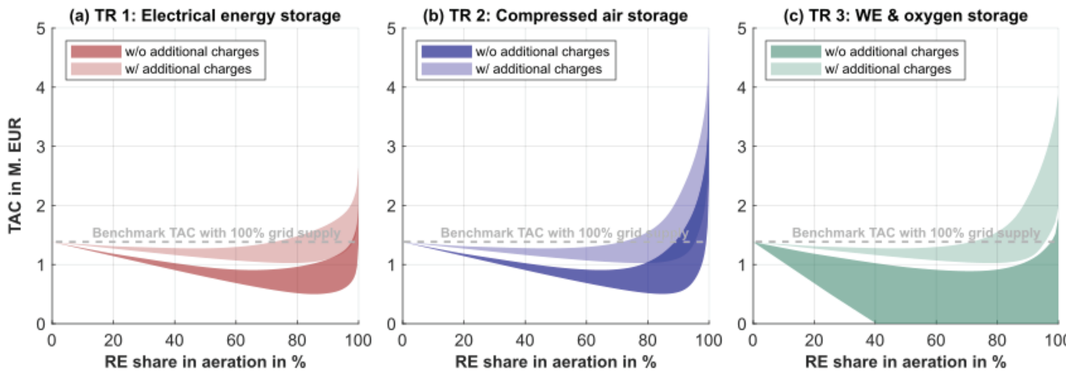

Figure 5: TAC of (a) TR 1, (b) TR 2 and (c) TR 3 over RE share with areas representing the resulting range of results for the different CAPEX and RE availability scenarios.

Since the results strongly depend on the considered economic assumptions and parameters, Figure 5 displays the range of TAC of all scenarios (pessimistic to optimistic costs and RE availabilities, with and without additional charges) for all TRs. The optimistic and pessimistic scenarios yield LCOE in a range of 39 to 81 EUR/MWh for PV and between 36 and 101 EUR/MWh for wind power. If CAPEX assumptions and RE availabilities are pessimistic and no additional charges are considered, minimal TAC are achieved at RE shares around 60% without installing a storage. With additional charges, no significant cost reductions are achieved compared to the benchmark TAC, but a significant increase in costs at high RE shares is occurring. Again, in all scenarios, TR 2 with a compressed air storage is the least economical to cover high RE shares. TR 3 is more economical than TR 1 if H_2 sales price covers its production costs, which is the case in the optimistic scenario and reference scenario without additional charges. If CAPEX and RE availability are pessimistic, or additional charges for RE supply are considered, H_2 production costs are not covered by sales revenues, making H_2 production and TR 3 uneconomical. Hence, if H_2 prices are sufficient, TR 3 is always the most economical option.

3.1.3 Analysis of varying electricity prices

The results discussed previously are valid for the considered costs of grid electricity supply at 260 EUR/MWh. However, electricity prices can vary as seen for the grid electricity price in the past with a further increase expected, or in the case of RE e.g. due to location dependent LCOE and additional charges. The impact of deviating grid electricity and RE supply prices on optimized TAC and the corresponding RE shares are investigated in the following (see Figure 6). Within that analysis, the RE share is not set as a constraint as before, but results from the optimization towards minimized TAC. PV prices are set 20 EUR/MWh below wind power prices as PV typically yields lower LCOE. Input parameters for CAPEX and RE availability are from the reference scenario.

The results for all TRs are summarized in Figure 6, displaying the TAC ratio (a) and RE share (b) of the TR that yields the lowest TAC. The dashed lines indicate the TR being most economic at the corresponding electricity prices. The color indicates the relative TAC as a ratio of the current TAC to the benchmark TAC with 100% grid supply for the corresponding electricity price. In the top left corner in Figure 6 (a), RE prices are above grid electricity prices. In that area, the cost ratio is one, as no cost reduction occurs. With RE prices below grid electricity price, optimized TAC are below benchmark TAC, as RE supply results in cost reductions. Minimum TAC are achieved at RE prices below 50 EUR/MWh in TR 3, as H_2 is produced at costs below the selling price, yielding revenues that exceed TAC. At grid prices of about 400 EUR/MWh and RE prices above 150 EUR/MWh, the installation of an electrical energy storage (TR 1) yields an economic advantage by utilizing excess RE supply. Figure 6 (b) shows the RE share that is achieved in the cost optimized system. In the top left corner, RE share is 0% and starts to increase if the RE price is below the grid electricity price. With RE prices

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below 50 EUR/MWh the RE share is close to 100%. With increasing electricity prices, RE shares above 75% remain economically feasible as long as the grid electricity price is twice as high as the RE price.

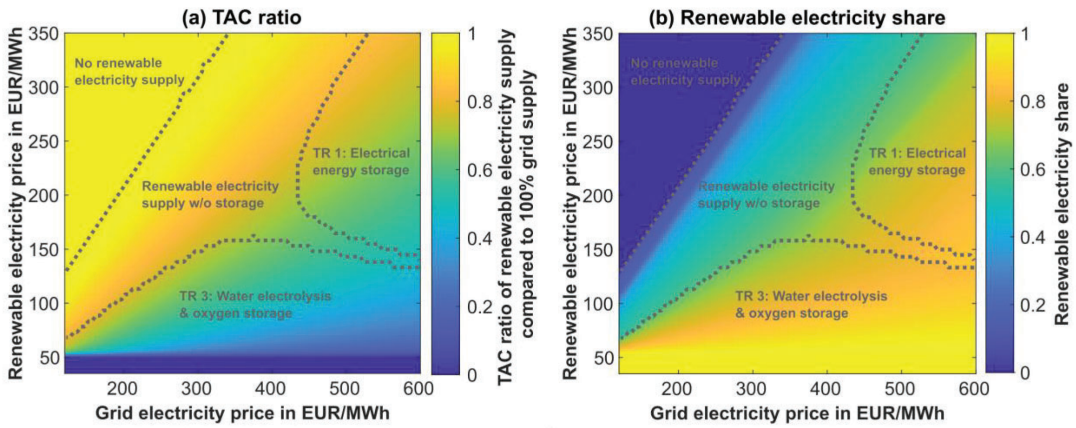

Figure 6: (a) Cost ratio of minimized TAC (including H_2 revenue) and benchmark costs of conventional aeration with 100% grid supply assuming the corresponding costs for grid electricity and RE supply. (b) Renewable electricity share of the optimized system. Dashed lines indicate which TR yields minimal costs at the corresponding electricity prices.

4 CONCLUSION

The present study investigated RE supply in WWTPs aeration of the biological treatment within a comprehensive techno-economic analysis, considering three TRs. The aim was to determine the economic potential of using RE in the aeration and to identify the most suitable technologies for that. The following are the main findings:

- Within the assumptions in the reference scenario, RE shares of up to 80%, and significant cost reductions of up to 50% are achieved without installing a storage option.
- In the scenario with pessimistic assumptions, cost reductions are up to 20% with RE shares around 60%, without installing a storage.
- With optimistic assumptions, minimal TAC are achieved at RE shares around 90% or higher with cost reductions above 50%.
- Applying additional charges for RE supply (e.g. grid fees, taxes, levies) diminishes the potential cost reduction. When considering additional charges, cost reduction is around 28% in the optimistic scenario and no cost reduction is achieved within pessimistic scenario.
- To acquire higher RE shares of up to 100% the installation of a storage is required.
- If a storage is installed, the electrical energy storage proves to be more economically efficient than compressed air storage within all analyzed scenarios.
- Storage and utilization of O_2 produced by water electrolysis is economically efficient if revenues from H_2 sales cover the major share of its production costs.

The case study considered one large-scale WWTP with its annual O_2 demand for the biological treatment and the corresponding parameters with regard to aeration (pressure differences, specific energy demand, OTE). Specific challenges, preconditions and implications for the aeration process and biological treatment with pure O_2, besides an increased OTE, are not taken into account. However, it was shown, that the results strongly depend on the underlying techno-economic assumptions. Even though three scenarios considering pessimistic, average and optimistic assumptions are investigated, the uncertainties within the analysis are not further quantified. Future work should address those issues and further investigate the use of O_2 from water electrolysis within WWTPs.

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NOMENCLATURE

A	Annuity factor	-	$\dot{m}$	Mass flow	kg/h
C	Total cost	EUR	P	Power	kW
E	Energy	kWh	p	Electricity price	EUR/kWh
ϵ	Specific energy demand	kWh/kg	r	Interest rate	-
f	Operational cost factor	EUR/(kW a)	λ	RE share	-

Subscript

CAPEX	Capital expenditures	ST	Storage tank
dep	Depreciation time	t	Time step
ES	Electrical energy storage	T	Time frame
i	Component	WACC	Weighted average cost of capital
η	Efficiency	WE	Water electrolysis
OPEX	Operation expenditures		

Abbreviations

H_2	Hydrogen	PV	Photovoltaic
LCOE	Levelized cost of electricity	RE	Renewable electricity
O_2	Oxygen	TAC	Total annual cost
OTE	Oxygen transfer efficiency	TR	Technology route
PPA	Power purchase agreement	WWTP	Waste water treatment plant

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