

construction of further expensive storage facilities or costly conversions in the sewer network, but can already be achieved with modern machinery and intelligent, dynamic control. The use of the CBR principle opens up new possibilities for systematically utilising empirical knowledge, linking it to real-time data and weather forecasts, and responding proactively to complex operating situations. The pilot application in Jena has shown that innovative technology can significantly reduce mixed water discharges, which not only offers ecological advantages but also contributes to more stable, energy-efficient and safer operation of the sewage treatment plant. It is particularly noteworthy that the approach developed remains adaptable in both technical and organisational terms, thus representing a transferable solution for many municipalities facing similar challenges. At a time of growing demands, dwindling resources and worsening climatic conditions, this form of intelligent sewer network management makes a practical, economical and sustainable contribution to sustainable water management.

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STRATEGY FOR APPLYING BESS AND CAES ENERGY STORAGE SYSTEMS IN SBR WASTEWATER TREATMENT PROCESSES

Mueller-Czygan G., Zhukova N.

Institute for Sustainable Water Systems, University of Hof, Germany

e-mail: guenter.mueller-czygan@hof-university.de, natalia.zhukova@hof-university.de

Sequencing Batch Reactor (SBR) technology is widely used in wastewater treatment plants (WWTPs) and is characterised by a cyclic aeration mode. These cycles cause fluctuations in electricity demand: during aeration, the power load rises sharply and then drops during the non-aeration phases like denitrification, sedimentation and clear water outlet. Aerobic biological treatment processes, based on activated sludge principles like Continuous Flow and SBR systems, are responsible for up to 70% of energy consumption. Of the total electricity demand at wastewater treatment plants [1]. Consequently, improving energy efficiency and flexibility of such facilities has a direct impact on efficiency and thus for sustainability of their operation. Against the backdrop of better utilization of renewable energies during periods of reduced sun activity (solar modules)

or calm winds (wind turbines), energy storage systems are considered a promising solution for compensating for lacks of available renewable energy or to take advantage of better tariffs when purchasing energy. With differentiated tariffs (day/night) or dynamic electricity prices, shifting part of the load from peak hours to night-time hours can significantly reduce costs [2]. Due to their inherent high operational flexibility, SBR wastewater treatment plants are very well suited for the optimal use of storage systems for effective energy management, as the cleaning process can be better adapted to the availability of renewable energies than continuous flow systems. The use of energy storage systems in SBR allows electricity to be accumulated during low tariff periods or when there is excess generation from renewable energy sources (RES), and during peak load hours, it can be used for aeration, thereby smoothing consumption from the grid and optimising costs during tariff periods.

BESS and CAES for WWTPs. Among energy storage technologies, the most common are battery energy storage systems (BESS) and compressed air energy storage (CAES) systems. Modern lithium-ion BESS have high efficiency ($\approx 90\%$) and fast response times, which allows them to be used for *peak shaving* by using pre-stored energy. Studies show that up to 50% of the daily load of SBR systems can be shifted in time using storage devices without compromising the technological process [3]. The disadvantages of BESS remain high cost and limited lifetime under deep cycling conditions, i.e., when batteries are frequently charged and discharged with a large depth of discharge (DoD), which accelerates aging and reduces the number of usable cycles [4].

CAES, on the other hand, is characterised by a long service life and relatively low specific energy storage costs and do not suffer from self-discharge [2] and are therefore suitable for storing large amounts of energy. In the context of treatment facilities, where CAES is currently no standard solution, modified schemes have been proposed: local compressed air tanks integrated into the aeration system. The idea is to use compressors to produce pressed air and to store it in tanks when there is a surplus of PV energy and use the compressed air for aeration later during peak hours, reducing the electricity consumption of blowers [2]. In the study [2] by Cottes et al. (2020), storage pressure was found to have only a minor impact on the overall system efficiency and economic performance (NPV), while storage volume showed a dominant influence.

Recent studies indicate that combining different types of storage can have a synergistic effect on the treatment plant's energy system [2, 5]. The synergistic effect refers to the complementary interaction between different storage types: chemical or electrochemical systems providing fast response and short-term balancing, while mechanical storage (CAES) offers higher capacity and long-duration stability. In [2], Cottes et al. (2020) demonstrated that integrating CAES with biogas-based CHP units reduces grid dependency through smoother load profiles, whereas [5] describes a real wastewater treatment plant in Germany where a hybrid network of PV panels, biogas-fueled CHP units, BESS, and heat storage ensures continuous and flexible energy supply by combining electrical and thermal storage systems. In the context of SBR technology, such a hybrid strategy operates by using BESS to shift the electrical demand of aeration cycles away from high-tariff periods, while CAES compensates for short-term peaks in air consumption at the beginning of aeration phases. Thus, the coordinated use of both storage types enables maximum utilization of renewable energy and ensures stable operation of aeration under fluctuating inflow and tariff conditions. This approach aligns with the broader trend of digitalisation and smart-grid integration in wastewater treatment plants. As noted by Müller-Czygan et al. (2023) [6], advanced energy monitoring and adaptive control systems enable flexible and energy-efficient operation of WWTPs, supporting the transition towards intelligent, tariff-responsive plant management.

Methodology and initial data (example of treatment plant Scheid). To study the effectiveness of different energy storage strategies, the small Scheid treatment plant (Hesse, Germany) was selected, which is characterised by sharp seasonal load irregularities: ~ 500 people live there permanently, while in summer the population, including tourists, reaches 3,500.

According to the operator's archive data, the months with the heaviest hydraulic and organic loads are May and August, when the average daily inflow ranges from ~ 75 to $314 \text{ m}^3/\text{day}$. In the modelling, the data for these "peak" months were taken as representative of the maximum loads.

The Scheid treatment plant operates on an SBR scheme with two parallel reactors, SBR1 and SBR2. The cycle of each reactor includes the phases of filling, aerobic reaction, settling and discharge of treated water (Fig. 1).

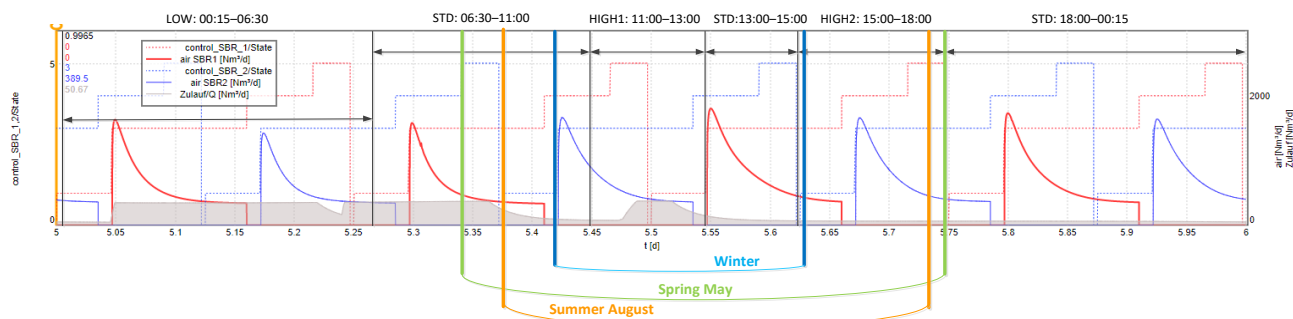


Fig. 1. Simulation of aeration for SBR 1 and SBR 2 at the Shayde wastewater treatment plant (Germany), tariff periods and seasonal distribution of solar generation. Results of a numerical experiment performed by the author in Simba 7 (Academic License license_simba7)

When analysing the smoothing of the energy consumption profile and the reduction of energy costs, renewable PV energy sources and storage devices with the following parameters are used:

- a 58 kW_p photovoltaic (PV) installation located on the roof of the treatment plant. For the latitude of Scheid, a specific output of $\sim 950\text{--}1000 \text{ kWh}$ per 1 kW_p per year is assumed [7,8]. The seasonal distribution of solar generation is uneven: in the winter months, the panel produces only $\sim 10\text{--}20\%$ of its summer output. Peak daily power generation values at midday in summer can exceed the total power consumption of the plant, which opens the potential for charging storage devices from excess PV energy.

- BESS: a lithium-ion storage device with an effective capacity of 20 to 50 kWh is considered. The maximum charging/discharging power is 10 kW (limited by the inverter), with an average round-trip efficiency of $\approx 90\%$. The battery is controlled by a tariff peak smoothing strategy: charging occurs when there is excess PV energy or during cheap LOW hours, discharging occurs during HIGH tariff hours to cover part of the load. The 20-kWh capacity is commensurate with $\sim 60\%$ of the average daily energy consumption for aeration in winter, while 50 kWh is sufficient to store almost two days' worth of demand (which is relevant in summer when there is excess generation from PV).

- CAES: a 5.5 kW compressor charges a 6 m^3 steel tank ($V_{\text{air}} \approx 55 \text{ Nm}^3$, $2 \rightarrow 12 \text{ bar abs}$) in approximately 2 hours, consuming about 6 kWh of electrical energy for a full charging cycle. The stored compressed air can subsequently be supplied to the aeration tanks through the existing system, thereby reducing blower energy demand. The equivalent electricity savings when using the full volume of compressed air are estimated at only $\sim 2.6 \text{ kWh}$. The low coefficient ($\approx 27\%$) is due to irreversible losses due to compression heat dissipation, but the energy of compressed air allows sharp peaks in air consumption to be cut. Compressed air is supplied at times when the required performance of the blowers briefly exceeds their nominal capacity. Table 1 below provides a comparative summary of the strategies.

Table 1. Energy balance of the Scheid SBR station by season

Indicator	Unit	Winter (Jan)	Spring (May)	Summer (Aug)
PV production	kWh/day	17	40	145
Energy demand (aeration)	kWh/day	30	30	30
Self-consumption (PV → aeration)	kWh/day	6	13	11
Energy import (Grid → aeration)	kWh/day	24	17	19
Energy storage – BESS (charging)	kWh/day	5 (partial charge)	20 (full charge)	20–50 (possible expansion)
Energy storage – CAES (charging)	kWh/day	6 (full charge)	6 (full charge)	12 (2 charging cycles)
Energy export (PV → Grid)	kWh/day	0	1	72–102
Use of storage devices	–	CAES at peak air consumption rates (≈ 1.2 hours)	BESS + CAES, covering expensive windows	BESS + CAES, double charging and discharging
Coverage of PV share of aeration requirements	%	~ 20	~ 43	~ 37
Key findings for the season	–	PV partially covers expensive windows, CAES reduces peaks	PV covers expensive windows, surplus charges BESS+CAES	PV covers daytime ventilation; surplus goes entirely to storage and the grid

Thus, analysis of management strategies has shown that BESS and CAES perform fundamentally different but complementary functions in the energy management of SBR stations. The main role of CAES is to ensure the quality of transition processes and compensate for short-term consumption peaks that occur at the beginning of aeration phase. Due to the instantaneous release of compressed air, CAES allows compressors to be unloaded during periods of sharp increases in consumption, smoothing out peak loads and stabilising the consumption profile. BESS, on the other hand, is effective for covering long load cycles throughout the day — it accumulates energy during periods of low tariffs or excess generation and provides power for aeration during hours of high electricity costs. It should be noted that, in the pilot setup for the Scheid WWTP, the CAES unit is dimensioned only for a partial airflow stream (6 m³ at 2–12 bar abs), serving as a short-term pneumatic buffer rather than a plant-wide storage system. Thus, the hybrid BESS + CAES strategy combines the advantages of both technologies: CAES performs local dynamic airflow equalisation and reduces instantaneous power peaks, while BESS provides energy-intensive daily balancing and fine-tuning according to tariff and technological conditions.

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MODERN METHODS OF SEWAGE SLUDGE DISPOSAL IN THE CONTEXT OF WATER RESOURCE PROTECTION

M. Myszura-Dymek¹, J. Gmitrowicz-Iwan¹, B. Futa¹, I. Kamińska²

¹Institute of Soil Science, Environmental Engineering and Management, University of Life Sciences in Lublin, Poland, magdalena.myszura-dymek@up.edu.pl, ²Faculty of Environmental Engineering and Energy, Lublin University of Technology, Lublin

Sustainable water resource management is a key element in ensuring access to safe drinking water and protecting the environment in an era of growing population and climate change. Improper wastewater treatment leads to the degradation of aquatic ecosystems and poses a threat to public health. Therefore, it is essential to implement modern and effective sewage sludge disposal methods that reduce pollution and recover water and raw materials. The aim of this paper is to review the latest research and technologies in the field of sewage sludge disposal, with particular emphasis on its role in protecting water resources. The analysis indicates that the development and dissemination of advanced treatment technologies, such as reverse osmosis, ultrafiltration, and ozonation, are crucial for increasing process efficiency and wastewater reuse. Combining biological methods with membrane technologies has yielded particularly promising results, enabling the near-complete removal of pathogens, heavy metals, and organic compounds.