Operational analysis and conclusions from the implementation of membrane technologies in public swimming pools

Analiza eksploatacyjna i wnioski z wdrożenia technologii membranowych w basenach publicznych

ANNA MIKA, EDYTA KUDLEK-TYMOSZUK, JOANNA WYCZARSKA-KOKOT, ANNA LEMPART-RAPACEWICZ

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Public swimming pool facilities are characterized by high water consumption associated with technological processes such as filter backwashing, pool water renewal, and compensation of operational water losses. To reduce the consumption of potable water and minimize technological wastewater discharge, membrane-based water recovery systems are increasingly implemented. This study presents an operational analysis and comparison of the water recovery systems implemented at three public swimming pool facilities (SP1, SP2, and SP3), which differ in technological configuration, membrane type, and integration with swimming pool water treatment systems. The research included analysis of technical documentation, on-site inspections, and evaluation of operational parameters related to water recovery and consumption. The results confirmed the high effectiveness of membrane technologies in reducing potable water consumption and technological wastewater discharge. In facility SP1, the recovery system covered approximately 91.7% of the water demand associated with filter backwashing, whereas in facilities SP2 and SP3, the recovery capacity exceeded the facilities' technological water demand. Membrane fouling, particularly in wastewater streams containing surfactants, cosmetics, and organic compounds, was identified as the main operational limitation. The results indicate that membrane technologies constitute an effective solution supporting sustainable water management in swimming pool facilities. However, their long-term operational efficiency strongly depends on appropriate wastewater stream selection, effective pre-treatment, and optimization of membrane cleaning strategies.
Keywords: swimming pools, membrane technologies, water reuse, membrane fouling, sustainable swimming pool management

Obiekty basenowe charakteryzują się wysokim zużyciem wody związanym z procesami technologicznymi, takimi jak płukanie złóż filtracyjnych, odświeżanie wody basenowej oraz uzupełnianie strat eksploatacyjnych. W celu ograniczenia zużycia wody wodociągowej oraz ilości ścieków technologicznych coraz częściej wdrażane są systemy odzysku wody wykorzystujące technologie membranowe. W pracy przedstawiono analizę eksploatacyjną i porównanie systemów odzysku wody wdrożonych w trzech publicznych obiektach basenowych (SP1, SP2 i SP3), różniących się konfiguracją technologiczną, rodzajem membran oraz sposobem integracji z układem uzdatniania wody basenowej. Badania obejmowały analizę dokumentacji technicznej, wizje lokalne oraz ocenę parametrów eksploatacyjnych związanych z odzyskiem i zużyciem wody. Uzyskane wyniki potwierdziły wysoką skuteczność technologii membranowych w ograniczaniu zużycia wody wodociągowej oraz redukcji ilości ścieków technologicznych. W obiekcie SP1 system odzysku pokrywał około 91,7% zapotrzebowania na wodę do płukania złóż filtrów, natomiast w obiektach SP2 i SP3 zdolność odzysku przekraczała zapotrzebowanie technologiczne tych obiektów. Najważniejszym problemem eksploatacyjnym okazał się fouling membranowy, szczególnie w przypadku ścieków zawierających surfaktanty, kosmetyki i związki organiczne. Wyniki analizy wskazują, że technologie membranowe stanowią skuteczne rozwiązanie wspierające zrównoważoną gospodarkę wodną w obiektach basenowych, jednak ich efektywność zależy od właściwego doboru strumieni ścieków, odpowiedniego przygotowania wody oraz optymalizacji procesów czyszczenia membran.
Słowa kluczowe: baseny, technologie membranowe, odzysk wody, fouling membranowy, zrównoważone zarządzanie obiektami basenowymi

Anna Mika[1,2] ORCID: 0009-0007-7733-039X, Edyta Kudlek-Tymoszuk[1] ORCID: 0000-0003-0068-1996, Joanna Wyczarska-Kokot[1] ORCID: 0000-0002-2284-8542, Anna Lempart-Rapacewicz[3,2] ORCID: 0000-0002-7524-1277; 1) Department of Water and Wastewater Engineering, Faculty of Energy and Environmental Engineering, Silesian University of Technology, 18 Konarskiego St., 44-100 Gliwice, Poland; 2) Transcom Sp. z o.o., 5 Józefowska St., 40-144, Katowice, Poland; 3)Faculty of Materials, Civil and Environmental Engineering, University of Bielsko-Biała, 2 Willowa St., 43-309 Bielsko-Biała, Poland; Corresponding author e-mail: anna.mika-shalyha@polsl.pl

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Introduction

The public swimming pool facilities belong to the group of buildings characterized by a high intensity of water and energy consumption [1-3]. Sanitary requirements related to swimming pool water quality, the need to maintain stable physicochemical and microbiological parameters, and the need to ensure adequate user comfort result in continuous treatment and replacement of significant water volumes [4, 5]. Modern swimming pool facilities constitute complex technological systems in which water and wastewater management plays a key role from operational, economic, and environmental perspectives [6, 7]. Water consumption in swimming pool facilities is associated with domestic and sanitary purposes, including showers, sanitary installations, cleaning processes, and catering services, as well as with technological processes directly related to the operation of swimming pool water treatment systems. The primary sources of technological water consumption include backwashing of filter beds, periodic pool water renewal required by sanitary regulations, compensation for operational water losses, and water demand for measurement systems and auxiliary installations. A significant operational issue is water loss resulting from evaporation from the water surface, water splashing by users, water carried out on the human body, and the operation of water attractions and overflow systems. Additionally, considerable volumes of technological wastewater are generated during filter backwashing, foot paddling pools and water refreshing. In facilities without water recovery systems, the entire volume of backwash wastewater is discharged into the sanitary sewer system, resulting in high consumption of potable water, increased load on the sewage infrastructure, and increased operational costs [1, 8].

To reduce water consumption and improve environmental performance, water recovery and recirculation systems are increasingly implemented in swimming pool facilities [9, 10]. Membrane technologies play a particularly important role in these systems, enabling the separation of suspended solids, organic compounds, and selected microbiological contaminants from backwash wastewater. The membrane processes most commonly applied in swimming pool water recovery systems include microfiltration (MF) and ultrafiltration (UF), operating either independently or in hybrid configurations combined with additional disinfection processes [11-13].

Membrane technologies enable high treatment efficiency and water recovery rates of approximately 80-90%, while simultaneously reducing potable water consumption and wastewater discharge volumes. However, the operational performance of membrane installations depends on numerous factors, including the qualitative composition of the backwash wastewater, the hydraulic loading of the membrane, the frequency of cleaning, the susceptibility to membrane fouling, and the effectiveness of pre-treatment processes [14-17].

An additional operational problem involves water losses associated with periodic membrane cleaning and concentrate discharge into the sewer system. Despite the increasing implementation of membrane technologies in swimming pool water management systems, a significant research gap still exists regarding the actual operational performance of these installations. The available studies mainly focus on laboratory or industrial applications [18-23], while analyses of the long-term operation of membrane systems in real public swimming pool facilities remain limited. In particular, there is a lack of comparative studies that address different technological configurations, membrane operational stability, implementation challenges, and the practical effectiveness of membrane-based water recovery systems operating in public swimming pool facilities.

The aim of this study is to conduct an operational analysis and comparison of membrane based water recovery systems applied in selected public swimming pool facilities. The scope of the study includes the evaluation of technological configurations of water recovery systems, the evaluation of operating parameters and comparison of technological configurations of water recovery systems, assessment of water recovery potential, identification of operational challenges, and analysis of the practical applicability of membrane technologies in public swimming pool facilities. Unlike previous studies focused on membrane fouling mechanisms [24] or wastewater management from a circular economy perspective [25], the present work provides a comparative assessment of different full-scale membrane recovery system configurations implemented in public swimming pool facilities. Particular attention is given to technological design, operational experience, implementation challenges, and the practical applicability of membrane based water recovery systems.

Materials and methods

The study was conducted through analysis of real full-scale membrane installations operating at three public swimming pool facilities, designated SP1, SP2, and SP3. The adopted methodology had an implementation oriented and operational character and was focused on evaluating the performance and effectiveness of water recovery systems under real operating conditions, taking into account both technological aspects and practical operational constraints associated with their application.

The research approach was based on the case study method, involving facilities that differ in technological configuration, water management strategies, and integration of membrane systems into swimming pool water treatment installations. The investigations conducted included an assessment of the applied design solutions, an analysis of membrane technology implementation, and an evaluation of system operation under real operating conditions. In addition, technological and operational limitations were identified, and the practical efficiency of water recovery and reuse was assessed.

In the first stage of the study, a detailed analysis of the technical, technological, and operational documentation of the investigated facilities was performed. The analysis included technological flow diagrams, membrane system design parameters, hydraulic configurations of water recovery units, integration methods for membrane installations with existing water treatment systems, and assumptions regarding the recirculation and reuse of recovered technological water. Based on the collected documentation, differences between the applied technological solutions were identified, together with the design assumptions adopted during the implementation stage of the systems.

The next stage involved on-site inspections and direct observation of the operation of the membrane system under real operating conditions. During field investigations, the organization of water management within the facilities, the operational strategies of the recovery systems, and the actual working conditions of the membrane installations were evaluated. Particular attention was paid to operational aspects such as hydraulic stability of the systems, frequency of membrane cleaning and backwashing processes, operational reliability, maintenance requirements, and degree of integration between recovery systems and the remaining elements of pool water treatment technology. The observations conducted enabled identification of discrepancies between design assumptions and actual operational practice.

An important part of the methodology was the analysis of operational data obtained from the investigated facilities. The analysis included parameters related to the water balance of the systems, including fresh water consumption, the volume of generated backwash wastewater, the technological efficiency of water recovery, and variability of operational parameters over time.

The frequency and intensity of membrane cleaning procedures, the appearance of membrane fouling behaviour, and the influence of operating conditions on the stability of the system were also evaluated. The operational data constituted the basis for assessing the effectiveness of recovery systems and determining their actual potential to reduce potable water consumption and minimise the discharge of technological wastewater.

To compare the capacity of the recovery systems with the water demand associated with filter backwashing, annual water demand values were estimated using operational data and engineering calculations. The frequency of filter backwashing was determined using historical data obtained from the Building Management System (BMS) and verified through consultations with facility operators. The volume of water used during individual backwashing events was estimated based on measured backwash durations, pump capacities, and filter surface areas. The resulting annual demand values were subsequently compared with the nominal recovery capacities of the analysed installations. Therefore, the presented demand-coverage indicators should be interpreted as estimates based on operational observations and engineering calculations rather than values derived from a complete long-term water balance.

Based on the analysis and observations, the main operational issues related to membrane installations in swimming pool facilities were identified. Particular attention was paid to the membrane fouling mechanism, the influence of the quality and composition on the membrane process, the necessity of periodic cleaning procedures, and limitations resulting from the technological configuration of the recovery systems. This enabled the assessment of actual implementation barriers and the identification of factors that affect the durability, operational stability, and efficiency of membrane systems.

The analysis of results was performed using a comparative approach, taking into account differences in the technological configurations of the investigated membrane systems, the varying operational conditions of the analyzed facilities, and seasonal variability of the operational parameters. The interpretation of results was carried out primarily in the context of the practical applicability of membrane technologies in water management systems of public swimming pool facilities, with particular emphasis on implementation efficiency, operational limitations, and potential optimization strategies for water recovery systems.

Characteristics of implemented recovery systems

In SP1, a single-stage technological water recovery system based on PVDF membranes was implemented for the treatment of the backwash wastewater generated during the pool filter backwashing processes. The system was integrated into the swimming pool water treatment installation and operates in a closed-loop configuration, enabling the reuse of recovered water for technological purposes. The nominal capacity of the membrane station is 15 m^3/h. The membrane installation was equipped with four Koch PURON® MP ultrafiltration modules based on polyester-reinforced PVDF braided hollow-fiber membranes operating in an outside-in configuration. The nominal membrane pore size was 0.03 µm, and the total active membrane area amounted to 204 m^2. The backwash wastewater generated during filter backwashing is directed to a sedimentation tank, where preliminary separation of suspended solids and sludge sedimentation takes place. The settled sludge is discharged into the sanitary sewer system, while the supernatant water is pumped to a vacuum filtration unit equipped with AFM (Activated Filter Media) glass media, which serves as a pretreatment stage for reducing suspended solids prior to the membrane process. It should be noted that the AFM filter constituted a pretreatment unit within the water recovery installation. The backwash water treated in the recovery system originated from the main swimming pool water treatment system, which is based on pressure sand filters. Following AFM filtration, the treated stream is directed to a buffer tank responsible for hydraulic equalisation and stabilization of the membrane system. Subsequently, the water is supplied to a single-stage membrane installation equipped with PVDF membranes. The membrane process provides the final polishing of the technological water stream and enables the removal of fine suspended particles and selected microbiological contaminants. The recovered water obtained after membrane treatment is disinfected by chlorine dioxide (ClO_2) dosing and subsequently stored in a reclaimed water tank. The recovered water is then reused for swimming pool filter backwashing processes, contributing to a reduction in potable water consumption and minimizing the volume of technological wastewater discharged into the sewer system. The implemented configuration represents a hybrid water recovery system that combines sedimentation, granular media filtration, and membrane separation processes to enhance water recovery efficiency and stabilize the quality parameters of the technological water stream.

Figure 1 presents a simplified block diagram of the water recovery system applied in SP1 facility.

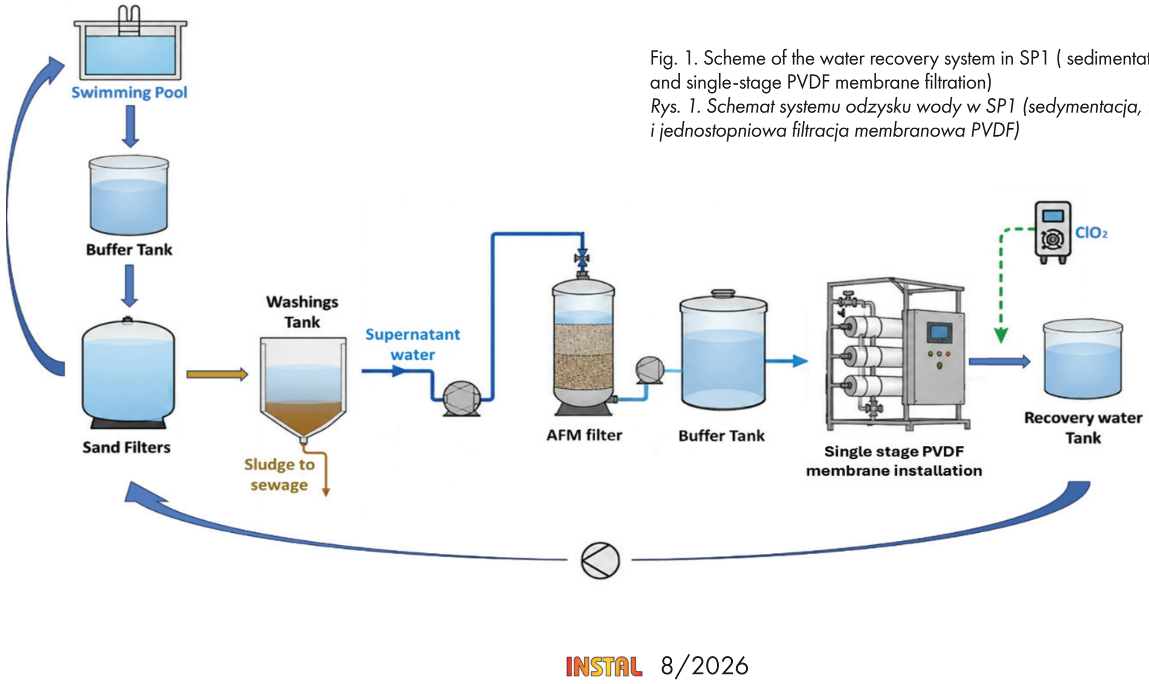

Fig. 1. Scheme of the water recovery system in SP1 (sedimentation, AFM filtration, and single-stage PVDF membrane filtration)
Rys. 1. Schemat systemu odzysku wody w SP1 (sedymentacja, filtracja AFM i jednostopniowa filtracja membranowa PVDF)

In SP2, a two-stage water recovery system based on PVDF ultrafiltration membranes was implemented for the treatment and reuse of technological wastewater generated during swimming pool operation. The membrane installation operates with a nominal capacity of 12 m³/h and was integrated into the swimming pool water treatment system in a closed-loop configuration.

Backwash wastewater generated during the pool filter backwashing processes is directed to a sedimentation tank. In addition, rainwater collected from the roof drainage system is introduced into the backwash water tank, increasing the volume of water available for recovery and reducing the facility's demand for potable water. The settled sludge is discharged into the sanitary sewer system, whereas the supernatant stream is pumped into a vacuum filter equipped with AFM glass media prior to membrane treatment. Following AFM filtration, the treated stream is directed to a buffer tank to stabilise the hydraulic conditions of the membrane installation. The buffer tank additionally receives swimming pool make-up water resulting from mandatory pool water renewal required by sanitary regulations. The volume of water introduced into the system is controlled based on the number of users entering the pool facility and in accordance with the applicable national sanitary regulations governing the operation of the public swimming pool. The pretreated water is subsequently supplied to the ultrafiltration system consisted of six Koch PURON® MP membrane modules arranged in two treatment lines, each containing three membrane modules. The modules were based on PVDF braided hollow-fiber membranes operating in an outside-in filtration mode with a nominal pore size of 0.03 µm. The total active membrane area of the installation was 306 m². The ultrafiltration process provides a final polishing of the recovered water stream and stabilization of its physicochemical and microbiological quality parameters. Recovered water obtained after the ultrafiltration process is disinfected by chlorine dioxide (ClO_2) dosing and stored in a reclaimed water tank. The treated water is then reused for the backwashing of the pool filter and replenishing water losses in the pool.

The technological configuration of the water recovery installation and its integration into the swimming pool water treatment system are presented in Figure 2.

The technological configuration implemented in SP3 was based on a hybrid membrane recovery system integrating ceramic membrane filtration and PVDF ultrafiltration. The pretreatment stage of the recovery system remained identical to that used in SP2 and included sedimentation and AFM glass media filtration prior to membrane treatment. Similarly to SP2, the installation operates in a closed-loop configuration and includes rainwater harvesting, as well as swimming pool water renewal streams within the recovery system. The main difference between SP3 and SP2 is the application of a ceramic membrane system as the first stage of membrane separation. The ceramic stage consisted of eight SiCBlox™ FX silicon carbide (SiC) flat-sheet membrane modules operating in an out-to-in filtration mode with a nominal pore size of 0.1 µm and a total membrane area of 55.2 m². The second treatment stage consisted of three Koch PURON® MP ultrafiltration modules based on PVDF braided hollow-fiber membranes with a nominal pore size of 0.03 µm and a total membrane area of 153 m². Consequently, the total membrane area of the SP3 recovery system amounted to 208.2 m².

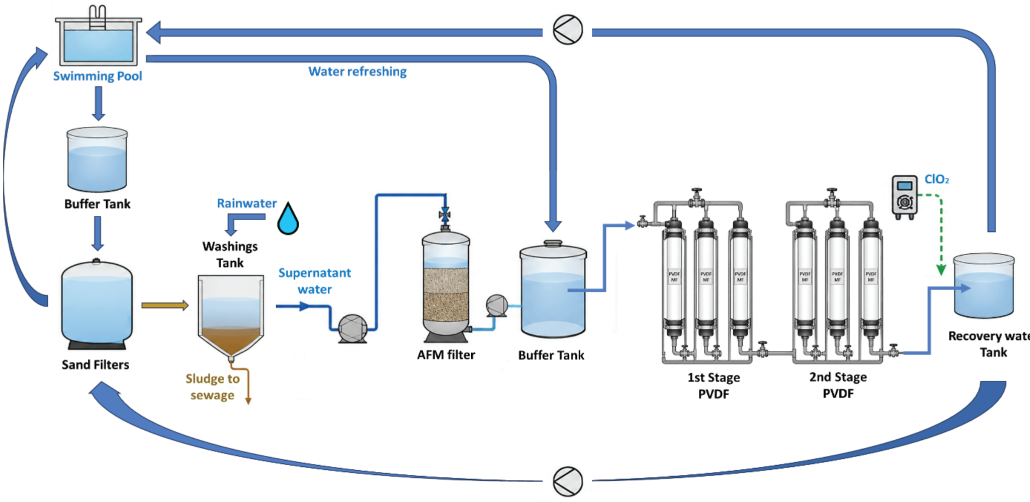

Fig. 2. Scheme of the water recovery system in SP2 integrated with the pool water treatment installation, including rainwater harvesting and two-stage PVDF ultrafiltration

Rys. 2. Schemat systemu odzysku wody w SP2 zintegrowanego z instalacją uzdatniania wody basenowej, obejmującego wykorzystanie wód opadowych oraz dwustopniową ultrafiltrację PVDF

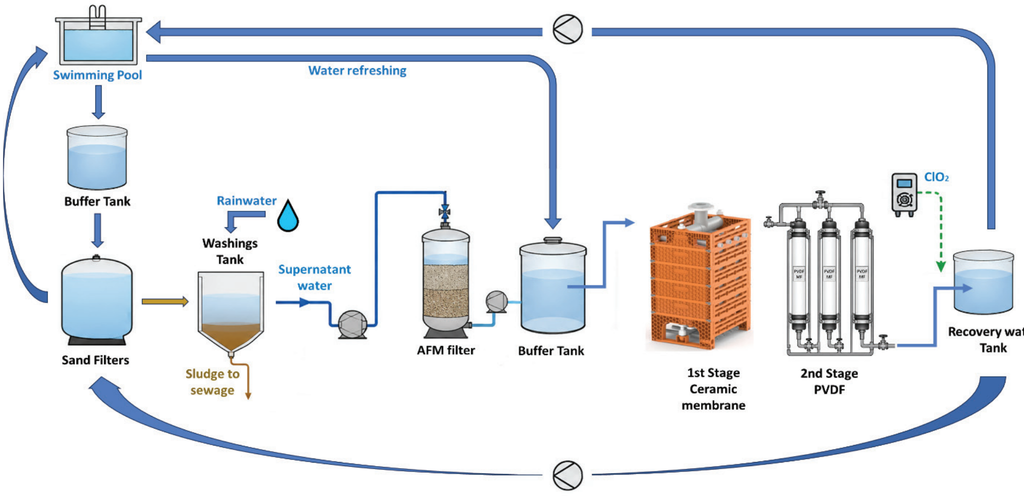

Fig. 3. Scheme of the water recovery system in SP3 employing ceramic membranes as the 1st-stage and PVDF membranes as the 2nd-stage of UF

Rys. 3. Schemat systemu odzysku wody w SP3 z zastosowaniem membran ceramicznych w 1 etapie oraz membran PVDF w 2 etapie UF

The ceramic membrane stage provides higher mechanical and chemical resistance, enabling operation under increased contaminant loading and more intensive cleaning conditions. Following membrane treatment, the recovered water is disinfected by chlorine dioxide (ClO_2) dosing and reused for technological purposes within the swimming pool facility.

The technological configuration of the SP3 water recovery system and its integration into the pool water treatment installation are presented in Figure 3.

Results

The conducted analyses enabled evaluation of the applied technological solutions and assessment of the impact of membrane systems on reducing potable water consumption and minimizing the volume of technological wastewater discharged into the sewer system.

Water recovery efficiency and coverage of technological water demand

Analysis of the three investigated water recovery systems demonstrated significant differences in water demand, wastewater generation, and operational efficiency between the analyzed facilities. The highest technological water demand was observed in facility SP1, characterized by a large scale water treatment installation and intensive operational load associated with high visitor capacity typical of aquapark type facilities. Based on operational data from the Building Management System (BMS), consultations with facility operators, and calculations of backwash water volumes using backwash duration, pump capacity, and filtration surface area, the annual water demand for filter backwashing in SP1 was estimated at approximately 128,900 m^3/year. Comparison of this value with the nominal production capacity of the recovery installation indicates that the system has the potential to cover approximately 91.7% of the water demand associated with filter backwashing processes. This indicates a water recovery efficiency exceeding 90%, demonstrating a substantial reduction in potable water consumption and technological wastewater discharge despite the facility's very high hydraulic load. In contrast, at facilities SP2 and SP3, the maximum production capacity of the recovery systems exceeded the annual technological water demand associated with filter backwashing processes. This indicates that the recovery installations were capable of fully covering the demand for technological water required for filter backwashing and provided an additional operational reserve capacity. The maximum annual recovery capacity of the implemented two-stage membrane systems was higher than the technological water demand associated with filter backwashing processes, indicating that the recovery installations were capable of fully covering the operational demand for technological water used in filter backwashing processes [26].

The obtained results clearly demonstrate that appropriately designed membrane recovery systems utilizing high quality membrane separation processes combined with chlorine dioxide (ClO_2) disinfection can fully satisfy the technological water demand associated with filter backwashing processes in medium sized public swimming pool facilities. However, this conclusion refers specifically to filter backwashing water demand and should not be interpreted as covering the total technological water demand of the facilities. In the case of SP2 and SP3, the integration of additional wastewater streams, including rainwater harvesting and pool water renewal streams, further increased the operational potential of the recovery systems and improved the overall water management efficiency of the facilities. It should be noted that the comparison performed in this study relates exclusively to water demand associated with filter backwashing processes.

Table 1. Comparison of technological configurations and operational parameters of water recovery systems in SP1, SP2, and SP3
Tabela 1. Porównanie konfiguracji technologicznych i parametrów eksploatacyjnych systemów odzysku wody w SP1, SP2 i SP3

Parameter	SP 1[1)]	SP 2[2)]	SP 3
Main swimming pool filtration system	Pressure sand filters	Vacuum activated glass bed filters	Vacuum activated glass bed filters
Quantity	44 pcs.	6 pcs.	6 pcs.
Swimming pool filters diameter range	650-2800 mm	1600-2600 mm	1600-2600 mm
Annual washings consumption	128 900 m^3/year	6 967 m^3/year	7659,2 m^3/year
Type of recovery station	Single-stage recovery station	Two-stage recovery station	Two-stage recovery station
Recovery station pretreatment	AFM glass media filtration	AFM glass media filtration	AFM glass media filtration
Nominal capacity of the water recovery installation	15 m^3/h	12 m^3/h	12 m^3/h
Maximum daily water recovery capacity	324 m^3/d	259,2 m^3/d	244,8 m^3/d
Estimated annual economic benefit	410 600 EUR/year[3)]	310 500 EUR/year[4)]	293 300 EUR/year[4)]
Maximum annual recovery capacity	118 260 m^3/year	94 608 m^3/year	89 352 m^3/year
Type of membranes	PVDF	PVDF + PVDF	SiC + PVDF
Membrane supplier	Koch Separation Solutions	Koch Separation Solutions	Koch Separation Solutions
Membrane model	PURON® MP	PURON® MP	SiCBlox™ FX + PURON® MP
Membrane type	Braided hollow-fiber UF	Braided hollow-fiber UF	Flat-sheet ceramic UF + braided hollow-fiber UF
Filtration mode	Outside-in	Outside-in	Out-to-in + outside-in
Nominal pore size	0,03 µm	0,03 µm	0,1+0,03 µm
Number of membrane stages	1	2	2
Number of membrane modules	4 × PURON® MP	2 × 3 PURON® MP	8 × SiCBlox™ FX + 3 × PURON® MP
Membrane area per module	51 m^2	51 m^2	6.9 m^2 (SiCBlox™ FX); 51 m^2 (PURON® MP)
Total membrane area	204 m^2	306 m^2	208,2 m^2
Type of recycled wastewater streams	Pressure filter washings	Pressure filter washings, rainwater, pool water refreshing	Pressure filter washings, rainwater, pool water refreshing

[1)] A comprehensive quantitative analysis of water consumption is provided in [24]
[2)] A detailed quantitative characterization of individual wastewater streams for one of the twin facilities is provided in [25]
[3)] SP1 (Mazowieckie Voivodeship): estimated using a combined water supply and wastewater tariff of 14.90 PLN/m^3 (3.47 EUR/m^3)
[4)] SP2 and SP3 (Dolnośląskie Voivodeship): estimated using a combined water supply and wastewater tariff of 14.10 PLN/m^3 (3.28 EUR/m^3)

The overall water demand of swimming pool facilities additionally includes pool water renewal, evaporation losses, splash-out losses, water carried out by bathers, and other operational water uses. Nevertheless, even under such conditions, the implementation of membrane recovery systems enables a substantial reduction in potable water consumption and minimizes the volume of technological wastewater discharged into the sewer system. In addition to reducing potable water consumption, the analysed recovery systems may generate significant economic benefits through reduced water supply and wastewater discharge costs. Based on the maximum annual recovery capacity and regional water and wastewater tariffs, the potential annual savings were estimated at approximately 410,600 EUR/year for SP1, 310,500 EUR/year for SP2, and 293,300 EUR/year for SP3. These values should be treated as indicative estimates, as they do not include investment costs, energy consumption, membrane replacement, or other operating expenses.

The comparative analysis also demonstrated the influence of system configuration and wastewater stream diversification on operational performance. Facilities SP2 and SP3, which use two-stage recovery systems and additional water streams, achieved higher operational flexibility and a greater degree of technological water demand coverage recovery potential compared to the single-stage recovery configuration applied in SP1.

Operational experience and implementation challenges

Operational analysis demonstrated that the real operating conditions of membrane installations significantly influence hydraulic stability and membrane durability. The systems operated in a cyclic mode consisting of permeate production and automatic cleaning processes performed after each production cycle. The hydraulic regeneration process included air and water backwashing, after which the system returned to the next filtration cycle. According to the adopted operational strategy, a single filtration cycle lasted 30 minutes, after which an automatic backwashing process was initiated. Hydraulic regeneration included air and water washing lasting 3 minutes and 10 seconds, after which the system returned to the subsequent filtration cycle. Additionally, periodic chemical membrane cleaning using the Clean-In-Place (CIP) method was carried out when a persistent decline in hydraulic performance or an increase in transmembrane pressure (TMP) above the manufacturer's recommended threshold was observed. Chemical cleaning procedures were performed using sodium hypochlorite solutions and citric acid solutions. Despite the use of automated cleaning procedures and periodic chemical regeneration, a gradual decline in membrane performance was observed, associated with progressive fouling. This phenomenon resulted in reduced permeate flow and increased hydraulic resistance within the system. Fouling intensity strongly depended on the type of treated wastewater stream and its level of contamination. A detailed analysis of the decrease in membrane performance over time was presented in the previous study [24].

Under long-term operating conditions, it was assumed that a decrease in membrane performance to approximately 70% of nominal capacity represents the threshold for membrane regeneration or replacement. However, the final decision depends on the operational strategy adopted by the facility operator and on the acceptable reduction in the system's hydraulic performance. During on-site inspections and operational analysis of the investigated facilities, significant differences were identified between individual technological wastewater streams. The results confirm that the actual efficiency and operational stability of membrane systems depend not only on installation design parameters but primarily on the characteristics of the treated wastewater, the operational strategy, and the effectiveness of membrane cleaning and regeneration processes.

Figure 4 presents a comparison of an unused PVDF membrane and a membrane with visible fouling deposits that require chemical regeneration.

Discussion

Technological configuration of implemented recovery systems

The analysis of the systems in SP1, SP2 and SP3 confirms that the technological configuration of the water recovery installations in swimming pool facilities should be individually adapted to the type of treated wastewater stream, the size of the facility, and the intended direction of reuse of reclaimed water. The facilities investigated applied systems consisting of sedimentation, AFM media filtration, and single- or two-stage membrane filtration, which is consistent with the approaches reported in the literature, where swimming pool backwash water recovery systems are commonly based on the combination of pretreatment processes, ultrafiltration, and final disinfection. Studziński et al. [10] demonstrated that a treatment system integrating flocculation, prefiltration, ultrafiltration, and ozonation can effectively treat backwash water from the swimming pool and enable its subsequent reuse.

The results obtained for SP2 and SP3 also indicate that extending the recovery system by incorporating additional streams, such as rainwater and swimming pool water renewal streams, increases the overall water balance potential of the installation. At the same time, the literature emphasises that the utilization of rainwater in swimming pool facilities requires careful consideration, as the quality of the rainwater strongly depends on the catchment surface, atmospheric contamination, and storage conditions. Rainwater harvesting has been identified as a promising supplementary water source for recreational and tourist facilities, including swimming pool installations, particularly in the context

Fig. 4. PVDF membrane: a) unused polyvinylidene fluoride (PVDF) membrane; b) fouled membrane surface with visible contaminant deposits requiring chemical regeneration [24]
Rys. 4. Membrana PVDF: a) nieużywana membrana z polifluorku winylidenu (PVDF); b) powierzchnia membrany z widocznymi osadami foulingowymi wymagająca regeneracji chemicznej [24]

of sustainable water management and potable water demand reduction [27, 28]. However, its application should be preceded by a detailed quality assessment and, if necessary, additional treatment processes.

From a design and operational perspective, the comparison between SP2 and SP3 is particularly significant, since the main difference between these systems involves the application of a ceramic membrane as the first filtration stage in SP3. Such a configuration may increase the resistance of the system to variable contaminant loading conditions and intensive cleaning procedures. This observation is consistent with general conclusions reported in the membrane technology literature, based on which membrane material selection and chemical resistance are key factors determining process stability, particularly in systems exposed to severe fouling conditions and frequent contact with chemical cleaning reagents [29-31].

Water recovery efficiency and impact on facility water management

The results obtained confirm the high potential of membrane technologies in reducing the consumption of potable water and minimizing the volume of technological wastewater discharged into the sewer system. In the case of SP1, the recovery system is capable of covering approximately 91.7% of the water demand associated with swimming pool filter backwashing processes, whereas in SP2 and SP3 the production capacity of the installations exceeds the technological demand resulting from filter backwashing operations. Similar environmental benefits have been reported in the literature, where pool backwash water recovery is considered an important approach to reduce water losses in aquatic facilities. Studziński et al. [10] emphasized that swimming pool filter backwashing processes generate significant water losses. Therefore, the implementation of backwash water recovery systems has considerable operational and environmental importance.

However, the comparison of SP1 with facilities SP2 and SP3 demonstrates that the production capacity of a recovery installation should not be evaluated independently of the actual water balance of the facility. In medium sized facilities, membrane recovery systems may fully satisfy the technological water demand, whereas in large scale aquaparks such as SP1, backwash water recovery can substantially reduce potable water consumption but may still be insufficient to cover the total water demand associated with pool water renewal, evaporation losses, water splashing, and other operational losses. Consequently, the design of water recovery systems should be preceded by a detailed analysis of the water balance and an assessment of which wastewater streams are the most appropriate for reuse [24].

The literature also emphasizes that the reuse of treated backwash water and other technological wastewater streams can reduce costs related to potable water and wastewater discharge [32-34]. However, it simultaneously generates additional operational costs associated with treatment processes, pumping, disinfection, and membrane maintenance. Wolska et al. [35] indicated that recirculation of pretreated backwash water may reduce environmental costs related to water abstraction and wastewater discharge, although additional treatment-related expenditures must also be considered.

Therefore, water recovery systems must be evaluated not only in terms of their maximum production capacity but also with respect to the facility's actual water demand, the quality of reclaimed water, the intended reuse applications, and the economic justification for meeting a specific water quality standard. Based on current local water and wastewater tariffs, the potential annual economic benefits associated with water recovery were estimated at approximately 410 600 EUR/year for SP1, 310 500 EUR/year for SP2, and 293 300 EUR/year for SP3. In practical applications, the most rational use of reclaimed water appears to involve technological purposes such as filter backwashing, compensation of selected operational water losses, toilet flushing, and cleaning operations, rather than consistently aiming to achieve water quality standards for potable or swimming pools.

Operational experience and implementation challenges

The most significant operational limitation observed in the analyzed installations was membrane fouling, leading to a gradual decrease in hydraulic performance and an increase in flow resistance. This observation is consistent with data from the literature [36-38] indicating that fouling represents the main challenge in the operation of microfiltration (MF) and ultrafiltration (UF) systems, while its intensity depends on the composition of the treated medium, including the presence of organic compounds, colloids, mineral deposits, biofilms and surfactants.

The membrane cleaning strategy also plays a crucial role in maintaining operational stability. In the investigated systems, a cyclic operating mode was applied, consisting of permeate production, air and water backwashing, and periodic chemical CIP (Clean-In-Place) cleaning procedures. Previous studies [17,39] have shown that maintaining an appropriate transmembrane pressure (TMP) and optimising backwashing frequency and CIP procedures are essential for stable membrane performance and limiting irreversible fouling. Studies conducted by Alhussaini et al. [34] in UF systems demonstrated that backwash triggering methods and operational strategies based on specific TMP values significantly influence hydraulic recovery and long-term process efficiency.

From an implementation perspective, the results obtained for SP1, SP2 and SP3 indicate that the primary challenge is not the technological feasibility of water treatment itself, but rather the maintenance of stable long-term installation operation. This requires careful selection of wastewater streams directed to recovery systems, expansion of pre-treatment processes for highly contaminated streams, and continuous monitoring of operational parameters, including permeate flux, TMP, backwash frequency, and CIP efficiency.

Consequently, membrane technologies should be considered an effective but operationally sensitive tool for water management in public swimming pool facilities. Their effectiveness depends not only on the selection of membranes, but primarily on the proper design of the entire technological system. Key factors include wastewater stream selection, hydraulic stabilization, appropriate pre-treatment, effective disinfection, and an operational strategy adapted to the actual hydraulic and contaminant loading conditions of the facility.

Conclusions

The analyses conducted confirmed the high effectiveness of membrane technologies in reducing the consumption of potable water and minimizing the volume of technological wastewater generated in swimming pool facilities. At the same time, it was demonstrated that the efficiency and operational stability of water recovery systems depend not only on the applied membrane technology but also on the installation's technological configuration, the types of treated wastewater streams, and the facility's operational conditions. The main contribution of this study is the comparative evaluation of three different full-scale membrane recovery system configurations operating in public swimming pool facilities. Unlike previous studies that focus on individual installations or specific operational aspects, the present work compares different technological approaches and identifies practical implementation experiences relevant to future membrane system applications for swimming pool water management.

- Membrane technologies allow for significant reduction of potable water consumption and technological wastewater discharge in swimming pool facilities.
- In medium sized facilities such as SP2 and SP3, the recovery systems were capable of producing larger volumes of reclaimed water than the actual technological filter backwashing water demand of the facilities.
- In SP1, which represents a large-scale aquapark with high hydraulic and operational loads, the recovery system covered approximately 91.7% of the water demand associated with filter backwashing. The general water demand exceeded the production capacity of the recovery installation.
- Membrane fouling was identified as the most significant operational limitation, leading to a decrease in hydraulic performance and the need for periodic membrane cleaning.
- Stable long-term operation of membrane installations requires appropriate wastewater pre-treatment, effective prefiltration, and optimization of membrane backwashing and cleaning processes.
- Membrane technologies constitute an effective tool that supports sustainable water management in public swimming pool facilities.

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Literature

[1] Maglionico M., & Stojkov I. (2015). Water consumption in a public swimming pool. Water Supply, 15(6), 1304–1311. https://doi.org/10.2166/ws.2015.095.

[2] Cardoso, B. J., Gaspar, A. R., Góis, J. C., & Rodrigues, E. (2018). Energy and water consumption characterization of Portuguese indoor swimming pools. In Proceedings of the CYTEF 2018 VII Congreso Ibérico, Ciencias y Técnicas del Frío. Valencia, Spain.

[3] Doménech-Sánchez, A., Laso, E., & Berrocal, C. I. (2021). Water loss in swimming pool filter backwashing processes in the Balearic Islands (Spain). Water Policy, 23(6), 1314–1328. https://doi.org/10.2166/wp.2021.217.

[4] Regulation of the Minister of Health of 9 November 2015 on the requirements for water in swimming pools. (2015). Journal of Laws of the Republic of Poland.

[5] DIN 19643. Treatment of swimming pool and bathing water. German Institute for Standardization.

[6] Smol, M., Adam, C., & Preisner, M. (2020). Circular economy model framework in the European water and wastewater sector. Journal of Material Cycles and Waste Management, 22(3), 682–697. https://doi.org/10.1007/s10163-019-00960-z.

[7] Kubiak-Wójcicka, K., Domszy, D., & Machula, S. (2022). Best practices in wastewater management in Poland with particular emphasis on swimming pool waters. In [Cost-efficient Wastewater Treatment Technologies] (pp. 485–504). https://doi.org/10.1007/698_2022_878.

[8] Piechurski, F. G. (2015). Water consumption in multifunctional indoor swimming pools on the basis of annual research. In K. Kuś & F. G. Piechurski (Eds.), Instalacje basenowe (pp. 107–128). Instytut Inżynierii Wody i Ścieków, Politechnika Śląska.

[9] Liebersbach, J., Żabnieńska-Góra, A., Polarczyk, I., & Sayegh, M. A. (2021). Feasibility of grey water heat recovery in indoor swimming pools. Energies, 14(14), 4221. https://doi.org/10.3390/en14144221.

[10] Studziński, W., Poćwiardowski, W., & Osińska, W. (2021). Application of the swimming pool backwash water recovery system with the use of filter tubes. Molecules, 26(21), 6620. https://doi.org/10.3390/molecules26216620.

[11] Alsoy Altinkaya, S. (2024). A review on microfiltration membranes: Fabrication, physical morphology, and fouling characterization techniques. Frontiers in Membrane Science and Technology, 3. https://doi.org/10.3389/frmst.2024.1426145.

[12] Pal, P. (2020). Introduction to membrane materials, processes, and modules. In Membrane-based technologies for environmental pollution control (pp. 3–69). Elsevier. https://doi.org/10.1016/B978-0-12-819455-3.00001-7.

[13] Shoshaa, R., Ashfaq, M. Y., & Al-Ghouti, M. A. (2023). Recent developments in ultrafiltration membrane technology for the removal of potentially toxic elements and enhanced antifouling performance: A review. Environmental Technology & Innovation, 31, 103162. https://doi.org/10.1016/j.eti.2023.103162.

[14] AlSawaftah, N., Abuwatfa, W., Darwish, N., & Husseini, G. (2021). A comprehensive review on membrane fouling: Mathematical modelling, prediction, diagnosis, and mitigation. Water, 13(9), 1327. https://doi.org/10.3390/w13091327.

[15] Wang, M., Wang, J., & Jiang, J. (2022). Membrane fouling: Microscopic insights into the effects of surface chemistry and roughness. Advanced Theory and Simulations, 5. https://doi.org/10.1002/adts.202100395.

[16] Hernández, M., Melián-Martel, N., Ruiz-García, A., & Del Río-Gamero, B. (2020). Fouling characterization during initial stage of cross-flow ultrafiltration. Journal of Water Process Engineering, 38, 101611. https://doi.org/10.1016/j.jwpe.2020.101611.

[17] Xiao, T., Zhu, Z., Li, L., Shi, J., Li, Z., & Zuo, X. (2023). Membrane fouling and cleaning strategies in microfiltration/ultrafiltration and dynamic membrane. Separation and Purification Technology, 318, 123977. https://doi.org/10.1016/j.seppur.2023.123977.

[18] Kowalska, I., & Klimonda, A. (2017). Application of nanofiltration membranes for removal of surfactants from water solutions. E3S Web of Conferences, 17, 00044. https://doi.org/10.1051/e3sconf/20171700044.

[19] Alresheedi, M. T. (2023). Understanding protein and polysaccharide fouling with silicon dioxide and aluminum oxide in low-pressure membranes. Membranes, 13(5), 476. https://doi.org/10.3390/membranes13050476.

[20] Turan, M. (2025). Membrane fouling and control approaches in membrane bioreactor systems: A review. Water, Air, & Soil Pollution, 236, 159. https://doi.org/10.1007/s11270-025-07794-6.

[21] Wang, S., Lu, X., Zhang, L., Guo, J., & Zhang, H. (2019). Characterization of the initial fouling layer on the membrane surface in a membrane bioreactor: Effects of permeation drag. Membranes, 9(9), 121. https://doi.org/10.3390/membranes9090121.

[22] Wang, G., Li, T., Yin, W., Zhou, J., & Lu, D. (2025). Effect of sodium hypochlorite disinfection on polyvinylidene fluoride membranes in microplastic ultrafiltration. Water, 17(1), 99. https://doi.org/10.3390/w17010099.

[23] Gonzalez-Gil, G., Behzad, A. R., Farinha, A. S. F., Zhao, C., Bucs, S. S., Nada, T., Das, R., Altmann, T., Buijs, P. J., & Vrouwenvelder, J. S. (2021). Clinical autopsy of a reverse osmosis membrane module. Frontiers in Chemical Engineering, 3. https://doi.org/10.3389/fceng.2021.683379.

[24] Mika, A., Wyczarska-Kokot, J., Lempart-Rapacewicz, A., & Gołombek, K. (2026). Membrane water recovery in swimming pools: Effectiveness, challenges and development perspectives. Water Resources and Industry, 35, 100364. https://doi.org/10.1016/j.wri.2026.100364.

[25] Mika, A., Wyczarska-Kokot, J., & Lempart-Rapacewicz, A. (2025). Wastewater management in swimming pools: A circular economy approach. Applied Sciences, 15(17), 9609. https://doi.org/10.3390/app15179609.

[26] Mika-Shalyha, A., Wyczarska-Kokot, J., & Lempart-Rapacewicz, A. (2024). Water consumption rates in indoor swimming pools: Analysis of design assumptions in the context of Green Deal implementation. Desalination and Water Treatment, 320, 100874. https://doi.org/10.1016/j.dwt.2024.100874.

[27] Szołdrowska, D., Włóka, D., & Smol, M. (2025). Circular economy of water: Rainwater harvesting (RWH) and reuse solutions. Desalination and Water Treatment, 323, 101257. https://doi.org/10.1016/j.dwt.2025.101257.

[28] Cao, S. (2024). Comparative analysis of greywater recycling and rainwater harvesting as supplementary water sources for conventional urban and tourist resort water supplies. Applied and Computational Engineering, 58, 94–100. https://doi.org/10.54254/2755-2721/58/20240699.

[29] Li, C., Sun, W., Lu, Z., Ao, X., & Li, S. (2020). Ceramic nanocomposite membranes and membrane fouling: A review. Water Research, 175, 115674. https://doi.org/10.1016/j.watres.2020.115674.

[30] Aba, N. F. D., Chong, J. Y., Wang, B., Mattevi, C., & Li, K. (2015). Graphene oxide membranes on ceramic hollow fibers: Microstructural stability and nanofiltration performance. Journal of Membrane Science, 484, 87–94. https://doi.org/10.1016/j.memsci.2015.03.001.

[31] Biscardi, P. G., & Duranceau, S. J. (2016). Ultrafiltration fouling reduction with the pilot-scale application of ozone preceding coagulation, flocculation, and sedimentation for surface water treatment. Desalination and Water Treatment, 57(57), 27433–27440. https://doi.org/10.1080/19443994.2016.1180266.

[32] Asano, T. (2007). Water reuse: Issues, technology, and applications. McGraw-Hill.

[33] Fernandes, E., & Cunha Marques, R. (2023). Review of water reuse from a circular economy perspective. Water, 15(5), 848. https://doi.org/10.3390/w15050848.

[34] Alhussaini, M. A., Binger, Z. M., Souza-Chaves, B. M., Amusat, O. O., Park, J., Bartholomew, T. V., Gunter, D., & Achilli, A. (2023). Analysis of backwash settings to maximize net water production in an engineering-scale ultrafiltration system for water reuse. Journal of Water Process Engine-

ering, 53, 103761. https://doi.org/10.1016/j.jwpe.2023.103761.
[35] Wolska, M., Kabsch-Korbutowicz, M., Solipiwko-Pieścik, A., & Urbańska-Kozłowska, H. (2025). Application of ultrafiltration for backwash water pre-treatment for recirculation into an infiltration water treatment system. Desalination and Water Treatment, 321, 101017. https://doi.org/10.1016/j.dwt.2025.101017.
[36] Prorok, V., Movrin, D., Lukić, N., & Popović, S. (2023). New insights into the fouling of a membrane during the ultrafiltration of complex organic–inorganic feed water. Membranes, 13(3), 334. https://doi.org/10.3390/membranes13030334.
[37] Sisay, E. J., Al-Tayawi, A. N., László, Z., & Kertész, S. (2023). Recent advances in organic fouling control and mitigation strategies in membrane separation processes: A review. Sustainability, 15(18), 13389. https://doi.org/10.3390/su151813389.
[38] AbuKhadra, D., Oren, Y., & Herzberg, M. (2025). New insights on the organic fouling mechanism of ultrafiltration membranes using hybrid QCM-D–LSPR. Journal of Membrane Science, 725, 124044. https://doi.org/10.1016/j.memsci.2025.124044.
[39] Kaykhaii, S., Herrmann, I., Hedström, A., Nordqvist, K., Heidfors, I., & Viklander, M. (2023). Enhancing stormwater treatment through ultrafiltration: Impact of cleaning chemicals and backwash duration on membrane efficiency. Water Reuse, 13(4), 634–646. https://doi.org/10.2166/wrd.2023.106.

Nadchodzące wydarzenia

	WRZESIEŃ	
8-10.09.2026	**NADARZYN**	WodKan-Tech, Targi Technologii i Urządzeń Wodno-Kanalizacyjnych; PTAK Warsaw Expo
8-10.09.2026	**NADARZYN**	HEATING TECH, Branżowe Targi Technologii Grzewczych; PTAK Warsaw Expo
8-10.09.2026	**NADARZYN**	Targi Pomp Ciepła; PTAK Warsaw Expo
13-16.09.2026	**MIĘDZYZDROJE**	XXX Jubileuszowe Forum Ciepłowników Polskich; Izba Gospodarcza Ciepłownictwo Polskie
14-16.09.2026	**GDYNIA**	Konferencja „Branża wod.-kan. – Ochrona i bezpieczeństwo infrastruktury krytycznej. Reagowanie w sytuacjach kryzysowych"
23-25.09.2026	**WROCŁAW**	XII Konferencja Naukowo-Techniczna oraz Jubileusz 75-lecia Wydziału Inżynierii Kształtowania Środowiska i Geodezji Uniwersytetu Przyrodniczego we Wrocławiu
29.09-1.10.2026	**NADARZYN**	BIOPOWER, Branżowe Targi Biogazu, Biometanu, Biopaliw i Biomasy; PTAK Warsaw Expo
	PAŹDZIERNIK	
8-9.10.2026	**WARCHAŁY**	XII Podlaska Konferencja Ciepłownicza
14-15.10.2026	**WROCŁAW**	Konferencja Bridge – Energy and Industry Dialogue, Energia w czasach niepewności
19-22.10.2026	**BESKIDY**	XV Międzynarodowa konferencja kotłów i transformacji energetycznej 2026; Politechnika Śląska
22-23.10.26	**TRESNA**	XIX Ogólnopolska Konferencja Naukowo-Techniczna; Wentylacja, Klimatyzacja, Ogrzewnictwo, Środowisko PZITS Kraków
	LISTOPAD	
4-6.11.2026	**JOZEFÓW k. WARSZAWY**	XXIII Konferencja Techniczna Izby Gospodarczej Ciepłownictwo Polskie (IGCP)
17-19.11.26	**NADARZYN**	FUTURE ENERGY, Targi Transformacji Energetycznej i Technologii Niskoemisyjnych; PTAK Warsaw Expo
24-26.11.26	**NADARZYN**	FIRE PROTECTION, Targi Technologii Zabezpieczeń Przeciwpożarowych; PTAK Warsaw Expo
	GRUDZIEŃ	
1-4.12.2026	**WARSZAWA**	Konferencja Problemy Badawcze Energetyki Cieplnej, PBEC2026
2-4.12.2026	**KRAKÓW**	VI Międzynarodowa Konferencja; Strategie wdrażania Zielonego Ładu; Woda, Surowce i Energia w Zielonej Transformacji
9-11.12.2026	**KRAKÓW**	VI Seminarium „Geoenergetyka i Geotermalne Pompy Ciepła" Ogólnopolska Barbórka Geotermalna i pierwszy prąd z geotermii
	2027	
	STYCZEŃ	
12-14.01.27	**NADARZYN**	Solar Energy Expo, Największe Targi Przemysłu Odnawialnych Źródeł Energii w Europie Środkowo-Wschodniej; PTAK Warsaw Expo
	LUTY	
9-11.02.27	**NADARZYN**	ECO, Targi ochrony środowiska, PTAK Warsaw Expo
23-25.02.27	**NADARZYN**	Targi HVAC; PTAK Warsaw Expo
	KWIECIEŃ	
14-16.04.27	**CZĘSTOCHOWA**	Konferencja „Mikrozanieczyszczenia w środowisku człowieka"; XXX lat Wydziału Infrastruktury i Środowiska Politechniki Częstochowskiej
	CZERWIEC	
9-10.06.27	**ZIELONA GÓRA**	Zjazd Dziekanów kierunku Inżynieria Środowiska; Uniwersytet Zielonogórski; Instytut Inżynierii Środowiska
10-11.06.27	**ZIELONA GÓRA**	VIII Międzynarodowa Konferencja Inżynieria i Kształtowanie Środowiska oraz obchody Jubileuszu 50 lat Inżynierii Środowiska w Zielonej Górze
	PAŹDZIERNIK	
13-15.10.27	**BRENNA**	XII Ogólnopolska Konferencja Naukowo-Techniczna; Aktualne zagadnienia w uzdatnianiu i dystrybucji wody; Politechnika Śląska