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Experiences with aerobic granular sludge for large urban wastewater treatment plants

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ABSTRACT

Practical experiences demonstrating the implementation of aerobic granular sludge (AGS) and its economic and technical suitability for large wastewater treatment plants (WWTPs) across various climate regions are presented. Applications include hybrid AGS configuration, in which AGS surplus sludge is directed into activated sludge reactors. This approach enhances and intensifies the processes of both continuous-flow or sequencing batch reactor (SBR) activated sludge systems. Additionally, the study compares ultrafiltration of AGS effluent with membrane bioreactor with membranes integrated in the activated sludge system. In the examined application case, AGS with downstream ultrafiltration achieved 39% lower operational costs, while providing a greater treatment capacity within a similar footprint. Overall, these findings confirm that AGS has matured into a fully developed technology, now also successfully applied worldwide within large and very large WWTPs.

Key words: aerobic granular sludge, cost & energy effective operation of large wastewater treatment plants, densification, hybrid, process intensification

HIGHLIGHTS

- Aerobic granular sludge technology developed into proven modern standard, also for large wastewater treatment plants.
- Presented case studies illustrate options for aerobic granular sludge (AGS) configuration and plant integration.
- Hybrid-AGS augments performance of activated sludge systems (densification).
- Techno-economic assessment of two case studies are presented that resulted in selecting AGS with tertiary ultrafiltration (more compact and significantly lower opex) above membrane bioreactor.

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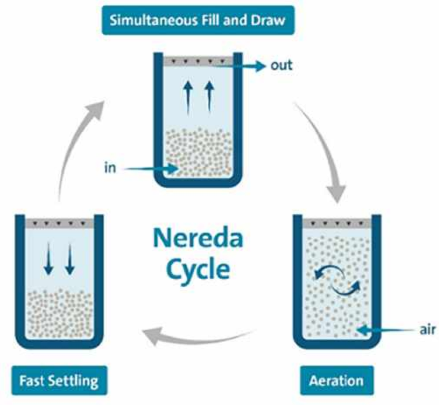
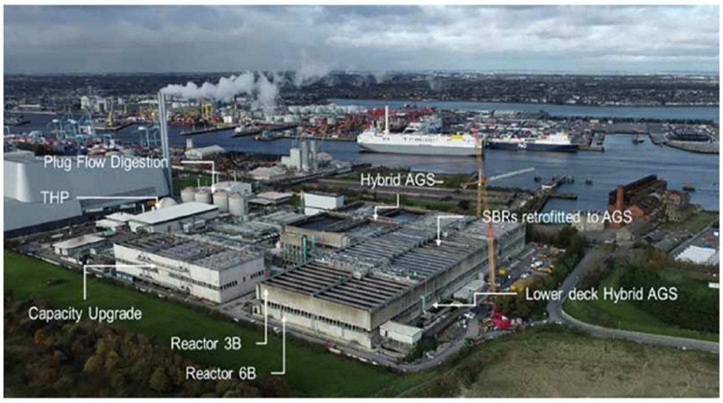
GRAPHICAL ABSTRACT





INTRODUCTION

Aerobic granular sludge (AGS) is an advanced biological treatment technology (de Kreuk & van Loosdrecht 2006; Chen et al. 2020) that combines the technical advantages of biofilm systems, such as compactness and high volumetric rates, with those of activated sludge, including the ability to achieve full biological nutrient removal, ease of operation, and no need for biofilm carriers. The technology, commercially known as Nereda® (trade name owned by Haskoning), was developed by the Dutch water sector and transformed from a breakthrough innovation into a modern, fully mature and sustainable wastewater treatment technology (Almemark 2007; Pronk *et al.* 2015a; GWI 2020). The technology employs one or more reactors in which (see Figure 1) a three-step cyclic operation is performed. This cyclic operation, that creates all the selection mechanisms (van Loosdrecht 2024) for biomass to form AGS, has clear similarities with activated sludge sequencing batch reactor (SBR) operation (Wilderer *et al.* 2001). However, important differences are that (1) the fill and draw step are combined while operating at a constant water level, (2) wastewater is fed from the reactor bottom under unmixed/unaerated conditions, and that (3) within the settling step, surplus sludge with poorest settling characteristics is selectively wasted. For larger wastewater treatment plants (WWTPs), multiple reactors are used which are fed in sequence enabling continuous treatment of the received wastewater.

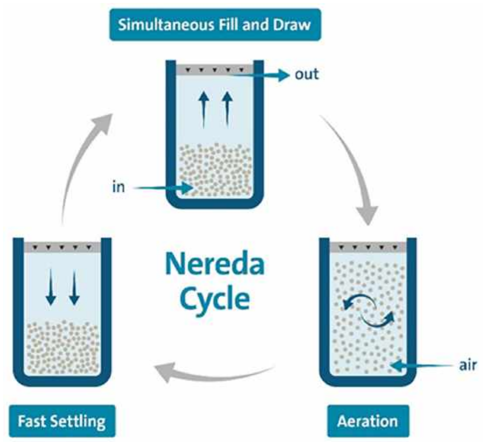


Figure 1 | Process cycle for aerobic granular sludge technology.

The first cycle step involves simultaneously feeding from the bottom and displacing treated water over fixed overflow weirs at the top of the reactor. The second step is aeration, where next to COD oxidation also P-uptake, nitrification, and denitrification occur. Due to the size of the granular sludge particle, an oxygen gradient forms across the aerobic granules when aerated. The outer layers are aerobic and the inner core is anoxic or

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anaerobic (de Kreuk *et al.* 2007). As result, nitrifiers and heterotrophic bacteria proliferate more in the aerobic outer layer of the granules, enabling the degradation of organics (COD removal) and nitrification (conversion of ammonia to nitrite/nitrate), respectively (Beun *et al.* 1999; de Kreuk *et al.* 2007). Simultaneously, nitrification–denitrification takes place, whereby the nitrates formed from nitrification are denitrified deeper within the anoxic core of the granules (Pronk *et al.* 2015a). Phosphate accumulating organisms (PAOs) in the aerobic granules enable enhanced biological phosphorus removal, whereby phosphate uptake occurs during aeration and phosphate-rich waste sludge is subsequently removed from the system (de Kreuk & van Loosdrecht 2004; de Kreuk *et al.* 2005a, b). Effective biological nutrient removal can therefore be achieved in a single reactor without the need for separate anaerobic and anoxic compartments, recirculation pumps, or mixers. The nitrogen removal in the aeration process cycle step can be further increased by applying pre- and/or post-denitrification using pulsed aeration phases within this aeration cycle step. The final stage is a fast settling phase followed by selectively wasting of the slower settling and more flocculent biomass.

Typically, when compared with similarly loaded activated sludge systems (Giesen *et al.* 2013; van Loosdrecht 2024, Pedersen 2024), AGS has the following advantages: (i) 25–75% reduction in treatment system footprint; (ii) 20–50% energy saving due to the reduced utilization mechanical equipment such as mixers, recycle pumps, etc.; (iii) capital and operational cost savings; and (iv) the granules exhibit enhanced resilience under less-favourable process conditions and incidents. In addition to phosphorus recovery facilitated by the extensive biological phosphorus removal ability, the biopolymers produced by the granule forming organisms open ups new resource recovery options, like Kaumera® (van Loosdrecht 2024).

Although all the well-understood biological selection mechanisms leading to aerobic granulations are intrinsically embedded in aforementioned cyclic reactor operation (Liu & Tay 2002, 2004; Schwarzenbeck *et al.* 2004; Tay *et al.* 2004; de Kreuk *et al.* 2005a, b; Winkler *et al.* 2011; Pronk et al. 2015b; van Loosdrecht 2024) and practical applications of this technology past the 100 milestone (Giesen *et al.* 2024), until recently, limited data were available in the literature on AGS for large WWTPs, which sparked scepticism with some practitioners and designers regarding the proven efficacy and suitability of AGS technology for large-scale WWTPs. Also, the cyclic operation intrinsic to AGS reactors was viewed by some as a potential disadvantage, with assumptions that such reactors would not be economically viable for large-scale WWTPs compared with continuous activated sludge or biofilm systems with a carrier. Also, some perceived that operating AGS with tertiary membrane filtration would not be possible.

With AGS technology implemented at several very large WWTPs, the technology has been successfully validated across various climates zones and this paper aims to disseminate pertinent data and application examples.

METHODS

A two-step approach is applied in this paper to disseminate practical data relevant to the applicability of AGS for large wastewater treatment applications:

1. Overview of technology development status and technical limitations
2. Practical application cases AGS-technology where AGS technology were evaluated and chosen for large WWTPs as the most economically attractive market offering.

RESULTS AND DISCUSSION

Technology development status and technical limitations

The first full-scale AGS-application dates back to 2005. By early 2020, the technology was, or was being, implemented within more than 80 wastewater treatment projects with capacity ranging from 5,000 to 2,400,000 P.E. (Chen et al. 2020). By early 2026, this increased to 132 (Haskoning 2026). The treatment plant capacity distribution of current applications is shown in Table 1, based on either biological or hydraulic average dry weather flow capacity, and an increasing number of large (≥100,000 P.E.) and super large (≥1,000,000 P.E.) wastewater treatment is observed in the pre-contract pipeline (Haskoning 2025).

The AGS technology is modular and there are no technical limitations to the number of reactors or individual tank volumes. However, in aforementioned references, aspects like redundancy and escalating costs associated with larger piping and valves, resulted in the largest reactor volumes being in the range of 9,000–13,000 m^3. This class of reactor volume has been in practical deployment since 2014, as reported for Garmerwolde WWTP, The Netherlands (Pronk *et al.* 2015b).

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Table 1 | Number and size distribution of AGS-nereda references per early-2026

Biological (60 g BOD/P.E.) and hydraulic (MLD average DWF) treatment capacity

Biological	Number	Hydraulic	Number
All	132	All	132
≥100,000 P.E.	42	≥50,000 m^3/day	20
≥500,000 P.E.	7	≥100,000 m^3/day	9
≥1,000,000 P.E.	4	≥500,000 m^3/day	2

Source: Haskoning (2026).

Applications are covering many climates, wastewater characteristics, and treatment objectives. Operation experience shows, that the AGS can effectively treat any type of wastewater that is also suitable for biological treatment through, e.g., activated sludge reactors, biofilm reactors, or membrane bioreactors (MBRs), and that effluent quality of plants embedding AGS is at least similar (Giesen *et al.* 2024; Naicker 2024). The operational references for example include applications that targets as low as ≤0.4 mg/l NH4-N (Germany), ≤5 mg/l TN (Netherlands), ≤0.05 mg/l TP (Australia), or ≤5 mg/l TSS (Brazil, Switzerland). Applications also cover a wide range of municipal wastewater strengths, as well as more complex biologically treatable wastewater of industrial origins. An example of an AGS plant treating relatively dilute municipal wastewater is the WWTP in Altena, Germany, which effectively treats wastewater with a comparatively low concentration of approximately 150 mg/l COD (Jardin 2024).

One of the key design and operational parameters of an AGS reactor is the specific biological loading rate (expressed e.g. in kg_{COD}/kg_{MLSS}/day). In general, this loading rate is not very different from that of activated sludge reactors. However, AGS reactors typically operate at much higher MLSS-concentration (8–15 kg/m^3 compared with 3–6 kg/m^3 in activated sludge reactors). This increased biomass concentration, in combination with the plug-flow and biofilm kinetic advantages, results in a significantly more compact reactor design (van Haandel & van der Lubbe 2012; Giesen *et al.* 2013; Chen et al. 2020). The DO-setpoint during main aeration is another key operational parameters, which with 1–2 mg/l is quite similar to operation of activated sludge.

Similar to activated sludge SBRs, the exchange ratio – the ratio of the wastewater volume ratio fed per cycle to the wet reactor volume – is a key design and operational parameter. In AGS reactors, this exchange ratio can be as high as 65%. Compared with conventional SBRs, this is significantly higher and, in combination with the higher biomass concentrations and the simultaneous feeding and decanting of treated water, results in a more compact reactor design.

AGS reactors for large WWTP can be fed either by gravity flow or by pumped feed. With gravity flow, the amount of wastewater treated per cycle obviously depends on the instantaneous received untreated wastewater flow and therefore the volume of wastewater that is being treated per AGS reactor cycle varies following the diurnal pattern. Feeding by pumps, in combination with equalization, enables the option to feed the AGS reactor in each cycle with the designed for maximal volume of wastewater and reduce the installed reactor volume. Such equalization can be achieved by using modern sewer pump station control and deploying the sewer network volume, or by making use of a buffer tank. Such buffer tank can be placed upstream or downstream the pretreatment works, but also in parallel. The later has the advantage that only part of the wastewater flow requires additional lifting.

For large WWTPs, the AGS reactors are typically configured into multiple treatment lines that treat equal portion of the wastewater flow. The number of reactors per line is flexible and depends on desired level of flexibility, redundancy, cost-efficiency, and storm flow peaking factor. For example when using six AGS reactors, these could be configured as six lines with each only one reactor. Not all lines will receive wastewater simultaneously as each reactor is operated with the three-step cycle. The configuration enables maximum operational flexibility, especially regarding the number of reactors that are fed simultaneously during peak flow. However, with gravity feeding, this configuration requires extensive flow splitting.

Alternatively, one could configure a single line with six reactors, reducing the flow split requirements but also flexibility. Although multiple reactors within the line could be fed simultaneously during peaking events, with gravity feeding the duration of the reactor feed/decant cycle step dependents on the total cycle duration as the three-step cycle is synced. Other configuration options include using two lines with three reactors each or

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three lines with two reactors each. The former can be continuously gravity-fed and requires only a basic flow split. For larger WWTPs, it is most common to use one or two aeration header system that provides air to all the reactors.

As illustrated by the aforementioned example, within one line, the cycle steps happening in each reactor need to be in sync. Additionally, the duration of a cycle step can vary, e.g., when a reactor receives a smaller volume of wastewater or less-concentrated wastewater, allowing the aeration step to be completed faster. Therefore, the reactors are typically operated not with a cycle of fixed duration of each cycle step, but with dynamic cycles where the duration of each cycle step is best tuned to the operational condition. This is meticulous structured and synced by a controller linked to SCADA and PLC, functioning as a transparent and fully adjustable co-pilot for the operator. This controller uses machine learning to forecast the typical diurnal flow pattern for each day of the week and proactively selects best cycle step durations, including the eventual pre- and post-denitrification phases within the aeration step. This machine learning also detects early transitions from dry weather flow to rain and storm events, pro-actively shortening the cycle duration while increasing the number of cycles for each reactor to cater to the required addition hydraulic treatment capacity (see Figure 2 for an example). Note that this reduction of the aerate/react phase during wet-weather flow has no, or only limited, implications for the obtained treatment performance, as the batches with diluted wastewater require less reaction time to achieve the targeted level of treatment. Furthermore, the controller uses signals of the basic process instruments such as pH and redox, and when available, also ammonium and nitrate, to optimize the duration of the various reaction phases and air utilization in the aeration step to achieve the best possible energy efficiency.

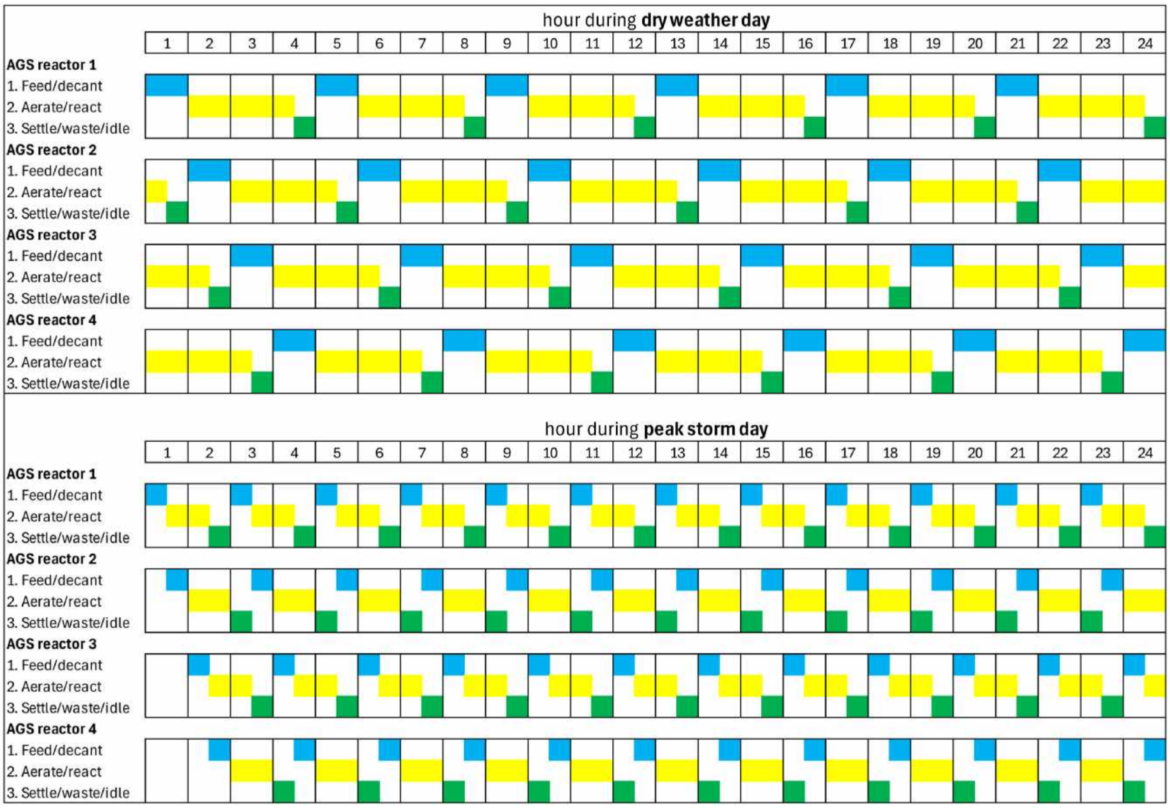

Figure 2 | Cycle structure example for a four-reactor AGS-line with gravity feeding during dry weather (top) and peak storm event (bottom).

Pretreatment requirements are similar to activated sludge: typically, 6 mm screens with optional primary clarifiers. Similarly, integration with post treatment technologies like tertiary filters and disinfection is not different from, e.g., activated sludge processes, as typical TSS-concentration, pathogen removal, UV- transmissivity, and membrane filterability after biological treatment are comparable (van Haandel & van der Lubbe 2012; Barrios-Hernández *et al.* 2020; Giesen *et al.* 2024). In terms of sludge processing, the characteristics and

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performance in thickening, digestion, and dewatering are very similar to processing of activated sludge. In some of the applications, the AGS reactors are operated, during start-up and/or during normal operation, in parallel to pre-existing activated sludge plants. This allows for a hybrid configuration in which the surplus sludge from the AGS reactors is not wasted to sludge treatment but directed to the activated sludge reactors. Given that the sludge settleability and biological nutrient removal capabilities of the surplus AGS are generally superior to activated sludge, this hybrid operation results in the densification and process intensification of the activated sludge train (van der Roest *et al.* 2015).

The complexity of AGS operation and maintenance is comparable with that of activated sludge systems. As in activated sludge SBRs, the process steps are fully automated and occur sequentially, and therefore representative biomass sampling must be carried out when the reactor is in main aeration phase. In plant operation it was experienced that process robustness of the AGS is significantly greater than activated sludge exposed to biologically unfavourable conditions, such as salinity fluctuations, pH excursions, large load variations or occasional inhibitory wastewater composition. This robustness is linked to the stability of the granule structure that remains its good settling characteristics, whereas activated sludge may deflocculate or develop bulking or pin-point flocs.

Example cases of AGS for large WWTPs

As shown in Table 1, AGS-technology has been selected, after extensive technology optioneering and competitive bidding processes, by tens of large and super-large WWTPs as the technically and economically most attractive market offering. In the following sections, some of such application cases are presented to further illustrate the practical application and potential benefits of AGS technology in large-scale wastewater treatment.

Utrecht WWTP, The Netherlands

This is one of the larger Dutch WWTPs that is in the heart of an urban environment. The pre-existing WWTP, originally built in 1959, required an upgrade to replace the outdated installation and meet the more rigorous effluent demands and increased population. The contractor consortium, that was awarded the design-build-operate-maintenance (10 years) tender, based their bid on AGS. The AGS reactor configuration is based on two trains with each three AGS reactors of 12,000 m^3 each (see Table 2). The circular reactors are constructed by prefab concrete segments and receive pumped feed from an upstream equalization tank. The new 430,000 PE WWTP, equipped with partial tertiary sand filtration, is in operation since 2019 and is considerably more compact than the original plant (see Figure 3). It is designed to realize nitrogen effluent concentrations half as low, and to use 30% less power.

Table 2 | AGS application characteristics Utrecht WWTP

Influent characteristics	Dry weather flow	2,500 m^3 /h
	Average flow	64,400 m^3 /day
	Maximum flow	13,200 m^3 /h
	COD	47,000 kg/day
	BOD	18,500 kg/day
	N	4,110 kg/day
	P	540 kg/day
	TSS	20,250 kg/day
Treated water targets	COD	125 mg/l
	TN	5 mg/l
	TP	5 mg/l
	TSS	8 mg/l
AGS configuration	Number of reactors	6
	Volume each	12,000 m^3
	Water depth	7.4 m
	Line configuration	2 lines, pumped feed
	Aeration	5 (+0) blowers servicing common header
Pretreatment	Screening	
	Grid removal	
Posttreatment	Gravity sand filter	Up to 1.8*DWF

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Figure 3 | New AGS-based WWTP of city of Utrecht (doted area left) projected on decommissioned activated sludge infrastructure (*Source*: www.Nereda.net).

Being located in the urban centre, and with a district heating station in the neighbourhood, in 2025, a heat exchanger and a 27 MW heat pump were taken into operation to recover annually approximately 600,000 GJ heat from the treated effluent and provide sustainable heat source to approximately 20,000 houses.

Yuen long effluent polishing plant (YLEPP), Hong Kong

This is an iconic project (see Figure 4) of the Drainage Services Department, the Government of the Hong Kong Special Administrative Region of the People's Republic of China, replacing an existing activated sludge plant in two stages (Stage 1: 100,000 m^3/day; Stage 2: +50,000 m^3/day) in order to meet advanced removal standards (Chan 2024). After positive assessment of compact technologies during a multi-year pilot that included AGS and Moving Bed Biofilm Reactor (MBBR), the project was tendered for construction, allowing bids for either AGS or MBBR. Several bids were submitted, and tender results showed that bids based on AGS received the highest ranking. During the aforementioned pilot, despite quite large wastewater salinity fluctuations, ranging from 0.5 to 11.8 g/l as NaCl due to the use of seawater for toilet flushing, no negative impact on the stability of the granules was observed and treatment performance could be maintained with the standard trouble shooting method. It was concluded that AGS system had demonstrated good operational stability, robustness, treatment performance, and adaptability to high-salinity wastewater (Chen 2019; Giesen 2019).

The treatment configuration (see Table 3) includes compact primary lamella settlers, 5 (+1) gravity fed rectangular AGS reactors integrated in a building structure, and followed by disc filtration and UV-disinfection. Sludge treatment includes anaerobic digestion with the option for co-digestion of food waste. Construction of Stage 1 is ongoing with target to commission in 2027.

AGS is comparatively energy efficient which helps YLEPP moving towards energy neutrality. Furthermore, the AGS process is controlled through a dedicated software which optimizes the utilization of aeration air in batch operations to achieve the greatest energy saving. Owing to the reduced energy demand in the AGS process, together with the extensive provision of PV panels on the rooftop of most of the buildings (installed capacity of about 3.0 MW) and the biogas harvested in the anaerobic digestion process of sewage sludge

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Figure 4 | Artist impression of Yuen Long Effluent Polishing Plant.

Table 3 | AGS application characteristics YLEPP

Influent characteristics	Dry weather flow	100,000 m^3 /day
	Maximum flow	10,833 m^3 /h
	COD	580/832 mg/l (avg/max)
	BOD	230/263 mg/l (avg/max)
	N	45/56 mg/l (avg/max)
	P	6/8 mg/l (avg/max)
	TSS	375/426 mg/l (avg/max)
Treated water targets	BOD	10 mg/l
	TN	10 mg/l
	TP	1 mg/l
	TSS	10 mg/l
AGS configuration	Number of reactors	5 Duty (+1 Standby)
	Volume each	10,000 m^3
	Water depth	11.4 m
	Line configuration	1 line, gravity feed
	Aeration	5 blowers servicing common header
Pretreatment	Screening	
	Grid removal	
	Primary lamella settling	
Posttreatment	Disk filter	
	UV	

from YLEPP and imported from other plants, the renewable energy generated would be sufficient to meet the annual power consumption of YLEPP, making YLEPP the first sewage treatment plant in Hong Kong able to attain energy neutrality at its commissioning in 2027.

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Table 4 | Historic and new discharge licence requirements

Parameter	Unit	Historic value	New value	Type
BOD	mg/l	25	25	Annual 95th percentile
		50	50	Annual maximum
COD	mg/l	125	125	Annual 95th Percentile
		250	250	Annual Maximum
TSS	mg/l	35	35	Annual 95th Percentile
		87.5	87.5	Annual Maximum
Ammonia – N	mg/l	***18.75***	–	Annual 95th Percentile
Total Nitrogen	mg/l		***10***	Annual Average
Total Phosphorous	mg/l		***1***	Annual Average

Ringsend STP, Dublin, Ireland

The secondary treatment facilities of Uisce Éireann (formerly Irish Water) at the Ringsend WWTP were constructed in 2000–2003, providing a treatment capacity of 1,640,000 PE. The treatment train included primary lamella settlers, followed by biological treatment in SBR, and seasonal UV-disinfection. The SBR comprises 24 ICEAS type of modules (a trademark owned by Xylem Water Solutions U.S.A., Inc,), each with a volume of 13,000 m^3, constructed in a two-tier configuration with 12 reactors above the 12 at lower tier. The plant required an upgrade to meet significantly increased treatment performance requirements (see Table 4) imposed by the Urban Wastewater Treatment Directive, due to discharge into the Lower Liffey Estuary, and to cater for a treatment capacity increase up to 2,400,000 PE (600,000 m3 /day). A significant complication in the upgrade was that the plant was landlocked, with only very limited space (~8,000 m^2) available for new construction (White 2018; Buyers-Basso 2024).

Uisce Éireann conducted various detailed studies for assessing feasible options to provide the required treatment capacity. These studies included, among others, using technologies like Deep Shaft Biological Reactor, Integrated Fixed-Film Activated Sludge (IFAS), MBBR, and MBR, as well as treating for carbonaceous removal only and utilizing a deep-sea outfall. The latter was evaluated as one of the more attractive and feasible options. When, in 2014, the large AGS reactors operational at Garmerwolde WWTP, the Netherlands, demonstrated the maturity of the technology at representative reactor scale, Uisce Éireann assessed retrofitting the SBRs into AGS as financially and environmentally the most attractive solution. The plant upgrade plan included constructing a new 400,000 PE Capacity Upgrade AGS facility on the available land, comprising six AGS reactors of 7,900 m^3 in two-tier structure, to initiate the SBR retrofit works and accommodate the additional future load ('Ringsend Wastewater Treatment Plant Upgrade Project' 2020), which is in operation since end 2021 (see Figure 5). Prior to tendering for the construction of the six new AGS reactors, Uisce Éireann had, as part of their overall de-risking strategy, retrofitted one of the upper-deck SBRs into an AGS reactor in 2017 and validated that the obtained treatment performance and robustness were in accordance with the projections (Buyers-Basso 2017). The retrofitted reactor (former SBR 3B) was also used to assess the obtained level of process intensification of the existing SBRs by operating as hybrid AGS reactors, receiving surplus AGS sludge. The advantage of a significant effect of hybrid AGS reactors would be retrofitting fewer SBRs, which is also important in view of the more complex construction accessibility for the lower deck SBRs.

During a trial period of approximately 1.5 years, the nutrient removal capacity as result of hybrid AGS operation was assessed in former SBR reactor 6B (average flow 17,471 m^3/day), which received the surplus sludge from the above-located AGS reactor (see Figure 4 and White & Buyers-Basso 2020) and compared with removal capacity of the SBRs. The results are shown in Table 5. Prior to the trial, the performance of the existing plant and SBR Reactor 6B were monitored for a 12-month period to establish a baseline and validate that the performance of 6B was indeed representative for the SBR reactors.

As can be seen, the hybrid AGS operation resulted in a significant nutrient removal capacity increase of the SBR. Based on this, and the assessed nutrient removal capacity of the AGS reactor 3B, it was projected that in addition to the newly constructed six AGS reactors, only eight upper deck SBRs were required to be converted into AGS reactors when operating in tandem with SBRs retrofitted into hybrid AGS reactors. Table 6 summarizes the AGS application characteristics.

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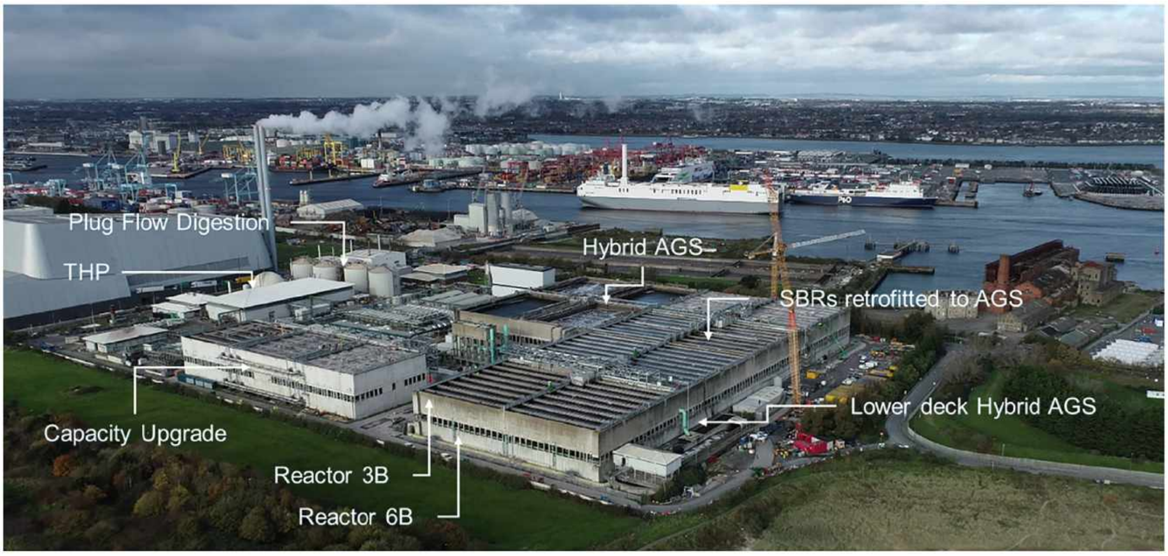

Figure 5 | Ringsend WWTP with retrofit to AGS nearing completion. Reactor 3A was already retrofitted into AGS in 2017 (in former SBR 3B) and used to validate performance of AGS and hybrid AGS in former SBR 6B (bottom). *Source*: Modified from Buyers-Basso (2024).

Table 5 | Monitored nutrient removal rate in hybrid AGS reactor compared with SBR reactor (average based on 12 months trial)

	Typical Ringsend SBR (volume 13,000 m^3)	Hybrid AGS 6B (volume 13,000 m^3)	AGS 3B (volume 12,500 m^3)
Nitrogen (kg N/day)	450	530	750
Phosphate (kg P/day)	40	60	107

Data source: White & Buyers-Basso (2020).

Table 6 | AGS application characteristics Ringsend

Design Influent characteristics	Dry weather flow	600,000 m^3 /day
	Maximum flow	49,700 m^3 /h
	COD	319,000/583,000 kg/day (avg/max)
	BOD	144,000/261,000 kg/day (avg/max)
	N_{Kj}	21,900/31,200 kg/day (avg/max)
	P	3,450/5,000 kg/day (avg/max)
	TSS	151,000/329,000 kg/day (avg/max)
AGS configuration SBR retrofit	Number of reactors	8 AGS +12 Hybrid-AGS
	Volume each	12,500/13,000 m^3
	Water depth	7 m
	Line configuration	6 lines in 2 tiers, pumped feed
	Aeration	9 blowers servicing common header
AGS configuration capacity upgrade	Number of reactors	6
	Volume each	7,900 m^3
	Water depth	7 m
	Line configuration	2 lines in 2 tiers, pumped feed
	Aeration	5 blowers servicing common header
Pretreatment	Screening	
	Grit Removal	
	Primary Lamella Settling	
Posttreatment	UV	Seasonal

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Process intensification of the plant's sludge treatment facility includes increasing the sludge digestion capacity of the four in parallel 4,400 m^3 anaerobic sludge digestors by 30%. This was achieved by retrofitting them into in series Ephyra (a trademark owned by Haskoning) advanced plug-flow digestion. Also, a Pearl (a trademark owned by Ostara Nutrient Recovery Technologies Inc.) unit has been incorporated to recover phosphate as a struvite fertilizer product (Buyers-Basso 2024).

Soreq WWTP, Israel

Located approximately 15 km west of the city center of Jerusalem, this facility is one of Israel's largest WWTPs. It serves a substantial portion of the city's catchment area and is situated in the Soreq valley, hemmed in by river bedding and hills on one side and national road 386 and hills on the other. The plant originally comprised four activated sludge treatment trains, but to cater for fast pollution growth while meeting stricter effluent discharge limits, addition of a fifth biological treatment train was required. Also, to facilitate advanced water reuse and comply with updated river water discharge standards (see Table 7), tertiary effluent filtration needed to be added, and due to the limited space available, it was decided to use ultrafiltration instead of the commonly applied sand filtration (Buchbut et al. 2024).

Table 7 | Updated water quality targets for river discharge

Parameter	unit	Monthly average	Max. value
COD	mg/l	≤70	100
BOD5	mg/l	≤10	15
N-total	mg/l	≤10	15
NH4-N	mg/l	≤1.5	2.5
P-total	mg/l	≤1	2
Suspended Solids	mg/l	≤10	15
Oxygen	mg/l	≥3	
pH		7–8.5	
Faecal Coli	CFU/100 ml	≤200	

The plant owner, Jerusalem Wastewater & Purification Enterprise Ltd (JWPE), opted for a technology for this fifth train that would cost-effectively provide maximum future treatment capacity using the limited remaining unbuilt plant terrain.

Before deciding constructing the fifth train, numerous optimizations were trialled and implemented to intensify the capacity and performance of the existing trains. These included hydrocyclone sludge densification, for which JWPE upgraded one of the biological treatment lines with modules of hydrocyclones in 2017. These treated the waste activated sludge and returned the hydrocyclone underflow to the biological reactor. It was anticipated that this operation would improve the settleability of the sludge in the biological reactor, enabling operation at increased sludge levels and resulting into more treatment capacity. The targeted intensification was further enhanced by dosing EPDM particles as growth bodies for the biomass. However, during the multi-year trial, no significant and consistent positive effect of the hydrocyclones on the performance could be observed (confirming that both metabolic and physical selection is necessary to achieve improved settling characteristics) and it was decided not to equip the other three biological treatment lines with hydrocyclone densification technology and to focus on expanding the WWTP with a fifth biological water train (Berends 2024; Buchbut et al. 2024).

For the additional fifth train, the most feasible treatment solutions were assessed to maximize the additional treatment capacity on the limited remaining, approximately 55,000 m^2 constrained by hills, the river, and the road. Various biological treatment options were evaluated, including AGS, MBBR, MBR, hybrid-MBR, activated sludge with pre-precipitation, and nitrogen removal in fixed-bed filters.

After a thorough assessment, two options emerged as the most attractives and were subsequently engineered (see Figure 6) to enable a detailed techno-economic comparison: (1) MBR discharging its effluent directly into the river and (2) AGS in combination with extension of the tertiary ultrafiltration.

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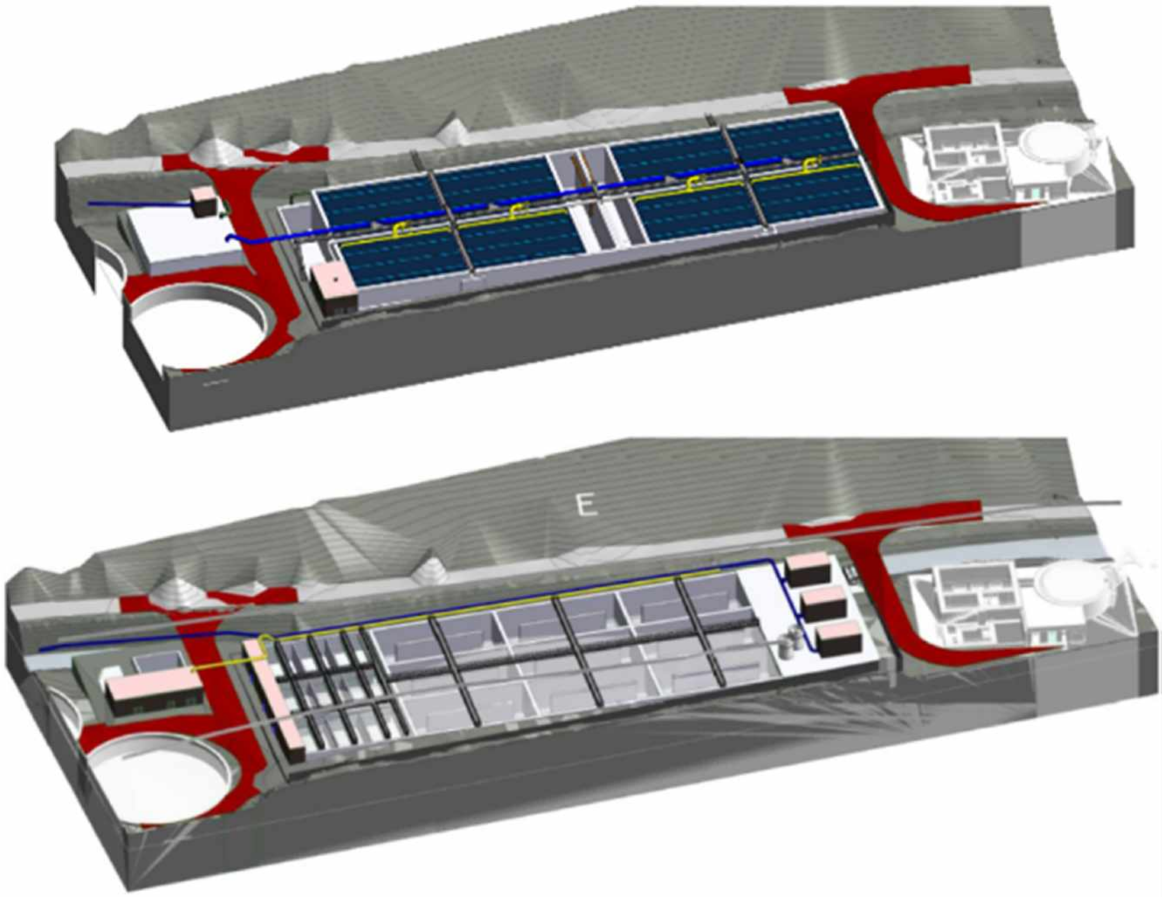

Figure 6 | 3D model for the 5th line based on AGS (top) and MBR (bottom) as specified in Table 8.

Figure 7 | Cedar Rapids Water Pollution Control Facility.

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Table 8 | Key-equipment sizing MBR and AGS scenario for train 5

MBR design	AGS design
Train 5 feed pump: 3(+1) × 1,250 m^3/h	Train 5 feed pump: 3(+1) × 1,445 m^3/h
Screening: 3x 2,000 m^3/h, 2 mm	Screening: 2(+1) × 1,445 m^3/h, 6 mm
Anaerobic tank: 12 × 630 m^3	AGS feed buffer: 3,500 m^3
Anaerobic mixer: 12 × 3 kW	AGS feed pump: 4 × 1,759 m^3/h
Anoxic tank: 3 × 3,309 m^3	
Anoxic propulsor: 6 × 3 kW	
Anoxic recycle pump: 6 × 2,500 m^3/h	
Anoxic/aerobic tank: 3 × 3,041 m^3	AGS reactor: 4 × 10,525 m^3, 9.4 m water level
Anoxic/aerobic propulsor: 6 × 3 kW	
Anoxic/aerobic recycle pump: 12 × 2,000 m^3/h	
Aerobic tank: 3 × 3,041 m^3, 9.5 m water level	
Aerobic mixers: 24 × 5.5 kW	
Aeration blower: 3(+1) × 12,000 Nm^3/h	AGS Aeration blower: 4 × 10,800 Nm^3/h
Post denitrification tank: 3 × 840 m^3	AGS Sludge Buffer: 2 × 1,200 m^3
Post denitrification mixers: 6 × 5.5 kW	
Submerged membranes: 160,000 m^2	Additional tertiary UF membranes: 142,700 m^2 (3,072 × ZeeWeed1000)
Membrane Tanks: 6 × 430 m^3	
Membrane aeration blower: 6(+1) × 4,000 Nm^3/h	AGS effluent buffer: 3,310 m^3
Permeate pump: 12(+2) × 390 m^3/h	AGS effluent pump: 3(+1) × 2,183 m^3/h
RAS pump: 6(+1) × 1,850 m^3/h	
WAS pump: 2 × 100 m^3/h	

The MBR scenario is based on three parallel trains of biological reactors and one common compartmented membrane tank, housing submerged membrane modules. The biological reactors have a process water depth of 9.5 m and consist of four compartments: anaerobic, anoxic, swing, and aerobic, followed by a post-denitrification section. Details of key-equipment sizing are summarized in Table 8. This scenario would result in a maximum additional daily average treatment capacity of 67,500 m^3/day, upgrading the plant to a total future capacity of 157,500 m^3/day.

The AGS scenario is based, also see Table 8, on one line comprising four AGS reactors with process water depth of 9.4 m. The reactors are configured with a pumped feed from existing upstream equalization buffer. Treated water is pumped toward the tertiary ultrafiltration unit where it is blended upstream with the treated wastewater from the four other biological treatment trains. The design includes the option to apply the hybrid AGS concept by directing the surplus sludge from the new treatment line into the existing four trains. The AGS scenario upgrades the plant to a total capacity of 169,500 m^3/day, with a direct treatment capacity increase of 75,000 m^3/day and a minimum additional capacity increase of 4,500 m^3/day in the existing four lines through the hybrid-AGS concept.

Upon completion of the design stage, an assessment was conducted on the associated investment and operational expenditures. This assessment was based on a detailed breakdown of equipment costs, quotations received from membrane suppliers, and reviews conducted by independent specialists. The results of this assessment are presented in Table 9. It is important to note that these costs are specific to the project purpose and that generic cost items that apply to both alternatives, such as the replacement of outdated equipment in the existing trains and the new pump station for feeding into the new train, have been excluded from the projections presented Table 9.

The capital expenditure required to achieve the additional treatment capacity of 67,500 m^3/day (for MBR) or 79,500 m^3/day (for AGS, including the hybrid aspect) is very similar, with a marginal difference of 2% that falls well within the estimate's accuracy tolerance. The operational costs for the AGS + UF combination are significantly lower (39%) compared with the MBR scenario. This cost reduction is primarily due to the relative differences in energy consumption, chemical usage, and membrane replacement costs. In addition to the cost benefits, the AGS option was assessed to have a lower risk profile and greater resilience. Also, this option

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Table 9 | Investment (capex) and operation cost (opex) estimates for both scenarios. AGS scenario data (price level 2020; NIS = New Israeli Shekel)

Plant capacity increase m^3/day	MBR 67,500	AGS + UF 75,000	AGS + UF + hybrid effect 79,500
Capex in NIS/(m^3/day)	1,791	1,863	1,758
Opex total in NIS/annum/(m^3/day) of which for	185	141	133
Electricity	68	49	46
Chemicals	68	55	52
Membranes	63	23	22
Power saving biogas	−106	−104	−98
Sludge disposal	89	91	86

Source: Buchbut *et al.* (2024).

offers flexibility in handling flows well above the design maximum by shortening the AGS reactor cycle times during extreme rain events, thereby reducing sewer overflow discharges under such conditions. Based on this techno-economic evaluation, JWPE decided to implement AGS with tertiary ultrafiltration for the fifth train and its implementation is currently underway and expected to be operational by 2028.

Large midwestern WWTP, USA

In recent years, several large-scale plants in the United States have been selecting AGS technology for plant capacity upgrades and preparation for meeting future nutrient removal requirements (Quimby 2024).

One such project is for the Cedar Rapids Water Pollution Control Facility (WPCF), a large 300,000 m^3/day municipal wastewater plant in Iowa (Figure 7) that receives a significant portion of its waste from nearby industrial sources. Accordingly, the plant sees high organic loads and has issues with other challenging conditions such as high sulphur content leading to high hydrogen sulphide levels and the associated hazards. The plant is currently using a combination of anaerobic and chemical/physical pretreatment technologies, along with both nitrifying and non-nitrifying conventional aeration basins.

The plant began initial work on evaluating AGS technology in 2017, conducting an onsite pilot test to determine treatability and to look at performance treating a variety of different waste stream combinations. Following the onsite pilot, further testing was done at the AGS demonstration facility owned by Aqua-Aerobic Systems in Rockford, IL, using simulated high-strength wastewater by dosing carbon and nutrients into Rockfords regular influent. As a result of these tests, the plant elected to pursue AGS for its upgrade, which will begin as a new 95,000 m^3/day (850,000 PE) AGS process train constructed on remaining available area and run alongside the existing conventional plant. Treatment targets for this phase are listed in Table 10.

Table 10 | AGS application characteristics Cedar Rapids WPCF

AGS influent characteristics phase 1 upgrade	Flow	95,000 m^3 /day
	COD	975 mg/l
	BOD	542 mg/l
	N_{Kj}	40.1 mg/l
	P	7.9 mg/l
	TSS	114 mg/l
Treated water targets	BOD	30 mg/l
	NH4-N	2 mg/l
	TSS	30 mg/l
AGS configuration SBR retrofit	Number of reactors	4
	Volume each	8,700 m^3
	Water depth	7.3 m
	Line configuration	1 line, gravity feed
	Aeration	3 blowers servicing 1 common header
Pretreatment	Screening and grid	
	Primary Settling	
Posttreatment	Chemical disinfection	

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Project groundbreaking was end 2024 and will add one line of four AGS reactors (see Table 10) with anticipated plant start-up in 2028. After the AGS train relieves the plant, in next phases, almost 50-year-old structures will be replaced by additional lines of AGS, eventually converting the entire plant over to AGS treatment exclusively.

CONCLUSIONS

Since its first full-scale application in 2005, AGS technology has evolved into a mature modern treatment alternative to other aerobic biological treatment processes such as activated sludge, MBR, and biofilm processes. The AGS references around the world demonstrate that the technology can effectively treat any type of wastewater suitable for biological treatment, achieving effluent quality at least comparable with that produced by, e.g., activated sludge reactors, biofilm reactors, or MBRs.

The references and application cases presented for large wastewater treatment applications, demonstrate that AGS is suitable, and has been proven (since 2014), also for this group of WWTPs. Also in this category, AGS provides treatment in combination with attractive techno-economic benefits, as the selection of technologies was based on either rigorous competitive tendering and/or detailed extensive system optioneering and scenario assessments.

The presented case of Cedar Rapids WPCF shows the ability of AGS to treat complex municipal and industrial wastewater mixtures. Similarly, the case of the Yuen Long Effluent Polishing Plant in Hong Kong illustrates the robustness of AGS to large fluctuations in salinity. These examples underline that, due to its widely demonstrated better process resilience compared with conventional technologies, AGS can be an attractive solution in situations where operational robustness under less-favourable conditions is critical.

The presented cases also illustrate that, especially at urban or land-limited sites, the compactness of the AGS technology is a significant advantage, enabling expansion of treatment capacity or improvement of treatment performance without the need to relocate or enlarge the WWTP footprint. In addition, the example of Ringsend WWTP demonstrates how existing biological reactors can be upgraded by retrofitting into AGS. Where the existing reactors in this case were of the SBR type, AGS applications in, for example, Lisbon (van der Roest & Giesen 2014) and Zurich (Giesen 2024) also include flow-through activated sludge reactors that have been converted into AGS reactors.

The example cases of Soreq and Ringsend WWTPs illustrate that applying the AGS-hybrid configuration, in which surplus AGS sludge is directed into activated sludge reactors, results in augmentation and process intensification of continuous-flow or SBR activated sludge systems.

The presented case of Soreq WWTP demonstrates that the combination of AGS and tertiary ultrafiltration can be an attractive, more compact, and more cost-efficient variant to MBR with membranes integrated into the activated sludge.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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