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Implementation at full scale of demand-driven biogas production from anaerobic digestion of sewage sludge

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ABSTRACT

In a net-zero emissions scenario, a secure supply of electricity involves renewable generators that can flexibly increase their production when needed. Currently, electricity generation from biogas in the water industry is most commonly at a steady level, given Anaerobic Digestion (AD) is traditionally operated in steady state. This research demonstrated at different scales that demand-driven biogas production from AD of sewage sludge is feasible. Performance parameters are not negatively affected by a flexible feeding schedule and stability parameters show transitional imbalances that do not threaten the overall process. This paper presents the trial implementation in digesters of volume 3800 m3, which became permanent. Economic and environmental benefits exist; however, in order to unlock the full potential of flexible electricity generation from sewage sludge, synergies between technical, operational and political factors in the water and energy sectors need to be developed.

Key words: demand-driven anaerobic digestion, energy recovery, operational performance improvement

HIGHLIGHTS

- Full-scale trials confirm the pilot- and demonstration-scale results.
- Successful implementation at full scale of dynamic feeding of anaerobic digestion.
- Dynamic feeding and flexible electricity generation have financial and carbon benefits.

INTRODUCTION

Due to concerns about climate change, many countries are progressing decarbonisation programmes. The United Kingdom (UK) has adopted a net-zero emissions strategy for 2050, while the water industry has publicly committed itself to the net-zero carbon target to be achieved by 2030. Given the large, planned contribution of wind and solar power generation to the decarbonisation of the electricity sector, this sector is considered easy to decarbonise. However, the security of electricity supply is threatened by the large use of these intermittent renewable energy sources. Therefore, other preferably renewable technologies are needed to provide flexible electricity generation to meet the peaks in demand.

Anaerobic digestion (AD) is a common technology used to recover energy from organic waste, such as sewage sludge (Appels *et al.* 2011). Research and practice have shared the opinion that the process performs better if operated in a steady state, which provides, in principle, a steady flow of biogas. However, the electricity market needs flexible renewable operators in its transition towards a decarbonised system (Lafratta *et al.* 2021a), and this makes the demand-driven biogas production from AD of interest.

The water industry is a significant local and renewable generator. Sewage is collected at the wastewater treatment plant (WWTP) and treated before being discharged to the environment. Sewage sludge is the by-product of sewage treatment, and it is then treated with AD in order to stabilise it for its safe disposal and nutrient reuse in the environment. A by-product of sewage sludge treatment with AD is biogas, which can be used to generate electricity. As the water industry represents a significant local renewable and distributed electricity user and

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generator, the electricity grid can take advantage of the opportunity of making the electricity generation at the WWTP flexible supported by demand-driven biogas production.

The aim of this study is to investigate the implementation of demand-driven biogas production as an innovative energy management strategy for an operational full-scale WWTP. Previous research demonstrates the readiness of this operational solution for full-scale implementation. Lafratta *et al.* (2020) present the experimental research carried out at the pilot scale (50 l AD active volume) under eight different conditions for both the conventional process (i.e., with no pre-treatment) and advanced AD (i.e., with the thermal hydrolysis process as a pre-treatment). This research showed the benefits of demand-driven biogas production and validated the technology in a laboratory environment, positioning the technology readiness level (TRL) (European Commission 2014) at level 4. Subsequent demonstration-scale experimental activities (18 m^3 AD active volume) evidenced the technical potential in a relevant operational environment (Lafratta *et al.* 2021b). The demonstration-scale trials were completed under conventional AD only, as this configuration is known to be more challenging from an operational perspective than advanced AD. Therefore, the operational solution and technology were deemed ready for trialling at full scale.

This paper investigates the potential full-scale application of demand-driven biogas production in the water industry. Gaida *et al.* (2017) found that the full-scale implementation of AD feed control is very rarely presented in the literature. The authors identified the main reasons for limited available full-scale research, as the (a) lack of an innovative culture, and solutions often too complex to gain support from plant management and operators, (b) lack of online instrumentation, and (c) resiliency and effectiveness of the control system to manage process instability.

Previous research demonstrated the suitability of this operational solution with other substrates than sewage sludge. For example, experimental work investigated AD in agricultural waste (Mauky *et al.* 2015; Zealand *et al.* 2017) or specific fast-degradation organics (Mulat *et al.* 2016; Laperrière *et al.* 2017). Other studies investigated demand-driven biogas production from organic agricultural waste with specific technologies dissimilar to the one commonly used in WWTPs (i.e., fixed bed disc reactor) (Terboven *et al.* 2017). Limited literature is available on research at the full scale of demand-driven biogas production from AD of other substrates. Mauky *et al.* (2015) investigated two reactors of 180 and 923 m^3 volume each, whereas Mauky *et al.* (2017) presented research on a 165 m^3 digester fed with agricultural waste. On the contrary, the study presented in this paper is the only one known to the authors and the first publicly documented implementation of demand-driven biogas production in the context of the water industry.

This paper presents the experimental activities carried out in an industrial operational environment and the full-scale application of demand-driven biogas production as an operational solution in the water industry. The trials were carried out at an active WWTP serving a population equivalent (PE) of approximately 440,000 in the London (United Kingdom - UK) area, with primary digester operating capacity of 7,600 m^3.

MATERIAL AND METHODS

The WWTP used for the full-scale trial and implementation treats sewage from an urbanised area in London (UK). After the preliminary treatment of the sewage, eight primary settlement tanks provide primary treatment, where primary sludge (PS) is produced. Surplus-activated sludge (SAS) is produced by an activated sludge plant and final settlement tanks. PS and SAS are pumped into buffer tanks, and then thickened in drum thickeners. The total volume of unthickened sewage sludge produced on site was 1,325 $\pm$ 192 m^3/day, with an average dry solid (DS) concentration of 4.09 $\pm$ 0.81%. Although it is not measured continuously, on average, the PS/SAS ratio is approximately 60% (Thames Water Utilities Ltd 2020).

The sewage sludge treatment configuration of this WWTP is Conventional Mesophilic Anaerobic Digestion (CMAD). The thickened blended sewage sludge is stored in a continuously mixed buffer tank of approximately 300 m^3 volume before being fed to two primary digesters of active volume of 3,800 m^3 each. As the volume of the digesters is defined, the volume fed returns the hydraulic retention time (HRT). Usually, the HRT is set at design between 12 and 16 days for a primary digester. According to the DS and volatile solids (VS) content of the feed, the organic loading rate (OLR) is calculated. The range of typical OLR for AD of sewage sludge is between 1.5 and 4.0 $kg_{VS}/m^3/d$ (Wilson *et al.* 2011). During the trial, the average OLR was 4.3 $\pm$ 0.5 $kg_{VS}/m^3/d$, which represents a high-loading rate and it is usually regarded as a stressful condition for the CMAD process. There was a minor day-to-day variation in the amount and quality of the sludge fed, and therefore, the OLR, due to the natural variation in the volume and strength of the sewage being processed through the WWTP. Two secondary ADs completed the treatment of the sewage sludge, of the same size as the primary digesters. The scope of this trial is limited to the primary digesters, which produce most of the biogas.

Activities were devised in order to mitigate the risks identified locally, as well as described in the literature by Gaida *et al.* (2017). In particular,

1. Early engagement with key business and operations stakeholders to ensure buy-in on the concept and to collaboratively devise and de-risk the trials to be accommodated within usual operations.
2. The trials were devised in phases and followed an incremental approach. Progress was regularly reviewed by and agreed upon with relevant stakeholders in order to facilitate support from plant management and operators.
3. Regular sampling and proactive monitoring of the key stability parameters.
4. Support from a new AD model presented by Lafratta *et al.* (2021c) and developed for demand-driven biogas production and to be industry-friendly.

The phases of the trial were as follows:

- Phase 1, from 13th August 2020 to 14th September 2020: an initial period of 1 month in which approximately 50% of the base load feeding volume was added for two consecutive hourly feeds to both digesters. The 'base load' feeds were 13 m^3/h, and the 'peak load' feeds were 20 m^3/h (i.e., an additional 'peak load' volume of 7 m^3/h).
- Phase 2, from 14th September 2020 to 1st October 2020: a subsequent period of one HRT, in which 100% of the base load volume was added for two consecutive hourly feeds to both digesters (i.e., doubling the volume at the peak time in comparison to the base load). The base load feeds were 9 m^3/h, and the 'peak load' time feeds were 18 m^3/h (i.e., an additional 'peak load' volume of 9 m^3/h).
- Phase 3, from 1st October 2020 to 16th October 2020: a final period of one HRT, in which approximately 100% of the base load volume was added for four consecutive hourly feeds to both digesters was tested (i.e., doubling the volume at peak load volume in comparison to the base load). The base load feeds were initially 10 m^3/h, subsequently reduced to 9 m^3/h, and the peak-time feeds, respectively, 19 m^3/h, and then 18 m^3/h (i.e., an additional 'peak load' volume of 9 m^3/h).

The sewage sludge feed characteristics per phase are presented in Table 1. The percentual increases in volume between phases are arbitrary; however, they were defined based on continuous performance reviews during the trials. In each phase, the base load value was reduced, aiming to keep the total volume fed each day the same. However, it needs to be noted that the feeding volumes refer to the volume of sewage sludge fed, which is variable on different days according to the sewage treated at the WWTP and the performance of the various processes on site. This is the reason in Phase 1 and the base load feed was 13 m^3/h, whereas it was 9 m^3/h during Phase 2 and 10 and 9 m^3/h in Phase 3. Natural variability can be observed within a day (with an increased flow in the morning and late afternoons, and reduced flows overnight), over a week (usually associated with work and leisure commuting patterns), and for specific reasons (for example, associated with holiday periods or heavy rainfall). However, the sludge holding tank mitigates such intra-day variability and ensures an average daily volume can be fed to the digesters. In addition to the variability in volumes, the DS concentration varies within a day according to several factors, including the characteristics of the unthickened sludge and the performance of the thickening process. The effects are mitigated by processes' control and mixing features in the various processes and stages of the WWTP; however, a variability in the quality of the sewage sludge fed to the digesters was

Table 1 | Sewage sludge feed characteristics

	Annual average	**Phase 1**	**Phase 2**	**Phase 3**
Volumetric feed (m^3/d)	296 ± 37	312 ± 21	318 ± 36	320 ± 45
Total dry solids feed (t_{DS}/d)	21 ± 3	22 ± 3	22 ± 3	23 ± 3
OLR ($kg_{VS}/m^3/d$)	4.00 ± 0.59	4.21 ± 0.55	4.32 ± 0.60	4.39 ± 0.49
DS concentration (%)	6.94 ± 0.88	7.07 ± 1.04	7.02 ± 0.57	7.03 ± 0.46
Volatile solid concentration (% DS)	74.48 ± 4.86	74.67 ± 0.87	73.58 ± 1.41	71.80 ± 2.46

observed and it is presented by the data in Table 1. While the setpoints of the Supervisory Control and Data Acquisition (SCADA) system (and hence the feeding regimes) controlled the volume of sewage sludge fed, the performance of the AD process is mainly affected by the amount of DS and VS contained in the sewage sludge.

The definition of the feeding regimes and the daily control of the AD process were performed with an adaptation of the three first-order reactions in the series 'Periodic Feeding' AD model developed and presented by Lafratta *et al.* (2021c). As this new AD model was developed to be industry-friendly, timely, simple, and fit for purpose, the equations were written in the appropriate language and code in a Microsoft® Excel® spreadsheet. Then, the solution is found numerically by integrating the resulting equations for the calculation of the biogas production rate with a time interval of 2 min. This interval is set to allow relatively high granularity. The model was implemented according to the methodology described by Lafratta *et al.* (2021c), considering (a) the HRT is set daily according to feed volume and f is calculated consequently, (b) the digester is assumed to be virtually partitioned in 'base load' and 'peak load' volumes, and hence $\tau = 1$ h and $\tau = 24$ h, respectively. For the 'base load', the feed of the same volume is assumed performed hourly. On the contrary, the 'peak load' feeds are interpreted as a daily feed of the same volume (i.e., the volume added to the 'base load'). This assumption is possible because the model is based on first-order reactions. The data collected in the period leading to Phase 1 (and presented in Figure 1) informed an initial calibration of the kinetics parameters (k_1, k_2, and k_3) of the model. The subsequent phases of the trials informed the refinement of the kinetics parameters, which were routinely recalibrated when the feeding conditions or other relevant operational parameters were changed. The weighted sum of the squared errors was used as the objective function to perform the calibration, with the period from the beginning of the feed to 3 h after the end of the feed assigned more weight (i.e., double) in an attempt to improve the accuracy of the model during the peak-time hours. The kinetics parameters as calibrated for Phases 2 and 3 are presented in Table 2. The accuracy of the model is assessed according to Batstone & Keller (2003).

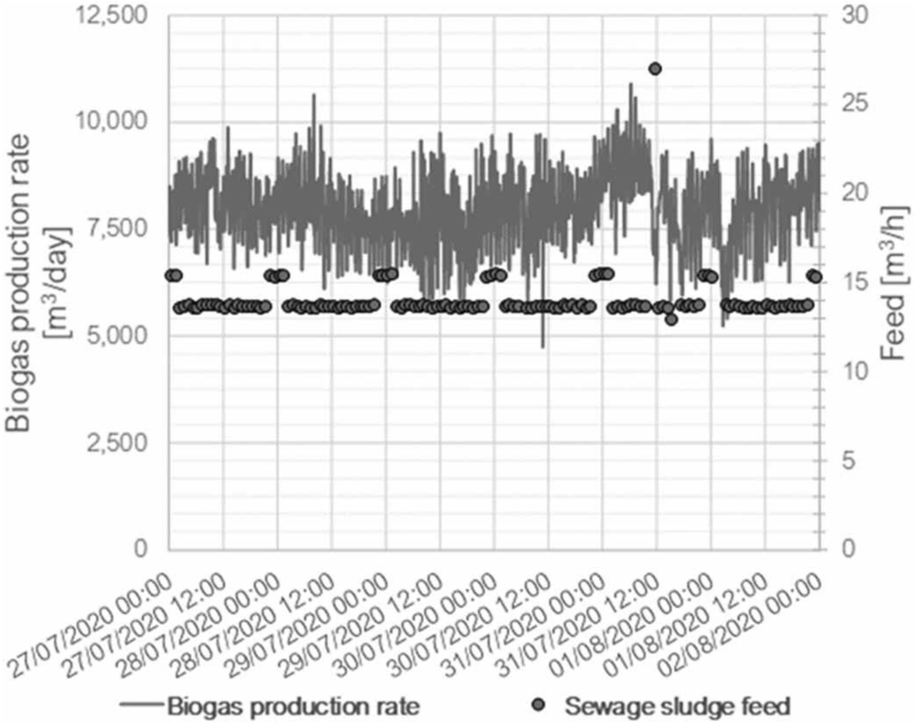

Figure 1 | Feed and biogas production rate during the pre-trial period.

The model was used daily to predict the biogas production rate and to manually optimise the peak time feed start time. As the trials were run at a live WWTP, the feeding regimes were calculated with the aim of increasing the biogas production rate during the real peak times of the tariff the site was subject to, while maintaining operational efficiency and compliance. The first two phases were a conservative and cautious ramp-up. The third

Table 2 | Periodic feeding AD model kinetics parameters, R^2_{rate} is the coefficient of determination, calculated over the initial 3 h after the peak-time feed and over the full period

	k_1 (day^{-1})	k_2 (day^{-1})	k_3 (day^{-1})	Weighted sum of squared errors (10^3 m^6/d^2)	$R^2_{\text{rate, 3 h}}$(%)	$R^2_{\text{rate}, \tau}$(%)
Phase 2	0.023	82.80	2.19	13,871.83	70.9	79.8
Phase 3	0.025	82.15	3.25	8,486.91	70.6	68.9

phase represented the ideal feeding regime driven by the demand defined by the tariff the site was subject to and informed by the application of the 'Periodic Feeding' AD. In Phases 1 and 2, the higher loading started at 14:00 in the expectation of a slow response from the process. Instead, in Phase 3, the 'peak load' feeding started at 15:00 and it ensured the availability of biogas from both digesters for the peak period between 16:00 and 19:00, which was the peak time period of the existing tariff scheme for the site. The peak period is driven by the charges added to the wholesale commodity costs, such as the Balancing Services Use of System (National Grid ESO 2020). These charges are higher when the security of the electricity supply is usually endangered, hence during daily periods of high demand, which for some areas in the UK are between 16:00 and 19:00 on weekdays.

The actual biogas production is not measured directly and needs to be calculated based on a specific methodology. The biogas flow is measured in a pipe downstream of the digesters. However, the digesters are fitted with floating roofs. Consequently, the actual biogas production rate is calculated based on the following measured parameters in addition to the biogas flow: the height of the roof, the level of the liquid digesting sludge, and the gas pressure in the storage allows the calculation of the volume of the biogas stored. As the gas pressure is measured as gauge pressure, the hourly atmospheric pressure at mean sea level measured in a location close to the WWTP is used to calculate the actual pressure of the gas (meteoblue® 2020). The ideal gas law is used to calculate the number of moles of gas stored, assuming the temperature of the gas as the temperature of the liquid phase (which is measured and recorded). Once the mass volume in moles is obtained, this value is multiplied by the molecular weight and divided by the density of the gas. The daily average biomethane composition is assumed unchanged for the whole day, as this was not recorded continuously. This allows the calculation of the value of biogas stored at time t and $t-1$. Finally, the biogas production rate from the AD process at time t (as the average of the biogas production rate between time t and $t-1$) is calculated as the sum of the biogas flow measured by the gas flow meters and the variation of the volume of biogas stored between time t and $t-1$ divided by the time interval. The resulting data are cleaned with a 5-point median signal filter (Harris *et al.* 2003) to facilitate the readability of the graphs.

The digester mixing has been assessed as adequate. The technology and quality of mixing is one of the fundamental differences between pilot- and larger-scale AD. While in the pilot scale a high quality of mixing is achievable, in the full scale the power consumption is an important factor in the balance with energy production (Naegele *et al.* 2012). In fact, industrial-scale reactors are generally not designed with the aim of achieving perfect or high mixing. In full-scale reactors, mixing is usually deemed adequate when the blending time is measured by a mixing test (for example, a tracer test with lithium chloride as a tracing agent (Horan *et al.* 1991; Bischoff & McCracken 1966)) is within 2 h from the start of the test (Thames Water Utilities Ltd 2014). The mixing in the digesters used in these trials has been measured by means of a tracer test following a methodology like the one cited above (Hosainy 2019). According to the results of the tracer test, the report defined the operational conditions to achieve adequate mixing as continuous with minimal dwell time and pumps running at or around their best efficiency point. These recommendations were followed throughout the daily operation, including during the trials presented in this paper.

RESULTS AND DISCUSSION

The biogas production rate shows a dynamic trend, responding to the demand-driven feeding regime. Figures 1–4 show the evolution of the biogas production rate and the hourly feed before and during the three stages of the trial. While the 'input signal' of the increased feed during the preparatory phases and then during Phase 1, shown, respectively, in Figures 1 and 2, did not suffice to reflect in a significant increase in the biogas production rate, the feeding regimes of the subsequent periods did. A spike in the biogas production rate is evident after the peak-time feeds of Phase 2 (presented in Figure 3), which justified the final ramp-up to implement the complete demand-driven feeding regime in Phase 3, the results of which are shown in Figure 4.

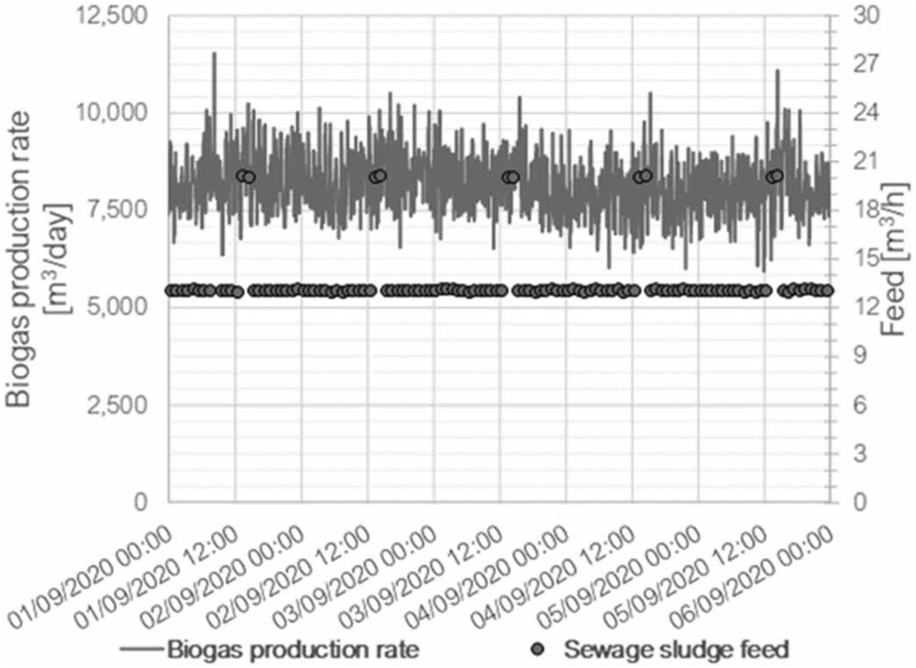

Figure 2 | Feed and biogas production rate during the Phase 1 of the trial: 50% of the base load volume was added for two consecutive hourly feeds to both digesters, starting at 14:00.

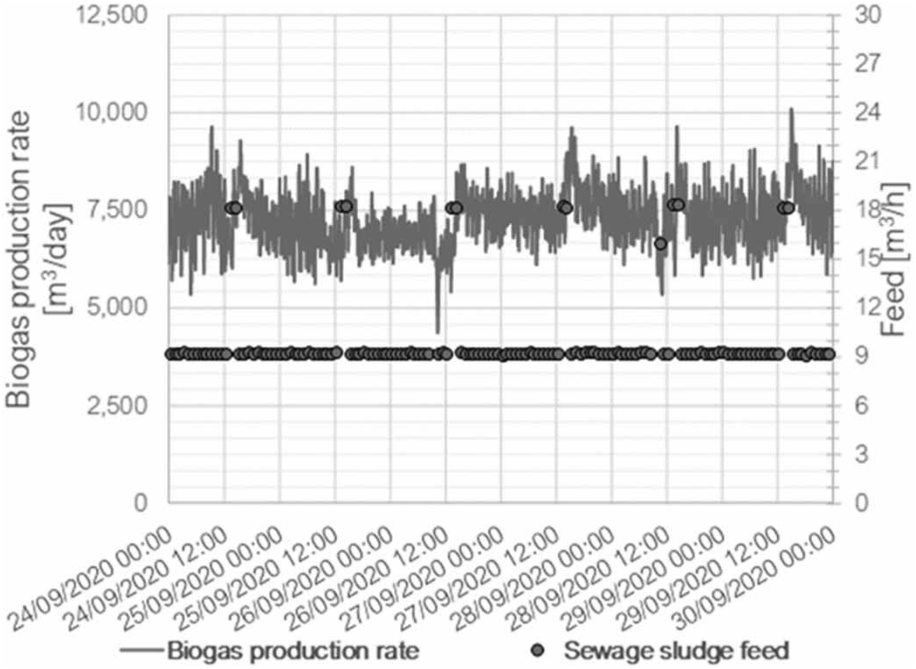

Figure 3 | Feed and biogas production rate during the Phase 2 of the trial: the 100% of the base load volume was added for two consecutive hourly feeds to both digesters, starting at 14:00.

The final demand-driven feeding regime noticeably influences the biogas production rate. Under this operational condition, the biogas production rate promptly increases after the first of the four peak-time feeds, making more biogas available for the Combined Heat and Power (CHP) generation units during the peak tariff period. Therefore, after the end of the trials on the 16th of October 2020, the Phase 3 feeding regime remained implemented in normal operation.

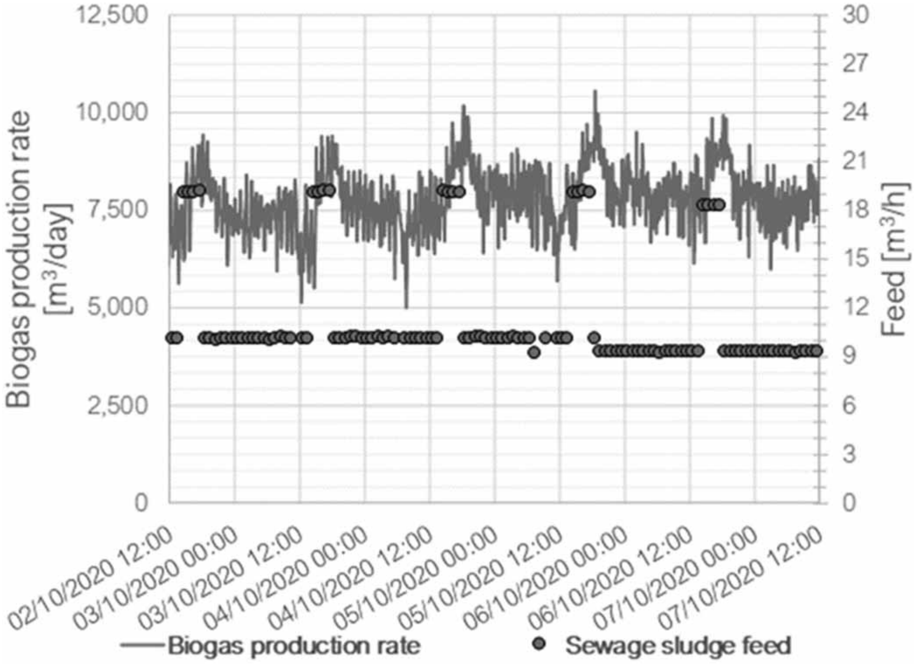

Figure 4 | Feed and biogas production rate during the Phase 3 of the trial: in which the 100% of the base load volume was added for four consecutive hourly feeds to both digesters, starting at 15:00.

The full-scale application of demand-driven biogas production provides useful insights into the upscale of the operational solutions tested at pilot (Lafratta *et al.* 2020) and demonstration (Lafratta *et al.* 2021b) scales. The preparatory activities and the support provided by the 'Periodic Feeding' AD model have been instrumental to start and control the trial and the ramp-up of the feeding regimes.

The biogas production rate increased with suitable *response* and *length* to meet the demand defined by the tariff of the site, as shown in Figure 4. Despite the relatively high-loading rate for a full-scale conventional AD, the demand-driven feeding regime provided the expected increase in biogas production rate within 30 min from the end of each feeding event, and the multiple peak-time feeds allowed the digesters to meet the length of the peak time period. While the trial and the SCADA system were designed for dispatchable generation (i.e., with an increase/a decrease in the output required by the electricity system operator within up to 4 h notice for a defined length of time) according to the local tariff, the quick response and a relatively shorter length of response in comparison to the pilot scale results suggest that conventional AD may be suitable for flexible generation (i.e., to meet increase/decrease in the output required by the electricity system operator within up to 30 min notice for an undefined length of time). In order to unlock a fully flexible AD system, an appropriate upgrade of the ancillary assets may be required according to the asset capacity availability.

All performance and stability parameters demonstrate the success of the trials, notwithstanding the high-loading rate. The main performance and stability indicators data of the trial are presented in Table 3.

Table 3 | Overview of daily performance and stability parameters

	Pre-trial	Phase 1	Phase 2	Phase 3
Volatile solids destruction (%)	51 ± 6	48 ± 7	50 ± 5	48 ± 3
pH (pH unit)	7.6 ± 0.0	7.6 ± 0.0	7.7 ± 0.0	7.6 ± 0.0
VFA/TA (or FOS/TAC)	0.14 ± 0.01	0.14 ± 0.01	0.13 ± 0.01	0.14 ± 0.01
Ethanoic acid (mg/l)	N/A	82 ± 9	78 ± 7	78 ± 5
Ethanoic/propanoic acid ratio	N/A	0.11 ± 0.02	0.15 ± 0.02	0.16 ± 0.02
Biogas yield (m^3/t$_{\text{DS fed}}$)	437 ± 58	443 ± 46	450 ± 60	444 ± 69
Biomethane concentration (%)	60 ± 1	61 ± 1	61 ± 1	60 ± 1

The overall performance of the AD process is generally similar while some metrics appear to show an improvement when the AD is operated under demand-driven feeding regimes. The VS destruction and biomethane concentration in the biogas appear similar under a steady state or demand-driven operation and consistent with reference values for high-rate CMAD. It is important to note that the data for the pre-trial refer to a much longer operational period and consequently higher variability is to be expected. Furthermore, the biogas yield appears to be higher when the digesters are operated under demand-driven feeding regimes. Although it was not possible to run a comparative trial with one digester operated under a demand-driven feeding regime and another under a steady state as a benchmark and consequently the data does not allow for an analysis of statistical significance, the trends observed at the full scale confirm the performance improvement observed at pilot (Lafratta *et al.* 2020) and demonstration scales (Lafratta *et al.* 2021b).

Similarly, the stability parameters report a healthy status of the digesters, which does generally not affected by the demand-driven feeding regime. The main stability parameters considered in this study are pH, the ratio between volatile fatty acids (VFA) and the total alkalinity (TA) – also known as FOS/TAC (*Flüchtige Organische Säuren/Totales Anorganisches Carbonat*) ratio because of its equivalent definition in German – the ethanoic acid concentration and its ratio with the propanoic acid. These parameters and their reference ranges are described in detail by Lafratta *et al.* (2020). In particular, the VFA/TA ratio is well within its healthy range. However, the ratio between ethanoic and propanoic acids appears to be increasing as the 'peak load' volumes are increased in the different phases. This was not considered as an element of concern because of the relatively low concentration of these acids, and because the 'imbalance' was mainly observed during the peak time sampling when a minor imbalance is to be expected. The sampling immediately ahead of the daily peak-time period regularly reported values similar to the status observed during the pre-trial period.

The results of the application of the 'Periodic Feeding' AD model show that its predictions have medium accuracy, i.e., good qualitative agreement. However, this was deemed an adequate trade-off of having an advanced AD model supporting the trials with biogas production rate prediction timely available to inform decisions (i.e., only a few hours after the samples and data were collected). The main results are outlined in Table 4 and visualised in Figure 5. The biogas production rate, the volatile solid and the VFA concentrations in the outflow, and the volatile solid destruction provide the necessary information for the demand-driven control of the AD plant, as shown in Table 5.

Table 4 | Accuracy of the prediction by the 'Periodic Feeding' model, R^2_{rate} is the coefficient of determination, calculated over the initial 3 h after the peak-time feed and over the full period, and $\Delta_{\mathrm{TBP,3h}}$ is the difference of the total biogas production after 3 h after the peak-time feed and over the full period

	Weighted sum of squared errors (10^3 m^6/d^2)	$R^2_{\mathrm{rate,3h}}$(%)	$R^2_{\mathrm{rate},\tau}$(%)	$\overset{\S}{\Delta}_{\mathrm{TBP,3h}}$ (%)	$\overset{\S}{\Delta}_{\mathrm{TBP,24h}}$ (%)
Phase 2	15,128.30	64.5	69.6	-0.9 ± 4.9	-0.1 ± 7.3
Phase 3	10,229.35	69.3	69.7	-3.5 ± 4.8	2.3 ± 5.5

Additionally, the support provided by the 'Periodic Feeding' AD model has been instrumental to control the feeding regime and to inform the site operation team of the SCADA setpoints needed both during the trial and for subsequent implementation into business as usual. Figure 5 presents the biogas production rate and visualises the performance of the model during a similar period presented in Figure 4, however, in comparison to the DS fed. While the main control parameter was the hourly volume of sewage sludge fed (and, hence, the visualisation of the performance against this parameter), the amount of organic matter available drives the biogas production. The variability of DS justifies the variability in the biogas production rate in the period reported in Figures 4 and 5, which would not be justified by attempting to simply link volumes of sewage sludge fed with biogas production.

Considering the operational nature of the site used for the trials, several constraints for the scope of the trial were identified:

- The UK Government's response to the COVID-19 outbreak limited the number of commuters and this WWTP was affected by experiencing an increased load in comparison to its historic capacity.
- Because of the unavailability of one of the three primary digesters existing on-site, the OLR on the two in operation was high (average OLR = 4.0 ± 0.5 kg$_{\mathrm{VS}}$/m^3/d in the 4 months before the trial (Thames Water

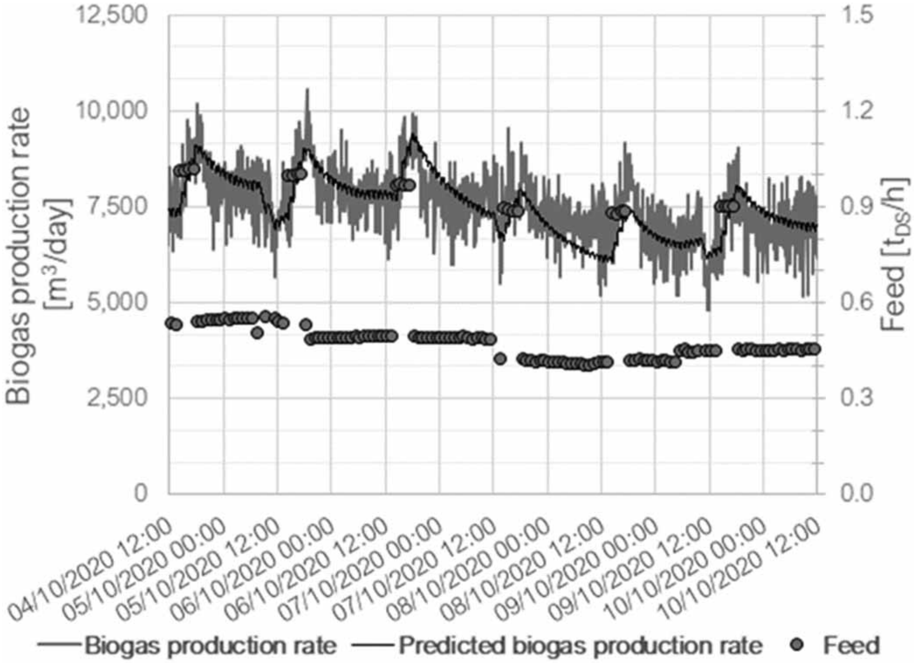

Figure 5 | Real and predicted biogas production rate and solid feed rate during Phase 3 of the full-scale trial under the demand-driven feeding regime.

Table 5 | Main operational parameters measured and predicted by the 'Periodic Feeding' model during the Phase 3 (*n* = 40)

	VS (%)	VFAs (mg/l)	Ethanoic acid (mg/l)	VSD (%)
Measured	2.73 ± 0.09	585 ± 49	78 ± 5	48 ± 3
Predicted	2.91 ± 0.12	616 ± 61	68 ± 11	44 ± 3

Utilities Ltd 2020)). Hence, the size of the additional feed for the peak load was limited. However, the success of the trial proves that the concept is valid even under a challenging operational condition.

- The two digesters are fed by the same pumping system and the pipework. While each digester is fed hourly, the feeding cycle is performed (and hence the feeding pump runs) half-hourly. Therefore, the additional volume of peak-time feed (defined by the pump running time) was limited by the start of the feed to the other digester (i.e., the maximum pump running time for each feed is 30 min).

Limitations to the implementation of demand-driven AD at minimal cost can be identified when

- Feeding pipework is shared among several digesters.
- A feeding pump is shared among several digesters, or its running speed and time are constrained.
- Ancillary assets to AD have limited spare capacity. For example, if sewage sludge or digester sludge holding tanks are designed with small volumes, or if other pre- or post-AD processes have limited capacity to vary the volumes they can process. In these cases, capital costs may be required in order to enable demand-driven AD feeding.

Additionally, in some cases, the management of heat production and use might possibly constitute an additional limitation or be of interest when heat is exported. For example, at the WWTP with the thermal hydrolysis process as a pre-treatment to AD in the advanced configuration, heat demand at the beginning of the peak time to process an increased volume of sewage sludge may be higher than the heat available from the CHP generation units, running with biogas produced in the 'base load'. However, this problem could be mitigated by increasing the CHP output ahead of the peak period and temporarily running down the amount of biogas stored.

In summary, demand-driven biogas production is proven as a feasible operational solution to maximise electricity generation at peak times. The limitations listed above could be easily overcome in order to capture the benefits of demand-driven biogas production in comparison, for example, to controlled biogas utilisation in

CHP engines by means of gas storage. While biogas storage can support flexible generation by storing biogas and hence making it available in peak time, it is costly to provide and its volume is limited due to explosive risk. In fact, safety regulations require risk management measures according to the volume of explosive material stored (such as The Control of Major Accident Hazards Regulations 2015 in the UK). Instead, demand-driven biogas production simply requires the storage of sewage sludge, which poses no real explosion hazard, while still allowing the production of biogas when needed. In this sense, demand-driven biogas production is complementary to biogas storage rather than mutually exclusive.

The permanent implementation of this operational solution at this WWTP shifted the generation of approximately 116 MWh in 1 year from the base load to peak time (Thames Water Utilities Ltd 2021). Based on the Great Britain electricity market analysis presented by Lafratta *et al.* (2021a), this equates to a saving to the national wholesale electricity market of an average GBP 5,150 and between 34 and 46 t_{CO2eq}. Significant larger operational cost savings were achieved by Thames Water by shifting the consumption of electricity to off-peak periods, thus avoiding the purchase of electricity and the payment of higher charges at peak times. However, as the operational carbon is accounted and reported based on yearly averages, no material carbon benefit could be claimed. Advanced carbon accounting methodologies could further incentivise good operational practices such as the one presented in this paper, for example, by using time- and/or location-based accounting.

CONCLUSIONS

The work presented in this paper completed the advancement of TRL of dynamic feeding of AD by proving its implementation in an operational environment at the full scale. The successful and seamless operation during the trial presented in this work led to the site to implement, in day-to-day operation, the dynamic and demand-driven feeding regime of the digesters. This represents the ultimate achievement of the experimental work of this research project, making an immediate impact on the daily operation of a WWTP.

The application of this operational solution shifted the generation of approximately 116 MWh in 1 year from the base load to peak time (Thames Water Utilities Ltd 2021).

Economic and environmental benefits suggested by the research are achievable in a live full-scale operational environment. From an economic perspective, dynamic feeding is financially beneficial, in particular when considered as an operational solution that may require minimal capital investment. For example, no capital investment was required for the application at the full scale presented in this paper. Other sites may require upgrades to ancillary equipment to the AD, such as additional pumps or reconfiguration of the feeding pipework. Additionally, flexible electricity generation increases financial resiliency by mitigating the risk of volatility of electricity prices. Finally, an environmental benefit of flexible electricity generation from sewage sludge lies in the potential contribution to reducing the carbon intensity of the services of the national electricity system to balance demand and supply in real time (i.e., balancing services) and of the grid at peak time, as it introduces a renewable generator into a market currently dominated by fossil-fuelled generators.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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