Energy aspects of wastewater management

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The Insights Series has been developed to highlight key findings arising from Energy Systems Integration Partnership Programme (ESIPP) research in decarbonised energy systems. These publications share new insights into various aspects of energy decarbonisation that have been gained from a multidisciplinary team of researchers in ESIPP from institutions across Ireland.

As the focus on the contribution of energy production to climate change increases, the need to identify opportunities for energy saving, energy generation and supporting the wider energy system become increasingly important. Wastewater treatment plants (WWTPs) account for a significant proportion of energy use in Ireland and globally. This research insight highlights opportunities for WWTPs to reduce energy consumption through demand response and showcase the role of data analytics to support decision making.

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Context

The Energy Systems Integration Partnership Programme (ESIPP) is a research programme, funded by Science Foundation Ireland, industry and philanthropy, and delivered by a multidisciplinary team of researchers from University College Dublin, Trinity College Dublin, NUI Galway, the Economic and Social Research Institute (ESRI) and Dublin City University. The research programme has three strands: (i) addressing operational and technical aspects of the network, (ii) identifying energy solutions for people in their homes and businesses, and (iii) informing energy policy and infrastructure investment to enable energy decarbonisation. One focus of research in ESIPP has been on methods to improve efficiency whilst reducing energy consumption and within wastewater management. These insights should provide insights to policymakers and industry stakeholders on future pathways to reduce the environmental impact of wastewater treatments.

Irish Water[1] achieved a 22.4% improvement in energy efficiency performance, the equivalent of saving over 51,000 tonnes of carbon by 2017 (Irish Water, 2018). To do this, Irish Water introduced a sustainable energy strategy to increase energy efficiency by 33% by 2020, which Ireland remains on track to meet (Irish Water, 2018). As a result, an additional target of a 50% increase in energy efficiency by 2030 has since been implemented which will see 75,000 tonnes of carbon avoided within the time frame (Coakley, 2020). Energy consumption per capita was an average of over 105 kWh on water and wastewater (Awe et al., 2016). This highlights that the water sector remains a resource intensive process in Ireland, utilising several inputs such as energy, chemicals and water which has the potential to generate greenhouse gas (GHG) emissions (Fitzsimons et al., 2016). Furthermore, as emission limits become more strict, the energy (and consumption of other resources) increases. Therefore a holistic approach is required to assess and balance the environmental impacts caused by these various contributions (wastewater effluent, energy consumption, chemicals) (Fitzsimons et al., 2016).

Wastewater treatment plants (WWTPs) can play a central role within the water-energy nexus as they consume large amounts of energy to remove pollutants and reduce environmental impact (Gu et al., 2016; Xu et al., 2017). Over the last few decades, wastewater treatment has aimed to improve sustainability through resource recovery and energy efficiency by providing flexibility and renewable energy production (heat recovery, biogas, incineration, micro-hydropower, power to methane) in the system.

Through environmental regulation, increased pressure is placed on WWTPs to enhance performance, often resulting in increased energy and chemical consumption (Puig et al., 2008). Wastewater infrastructure faces key challenges including demographic and economic growth, whilst mitigating climate change, meeting regulatory requirements and net zero-carbon targets in Ireland. The Urban Waste Water Treatment Directive focuses on urban wastewater, with Article 1 of the directive aiming for the '*collection, treatment and discharge of urban waste water and the treatment and discharge of wastewater from certain industrial sectors*' (European Commission, 2021). In addition, the EU Water Framework Directive (2000/60/EC) commits EU member states to aim for a 'good status' for all ground and surface waters (rivers, lakes, transitional waters, and coastal waters). This directive is

[1] A utility company introduced in Ireland by the Irish Government as a result of the Water Services Act (2013) to provide safe, clean and wastewater services to water users in Ireland (Irish Water, 2021).

the key driver for discharge limits in most WWTPs (See **Figure 1**) (McNamara et al., 2017). These laws are hoped to attain the required level of water quality set out in the act including: emissions from energy production and ecotoxicity from sludge application to land (McNamara et al., 2017).

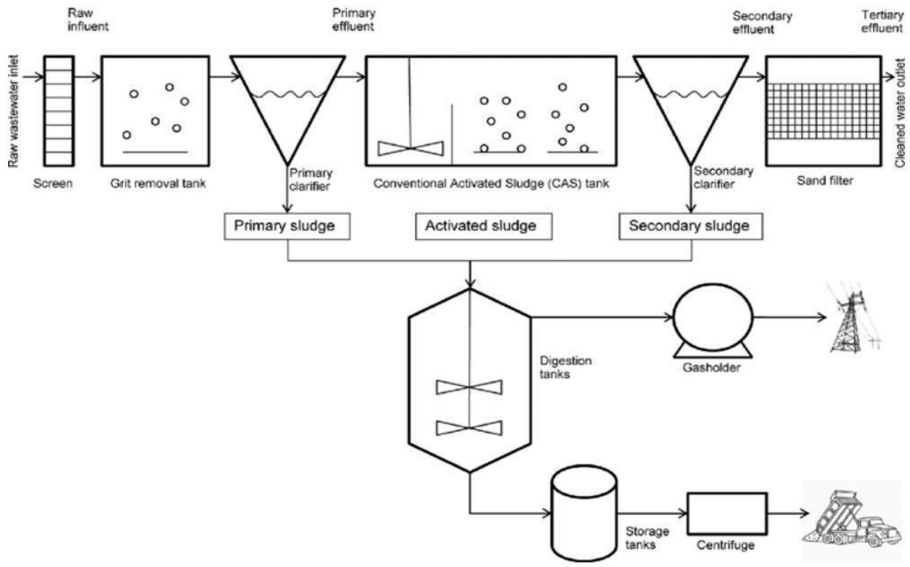

Figure 1: Typical wastewater treatment plant processes with sand filtration as an example of tertiary treatment (Source Berthod et al., 2016).

Through a clear connection between resource consumption and WWTP performance, benchmarking strategy can be used to assess resource consumption, whilst evaluating WWTP performance (Doherty et al., 2017). Without intervention, WWTPs will become more resource intensive as they strive to meet environmental regulations (Doherty et al., 2017). Over time, the wastewater treatment industry has created several methods to improve the energy efficiency (Ho et al., 2014). There are also opportunities for WWTP to provide demand response to the electricity system which can provide a revenue stream to the WWTP owners/operators while also providing system services and flexibility to the electricity system, enabling the integration of higher levels or renewable energy.

Research in ESIPP focuses on some of the energy aspects of WWTPs including the implementation of demand response and improving the energy efficiencies of the processes used while ensuring environmental standards for effluent quality are maintained.

Implementation of demand response in wastewater treatment plants

Due to the variability in energy supply from renewables within the energy generation mix, smarter consumption of electricity on both the grid and consumer side are necessary (O'Connell et al., 2014). Power systems with inflexible generation and a high share of variable renewable (wind and solar) technologies provide a significant potential for demand response (Kirchem et al., 2020). Inflexible generation refers to the systems capability to accommodate variation within the net-load through variability in electricity and demand side generation (Ahmadiahangar et al., 2020). For example, factors that impact renewables such as wind speed or global irradiance leading to the electricity supply not being constant (McPherson and Stoll, 2020).

Demand response refers to one side of demand side management (DSM), specifically the adjustment of end-user behaviour to reduce/shift electricity consumption in relation to energy availability and price (Liu et al., 2021). It can provide multiple benefits to the operating system and economic efficiency, while simultaneously reducing system marginal cost variability (Liu et al., 2021). Through the use of a time-based pricing structure, (e.g. time-of-use tariffs, peak demand charging, real-time pricing, and extreme day pricing), demand response can be introduced to customers (Liu et al., 2021). By incentivising large energy users, through subsidies and enabled by smart meter data, to shift demand consumption away from peak times when electricity prices are highest, electricity demand and costs can be reduced (Palensky and Dietrich, 2011).

Demand response has the potential to be used in wastewater treatment as significant energy is required for pumping and aeration (Kirchem et al., 2020). The distribution of electricity consumption within WWTPs varies depending on the size of the plant, nutrient removal technologies, discharge standards and indented end-use of the effluent (Kirchem et al., 2020; Liu et al., 2021). Most electricity used within WWTPs is required for the aeration in the activated sludge process and the wastewater pumping, ranging from between 10.2% to 71% of total electricity consumption (Kirchem et al., 2020). Depending on the topology of the plant, the inflow pumps consume up to 15% (Kirchem et al., 2020).

Demand response has the potential to reduce peak demand whilst simultaneously providing knock-on benefits to the grid in the form of demand shaping and load flexibility (Liu et al., 2021). DSM in WWTPs can reduce forecasting errors, flexibility and ensure efficient and secure power system operation. WWTP operators may have concerns about DR actions on effluent quality, therefore optimizing the energy cost is necessary (Liu et al., 2021).

ESIPP research in demand response

Demand response modelling

Demand Response (DR) models can be grouped into two categories. Firstly, energy system models which focus on the system perspectives of the optimal utilisation of DR and secondly, processing schedule models which are used to analyse DR strategies for the end user (Kirchem et al., 2020). Analysis using a sector-integrating energy system model to represent the wastewater treatment process and power system dynamics does not yet exist. This is because there is limited literature addressing DR models within the energy-water-nexus. However, existing models often over or underestimate the available DR potential from an industrial end user for two main reasons (Kirchem et al., 2020). Firstly, the interaction between power system operation and industrial process operation caused by DR is not taken into account. Second, models abstract from critical physical process constraints affecting the DR potential. Several case studies have been used to help indicate the potential for WWTPs to provide DR, however no studies acknowledge the endogeneity of energy prices which arises from a large-scale utilisation of DR (Kirchem et al., 2020). Therefore, wastewater treatment process related constraints should be applied to an integrated energy systems model.

Scheduling strategies for demand response

Understanding the energy flexibility within a WWTP through a controlled scheduling of sludge processing reject water under long-term, plant-wide and dynamic context, is important when evaluating energy cost and control strategies (se**e Figure 2)** (Liu et al., 2021). Reject water scheduling strategies, without other active controls (e.g. aeration), demonstrated a 63.4% average peak demand mitigation and €10,755 cumulative annual energy cost savings on a 100k population equivalent WWTP without a deterioration in effluent quality (Liu et al., 2021). This demonstrates the importance of DR in saving electricity demands and costs. Analysis of different reject water scheduling control strategies demonstrated that reject water scheduling can be an effective tool for energy cost optimisation under alternative electricity tariff structures (Liu et al., 2021).

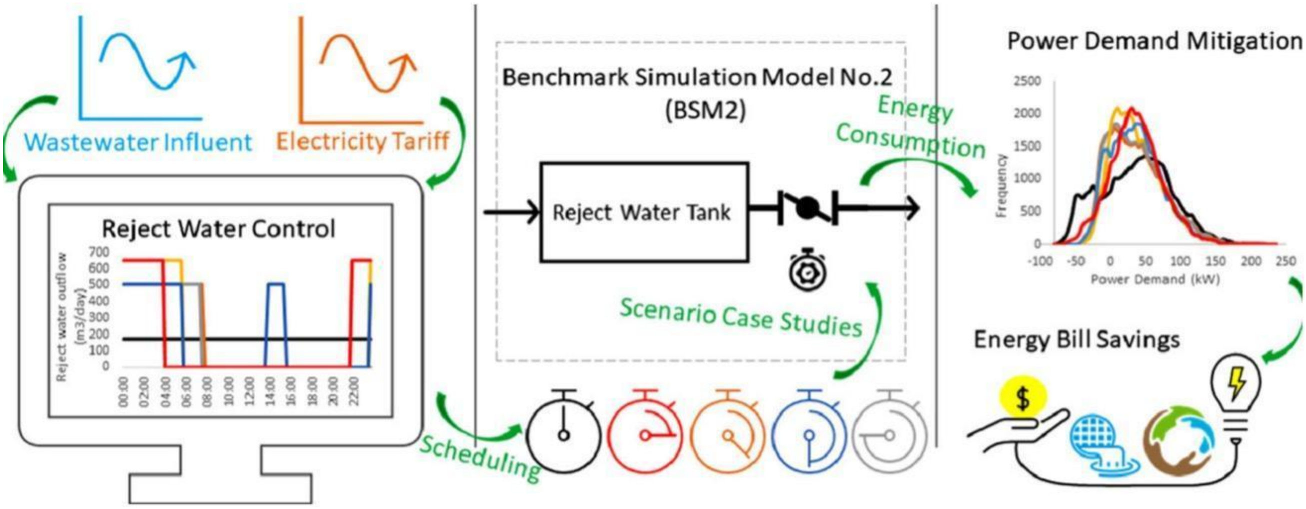

Figure 2: Demand response through reject water scheduling in water resource recovery facilitates (Source: Liu et al., 2021).

Demand shedding opportunities

Demand shedding through aeration control, subject to maintaining the plant operational limits, could have a large impact on the WWTP DR potential (Giberti et al., 2020). Decreasing aeration has, however, the potential to promote the settling of particulate components present in the reactor mixed liquor (Giberti et al., 2020). Simulations that neglect this particulate settling can underestimate DR impact on the effluent quality, predicting lower ammonia concentrations. A model that includes this phenomenon was proposed, generating more realistic trends for the biological processes kinetics as well as for the total suspended solids concentration within the aeration tank, in the secondary clarifier and in the effluent. This research is ongoing and the model still needs to be calibrated and validated against real data. For this purpose, sensors for the sludge blanket depth and the total suspended solids concentration in the stream that leaves the aerated tank would be necessary, together with the possibility of operating the aeration system intermittently.

Leachate co-treatment

Leachate is an extremely polluted wastewater which is primarily generated through the seepage of rainwater through waste piles. As this permeates downward, organic and inorganic compounds dissolve and present in the waste and leaches as a complex wastewater (Dereli et al., 2020c). Leachate composition varies widely depending on various characteristics including climate, waste characteristics and landfill operation. Leachate has to be collected and properly treated to minimise negative impact on surface and ground water sources as it has the potential to be generated several decades after the closure of landfill sites (Renou et al., 2008).

Changes in landfill management, brought by the EU directives, have resulted in a decrease in the volume of leachate produced per tonne of waste landfilled and increased leachate strength (Brennan et al., 2017; Brennan et al., 2016). For example, a study in Ireland stated that whilst young landfills accounts for less than 50% of total leachate by volume, they do account for 70% of the total annual leachate chemical oxygen demand load and approximately 80% of total five-day biochemical oxygen demand and NH_4-N loads (Brennan et al., 2017, 2016).

Leachate can be treated by using on-site and off-site plants. Combined leachate treatment at municipal WWTPs is pertinent depending on the leachate composition, treatment plant configuration and capacity (Dereli et al., 2020c). Furthermore, increased carbon and ammonium loading from leachate can have significant impacts on electricity usage due to increased aeration requirements in a municipal WWTP practicing co-treatment (Dereli et al., 2020c).

ESIPP research on leachate co-treatment

Although leachete co-treatment has been practiced all over the world for many years, there were no review papers in literature that critically discuss the pros and cons of combined treatment of leachate with municipal wastewater. Dereli et al. (2020a) reviewed the processes and technologies used for leachate co-treatment and its implications for municipal WWTP performance for the first time.

Methods for co-treatment

Due to the changing characteristics of leachate and stringent discharge limits in WWTPs, different methods for the co-treatment of leachate in WWTPs have been implemented (Dereli et al., 2020a). This includes traditional aerobic and anaerobic processes and emerging technologies (e.g. anaerobic and aerobic membrane bioreactors, aerobic granular sludge systems, partial nitrification and anammox, membrane aerated biofilm reactor). In order to remove the emerging contaminants from leachate, additional processes are required which may be costly, for example, activated carbon adsorption, advanced oxidation and membrane filtration (Dereli et al., 2020a). However, implementing new technologies in WWTPs has the potential to bring several opportunities such as higher nitrogen removal efficiency, better micropollutant removal, reduced energy demand through more advanced aeration methods whilst enhancing energy efficiency, increased resilience against toxicity shocks and cost effectiveness for leachate co-treatment (Dereli et al., 2020a). These all have potential to improve the efficiency of wastewater treatments.

Co-treatment of leachate is expected to decrease, especially in high income countries due to changes in solid waste management, leachate characteristics and stringent discharge standards. However, it will still be practiced where funds are limited therefore implementing emerging technologies may balance costs and treatment efficiency. Therefore future studies should consider how the implementation of these processes can reduce costs for widespread implementation.

Leachate feeding strategies

Developing smarter leachate feeding strategies, under a realistic time of use energy prices (municipal wastewater loads and electricity prices), costs of WWTPs can be reduced (Dereli et al., 2020b). A combined leachate treatment resulted in deterioration in the quality of discharged wastewater with a 12-20% increase in the effluent quality index (Dereli et al., 2020b). Furthermore, it adversely affected the aeration energy demand and cost of the plant by increasing them by 1.7-2.3% and 0.8-2.5%, respectively (Dereli et al., 2020b). Therefore leachate co-treatment could be used to mitigate by adjusting leachate flow based on effluent ammonium concentrations and by using advanced process control i.e. feedback ammonium control for dissolved oxygen regulation in aerobic reactors.

Data driven models for energy systems integration of WWTPs

Without intervention, WWTPs could become resource intensive, therefore it is important to understand the tools and methods used to measure wastewater resource efficiency in a standardised and efficient manner (Doherty et al., 2017). Current systems offer detailed analysis of many aspects of wastewater treatment, however, do not assess the accuracy of the data used for performance assessment. Therefore WWTPs must enhance performance due to the stringent environmental regulations with data availability and accuracy restricting the success of the benchmarking.

Influent flow and load forecasting for demand side management of WWTPs

Unlike most industrial processes, which rely on a supply of raw materials with strictly regulated and consistent quality, a WWTP needs the ability to deal with an influent that is highly dynamic (Olsson, 2012). In fact, from a control system perspective, the influent variations can be considered as one of the disturbances that affect the process, both in terms of effluent quality and energy consumption.

The ability to forecast key features of a wastewater treatment plant influent such as its flowrate and the pollutant loads is therefore a useful tool to inform and advise the plant operation. This is especially important for the exploitation of the plant flexibility in the context of demand response (DR) programmes. The knowledge of the future plant loading conditions can allow for more accurate estimates of the effects that a certain DR strategy will have on the quality of the effluent, which remains of the utmost importance. For instance, operational strategies that are aimed at the temporary reduction of the plant energy consumption may be advised against in case the plant is expected to receive large quantities of pollutants, and vice-versa.

While, in principle, it should be possible to build deterministic models of the catchments, the high number of variables and parameters involved would make their calibration particularly complex. For this reason, data driven models that only necessitate historical data are gaining relevance to address the forecasting problem. In particular, autoregressive moving average (ARMA) models and machine learning techniques such as neural networks can be used to generate the forecasts (Li et al., 2019; Boyd, et al., 2019) .

This research focuses on the calibration of different data driven models to generate hourly forecasts that are then implemented into a rule-based control system that adjusts the plant operation (e.g. aeration intensity) based on the future loading conditions and electricity price.

Key insights and application

The presented research highlights that the motivation behind implementation of emerging wastewater treatment technologies include: energy efficiency, water reuse and material recovery initiatives, the need for the removal of emerging pollutants and mitigating GHG emissions of WWTPs (Dereli et al., 2020a).

Increasingly stringent WWTP emission limits represent a significant pressure on WWTPs in terms of energy use and material recovery. In this context, modelling can act as an important tool to develop smart control strategies in line with energy system integration concepts. For example, a number of methods to aid management of nitrogen rich streams (e.g. leachate, sludge processing reject water) have the potential to improve energy recovery and efficiency (Dereli et al., 2020a) because treating these effluents during off-peak hours has the potential to reduce energy costs but also complies with discharge limits (Dereli et al., 2020b). However, a majority of these studies still need to be calibrated and validated against real data. Therefore including site-specific experiments may be necessary to determine appropriate results.

Wastewater treatment remains an energy-intensive process, therefore a coordinated DR programme for WWTPs could have a significant potential to reduce demand on the power system. By time-varying the electricity rates, plant operators can achieve electricity costs savings. By introducing schemes like time-of-use tariffs and offering lower electricity rates during off-peak hours, whilst simultaneously penalising high electricity consumption during peak hours with higher rates, operators can shift to low cost alternatives. As Ireland continues to transition towards low carbon energy, the need for flexibility within the energy market is also likely to increase. Therefore WWTPs need to take advantage of the opportunities for DR and seek to expand their use. In this context, emerging research areas such as the increased use of data-driven models, artificial intelligence, Internet of Things and Digital Twins will support decision making, minimise costs and improve efficiency in wastewater management.

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