Water Research 220 (2022) 118673

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Where is the greatest potential for resource recovery in wastewater treatment plants?

D. Renfrew [a], V. Vasilaki [a], A. McLeod [b], A. Lake [b], S. Danishvar [c], E. Katsou [a,*]

[a] Department of Civil & Environmental Engineering, Institute of Environment, Health and Societies, Brunel University London, Uxbridge Campus, Middlesex, UB8 3PH, Uxbridge, UK

[b] Jacobs Engineering Group Inc. 2nd Floor Cottons Centre, Cottons Lane, London, SE1 2QG, England

[c] Digital Manufacturing Centre at College of Engineering, Design and Physical Sciences, Brunel University London, Uxbridge Campus, Middlesex, UB8 3PH, Uxbridge, UK

ARTICLE INFO

Keywords:
Resource recovery
Circular economy
Multi-criteria analysis
Wastewater treatment
Global sensitivity analysis

ABSTRACT

The restorative and regenerative ability of the circular economy has led to the rapid growth of this concept over the past decade, as it facilitates the broadly adopted principles of sustainable development and beyond, through restorative and regenerative actions. The water sector is poised to benefit from this transition, due to its intrinsic circularity and the resources it handles, predominantly found in wastewater, that are valuable and critical. Currently, the vast range of resource recovery technologies coupled with few industrial examples hinder strategic decision making. Resource recovery on a regional scale improves market share and mitigates investment risk, therefore, a structured approach has been developed for the selection of priority technologies to act as a guide for strategic planning. A representative UK wastewater model acts as the baseline, with multi-criteria analysis used to select resources and create an enhanced resource recovery scenario. It was found that implementing the recovery of 5 'priority resources' (and technology pathways) increased nitrogen and phosphorus recovery by 68% and 71%, respectively. Lastly, the need for a cross-cutting approach for the holistic assessment of circular solutions is discussed.

1. Introduction

As governments implement ambitious targets to curb the anthropogenic impact of climate change, industrial practices must change in tandem. It has been recognised that further action is needed to ensure planetary health, which has led to the rapid growth of the circular economy (CE) concept over the past decade (Kirchherr et al., 2017). The Ellen MacArthur Foundation define the CE as "*one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles*" (Ellen MacArthur Foundation, 2015). CE practices are linked with achieving many Sustainable Development Goals, facilitating sustainable development (Panchal et al., 2021) and beyond, by actively restoring and regenerating material and energy cycles (Jazbec et al., 2020). The water sector is uniquely poised for this transition, due to its intrinsic circularity and the environmental, economic and social value of capturing the resources it handles (Mihelcic et al., 2017).

The water sector handles an array of resources, predominantly found in wastewater, that are valuable and critical, bestowing opportunities for revenue generation and diversification. Resources recovered from wastewater fall into many categories such as water, energy, biofuels, fertilisers and biopolymers (Kehrein et al., 2020a), some of which are becoming increasingly scarce due to growing global population and urbanisation (Dagilienė et al., 2021). Investment in resource recovery infrastructure enables water utilities to realise benefits that reach far beyond revenue generation. Resource recovery is intrinsically linked to sustainable and circular practices such as process intensification, resource circularity and waste valorisation, which can reduce plant footprint, improve operating costs, increase energy efficiency, reduce negative externalities and offset the carbon footprint of wastewater treatment facilities (Coma et al., 2017; Gherghel et al., 2019; Kehrein et al., 2020a; Ruiken et al., 2013).

These prospective benefits have resulted in extensive work in recent decades, by both academia and industry, to develop technologies that shift the focus of wastewater treatment plants from pollutant removal to resource recovery facilities (Kehrein et al., 2020a). This has resulted in a multitude of technological options for the extraction of resources from wastewater, providing water utilities with ample choice along the entire

* Corresponding author.
E-mail address: evina.katsou@brunel.ac.uk (E. Katsou).

https://doi.org/10.1016/j.watres.2022.118673
Received 23 November 2021; Received in revised form 28 April 2022; Accepted 23 May 2022
Available online 25 May 2022

treatment pathway for plant design and process retrofitting (Kehrein et al., 2020c). However, decision makers must consider trade-offs between the benefits of selected technologies and the potential impacts when identifying which resources to target for recovery. Furthermore, on a practical level plant operators have limited experience in innovative resource recovery technologies, with few full-scale examples of evidence-based assessments for process optimisation. The latter, creates challenges for selection of priority resource recovery technologies and strategic planning, especially whenever necessary factors such as cost, risk, and market potential need to be incorporated into decision making.

With the current emphasis placed on resource recovery and circularity, there seems to be disproportionately few methods, or examples of evaluating the resource recovery alternatives in wastewater treatments plants (WWTPs) to support decision making (Chrispim et al., 2020). Efforts to systematically investigate the resource recovery potential of WWTPs focus on site-specific assessments. For instance, Kehrein et al. (2020c) developed a framework for strategic planning and process design of water resource factories (SPPD-WRF). The SPPD-WRF aims to integrate resource recovery metrics in the site-specific design of treatment processes, thereby making resource recovery a measurable process design objective on a plant scale (Kehrein et al., 2020c). Similarly, the framework developed and implemented by Chrispim et al. (2020) at a large WWTP in Sao Paulo, focused on site-specific evaluation of resource recovery technologies through energy, water and nutrient recovery analysis, whilst considering the broader influences of market demand, legislation, technological options, and stakeholders.

The identification of resource recovery alternatives on a regional/sectoral level gives water utilities the ability to improve market share, mitigating some investment risk, and enables strategic planning of circular solutions by the water sector. A study in Scotland aimed to quantify available resources and estimate their commercial value in wastewater (CREW, 2018). The authors achieved this valuation, alongside estimations of potential carbon savings, but provided no methodology to support decision making for optimising resource recovery strategies on this scale, whilst considering wider impacts. There are studies which advocate for the wider assessment of resource recovery scenarios; however, poor data availability, costs and design complexity is restricting the use of integrated approaches for effective decision making (Kehrein et al., 2020a, 2020c; van der Hoek et al., 2018). Therefore, there is a need for a structured approach to support decision-making by assessing resource recovery potential from wastewater on a regional scale, to select appropriate technologies for a given scenario.

Given that water utilities monitor material and energy flows, there is data available for measuring their current position within the CE, and monitoring and/or estimating the potential of the water sector's transition as circular strategies are adopted, such as resource recovery. This work aims to detail an approach for supporting water utility companies through planning and identification of strategies for resource recovery from wastewater on a regional scale.

2. Methodology

The structured approach proposed for the identification of resource recovery strategies on a regional scale is detailed in Fig. 1. It starts with understanding the baseline scenario through construction of a system model, which is crucial as it enables performance improvements to be benchmarked. This is achieved through material flow analysis (MFA) and substance flow analysis (SFA). Next, a combination of market analysis and multi-criteria analysis (MCA) are used to rank and select resource recovery options. A long list of resources (with associated technology pathways) has been developed based on previous studies in literature (UKWIR (Aunon et al., 2015) and CREW (CREW, 2018)), and shortlisted using technology readiness level (TRL). The 'priority resources' are identified by scoring shortlisted resources using a range of criteria such as cost, carbon, and treatment impacts. Altering criteria weighting, permits the investigation of how future scenarios (i.e. prioritizing carbon impacts) can affect the priority resources. The selected resource recovery options are implemented within the model to create an updated 'resource recovery scenario' to understand the improvements achieved by retrofitting the technologies. Lastly, a six capitals approach is discussed as part of the need for a holistic value assessment, for strategic planning of resource recovery technologies.

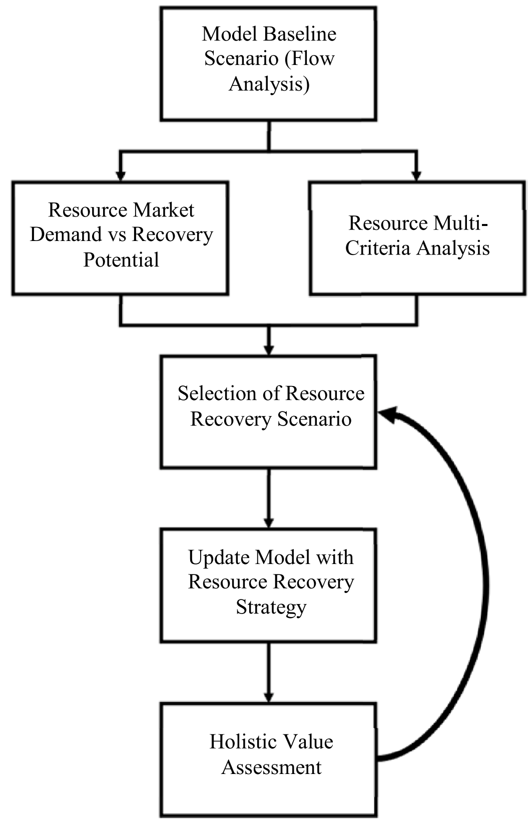

Fig. 1. Steps of the structured approach developed for selecting regional resource recovery strategies.

2.1. Baseline scenario model

The first step is to establish a baseline scenario model for benchmarking purposes, to allow the gains made by implementation of resource recovery technologies to be investigated. MFA and SFA are conducted to identify unnecessary waste of natural resources, energy and materials along process chains as suggested by the OECD (2008). This information is used for the investigation of resource recovery strategies.

To improve understanding of the approach presented in this work, the UK wastewater sector was used as an example. A mass balance to represent the UK wastewater sector was constructed together with MFA (chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), volatile suspended solids (VSS), water) and SFA (nitrogen (N), phosphorus (P), organic carbon (OC)). Input data for the mass balance model was taken from publicly available databases and literature for the year 2018/19 for England and Wales including: population equivalent (PE) served, flow handled (facilities PE $>$ 25,000), sludge composition, type of wastewater treatment and sludge management processes (European Environmental Agency, 2018; OFWAT, 2019; Smyth et al., 2021) (Northern Irish and Scottish flows were calculated from reported PE and typical wastewater production per capita from literature). The 2018/19 operating year was chosen as this is the most recent price reporting year for OFWAT (PR19). Standard wastewater loadings were used, with removal efficiencies and kinetic parameters taken from literature (Tchobanoglous et al., 2014).

This information was combined to produce a representation of the UK wastewater sector, which is visualised in Fig. 2 and displays system boundaries. The UK wastewater treatment sector was represented using eight wastewater treatment methods, six sludge treatment options and three types of solids disposal. The wastewater pathways are as follows: conventional activated sludge (CAS) with preanoxic zone (A), trickling filter (TF) (B), phosphorus removal (assumed to be chemical) (C), disinfection (D), postanoxic denitrification (E) and phosphorus removal and postanoxic denitrification (F). The fraction of influent wastewater handled by each treatment pathway is: A 44%, B 4%, A + C 31%, A + D 13%, B + C 3%, B + D 3%, B + E 1%, and B + F 1%. Finally, 99.2% of influent wastewater is discharged from the process. The sludge treatment and disposal pathways are as follows: primary sludge (1), waste activated sludge (2), advanced anaerobic digestion (AAD) (assumed thermal hydrolysis (TH) pretreatment) (3), anaerobic digestion (AD) (4), liming (5), incineration (ash landfilled) (6), composting (7), land reclamation (8), farmland application (9) and landfill (10). Sludge production is split: 61% primary and 39% waste activated sludge. The fractions of sludge sent to each treatment system are: 52% AAD, 34% AD, 3% liming, 7% incineration, and 0.1% composting (the remaining 4% is untreated). Finally, sludge disposal fractions for each method are: 3% land reclamation, 95% farmland application, and 2% landfill. The values and parameters used for the construction of the mass balance model are summarised in Tables S1-S3 (supplementary material).

2.2. Market potential analysis

This section describes the methodology followed for the estimation of the market potential of recovered resources for the UK market. The market potential of a product reveals the extent to which it can fulfil the current market needs. It therefore indicates the potential demand for recovered resources, and in the context of this work, highlights the position of wastewater resources within the circular economy on a regional scale. If the potential market penetration is low, then the potential uptake of a new product or feedstock is less likely. Thereby, it is important to understand the market potential of resources available in wastewater before significant investments are made. Kehrein et al. (2020a) published a critical review of technologies available to recover resources from municipal WWTPs and calculated the market potentials for the Netherlands and Flanders (Belgium). Each resource was considered independently, so the market potential represents the maximum resource recovery that could be achieved under ideal circumstances using appropriate technologies. This includes the calculation of the absolute market potentials, meaning additional aspects such as market viability, incentives and regulations were not considered. The market potential calculation by Kehrein et al. (2020a) was performed, alongside a review of recovery technologies and bottlenecks, to inform decision makers on the resources in wastewater. Here it is used as the basis to analyse the attractiveness of UK wastewater resources in terms of their potential market demand and goes further by integrating the results in a category of the MCA for the selection of priority resources.

The market potential is found by calculating the total amount of a product that can be recovered from wastewater compared to the total market demand for that product. The market demand for each resource was taken from relevant governmental and industrial reports, with values chosen as close to the modelled time period as possible (2018/19) (Agricultural Industries Confederation, 2021; AHDB, 2019; Alberici et al., 2017; Baumann and Westermann, 2016; Department for Business Energy and Industrial Strategy, 2020; Department for Environment Food and Rural Affairs, 2018; Department for Transport, 2020; Eurostat, 2019; Grand View Research, 2021; Mineral Products Association, 2018). The resources chosen for this analysis were a combination of those shortlisted for MCA (based on TRL) and those from the assessment by Kehrein et al. (2020a) to enable comparisons between the UK and Netherlands/Belgium for validation of results. The next stage was to establish the amount of recoverable resources from UK wastewater streams. The total resources handled were calculated utilising the wastewater loads from the mass balance model and reported sludge production (OFWAT, 2019). Removal efficiencies from literature were applied to calculate the fraction of each resource that could potentially be recovered (Kehrein et al., 2020a; Mills, 2016; Organics Group, 2020; Palmieri et al., 2019; Soares et al., 2021; Tchobanoglous et al., 2014) and are summarised in Table S5 (supplementary material).

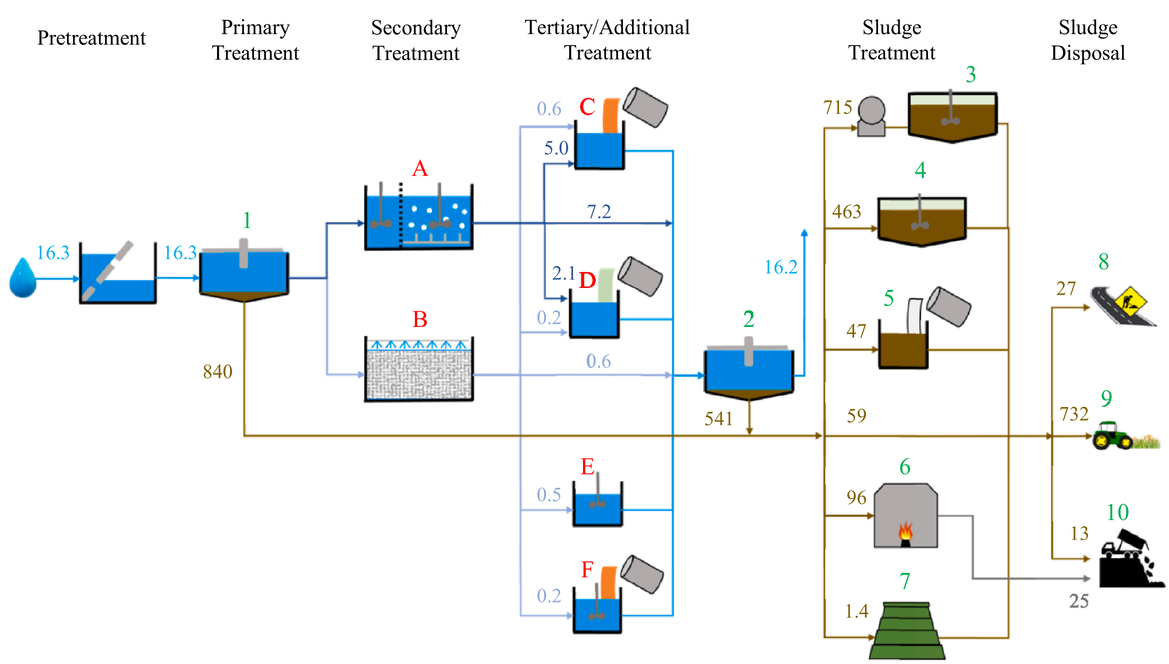

Fig. 2. Representation of the UK wastewater system mass balance model. The wastewater line is coloured blue and treatment systems are labelled A-F with flowrates in Mm^3/d. The sludge line is coloured brown, and treatment and disposal systems labelled 1–10 with sludge flowrates in ttDS/a.

2.3. Multi-criteria technology selection

This section explains the approach followed in the MCA for the identification of the 'priority resources' considering different scenarios. The MCA methodology was developed as part of a project commissioned by UK Water Industry Research (UKWIR) to understand the greatest sustainable economic benefit for resource recovery from the water cycle (UKWIR, 2021). The MCA was used to assess the resource recovery opportunities in the UK wastewater sector.

Initially the selected categories for the MCA were recovery potential, market potential, treatment impacts, cost, and carbon impacts. The criteria were chosen to establish how technologies would impact business goals of water utility companies. Additional criteria were also included in the MCA to align with UK water utilities who are increasingly adopting the capitals concept for holistic value assessment of their systems to maximise stakeholder benefits, as evidenced by their inclusion in the total value and impact assessment by Yorkshire Water (2018). Capitals are used to broaden the scope of assessments for decision making, by recognising the effects businesses have on a system and monetising their impacts. Environmental, human, social, natural, intellectual, financial, and relationship capitals have been linked with, and can be seen as an extension of sustainability pillars by water utilities. To reflect this, and provide a holistic assessment of recovered resources, the MCA incorporates the 6 capitals listed, alongside the initial assessment categories.

2.3.1. Scoring

A long list of resources was drawn from previous work by UKWIR (Aunon et al., 2015) and CREW (CREW, 2018). A discussion on the resource recovery technologies analysed in this study is provided in Section 3 of the supplementary material. The resource recovery technologies were shortlisted by assessing the TRL. The in-house experience and industrial knowledge of Jacobs Engineering Group Inc. was used to evaluate resource recovery technologies and determine a near term resources shortlist (and technology pathway), by screening opportunities with TRL $>$ 7 (*system prototype demonstration in operational environment)* (UKWIR, 2021). Some longlisted resources were considered unlikely to be near term despite their associated processes attaining TRL 7 or above, and not included in the shortlisted resources. This resulted in a shortlist of 13 relevant resource recovery opportunities and associated technology pathways which are given in Table 1.

Once shortlisted, a semi-quantitative scoring system between 1 (lowest) and 5 (highest) was applied to the chosen criteria which evaluate aspects of economically sustainable resource recovery (scoring criteria guidance provided in Table S6 of supplementary material). Scores for each technology were decided using in-house expertise of Jacobs Engineering Group Inc. (UKWIR, 2021) with exception of the market potential, which utilises the results calculated in Section 2.2.

Table 1
Shortlisted resources and associated recovery technologies.

Shortlisted Resource	Recovery Technology
Biochar	Advanced Thermal Treatment (AAT) – pyrolysis or gasification
Biogas	AAD – enzymatic or thermal hydrolysis
Biogas	Co-digestion
Biosolids	AAD, Advanced Dewatering, Biodrying
Biomethane	Membrane/Water Scrubbing
Biopolymers	Aerobic Granular Sludge (AGS) Extracellular Polymeric Substances (EPS)
Fats, Oils, Grease (FOG)	Dissolved Air Flotation
Grit	Pretreatment Removal
Heat	Effluent Heat Pumps
Hydrogen	Reverse Osmosis (RO) and Effluent Electrolysis
Nitrogen	Air/Thermal Stripping of Sludge Liquors
Phosphorus	Struvite Precipitation
Syngas	AAT – pyrolysis or gasification

2.3.2. Scenario analysis

To investigate the sensitivity of the recovery options to future scenarios, criteria weightings were applied to reflect the possibility of short-term changes to the status quo in areas of compliance, carbon, and resource efficiency legislation (UKWIR, 2021). The results were used to calculate a final average score (and ranking) for resource recovery strategies by considering sensitivity to the following scenarios:

- **Status quo** – business as usual which focusses on viable markets for recovered resources, cost of implementation, impacts on treatment capacity and resulting compliance.
- **Emissions compliance** – focuses on water and air emissions which drives treatment of final effluent and intermittent discharges to more stringent standards and improved environmental/social outcomes.
- **Carbon reduction** – assumes companies have carbon related targets for operational and embodied carbon which mandate reduction in carbon sources and creation of carbon sinks (increased sequestration).
- **Resource max** – assumes numerical targets and metrics aligned with resource recovery; resource efficiency and principles of the waste hierarchy and circular economy are applied with focus on sustainable resource recovery, minimisation of waste and keeping resources in use at maximum value.

The scenarios and weightings presented have been constructed by industrial experts. Full explanation of technology scoring and scenario weighting can be found in Tables S7-S9 (supplementary material).

2.3.3. Global sensitivity analysis

Global sensitivity analysis (GSA) was conducted, to improve the understanding of which criteria and scenario weights have the most significant influence on the final scores achieved, and therefore the final resource ranking. GSA assesses the impact that varying model inputs, within a specified range, has on output results. For GSA the range of variable inputs are all considered simultaneously (Sarrazin et al., 2016). Sobol' sensitivity analysis was applied; the Sobol sequence is a quasi-random, low-discrepancy sequence used to generate uniform samples of parameter space (Sobol′, 2001). The Sobol' scheme is extended with Saltelli's sampling scheme (Saltelli, 2002) from SAlib Python package (Herman and Usher, 2017) to reduce error in the resulting sensitivities. Sobol (variance based) GSA was run for 414,000 iterations on each resource, with bounds allowing input fluctuations of $\pm$10% to calculate the sensitivity of input parameters (MCA criteria scores and scenario weightings) on MCA output results (Sobol′, 2001). The sensitivity of resources to each criterion is presented as the sensitivity index, with the sum of indices equalling 1. The greater the sensitivity index of a given criterion, the greater influence it has on the final score of each resource and therefore ranking.

2.3.4. Priority resource selection

The average score achieved across the 4 investigated scenarios was used to create a final ranking, with the top 5 identified as 'priority resources'. An interaction matrix was constructed to show how each of the priority resources can be combined with the other shortlisted technologies to create integrated resource recovery strategies. Case studies focusing on the recovery of priority resources were used to understand additional resource recovery opportunities that could be exploited. These were divided into technologies which are required as part of the process for priority resource capture (x), as well as other strategies with the potential to enhance system performance (xx). This produces integrated resource recovery schemes that focus on the best performing resources for a given scenario, additional resources that can be captured, and potential process enhancements. To decide the final strategy, treatment methods from the original mass balance model are compared with resource recovery schemes to evaluate potential performance.

2.4. Evaluation of resource recovery scenario

Following the provision of five priority resources (and their associated technology pathway) to target within the studied UK example, the baseline scenario was updated accordingly to estimate the potential gains in nutrient recovery. MFA and SFA of the updated resource recovery scenario model show how nutrients flow around the new system, enabling comparisons to be drawn in terms of nutrient recovery and revealing the enhancements of implementing resource recovery technologies. When creating the resource recovery scenario, it is important to remain realistic in terms of application of the priority resources and technologies. For example, even though AGS systems may improve resource recovery (EPS and struvite recovery), it is not reasonable to consider that all WWTPs will utilise this technology. Therefore, a more pragmatic and representative approach is to target systems that already have P removal, due to the phosphorous accumulating properties of AGS systems.

3. Results and discussion

3.1. Baseline scenario material and substance flow analysis

This section shows the results of the baseline UK model. In the UK, 5946 Mm^3/a of wastewater is handled, 1.38 MtDS/a of sludge is produced, and 0.77 MtDS/a of treated solids are disposed. The results of the MFA and SFA were used to construct Sankey diagrams, which are shown in Fig. 3. Sankey diagrams are commonly utilised to summarise flow analysis as they enable the viewer to be exposed to not only how materials flow around a system but also the magnitude of these flows, as the width of the flow is proportional to its magnitude. Sankey diagrams were generated using Microsoft Power BI software (Microsoft Corporation, 2014).

Secondary/tertiary treatment nutrient assimilation and effluent discharge are significant hotspots of the system, where large fractions of nutrients are lost. Of the total influent N and P, it was calculated that 8% and 25% are currently recycled through farmland application, respectively, which occurs due to 95% of biosolids being recycled to farmland during the year studied. This high fraction is due to the fact that all of the reported sludge treatment methods comply with the Biosolids Assurance Scheme (BAS). The BAS aligns practices with government strategies for

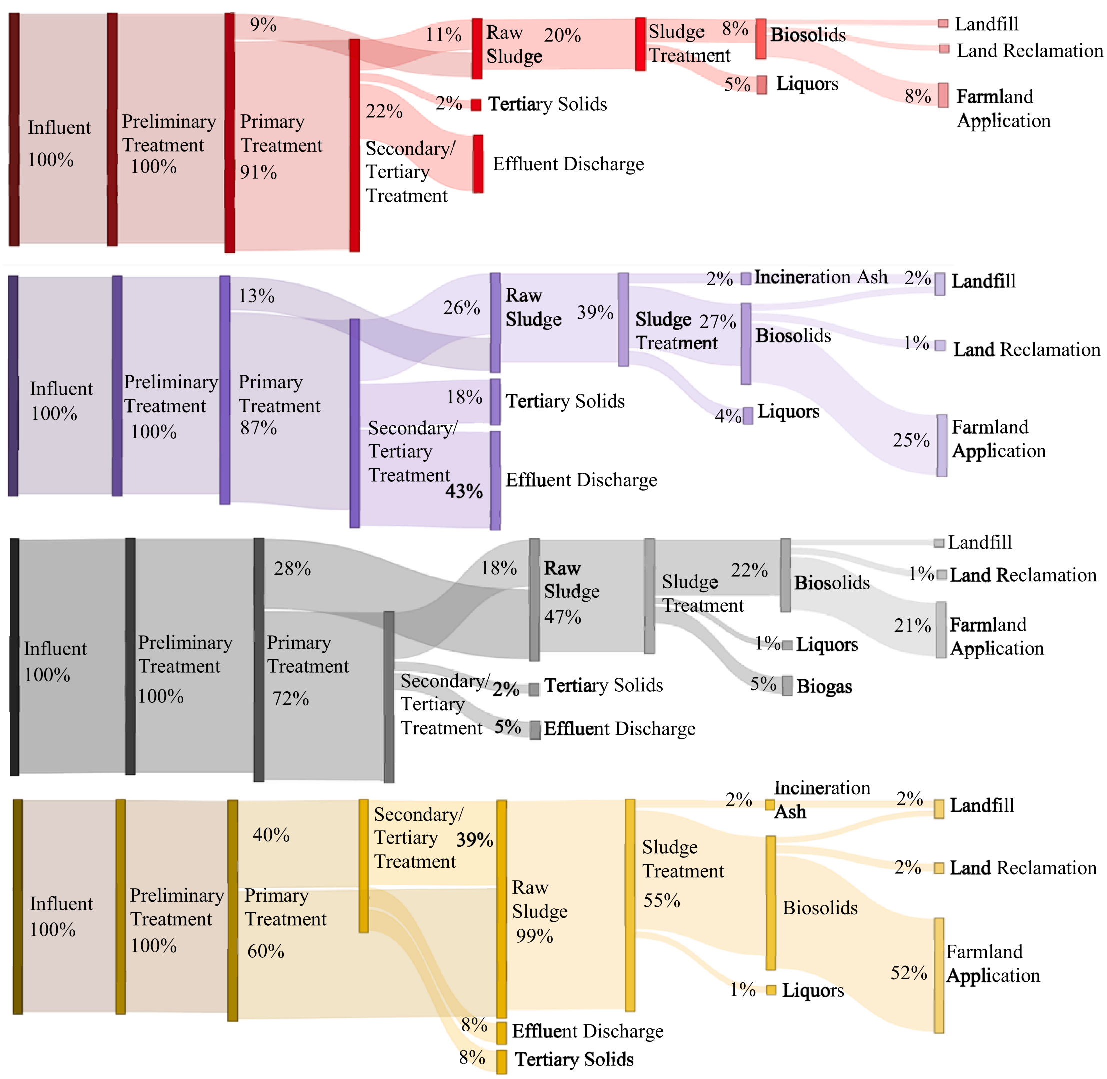

Fig. 3. Sankey diagrams representing the flow of substances through a model of the UK wastewater system. The results of SFA are shown here for nitrogen (red), phosphorus (purple), organic carbon (grey) and total suspended solids (yellow). The percentage of influent nutrients present in each flow are given, any flows with <1% are not labelled.

beneficial use of sludge (Biosolids Assurance Scheme 2020). Although, low nutrient recovery rates suggest that using biosolids in this way might not be the optimal method for recovery in the current scenario. Of influent OC, 26% was recovered through farmland application and biogas production. It should be noted that the percentages quoted, are the total quantity of nutrients applied to farmland, as the availability of N and P to the next crop yield are 15% and 50%, respectively for biosolids application (AHDB, 2019). This means that not all nutrients will be usefully recycled during the year of application. The modelling of N recovery in Amsterdam-West WWTP (1,014,000 PE) estimates that 11% is recovered when 100% of digested sludge is applied to land (van der Hoek et al., 2018). This is comparable with the model's estimate, considering that not all sludge is digested or applied to land. MFA and SFA of the UK example reveal that a large fraction of nutrients in wastewater nutrients are not recovered; this does mean there is significant scope for improvement through implementation of resource recovery technologies.

3.2. Market potential analysis

Market potentials for UK wastewater resources are summarised in Table 2. The market potential reveals the UK market demand for the resources studied, the quantity of resources that are potentially recoverable, and the ratio of these values.

Table 2 shows that technology for the production of fuels and subsequent energy and electricity generation (whether gasification, AAD or anaerobic membrane bioreactors (AnMBR)) can substitute little more than 1% of UK demand. However, the water sector consumes approximately 3% of UK energy so there is potential to move towards improved sector self-sufficiency (Majid et al., 2020). Grit recovery has limited market potential, meaning sustainable disposal (e.g. land reclamation) may be more appropriate rather than marketing it as a valuable product.

Cellulose, single cell proteins (SCP), biochar, volatile fatty acids (VFAs), struvite and biosolids (NP) have theoretical market potentials between 4% and 24%. Therefore, it has been shown that these resources can substitute a significant fraction of the current market, meaning there should be a demand from businesses to utilise them as feedstocks.

Water reuse (ultrafiltration (UF), micro filtration (MF) and RO), CO_2 generation, heat recovery, phosphorus recovery (sludge), propionate and hydrogen production have market potentials greater than 25%. This shows that wastewater can provide a significant fraction of the current market demand, creating attractive opportunities to improve the sustainability of some industrially useful feedstocks. It was shown that large scale polyhydroxyalkanoates (PHA) and EPS production may in fact

Table 2
Summary of UK resource market demand, recoverable quantity of resources and resource market potential.

UK Market Potential of UK Water Resources Resource Demand	Demand	Unit	Resource Recovered	Recovery	Unit	Market Potential
Water (total abstraction)	12,341.9	M m^3/a	Water (total content)	5887.0	M m^3/a	**47.7%**
			Water (MF-UF)	5004.0	M m^3/a	**40.5%**
			Water (MF-UF/RO)	3753.0	M m^3/a	**30.4%**
Water (public supply)	5639.1	M m^3/a	Water (total content)	5887.0	M m^3/a	**104.4%**
			Water (MF-UF)	5004.0	M m^3/a	**88.7%**
			Water (MF-UF/RO)	3753.0	M m^3/a	**66.6%**
Energy (Natural Gas)	3158.0	PJ/a	CH_4 (from COD AD)	32.5	PJ/a	**1.0%**
Electricity Consumption	1244.1	PJ/a	Electricity CH_4 (CHP)	12.3	PJ/a	**1.0%**
			Electricity (sludge co-combustion)	3.9	PJ/a	**0.3%**
Derived Heat Consumption	150.1	PJ/a	Heat CH_4 (CHP)	13.0	PJ/a	**8.7%**
			Effluent Heat (heat pump)	123.0	PJ/a	**82.0%**
Cellulose (paper production)	3851.0	kt/a	Influent Cellulose	567.5	kt/a	**14.7%**
			Co-combustion Energy	7.8	PJ/a	**0.2%**
			Electricity (cellulose co-combustion)	2.3	PJ/a	**0.2%**
			Heat (cellulose co-combustion)	3.9	PJ/a	**2.6%**
CO2 consumption	450.0	kt/a	CO_2 from Biogas (sludge AD)	178.1	kt/a	**39.6%**
			CO_2 from Biogas (influent COD)	964.5	kt/a	**214.3%**
Nitrogen (Mineral Fertiliser - farm application)	1038.0	kt/a	Influent N	236.9	kt/a	**22.8%**
			Raw Sludge N	53.2	kt/a	**5.1%**
			Raw Sludge Biodrying	37.3	kt/a	**3.6%**
			Biosolids N	42.1	kt/a	**4.1%**
Ammonia			N Fertiliser	10.9	kt/a	**1.1%**
Phosphorous (Mineral Fertiliser - farm application)	81.3	kt/a	Influent P	45.2	kt/a	**55.6%**
			Struvite P	15.8	kt/a	**19.5%**
			Raw Sludge P	26.2	kt/a	**32.2%**
			Recoverable P (Wet Chem)	23.6	kt/a	**29.0%**
			Biosolids P	18.4	kt/a	**22.6%**
AnMBR			CH_4 (AnMBR + AAD)	16.2	PJ/a	**0.5%**
			Electricity from CH_4 (CHP)	6.1	PJ/a	**0.5%**
			Heat from CH_4 (CHP)	6.5	PJ/a	**4.3%**
Gasification (Syngas)			Energy (Syngas)	24.5	PJ/a	**0.8%**
			Electricity (CHP)	9.3	PJ/a	**0.7%**
			Heat (CHP)	9.8	PJ/a	**6.5%**
Soil Conditioner	1805.0	kt/a	Biochar (pyrolysis)	319.1	kt/a	**17.7%**
Grit	61,700.0	kt/a	Grit Removal	307.3	kt/a	**0.5%**
UK HGV Transport	17.4	bvm	Electrolysis of 0.32% Effluent	17.4	bvm	**100%**
UK HGV Sludge Transport	5.9	mvm	Electrolysis of 0.00011% Effluent	5.9	mvm	**100%**
Animal Feed N	222.1	kt/a	Influent N	236.9	kt/a	**106.7%**
			SCP (AD digestate)	53.2	kt/a	**24.0%**
Global Market Potential of UK Water Resources						
Resource Demand	**Demand**	**Unit**	**Resource Recovered**	**Recovery**	**Unit**	**Market Potential**
VFA (Acetate)	16,000.0	kt/a	Acetate Recovery	483.8	kt/a	**3.0%**
VFA (Propionate)	380.0	kt/a	Propionate Recovery	219.9	kt/a	**57.9%**
VFA (Butyrate)	500.0	kt/a	Butyrate Recovery	100.0	kt/a	**20.0%**
PHA	35.9	kt/a	PHA Recovery	319.8	kt/a	**891.3%**
Alginate	43.0	kt/a	EPS (from sludge)	226.2	kt/a	**525.6%**

saturate markets, however, demand for these biopolymers is growing (Grand View Research, 2021). Due to its energy density the market potential of hydrogen was studied by calculating the fraction of wastewater effluent that must be electrolysed to fulfil fuel demands of heavy goods vehicles (HGV). It was shown that only 0.0001% of effluent should undergo electrolysis to supply all HGV miles, 5.9 mvm (million vehicle miles), required for sludge transportation.

The market potentials calculated in Table 2 are in agreement with those calculated by Kehrein et al. (2020a), as the trends and magnitudes are similar to those seen for the Netherlands and Belgium. The calculation of UK market potentials in this study gives an example of how to provide quantitative results to feed the MCA scoring whenever data is readily available, rather than relying exclusively on qualitative criteria. The results can also be used as a validation of selected priority resources as they have been calculated considering data that is specific to the UK scenario.

3.3. Multi-criteria analysis

3.3.1. Scoring and investigation of future scenarios

This section discusses the results from the MCA considering both the unweighted scores and the weighted scores for the investigation of potential future scenarios. The unweighted scores for each resource are highlighted in Fig. 4, revealing the individual scoring for each category. When each category is given equal weighting, the total scores range from the lowest of 19 (FOG) to the highest of 32 (heat from heat pumps), out of a maximum of 40.

Results from the application of criteria weightings to study the impact of potential future scenarios to the ranking of technologies are summarised in Fig. 5. The final scores were calculated by averaging the weighted scores for each resource across the four scenarios. This revealed after weighting, that again heat recovery through utilisation of heat pumps was ranked highest, and FOG recovery the lowest. The resources that experienced the greatest range over the scenarios were hydrogen, syngas (AAT), and biogas (co-digestion). Currently hydrogen generation requires large inputs of electrical energy so may be limited if strict emissions limits were implemented, but it performs strongly in terms of recovery and market potential. Although the carbon benefits and recovery potential for syngas are high, undesirable cost and market potential (for energy generation) results in large fluctuations between scenarios. At present co-digestion is not a viable recovery option in the UK due to regulatory limits, however, any updates to facilitate its implementation would result in enhanced generation of biogas, meaning its use is uncertain.

3.4. Global sensitivity analysis

This section summarises the results of the GSA completed for the scoring of shortlisted resources, to investigate the impact of uncertainties in the scenario weightings and criteria scores. Fig. 6A shows the results of the GSA conducted on MCA scores. The greater the sensitivity index, the greater the influence that a specific MCA criterion score or the weightings of a potential future scenario has on the final score of a technology. Regarding the MCA categories, carbon has the largest influence on seven out of the thirteen shortlisted resources, followed by market potential and treatment impacts with the largest influence on three resources each. When considering only the potential future scenarios, scoring was most sensitive to carbon reduction measures, which may be due to the fact that circular solutions are seen as an important route to carbon neutrality for the water sector. The final score of the technologies had the lowest sensitivity to human and intellectual capital, shown to have the lowest influence for ten of the thirteen shortlisted resources. This criterion had the lowest weighting for all four scenarios investigated and there was little variation in awarded scores. As more emphasis is placed on maximising the 6 capitals, it is likely that greater focus will be placed on these criteria by businesses in the future.

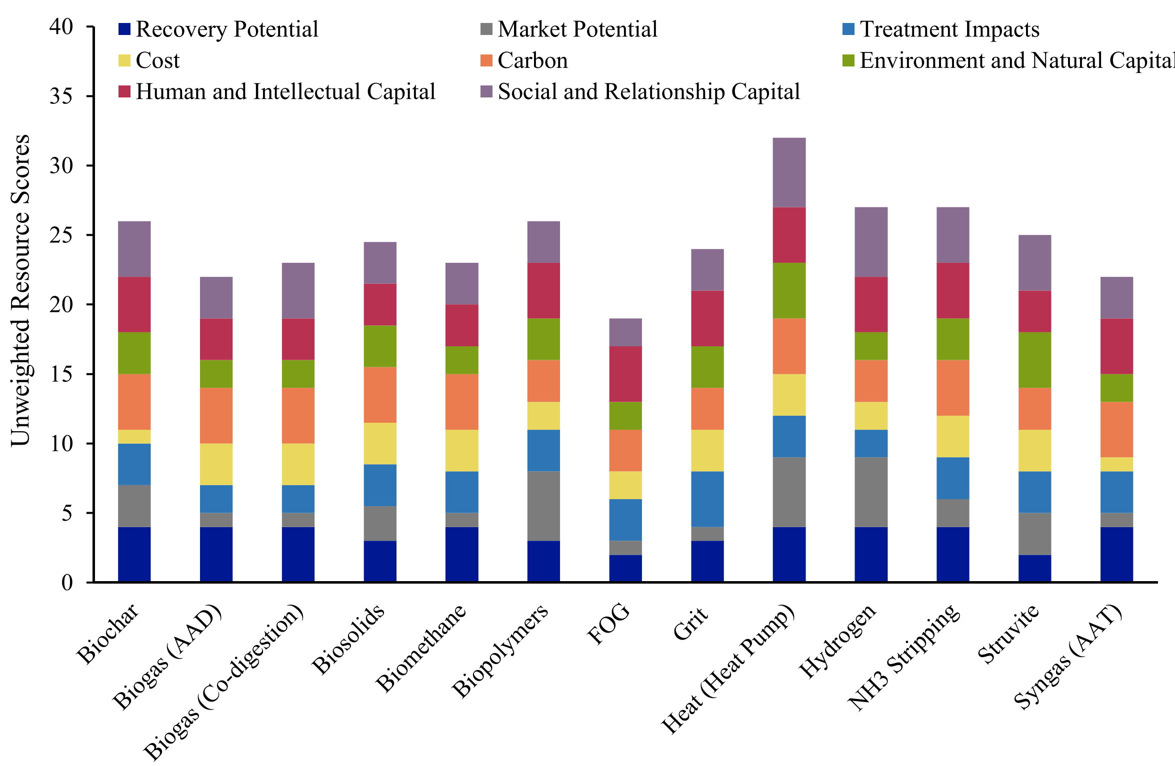

Fig. 4. Unweighted assessment criteria scores for shortlisted, near-term resource recovery opportunities from UK wastewater.

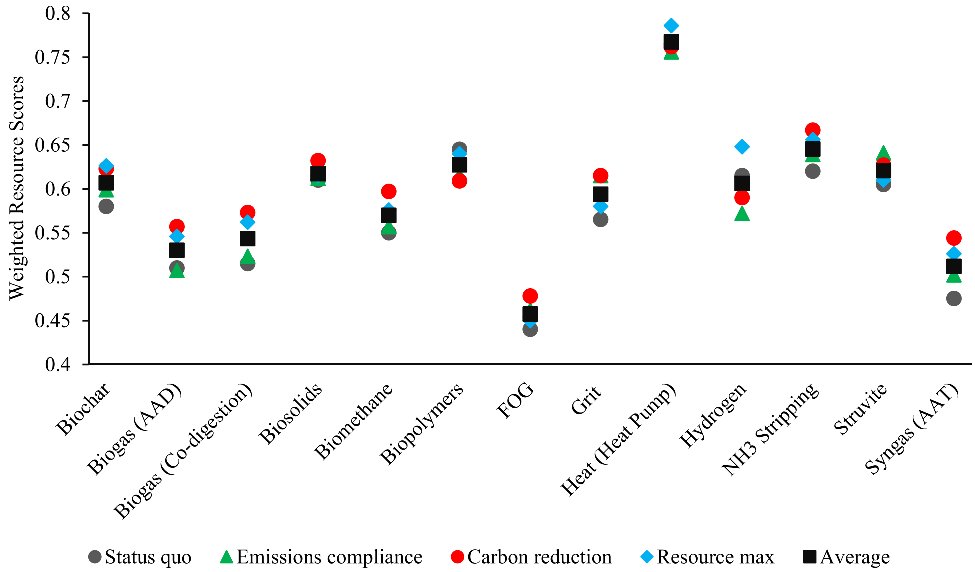

Fig. 5. Sensitivity analysis results from the application of 4 potential future scenarios through assessment criteria weighting: status quo, emissions reduction, resource max and carbon reduction (based on the figure in report by UKWIR (2021)).

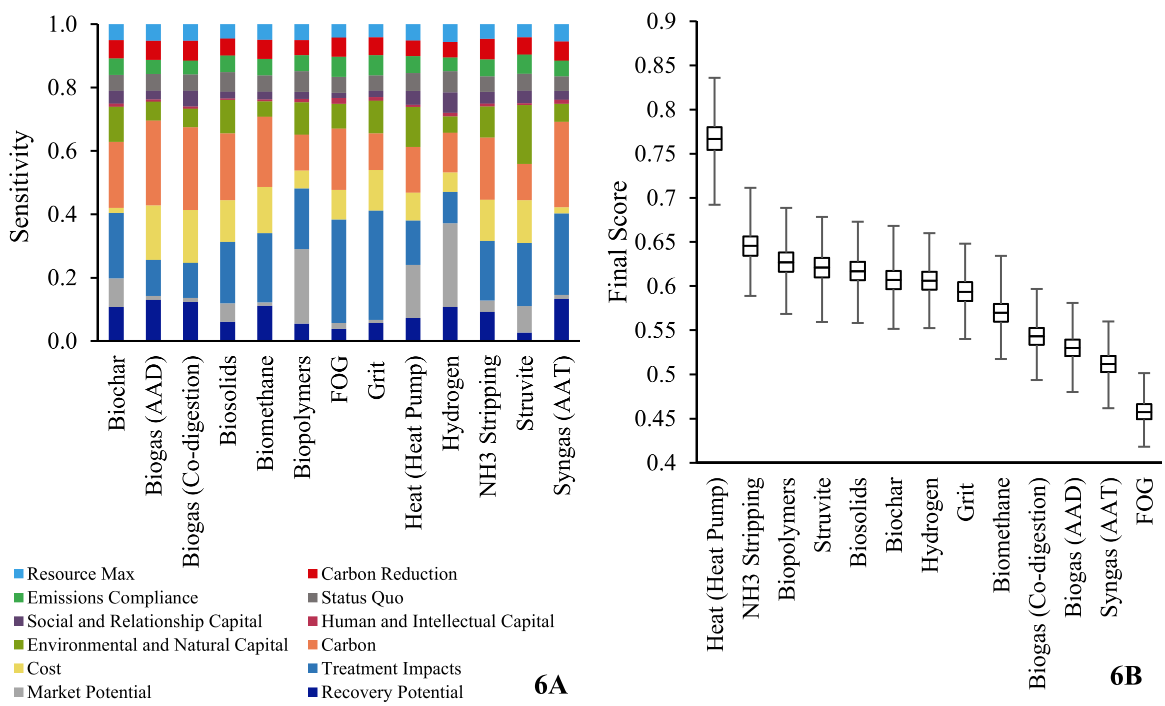

Fig. 6. A. Results of the global sensitivity analysis conducted on MCA inputs (criteria scoring and scenario weightings) showing their influence on resource ranking scores. Fig. 6B. Box plots of the final scores over the 414,000 iterations completed during GSA.

Box plots have been drawn in Fig. 6B to reveal the variance exhibited by each resource and its associated technology across all iterations of the GSA. The resources are ordered in terms of median scores, and heat recovery is the top performer, as even the minimum score recorded for heat is higher than the median score of any other. After heat recovery, the scores plateau somewhat, until biomethane where there is a decline which reveals that selection of methods for the recovery of chemical energy may not be favourable. Comparing resources by applying this method helps to ensure robust selection of resources, as it confirms the top ranked options perform well over a range of conditions and should be resilient to system changes and scoring uncertainty.

3.5. Priority resource selection

The investigation of different scenarios and GSA enabled the ranking of the different technologies. The final average values were used to rank wastewater resources and the top 5 are highlighted as 'priority resources', which are heat (heat pumps), ammonia (stripping), biopolymers (EPS), struvite, and biosolids. These are deemed priority resources as they have performed best across the multiple objectives of the MCA, as well as showing resilience and consistency to potential future influences, and are summarised in Fig. 7. Three of the priority resources align with the five resources with the greatest market

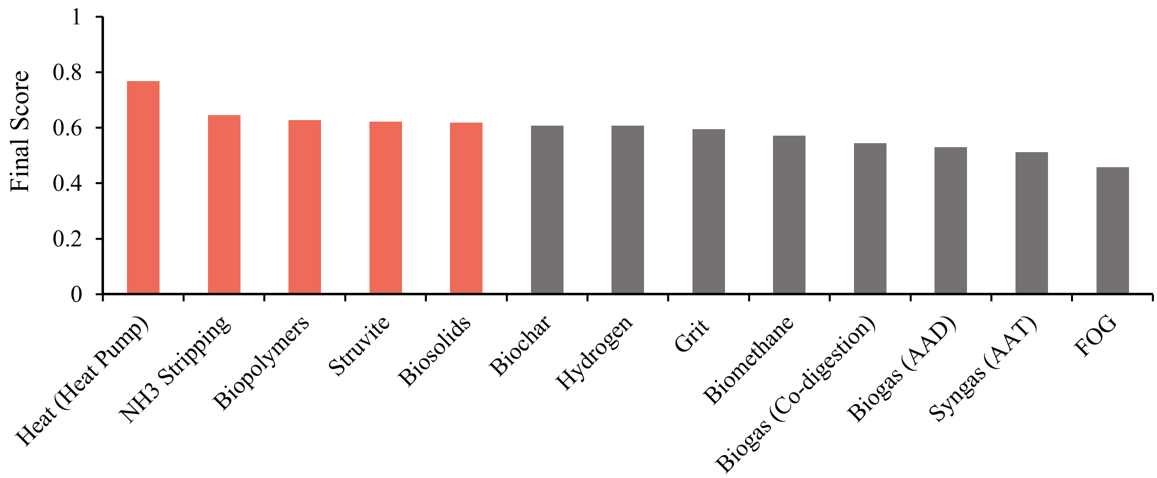

Fig. 7. Wastewater resources score ranking with 5 top performing resources highlighted in red.

potentials calculated by Kehrein et al. (2020), which are EPS, heat and biosolids (Kehrein et al., 2020a). A report for Scotland also names heat recovery via heat pumps as a resource with significant potential and concludes that biopolymer resources are promising in terms of recovery and market value (CREW, 2018). The comparison in Fig. 5 provides confidence that even if the analysed system experiences changes, then selected resources should still perform effectively, therefore, supporting the robustness of priority resource selection. Fig. 6B further supports this selection by revealing the extent to which uncertainty in scoring influences technology ranking, as priority resources still outperform the others over the range investigated during GSA.

3.6. Resource recovery scenario results

This section discusses the results from the implementation of the integrated resource recovery scenario within the UK wastewater example. The resource recovery scenario is developed from the selected priority resources and the results of MFA indicate the gains in terms of nutrient recovery compared with the baseline scenario.

3.6.1. Resource recovery scenario development

Potential integrated resource recovery scenarios are discussed in this section and shown in the interaction matrix (Table 3). Realistic scenarios for integration of resource recovery solutions were identified based on the results of the MCA, revealing how recovering priority resources can be coupled with technologies for co-production of other shortlisted resources (maximizing resource recovery efficiency) based on case studies (Biosys, 2021; CENTRISYS-CNP, 2021; Kehrein et al., 2020b; Severn Trent, 2021; The Royal Borough of Kingston Upon Thames, 2021) and literature (Gherghel et al., 2019; Kehrein et al., 2020a).

Table 3
Matrix identifying which resources are currently integrated in case studies of priority resource recovery (x), and others that enhance recovery in terms of yield or energy efficiency (xx).

Resources	Priority Resource Recovery Schemes Heat (Heat Pump)	NH3 Stripping	Biopolymers	Struvite	Biosolids
Heat (Heat Pump)	x	xx	xx	xx	xx
Hydrogen					
NH_3 (Stripping)		x			
Biopolymers			x		
Biochar					
Biosolids	xx	x	x	x	x
Struvite			x	x	
Grit					
Biogas (Co-digestion)		xx		xx	xx
Biomethane					
Syngas (AAT)					
Biogas (AAD)	xx	x	x	x	x
FOG					xx

The combination of priority resource recovery with additional technologies for the creation of an integrated scenario is discussed in the following paragraphs. This part of the assessment is necessary as it enables the construction of an appropriate integrated system of technologies that is representative of specific cases.

Heat pumps that capture heat from effluent streams have highly generic applications, so could be potentially integrated with most shortlisted resources. Processes for biogas and biosolids have been highlighted to potentially enhance heat recovery efficiency as they can be exploited for on-site heating. This is due to barriers such as heat losses encountered by exporting heat and the infrastructure costs associated, so usage on site is preferred to maximise recovery (Nagpal et al., 2021). On-site recovery could be used for heating process units (biological treatment, AD processes for biogas generation) or applied for advanced biosolids treatment, including biodrying and dewatering applications (Kehrein et al., 2020a).

Ammonia stripping has been shown to be more efficient (in terms of energy and recovery) when conducted on digestate or digester reject liquors, as they are highly concentrated with nitrogen (van der Hoek et al., 2018). Therefore, systems that employ this ammonia recovery strategy will have anaerobic digestion on site, producing biogas and biosolids. Additionally, to enhance performance of the ammonia recovery system, co-digestion could be considered to increase the nutrient concentration of digester streams (Montusiewicz and Lebiocka, 2011) (although co-digestion is currently prohibited in UK). Ammonia can be directly combusted to generate energy or used to produce fertiliser and although processes that utilise it for energy recovery tend to consume more energy than is recovered, and barriers such as low production rates and high cost compared with industrial fertilisers limit uptake (Kehrein et al., 2020a).

Biopolymers (EPS) are present in the solid fraction produced from AGS systems. Enhanced biological nutrient removal occurs due to the presence of phosphate accumulating organisms in AGS systems, therefore, after EPS extraction phosphorus can be recovered as struvite (Kehrein et al., 2020b). Controlled release of the accumulated phosphorus requires subjecting sludge to anaerobic conditions, so AD can be used to simultaneously produce biogas and biosolids. TH may help disrupt the large flocs/granules produced during AGS treatment enhancing yields. Establishing an integrated scenario will improve the viability of this resource recovery scheme as currently the EPS market still needs to be fully established due to the high cost of production (Tavares Ferreira et al., 2021).

Struvite recovery, via controlled precipitation, captures phosphorus and nitrogen from concentrated streams after sludge digestion where nutrients have been solubilised. Therefore, biogas and biosolids production is a prerequisite of this recovery scheme. Struvite production is limited compared with industrial fertilisers due to the scale of viable plants, maintenance costs and issues with product quality (Ghosh et al., 2019). To enhance the degree of struvite recovery, co-digestion could be utilised to increase nutrient load of digester streams, and renewable heat recovered via heat pumps employed for various on-site applications.

Biosolids are produced from AD systems and this resource is currently widely adopted by the UK water sector. However in the UK, The Sludge (Use in Agriculture) Regulations must be adhered to before application of sewage sludge to land, which specifies the of type of activity and contaminant limits that must be met (Public Health England and Wales and Public Health Scotland, 1989). Additionally, the introduction of new legislation may impact the practicalities of spreading biosolids produced from sewage sludge (Severn Trent, 2021). There are many ways to integrate other resource recovery practices to enhance biosolids generation, such as using heat pumps to generate renewable energy to support heating required for sludge digestion. Co-digestion of sewage sludge and municipal solid waste has been successfully exploited across Europe, in countries including Denmark, Germany and Switzerland, to improve biosolids nutrient loading and biogas yields (Cavinato et al., 2013). Regulatory issues prohibit co-digestion in the UK as it makes the process complex and expensive, specifically around the use of food waste where Animal By-Product Regulations mitigate the digestates scope within The Sludge (Use in Agriculture) Regulations (CIWEM, 2011). In Europe there are no such issues, with slaughtered animals that were fit for consumption requiring only a simple, thermal sanitation step before AD (Holm-Nielsen et al., 2009).

Based on this analysis, an integrated system for the recovery of priority resources, and co-production of additional resources, can be created using appropriate technologies for the specific case analysed. Treatment trains representative of the existing UK asset base from the baseline model were compared with technologies required for the recovery of priority resources to decide on the final integrated resource recovery scenario. It was shown that the priority resource recovery pathways require, and are even enhanced by, the integration of AAD for the production of biosolids and biogas, therefore the scenario integrated within the baseline model is as follows:

- Treatment trains with P removal are replaced with AGS processes for EPS and struvite recovery
- Addition of NH_3 stripping to remaining (non-AGS sludge treatment) AD systems
- Addition of TH pretreatment to remaining (non-AGS sludge treatment) AD systems
- Resultant biosolids utilised for farmland application
- Thermal energy generation from heat pumps on effluent streams is compared with chemical energy from biogas

3.6.2. *Resource recovery scenario material and substance flow analysis results*

In this section, the resultant scenario provided in Section 3.4.1 is implemented within the baseline model to quantify the impacts of the implementing resource recovery technologies. The CAS and TF treatment schemes with P removal (34% of total flow) were replaced by AGS systems, which produce additional EPS and struvite resources. Reported data from a full scale Nereda® granular sludge plant in Garmerwolde, Netherlands (Pronk et al., 2015) was used to model the AGS process. Sludge, struvite, EPS, and biogas production rates were taken from literature (Guo et al., 2020; Kehrein et al., 2020b). TH units were integrated with AD processes used to treat the sludge produced by the remaining system to enhance biogas production and bioavailability of nutrients (Morgan-Sagastume et al., 2011). Thermally driven ammonia stripping was implemented on the concentrated liquor streams of the AAD systems to enhance nitrogen recovery (Organics Group, 2020). The quantity of energy from biogas production is compared with the potential of heat pumps on effluent streams for energy recovery. The parameters used for these calculations are summarised in Table S4 (supplementary material).

The reconfigured model favouring resource recovery practices was used to conduct MFA and SFA to investigate the degree to which nutrient recovery is improved. This resulted in decreased sludge (1.13 MDS/a) and biosolids (0.66 MDS/a) production, which is influenced by the relatively low generation by AGS systems. Fig. 8 shows the results of the MFA and SFA for the updated resource recovery scenario. The influence of focussing on resource recovery is shown in Fig. 8 by the greater variety of product streams generated, such as EPS, struvite, and ammonia.

The results from Fig. 8 were used to calculate the nutrients recovered in the resource recovery scenario and then compared with the baseline values to calculate gains achieved, which are summarised in Fig. 9. Although biosolids production decreased by approximately 0.1 MtDS/a, the effect of TH meant that the nitrogen content was consistent between scenarios (50.5 tN/d and 50.2 tN/d in baseline and resource recovery scenarios, respectively). Thermal stripping of digestion liquors recovered 21.2 tN/d, and additionally 12.1 tN/d and 1.5 tN/d was captured in EPS and struvite, respectively. This increased the recovery of nitrogen by 68% compared with the baseline. Enhanced P recovery was mainly influenced by the phosphorus accumulating properties of AGS systems, which resulted in a greater fraction being applied as biosolids (46.0 tP/d). Struvite and EPS further supplemented this by recovering 3.4 tP/d and 4.5 tP/d, respectively, resulting in an increase of 71% compared with the baseline scenario for P recovery through the existing mix of biological and physio-chemical treatment processes. There was minimal impact on the recovery of OC, due to the balance of reduced sludge production of AGS systems, increased biogas generation of AAD processes, and the recovery of EPS. These results demonstrate the potential to achieve significant advances in recovery of N and P from UK wastewater. Energy recovery yields were compared for biogas generation and effluent heat pump strategies. The energy stored in biogas generated by the system is equivalent to 4.6 PJ/a; however, 6.4 MJ/m^3 of energy can be captured from effluent wastewater. Therefore, it was calculated that heat pumps are required on approximately 12% of the total flow to match energy recovery from biogas.

Even in the updated resource recovery scenario, large quantities of nitrogen are assimilated during wastewater treatment, but the low N concentration of wastewater influent limits efficiency of pretreatment recovery. However, 80% of influent N (van der Hoek et al., 2018) (and 50% of influent P (Mo and Zhang, 2013)) is in the form of urine; thus, potentially warranting an investigation into investment in separate collection infrastructure to enhance nutrient recovery in this scenario. For example, it was shown that adding urine to the stripper inlet stream equivalent to 10% of sludge liquor volume translates to approximately 40% increase in ammonia concentration (Morales et al., 2013). When assessing the use of heat pumps for the recovery of thermal energy, it was shown to be approximately 8 times greater than the chemical energy from biogas, which is in agreement with the values of Hao et al. (2019).

3.7. *Use of a capitals assessment*

This work provides a structured approach that guides the selection of resource recovery technologies, to accelerate their adoption by the water industry. Regional analysis is required for understanding the reaction of systems to certain scenarios, making it vital for planning and refining of strategic approaches (Superti et al., 2021). This approach can

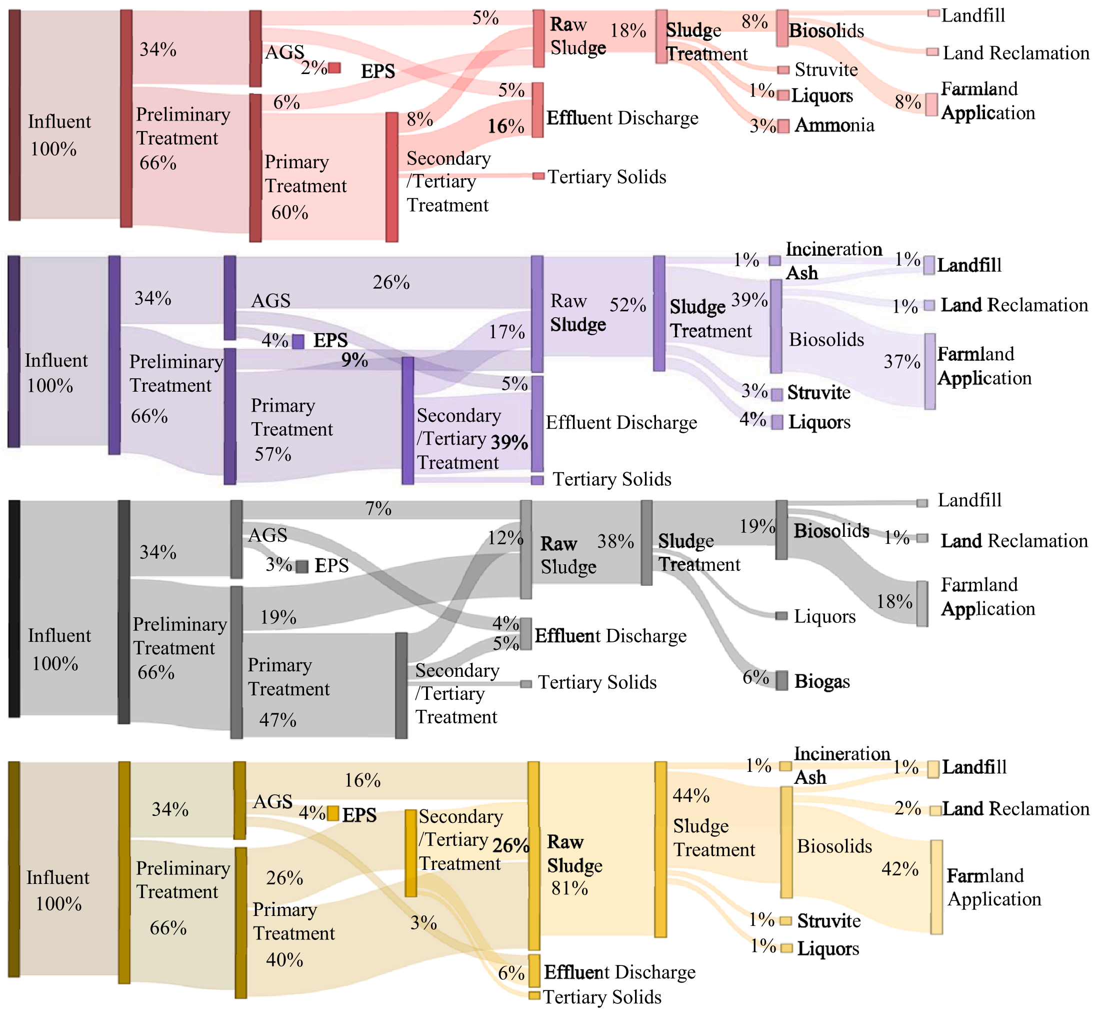

Fig. 8. Sankey diagrams representing the flow of substances for the updated resource recovery scenario. The results of SFA are shown here for nitrogen (red), phosphorus (purple), organic carbon (grey) and total suspended solids (yellow). The percentage of influent nutrients present in each flow are given, any flows with <1% are not labelled.

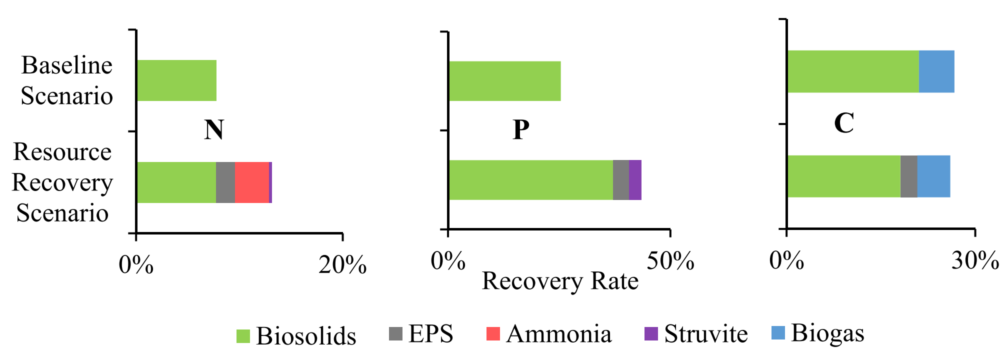

Fig. 9. The recovery rate of N, P and C as a percentage of the influent comparing the resource recovery scenario with the baseline scenario.

be used as a strategic planning tool for circular solutions on a regional level, enabling structural changes to be achieved for enhancement of the water sector's CE transition.

The inclusion of the 6 capitals in this assessment alongside more traditional criteria enables the assessment to go further than the typical focus of financial and manufactured capital, resulting in a more holistic evaluation of technologies. The use of a capitals assessment is seen as a way to maximise value creation in a more inclusive way, which is evidenced by their incorporation within national water strategic plans, including the UK strategy of Water Innovation 2050 (2020) and Water Services Association of Australia circular economy transition (Jazbec et al., 2020). Their inclusion in this approach aims to identify technologies that generate greater net sustainability of the entire system. However, the assessment of capitals relied on expert judgement scoring (UKWIR, 2021), so to fully understand the value of capturing resources, the next phase of the assessment should be to quantify the capitals to act as the final validation of selected technologies. The method developed by Yorkshire Water (2018) could act as a starting point for this, as it places value on circular flow of resources and a cost on negative externalities. This will require more detailed analysis of the studied system, such as LCA to expand the assessment for incorporation of other sustainability aspects.

The recommended technologies provided by the regional assessment are required to act as the foundation for further analysis by individual water utilities or treatment sites. For the UK example, it was recommended that heat, ammonia, biopolymers, struvite and biosolids should be priority resources. Local factors should be included for selection in these specific cases as there are many alternative methods, technologies, drivers, and barriers to consider at this scale, which could be accounted for in a quantitative capitals assessment. Therefore, there is a need for the development of a holistic value assessment to enable the conclusive appraisal of implementing circular solutions at any scale.

4. Conclusion

A structured approach is proposed for selecting technologies for resource recovery from wastewater, acting as strategic planning tool to accelerate the water sectors CE transition. The proposed approach utilises MCA to select resources (and associated technology pathways) for recovery on a regional scale. The resultant strategy is then implemented within a model of the baseline scenario to quantify improvements achieved in terms of nutrient recovery. The UK wastewater sector is used as an example, using data reported by water utilities for the year 2018/19, revealing that 8% and 24% of nitrogen and phosphorus, respectively are recovered in the present model. MCA scored resources based on aspects such as cost, carbon, market potential and treatment impacts, and investigated sensitivity to future scenarios and scoring uncertainty. The five 'priority resources' for this scenario are heat (heat pumps), extracellular polymers (AGS), ammonia (stripping), struvite and biosolids. The recovery of these resources was integrated into the modelled system to create an updated resource recovery scenario. This increased the recovery rate of nitrogen and phosphorus by 68% and 71%, respectively, however, large fractions of nitrogen are still assimilated highlighting the potential need for source separation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the Horizon 2020 Research and Innovation Programme Water Mining (grant agreement No 869474). The authors would also like to acknowledge the support provided by Morad Danishvar in completing the sensitivity analysis as part of this work.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2022.118673.

References

Agricultural Industries Confederation, 2021. Fertiliser consumption in the UK (Annual Summary). https://www.agindustries.org.uk/resource/fertiliser-consumption-in-the-uk.html/.

AHDB, 2019. Nutrient Management Guide (RB209). https://ahdb.org.uk/nutrient-management-guide-rb209.

Alberici, S., Noothout, P., Mir, G.U.R., Stork, M., Wiersma, F., 2017. Assessing the potential of CO2 utilisation in the UK. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2_1_.pdf.

Aunon, E., Ryan, S., Sawyer, R., 2015. Municipal sewage: one man's waste, another man's treasure! London. https://ukwir.org/eng/reports/15-PM-03-5/145974/Municipal-Sewage-One-Mans-Waste-Another-Mans-Treasure.

Baumann, I., Westermann, P., 2016. Microbial production of short chain fatty acids from lignocellulosic biomass: current processes and market. Biomed. Res. Int. https://doi.org/10.1155/2016/8469357, 20168469357.

Biosolids Assurance Scheme, 2020. Standard guidance notes. https://assuredbiosolids.co.uk/scheme-documents/.

Biosys, 2021. Tully AD plant Ballymena. https://www.byosis.com/case-studies/ballymena-plant.

Cavinato, C., Bolzonella, D., Pavan, P., Fatone, F., Cecchi, F., 2013. Mesophilic and thermophilic anaerobic co-digestion of waste activated sludge and source sorted biowaste in pilot- and full-scale reactors. Renew. Energy 55, 260–265. https://doi.org/10.1016/j.renene.2012.12.044.

CENTRISYS-CNP, 2021. Water reclamation facility upgrades system for struvite recovery. https://www.centrisys-cnp.com/municipal-case-studies/water-reclamation-facility-upgrades-system-for-struvite-recovery.

Chrispim, M.C., de M. de Souza, F., Scholz, M., Nolasco, M.A., 2020. A framework for sustainable planning and decision-making on resource recovery from wastewater: showcase for São Paulo Megacity. Water 12. https://doi.org/10.3390/w12123466.

CIWEM, 2011. Co-digestion of sewage sludge and waste. https://www.ciwem.org/assets/pdf/Policy/Policy-Position-Statement/Co-digestion-of-sewage-sludge-and-waste.pdf.

Coma, M., Martinez-Hernandez, E., Abeln, F., Raikova, S., Donnelly, J., Arnot, T.C., Allen, M.J., Hong, D.D., Chuck, C.J., 2017, Organic waste as a sustainable feedstock for platform chemicals. Faraday Discuss. 10.1039/c7fd00070g.

CREW, 2018. Water and the circular economy - where is the greatest sustainable economic benefit for resource recovery in the water cycle? https://www.crew.ac.uk/publication/circular-economy.

Dagilienė, L., Varaniūtė, V., Bruneckienė, J., 2021. Local governments' perspective on implementing the circular economy: a framework for future solutions. J. Clean. Prod. 310, 127340 https://doi.org/10.1016/j.jclepro.2021.127340.

Department for Business Energy and Industrial Strategy, 2020. UK energy in brief 2020. https://www.gov.uk/government/statistics/uk-energy-in-brief-2020.

Department for Environment Food and Rural Affairs, 2018. Animal feed statistics for Great Britain – December 2017. https://www.gov.uk/government/statistics/animal-feed-production.

Department for Transport, 2020. Road traffic statistics. https://roadtraffic.dft.gov.uk/summary.

Ellen MacArthur Foundation, 2015. Towards a circular economy: business rationale for an accelerated transition. https://ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition.

European Environmental Agency, 2018. Urban waste water treatment viewer 2018 (provisional data). https://eea.maps.arcgis.com/apps/MapJournal/index.html?appid=a4b0695edb6645a2a74e35887cf7a974&embed=true.

Eurostat, 2019. Total paper and paperboard production. https://data.europa.eu/data/datasets/zep5cpgfhgsgfhwxspr6zg?locale=en.

Gherghel, A., Teodosiu, C., De Gisi, S., 2019. A review on wastewater sludge valorisation and its challenges in the context of circular economy. J. Clean. Prod. 228, 244–263. https://doi.org/10.1016/j.jclepro.2019.04.240.

Ghosh, S., Lobanov, S., Lo, V.K., 2019. An overview of technologies to recover phosphorus as struvite from wastewater: advantages and shortcomings. Environ. Sci. Pollut. Res. 26, 19063–19077. https://doi.org/10.1007/s11356-019-05378-6.

Grand View Research, 2021. Alginate market size, share & trends analysis. https://www.grandviewresearch.com/industry-analysis/alginate-market.

Guo, H., Felz, S., Lin, Y., van Lier, J.B., de Kreuk, M., 2020. Structural extracellular polymeric substances determine the difference in digestibility between waste activated sludge and aerobic granules. Water Res. 181, 115924 https://doi.org/10.1016/j.watres.2020.115924.

Hao, X., Li, J., van Loosdrecht, M.C.M., Jiang, H., Liu, R., 2019. Energy recovery from wastewater: heat over organics. Water Res 161, 74–77. https://doi.org/10.1016/j.watres.2019.05.106.

Herman, J., Usher, W., 2017. SALib: an open-source python library for sensitivity analysis. J. Open Source Softw. 2, 97. https://doi.org/10.21105/joss.00097.

Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresour. Technol. 100, 5478–5484. https://doi.org/10.1016/j.biortech.2008.12.046.

Jazbec, M., Mukheibir, P., Turner, A., 2020. Transitioning the water industry with the circular economy. https://www.wsaa.asn.au/publication/transitioning-water-industry-circular-economy.

Kehrein, P., van Loosdrecht, M., Osseweijer, P., Garfí, M., Dewulf, J., Posada, J., 2020a. A critical review of resource recovery from municipal wastewater treatment plants – market supply potentials{,} technologies and bottlenecks. Environ. Sci. Water Res. Technol. 6, 877–910. https://doi.org/10.1039/C9EW00905A.

Kehrein, P., van Loosdrecht, M., Osseweijer, P., Posada, J., 2020b. Exploring resource recovery potentials for the aerobic granular sludge process by mass and energy balances – energy{,} biopolymer and phosphorous recovery from municipal wastewater. Environ. Sci. Water Res. Technol. 6, 2164–2179. https://doi.org/10.1039/D0EW00310G.

Kehrein, P., van Loosdrecht, M., Osseweijer, P., Posada, J., Dewulf, J., 2020c. The SPPD-WRF framework: a novel and holistic methodology for strategical planning and process design of water resource factories. Sustainability 12. https://doi.org/10.3390/su12104168.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Majid, A., Cardenes, I., Zorn, C., Russell, T., Colquhoun, K., Bañares-Alcantara, R., Hall, J.W., 2020. An analysis of electricity consumption patterns in the water and wastewater sectors in South East England, UK. Water 12. https://doi.org/10.3390/w12010225.

Microsoft Corporation, 2014. Power BI: interactive data visualization BI tools. https://powerbi.microsoft.com/en-gb/.

Mihelcic, J.R., Ren, Z.J., Cornejo, P.K., Fisher, A., Simon, A.J., Snyder, S.W., Zhang, Q., Rosso, D., Huggins, T.M., Cooper, W., Moeller, J., Rose, B., Schottel, B.L., Turgeon, J., 2017. Accelerating innovation that enhances resource recovery in the wastewater sector: advancing a national testbed network. Environ. Sci. Technol. 51, 7749–7758. https://doi.org/10.1021/acs.est.6b05917.

Mills, N., 2016. Unlocking the full energy potential of sewage sludge. https://openresearch.surrey.ac.uk/esploro/outputs/doctoral/Unlocking-the-full-energy-potential-of-sewage-sludge/99515301502346.

Mineral Products Association, 2018. Profile of the UK Mineral Products Industry. https://www.mineralproducts.org/Homepage-Promotions/Profile-of-the-UK-Mineral-Products-Industry.aspx.

Mo, W., Zhang, Q., 2013. Energy–nutrients–water nexus: integrated resource recovery in municipal wastewater treatment plants. J. Environ. Manag. 127, 255–267. https://doi.org/10.1016/j.jenvman.2013.05.007.

Montusiewicz, A., Lebiocka, M., 2011. Co-digestion of intermediate landfill leachate and sewage sludge as a method of leachate utilization. Bioresour. Technol. 102, 2563–2571. https://doi.org/10.1016/j.biortech.2010.11.105.

Morales, N., Boehler, M.A., Buettner, S., Liebi, C., Siegrist, H., 2013. Recovery of N and P from urine by struvite precipitation followed by combined stripping with digester sludge liquid at full scale. Water 5, 1262–1278. https://doi.org/10.3390/w5031262.

Morgan-Sagastume, F., Pratt, S., Karlsson, A., Cirne, D., Lant, P., Werker, A., 2011. Production of volatile fatty acids by fermentation of waste activated sludge pre-treated in full-scale thermal hydrolysis plants. Bioresour. Technol. 102, 3089–3097. https://doi.org/10.1016/j.biortech.2010.10.054.

Nagpal, H., Spriet, J., Murali, M.K., McNabola, A., 2021. Heat recovery from wastewater—a review of available resource. Water 13. https://doi.org/10.3390/w13091274.

OECD, 2008. Measuring material flows and resource productivity Volume I. The OECD Guide. https://www.oecd.org/environment/indicators-modelling-outlooks/MFA-Guide.pdf.

OFWAT, 2019. Data tables and models, price reviews. https://www.ofwat.gov.uk/regulated-companies/price-review/2019-price-review/data-tables-models/.

Organics Group, 2020. Thermally-driven ammonia strippers: ammonia stripping with waste heat. https://organics.uk/about-us/.

Palmieri, S., Cipolletta, G., Pastore, C., Giosuè, C., Akyol, Ç., Eusebi, A.L., Frison, N., Tittarelli, F., Fatone, F., 2019. Pilot scale cellulose recovery from sewage sludge and reuse in building and construction material. Waste Manag. 100, 208–218. https://doi.org/10.1016/j.wasman.2019.09.015.

Panchal, R., Singh, A., Diwan, H., 2021. Does circular economy performance lead to sustainable development? A systematic literature review. J. Environ. Manag. 293, 112811 https://doi.org/10.1016/j.jenvman.2021.112811.

Pronk, M., de Kreuk, M.K., de Bruin, B., Kamminga, P., Kleerebezem, R., van Loosdrecht, M.C.M., 2015. Full scale performance of the aerobic granular sludge process for sewage treatment. Water Res. 84, 207–217. https://doi.org/10.1016/j.watres.2015.07.011.

Public Health England and Wales, Public Health Scotland, 1989. The Sludge (Use in Agriculture) regulations 1989. https://www.legislation.gov.uk/uksi/1989/1263/made.

Ruiken, C.J., Breuer, G., Klaversma, E., Santiago, T., van Loosdrecht, M.C.M., 2013. Sieving wastewater – Cellulose recovery, economic and energy evaluation. Water Res.. 47, 43–48. 10.1016/j.watres.2012.08.023.

Saltelli, A., 2002. Making best use of model evaluations to compute sensitivity indices. Comput. Phys. Commun. 145, 280–297. https://doi.org/10.1016/S0010-4655(02)00280-1.

Sarrazin, F., Pianosi, F., Wagener, T., 2016. Global Sensitivity Analysis of environmental models: convergence and validation. Environ. Model. Softw. 79, 135–152. https://doi.org/10.1016/j.envsoft.2016.02.005.

Severn Trent, 2021. Biosolids recycling. https://www.severntrent.com/sustainability-strategy/environment/bioresources/biosolids/.

Smyth, M., Brookes, A., Riches, S., Bungay, S., 2021. A predictive model to determine ammonium levels in digestate liquors. In: European Biosolids and Organic Resources Conference https://conferences.aquaenviro.co.uk/proceedings/predictive-model-determine-ammonium-levels-digestate-liquors/.

Soares, A., Vale, P., Kim, J.E., Hofman, J., 2021. Factsheet – anaerobic membrane bioreactor (AnMBR). https://mp.uwmh.eu/media/factsheets/Factsheet1_AnMBRDegassing_unit_JvkOXFZ.pdf.

Sobol′, I.M., 2001. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. Math. Comput. Simul. 55, 271–280. https://doi.org/10.1016/S0378-4754(00)00270-6.

Superti, V., Merino-Saum, A., Baur, I., Binder, C.R., 2021. Unraveling how the concept of circularity relates to sustainability: an indicator-based meta-analysis applied at the urban scale. J. Clean. Prod. 315, 128070 https://doi.org/10.1016/j.jclepro.2021.128070.

Tavares Ferreira, T.J., Luiz de Sousa Rollemberg, S., Nascimento de Barros, A., Machado de Lima, J.P., Bezerra dos Santos, A., 2021. Integrated review of resource recovery on aerobic granular sludge systems: possibilities and challenges for the application of the biorefinery concept. J. Environ. Manag. 291, 112718 https://doi.org/10.1016/j.jenvman.2021.112718.

Tchobanoglous, G., Stensel, H.D., Tsuchihashi, R., Burton, F., 2014. Wastewater Engineering Treatment and Resource Recovery, 5th ed. McGraw-Hill Education, New York.

The Royal Borough of Kingston Upon Thames, 2021. England's first sewage-powered heating scheme planned for Kingston. https://www.kingston.gov.uk/news/article/80/england-s-first-sewage-powered-heating-scheme-planned-for-kingston.

UKWIR, 2021. Where is the greatest sustinable economic benefit for resource recovery in the water cycle? https://ukwir.org/final-report-for-where-is-the-greatest-sustainable-economic-benefit-for-resource-recovery-in-the-water-cycle.

van der Hoek, J.P., Duijff, R., Reinstra, O., 2018. Nitrogen recovery from wastewater: possibilities, competition with other resources, and adaptation pathways. Sustainability 10. https://doi.org/10.3390/su10124605.

Water Innovation 2050 2020. UK 2050 water innovation strategy. https://spring-innovation.co.uk/app/uploads/2021/12/UK-2050-Water-Innovation-Strategy.pdf.

Yorkshire Water, 2018. Total impact and value assessment - methodology report. https://www.yorkshirewater.com/media/hm2dfl0b/tiva-methodology-report.pdf.