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APPLYING CIRCULAR ECONOMY THINKING TO INDUSTRY BY INTEGRATING EDUCATION AND RESEARCH ACTIVITIES

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ABSTRACT
Collaboration between universities and external organisations offers opportunities for multiple and mutual benefits, including the development of employability skills in students. This paper outlines the educational approach taken and results achieved when under- and post-graduate students were tasked with working with a water supply and waste water treatment company (Southern Water; SW) with the aim of identifying opportunities to apply circular economy thinking to SW's operations at a waste water treatment plant (WWTP) in England. The students were presented with a "real-world" consultancy task to identify and evaluate the waste streams within the WWTP process and produce options for their reduction, recovery and reuse without hindering operational effectiveness. The mutual benefits of this collaborative venture were demonstrated via: i) the utility of students' recommendations and SW's desire to participate in and fund follow-up activities, including academic consultancy, MSc and PhD projects; ii) positive feedback from SW and the students; and iii) the quality of the exercise as a vehicle for academic learning and development of professional and employability skills. Academics can address the challenge of simultaneously needing to develop students' employability skills whilst covering core topics required by professional bodies by deliberately incorporating open-ended, real-world industrial activities into teaching and learning activities within assessed modules. Active learning approaches to education in waste and resource management incorporating consultancy-style work of this nature are strongly recommended.

1. INTRODUCTION

Increasing numbers of young people attending university, driven by government policies recognising the links to the growth of the economy (Glover et al., 2002), has resulted in many students struggling to find appropriate employment upon graduation. A degree qualification is no longer a guarantee of a job, and this is reflected in the attitudes of many students who report that they chose to study at university not solely for academic advancement but to make them more employable (Glover et al., 2002; Gedye et al., 2004).

Studies have shown that that students who opt for degrees that contain work placements are better placed for employment when they graduate compared with students who lack this experience (e.g. Bowes and Harvey, 2000). The most valued skills for employers have been reported as research skills; ability to work in teams; and production of professional reports (Kemp et al., 2008). However, it is not always possible to squeeze a work placement into the formal programme of some degree subjects, especially if they are accredited by a professional body that requires core topics to be covered in a degree's syllabus. Modern academics therefore have to think of other ways to provide students with opportunities to develop their employabiity skills. Employability is commonly considered as a set of personal qualities (e.g. self-confidence, efficacy, reflectiveness, flexibility, international outlook), accomplishments, practitioner skills and understanding that make individuals more likely to secure employment and to be successful in their chosen occupations. Employability skills are becoming a vital yardstick for career success (Carbery and Garavan, 2005).

Academics at the University of Southampton's Centre for Environmental Science (CES) have addressed the challenge of simultaneously needing to develop students' employability skills whilst covering all the core topics required by professional bodies by deliberately incorporating them into a range of non-work placement modules. In particular, academics at the CES have, over a long period, developed,

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initiated, and delivered educational activities focused on waste and resource management that involve collaboration between university students and staff with external organisations. These activities have multiple aims, including:

- Generating new knowledge relating to case studies that exemplify the implications and impacts of waste-related research across a range of spatial scales;
- Providing students with real-world, in situ experiences as a means to enhance their skills with regard to problem-solving, sustainability, team-working, consultancy and employability;
- Providing mutual benefits to external organisations, universities and students, through sharing of resources to extend their value and impact.

Jensen et al. (2015) and Strayer (2012) have demonstrated that this type of approach - the incorporation of open-ended, real-world industrial examples into teaching and leaning strategies - acts to motivate students to produce work of a higher quality and depth than would normally be expected.

This paper outlines the educational approach taken and results achieved when under- and post-graduate students were tasked with working with a waste water treatment company (Southern Water; SW) with the aim of identifying and applying circular economy thinking to SW's operations at a major waste water treatment plant (WWTP) in England during October-December 2016.

1.1 The circular economy

The global economy has been built almost exclusively on the foundations of a linear model of extraction, production, consumption and dispose of as waste. The negative effects caused by this model are threatening the welfare of natural ecosystems and affecting the stability of the global raw materials market (Ghisellini et al., 2016). The acceleration of resource use globally, with many countries becoming more industrialised and with ongoing development of innovative technologies, is starting to threaten raw materials depletion.

The circular economy (CE) is based on a natural ecosystem concept, having a closed loop of material flow. The CE is an expansion of the waste hierarchy, whereby conventional waste streams that were often a cost to an organisation are viewed as source of resources and revenue, whilst minimising or even reversing their environmental impact. Adopting a CE will not only bring environmental benefits but could save the UK up to £700 million annually (Ellen MacArthur Foundation, 2017). Recovering resources from previously used materials will replace the need to extract virgin resources via mining, practices that are expensive (Mueller et al., 2017) and are associated with environmental impacts. The subsequent resource efficiency and environmental benefits that would follow with the adoption of a CE economy are significant (Curran and Williams, 2012). The European Commission has adopted an ambitious circular economy package, which contains proposals for legislation on waste to foster Europe's transition towards a circular economy (European Commission, 2015).

The ongoing challenges of non-renewable energy depletion and subsequent environmental pollution is encouraging businesses to look at wastewater as a resource due to the large potential for energy generation, material extraction and reuse. Considerable amounts of materials including metals, pharmaceuticals and nutrients enter WWTP and are either removed or lost in the effluent to the environment. The substances and materials, particularly nutrients and metals could theoretically be harvested from the wastewater and sold for reuse. There is also large potential for energy recovery through the capture of heat from wastewater and generation of biogas from treated sewage sludge.

In fact, wastewater treatment facilities have been considered at as a critical area for the implementation of CE thinking on the international stage. Karmenu Vella, EU Commissioner for the Environment, Maritime Affairs and Fisheries, said that "the greatest potential in relation to the circular economy is in the reuse of municipal wastewater". He goes on to say that it is "an economic opportunity that European Union companies could take up even more (Brockett, 2015)." It is clear that with international recognition, projects to bring about CE thinking in wastewater treatment will be supported and viewed as necessary in future years.

In the United Kingdom, there has been some small-scale adoption of CE processes in the wastewater sector (Table 1). However, the rate of uptake is limited. This project provided a novel opportunity to combine education and research activities via a preliminary study that aimed to inform Southern Water about the range of realistic, cost-effective options available with respect to the application of CE thinking to its operations.

1.2 Study location and characteristics

Southern Water is a private waste water treatment company based in the South of England with a water supply and treatment area of over 10,530 km^2. The company currently has 365 waste water treatment facilities in Hampshire, Kent, Sussex and the Isle of Wight, treating and recycling 718 million litres of waste water daily. The UK Environment Agency is SW's environment regulator and ensures that both UK and EU environment standards are met.

The studied WWTP (Millbrook) is owned by SW and located within the Western Docks in Southampton. The WWTP has undergone a number upgrades including a £20 million renovation in 1997 consisting of the enhancement of the anaerobic digester (AD) and sludge treatment to provide secondary treatment. Millbrook WWTP currently treats a mixture of sludge and wastewater from 250,000 people, nearly half of which is brought in from the region's smaller WWTPs. The facility consists of largely traditional wastewater treatment components including preliminary screening, primary treatment, nutrient removal and secondary treatment. It is designed to treat a full flow of 850 l/s before discharging into the River Test estuary. Approximately 14,000 t of sludge is converted into 10,000 t of bio solids soil enhancer each year via mesophilic anaerobic digestion with a hydraulic retention time of 15 days, and then sold to a variety of outlets for beneficial land use. Figure 1

TABLE 1: Examples of the current circular economy practices in operation or planning within wastewater treatment works nationally and globally.

Recovery method	Water company	Status of operation	Companies involved	Potential	Reference
Co-digestion food waste	Thames Water	Full scale	EcoGenR8	40,000 t yr^{-1} food waste, 13,000 MWh to the grid.	EcoGenR8 (2013)
Co-digestion food waste	Wessex Water	Full scale/ pilot	GENeco	35,000 t yr^{-1} food waste, 8,300 homes equivalent of methane.	Wessex Water (2015)
Latent heat from sewage	Scottish Water	Pilot	SHARC Energy Systems	95% of heat requirement of a large campus site.	Scottish Water (2017)
ANAMOX and phosphate recovery	Severn Trent Water	Full scale	NMC Nomenca	PE > 650,000 treated, reduced energy costs (aeration) phosphate and ammonia recovered as struvite. Reduced maintainance costs ~£70,000 and 2 tonnes of struvite fertiliser produced daily.	North Midland Construction (2016)
Difgen – fresh water hydro power recovery	Scottish water	Water turbine recovering energy from freshwater flow control	Zeropex	£800k investment, returning £147k annually by producing 600 MWh yr^{-1}.	Scottish Water (2017)
Micro-algal biofuel	Aqualia (Spain)	Pilot	FP7 consortium	Recovery of CO_2 (from biogas) nutraceuticals (from the microalgae) removal of nutrients and production of biomass.	Maga (2016)
Phosphorus recovery	Edmonton WWTP (Canada)	Struvite precipitation and recovery	Ostara, Pearl	2,000 tonnes of struvite produced annually. Reduction in maintenance costs	Linderholm et al (2012)
Energy recovery (FOG)	Thames Water	FOG recovery and energy production	2OC	19MW facility in East London, using FOG from households, businesses and industry with Thames water collecting and delivering the fat.	Power Technology (2017)
Carbon capture	NA	Carbon capture and algal biomass growth	Boots Ltd and PML	Capture exhaust carbon and use a feedstock for algal cultivation.	Levidow et al., (2014)

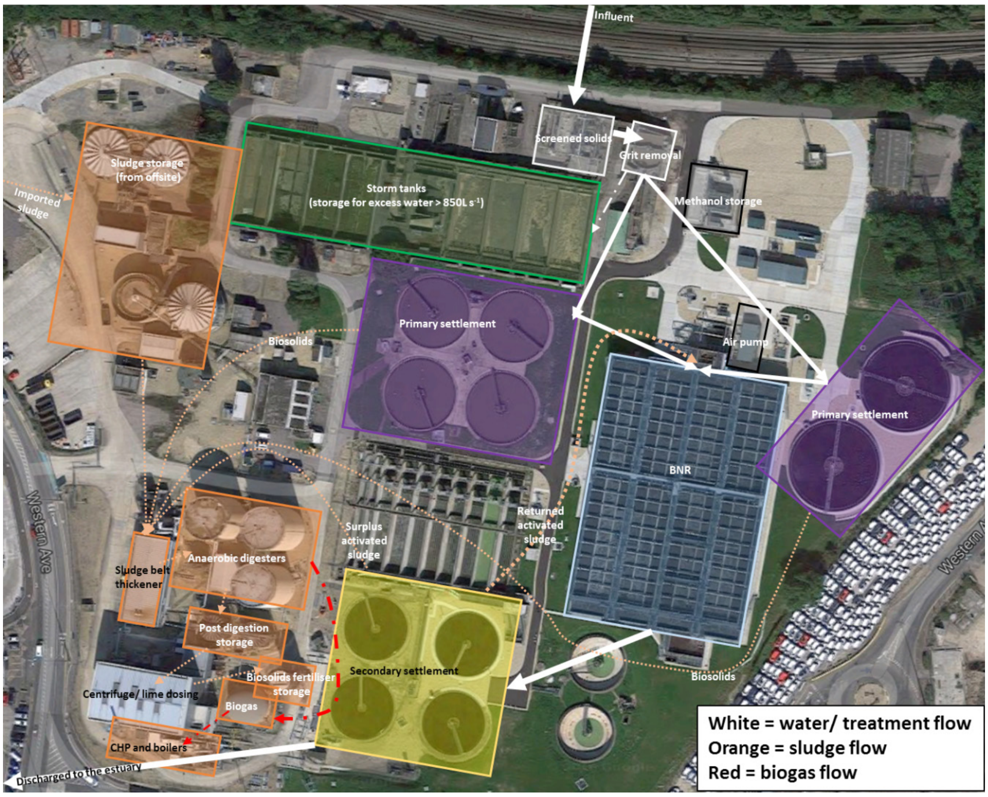

FIGURE 1: Aerial view of the Millbrook site detailing the flows of wastewater (white arrows), biosolids and activated sludge (orange dotted arrows), and biogas (red dotted arrow) between the labelled treatment areas.

provides a site map of the WWTP, highlighting:

- 6 primary settlement tanks
- 4 secondary settlement tanks
- 1 tertiary treatment flow system
- 3 anaerobic digesters
- 8 storm flow tanks
- 1 biogas storage silo.

Millbrook WWTP is typical of the UK evolution of wastewater treatment facilities and adjacent brownfield sites, with old, new and decommissioned infrastructure present. As this facility is located within one of the UK's busiest shipping ports there is limited room for expansion, and legacy piping for both the facility and dockyard reduce further the capacity for redevelopment.

2. METHODOLOGY

2.1 Students' Task

The task was set as part of a suite of assessments for the University of Southampton's module in "Sustainable Resource Management". This is an optional module available to students in the final year of a Bachelor's (BSc) degree and to students studying at Masters (MSc) level; these students are studying at levels 6 and 7, respectively, within the UK's Frameworks for Higher Education Qualifications (QAA, 2014).

SW tasked the university, through this module, to scope ideas to apply a CE approach to their entire wastewater operations. To maximise the impact and effectiveness of this research, the students were directed to work in parallel with the academics with focus on a single WWTP (section 1.2), thereby enabling students to join in with current research driven by industry. Prior to a site visit, students were extensively briefed on current wastewater technologies and operations, shown example data and a selection of CE concepts that had already been applied to SW operations. Examples of good research practice and a scaffolded schema were presented to the students to aide in their research development. A virtual initial tour of the site was delivered, along with a health and safety briefing. An extensive online repository of review papers, technical reports, images and commercial operational data was produced with students gaining access immediately. Students initially participated in an accompanied site visit to Millbrook WWTP to view the site and observe its operations in situ. They were expected to take their own notes during the site visit and were given an opportunity to discuss with SW representatives and ask questions; normal obligations associated with site visits and professional consultancy projects were followed. SW supplied several years of daily and hourly operational site data which was made available to the students. No further instructions, data or advice were directly given to the students unless explicitly asked, to which any outcomes were shared with all students promptly.

The students were tasked to identify and evaluate the major and minor waste streams within the WWTP process and produce options for their reduction, recovery and reuse without hindering the operational effectiveness of the site. They were subsequently required to produce a report that:

- Identified waste streams generated by the operations within and upstream of the Millbrook WWTP.
- Determined potential methods for reducing, recovering and/or processing selected waste materials using adaptions to the current systems deployed.
- Estimated the income/reduced costs of each recovery method.
- Identified and summarised processes and/or industrial networks that incorporate circular economy thinking within the WWTW setting that could be practically and realistically deployed by SW.
- Provided a priority list of 3 potential improvement projects, ranked by likely benefit (including economic, social, environmental, energy, efficiency, system, reputational, etc.).
- Provided a concise summary of how the findings could contribute to the adoption of circular economy operations throughout SW.

2.2 Collation of results and report generation

After submission, the students' work was marked with the methodologies, recovery techniques and relationships recorded. A comprehensive list was produced that complemented the work undertaken by staff at the university. Where CE ideas had already been identified by staff members, all new references, methodologies and equations were added. If ideas or techniques had not previously been identified or explored, then a more comprehensive investigation of the students' work was undertaken to check both the practicality and feasibility of the ideas. Regardless of their suitability, all CE ideas (once processed) were presented to SW, along with summaries of their suitability to allow SW to both approve ideas and act as a reference source for all potential CE approaches.

It should be noted that the emphasis of these student reports was to present all ideas, both "good" and "bad". The rationale for this was to explore an open-minded approach to the possibilities that could be available and are often overlooked by institutionalised experts. As the Masters students can come from a variety of backgrounds, reports were marked based on the student's research method and understanding of the direct/ indirect benefits of adopting a CE approach. Their direct understanding of the science and engineering principals in this instance was not directly marked, as this would give an unfair advantage to pure science and engineering graduates.

3. STUDENT REPORT OUTCOMES

In this section, examples of some of the key results generated for SW by this collaborative approach between staff and students are presented in order to illustrate the work undertaken. A confidential, commercial project report that incorporates some of these results was delivered to and approved by SW in early 2017. Within the reports submitted by the students, a broad range of ideas was generated. Cumulatively, the students produced an extensive list of ideas and the standard of work was high. The ideas produced included recovery of:

- Micro-plastics
- Nutraceuticals/ Pharmaceuticals
- Sewerage latent heat
- Fats, oils and grease (FOG)
- Metals
- Screened solids and grits
- Chemical nutrients (N, P, K)
- Organic materials
- CO_2
- Energy via anaerobic digestion
- Micro algae
- Exhaust heat
- Gravitational energy
- Waste water effluent
- Water effluent as a water source for crop production (aquaculture)
- Space for utilisation

In this section, four examples of some of the key results provided by a range of "good students", both from the environmental science pathway and engineering graduates are presented in order to illustrate the flow of work undertaken with the benefits to SW highlighted. The figures produced by the students are presented unedited, as is the text produced by the students, although mirror edits have been made to suit the required format for this publication. The results have been benchmarked with the literature and by SW with the exception of the economic costs, which are necessarily rough estimates.

3.1 Student A: Waste streams generated

The identification of waste streams and their current utilisation created a valuable starting point for further analysis of resource recovery. This also allowed SW to clearly identify all the resources that are currently underutilised within their operations. Student A reports a good example of the initial scoping of resources, determined by the site visit, discussions with SW staff and online resources:

"Table 2 provides a summary of all physical waste streams identified and indicates the presence of key contained resources which may prove a source of revenue generation through recovery and resale. Any current utilization of such materials is also detailed. As is evident from Table 2, Millbrook WWTP is currently operating significantly beneath its potential with respect to utilization of circular economy applications for the recovery of available resources. Though resource cycling is present, for example the recycling of sludge nutrients for use as soil enhancer, the variety of materials that are not currently utilized underlines the opportunity for further revenue generation through the application of circular economy principles".

TABLE 2: Summary of identified waste streams, their contained resources and current utilisation by Southern Water.

Stage generated	Waste/resource stream	Contained resources	Current utilization
Primary influent treatment	Screenings	Plastics, textiles	Utilized - composted alongside grits in hot rot facility
	Grits	Minerals	Utilized - composted alongside screenings in hot rot facility
		Organics	Utilized - composted alongside screenings in hot rot facility
	Sludge/biosolids	Nutrients: (N + P)	See anaerobic digestion -> digestate
		Metals	See anaerobic digestion -> digestate
		Organic C	Utilized - methanogen food source during anaerobic digestion
	FOG	Hydrocarbons	No dedicated utilization - co-digested with sludge
Secondary influent treatment	BNR products	Gaseous N	Not utilized - released to atmosphere
	Activated sludge	Denitrifying bacteria	Utilized - pumped upstream of BNR, recycling of bacteria
		Nutrients: (N + P)	See anaerobic digestion -> digestate
		Organic C	Utilized - methanogen food source during anaerobic digestion
Anaerobic digestion	Biogas	CO_2, CH_4	Partly utilized: • 90% utilized as fuel for CHP • 0% wasted (flue) due to insufficient CHP capacity
	Digestate	Nutrients: (N + P)	See centrifugation -> De-watered digestate + reject water
		Metals	See centrifugation -> De-watered digestate + reject water
Centrifugation	Reject water	Nutrients: (N + P)	Not utilized - re-enters WWT process
		Dissolved metals	Not utilized - re-enters WWT process
	De-watered Digestate	Nutrients: (N + P)	Utilized - sold to agricultural industry as soil enhancer
		Trace metals	Utilized - sold to agricultural industry as soil enhancer
Post-treatment	Treated effluent discharge	Dissolved metals	Not utilized - released to Solent (Strait of water on the UK South Coast)
		Nutrients: (N + P)	Not utilized - released to Solent
		Pharmaceuticals	Not utilized - released to Solent
		Nutraceuticals	Not utilized - released to Solent
		Microplastics	Not utilized - released to Solent

3.2 Student B: Metal recovery

Metal recovery was identified by all students as a key area that could benefit from CE adoption with WWT. The breadth of recovery technologies explored was extensive, with both direct and indirect benefits explained, e.g. "the presence of toxic metals within biosolids soil enhancer and the benefits of their removal on both quality and health (Singh and Agrawal, 2008; Li et al., 2014; Nancharariah et al., 2015)". Table 3 highlights some of the key technologies explored by the students and synthesised further for delivery to SW. The example below is typical of the student's response, presenting the ideas available without the full technical understanding of where within the WWT process these technologies could be directly deployed. Students were not directly penalised, as it was the benefits of application with its potential and not the engineering that was assessed. The findings from Student B are outlined within Table 3.

3.3 Student C: Biogas for Transportation

Environmental impacts were a primary driver for the majority of students due to the nature of their degree pathways. Student C delivered a good example of a comparative analysis with estimations on both the environmental benefits and economic returns:

"To be suitable for use as a transport fuel, biogas must be upgraded to biomethane (Larsson et al., 2016), which involves removing trace gases and CO_2 offsite in an external production plant (Bates, 2015). Biomethane produced may be supplied as either Liquefied Biomethane (LBM) or Compressed Biomethane (CBM) (Bates, 2015); the fuel can be transported by road from the external production plant in pressurised containers to an onsite dispensing station at the WTTP. This provides the opportunity for onsite vehicles to be powered by on-site produced biogas.

An interesting adoption of biogas into transport is demonstrated by the 'POOBUS' operating in Bristol; it is a 40-seat Bio-bus which runs on biomethane generated from sewage and food waste (Geneco, 2015). It is estimated that a single passenger's annual food and sewage waste would fuel the bio-bus for 37miles and releases up to 30% less CO_2 (Geneco, 2015). This would provide an effective cascade system if bus fleets in Southampton were to adopt the same technology. It is reported that emissions associated with production, dispensing and use of biomethane in vehicles are 74% lower than conventional gaseous fuels as seen in Table 4.

Table 5 summarises the financial aspects of utilising biogas as a transport fuel".

3.4 Student D: Hydroelectric power generation

Below is an example of a student's fully explored adoption of a CE method into SW operations. Here the students have utilized the site visit, online resources and commercial data. Unlike the example above in 3.2, we have locations for potential sites with justifications. It should be noted that the identification of low head height energy recovery potential has now been raised within SW, with their own innovation team exploring this CE method further:

"The UK water treatment industry has voluntarily agreed a target of 20% renewable energy power consumption by 2020 (Environment Agency, 2009). The water flowing through large WWTWs provides a potential source of

TABLE 3: Basic description of the process used in BES metal recovery (adapted from Wang and Ren, 2014)..

Methods	Description
A	Metals such as Au (III), Cu (II) and Fe (III) which have a redox potential greater than the anode potential (-300mV), are reduced on abiotic cathode. Process allows the metals to be directly used by the electro accepter with no additional power supply needed.
B	Cd (II) Ni (II), Pb (II) and Zn (II), have lower redox potentials than the anode potentials. For them to be reduced, external power is needed drive the electrons from, the anode to the abiotic cathode.
C	Microbial reduction of metal oxides such as Cr (VI) on a bio-cathode. The metal recovery process involves dissimilatory metal reduction through using the metal as an external electro acceptor. Dissimilatory metal reducing bacteria include Trichococus pasteurii and Pseudomonas aeruginisa.
D	This stage is a combination of both stages B and C. Metal conversion using a bio-cathode which requires external power. Metal ions can be extracted from solutions and adsorbed onto biofilms on electrodes. Microorganisms that are present on the electrode reduce the metals during microbial respiration.

TABLE 4: Greenhouse Gas savings from use of biomethane (adapted from Bates, 2015).

	Biomethane (kg CO_2 eq/GJ)	Conventional gaseous fuels (kg CO_2 eq/GJ)	% saving in GHG emissions
CBM from AD	18.5	68	74
LBM from AD	19	75	74

**Excluding emissions occurring during use of Bio methane in vehicles as these are vehicle dependent. They will however be identical from use of bio methane or conventional fossil fuel.*

TABLE 5: Financial considerations of utilising biogas as a transport fuel (adapted from Kollamthodi et al., 2016).

Financial Biogas upgraded fuel	Production costs (Euros/GJ)	Total cost for delivery and dispensing (Euro/GJ)	Price (Euros/ GJ)
Compressed Biomethane	7.28-10.20	2.77-5.72	5.7
Liquefied Biomethane	12.86-15.76	2.73	6.4

**note euro: European biogas market is the most developed.*

renewable energy that may be reclaimed and transformed into electricity, this electricity can then be fed back into the system, or, sold to the national grid (Capua et al., 2014). The tanks and channels within a WWTW generally allow the implementation of hydropower technology (Berger et al., 2014); however, the main challenge associated with such installations is that the new utilities may interfere with the flow rates and effectiveness of the facility.

Hydropower systems operate with the use of a turbine, which is selected based on the flow rate or head (water pressure) of the system (Capua et al., 2014). Kinetic energy, in the form of falling water flows through the turbine, whereby it is converted into mechanical energy as the turbine spins. (Sektorov and Savvin, 1967). The most likely location for a hydropower turbine within the WWTW would be the outlet after the tertiary stage of treatment, this way, no processes would be affected and the flow rate would be adequately high. It would also have the compound advantage of not requiring screens and rubbish racks to protect the turbines, since the water would have already been treated further back in the process (Berger et al., 2014).

UK legislation currently indicates that planning permission must be sought from the local planning authority for the introduction of hydropower infrastructure to a business. Environmental permits will also need to be obtained from the Environment Agency to ensure that the utilities do not have a negative effect on the quality of the water effluent (Environment Agency, 2013).

The framework for this power estimation is based off of a 2013 scoping study into the feasibility of hydroelectric power in the Upper Blackstone Water Pollution Abatement District (UBWPAD) WWTW in New England, USA. This site was selected to substitute missing data from Millbrook because of the similarity of infrastructure, PE, catchment size and flow rates (Capua et al., 2014).

The equation used to determine power output from a hydropower turbine is:

$$P = \eta \rho w g Q H$$

Where:
P = power (kW)
η = efficiency of the turbine (unitless)
ρw = density of the water (kg/m^3)
g = acceleration due to gravity (m/s^2)
Q = flow of water through the turbine (m^3/s)
H = head (m).

- For efficiency, it is assumed that with modern hydropower turbine 90% efficiency levels can be reached in accordance with estimations (Environment Agency, 2009)
- The density of water is 1000 kg/m^3
- Gravitational acceleration is a constant of 9.81 m/s^2
- The maximum flow of water through the turbine at Millbrook is 850 l/s which is equal to 8.5 m^3/s
- The head (difference in height between effluent output and the height of the River Test is unknown and therefore will be assumed to be the same as in UBWPAD at 1.7 metres.

Therefore, the potential power output per hour is:

$$P = \eta \rho w g Q H = (0.9)(1000\ kg/m^3)(9.81\ m/s^2)(0.85\ m^3/s)(3.6\ m) = 27.02\ kW$$

The potential variations in power output depending on flow are outlined in Table 6.

The most tried type of hydropower turbine in large WWTWs are micro turbines. Micro turbines only require a medium-sized flow rate and a small head size (2-12m) (Capua et al., 2014) and the model suggested is manufactured by Toshiba and installation costs range from £5,700 - £25,000 depending on the precise size of the blades and mechanisms required. The Toshiba model is appropriate for Millbrook because the flow rates required for power output (150l/s - 900l/s) fall within the ranges of the WWTW (150 l/s - 900 l/s).

In all cases, the most conservative figures are used to estimate costs and potential savings, unless otherwise specified.

Table 7 outlines the cost-benefit analysis of hydropower implementation at Millbrook".

TABLE 6: Variation in power output.

	Low Flow	Peak Flow	Median Flow
Flow rate (m^3/s)	0.13 m^3/s	0.85 m^3/s	0.49 m^3/s
Power produced by turbine (kWh)	4.13	27.02	15.57

TABLE 7: Cost-benefit analysis of hydropower implementation at Millbrook.

	Low Flow	Peak Flow	Median Flow
WWTW Energy Use/year (kWh)	5,194,680	22,408,080	13,801,380
Hydropower energy production per year (kWh)	36,178	236,695	136,393
% of total energy made by hydropower	0.7%	1.1%	1.0%
Current buying price of national grid for electricity (£/kWh)		£0.09648	
Money made per year if sold to national grid	£3,490	£22,836	£13,159
Installation costs		£30,000	
Buy-back time (median flow)		2.3 years	

4. DISCUSSION

4.1 Student engagement

Students initially were unfamiliar with the open ended, broad ranging concept of this research and report writing style. Typically within an education setting assessed summative work follows an almost standard protocol, whereby the students are directly led to a fixed set of answers. As the staff setting the work were undertaking the research in parallel with the students, some students initially felt overwhelmed. In contrast, the majority of students began to excel and enjoy the freedom that this style of open research allowed, enabling them to utilize all the skills they have developed throughout their degree simultaneously. All students benefited from the scaffolding provided to support their research and analysis with >1,000 site visits by the students to their online teaching resources. Students that struggled with the concept benefited from direct mentoring and intervention to guide them through the process.

4.2 Improvements to SW's systems

The students offered a range of suggestions that could assist SW to improve its waste management practices. These varied from the adoption of currently available recovery technologies, to incorporating novel local relationships with the solid waste management sector and other industries.

The majority of ideas involved altering the current waste treatment processes used at the Millbrook site, with other suggestions of upstream energy recovery and FOG recovery/ prevention. The combined use of student and staff research enabled a wide spectrum of ideas to be explored, with benefits and limitations fully explored. Several of these ideas are being taken forward by SW for further investigation.

4.3 Benefits of collaboration

The benefits of this collaborative approach to SW include:

- Access to internationally recognized academics with specialist knowledge and skills.
- Access to resources such as professional/expert/research journals and specialist software that would not normally be available to them.
- Access to new ideas, concepts, fresh approaches and modern thinking, as well as a more international outlook.
- Access to an independent and highly skilled workforce that provides broad and deep expertise and skills that are not available within the organization and who are not influenced by commercial pressures or constrained thinking.

The outputs from the students' work fed into a professional consultancy report commissioned by SW from the University of Southampton. Upon delivering the report to SW's operations, innovation and management leaders they took a highly positive view of the work, its message and recommendations made. SW recognized the value of continuing work with the University of Southampton via their subsequent desire to participate in and fund follow-up activities, including academic consultancy, MSc and PhD projects.

From the university's perspective, there are also numerous benefits from collaborative working with a commercial organisation:

- Access to practicing professionals with a deep understanding of the practical, logistical, financial and political implications of project/policy implementation.
- Improved employer engagement and student employability profiles and access to high quality work placements.
- Contemporary views of workplace timescales and the financial and other constraints faced by large commercial organisations.

However, organizing and managing this type of collaborative activity through to a successful conclusion is not straightforward, as outlined in Williams and Shaw (2017).

4.4 Student performance and feedback on the module and assessment task

Overall, the consultancy-style reports submitted by the 42 students ranged from weak to excellent (mark range 12-93%; mean 61±20%) with 18 students achieving distinction (mark >70%) grades and 7 students failing (mark <40%).

We have found that this type of bipolar mark range is common when we set real-world assignments for students. We discussed the reasons for this in detail in Williams and Shaw (2017) and the same points apply in this case study.

A selection of typical (unedited examples) of verbatim feedback from the students to the staff are provided below. In addition, a number of students provided direct verbal feedback which indicated that the overall experience was very positive.

- "I enjoyed the general quality of the lectures and the challenging assignments."
- "I thought the coursework was a great way of improving my understanding of the circular economy through realistic application in the wastewater sector."
- "Challenging coursework – inspirational."
- "Coursework excellent for mirroring industry – good to talk about in interviews."
- "Coursework made us think more deeply about environmental problems."

A small number of students were unhappy with various aspects of the assignment, as illustrated by the unedited quotes below; note there are some contradictions:

- "The coursework was too large for its weighting which tended to increase stress on time management."
- "Coursework is too big to be 30% of one module."
- "Coursework felt irrelevant to the lecture content, would have preferred a visit and coursework based on household waste handling."
- "Coursework was, in my point of view, too challenging in the timeframe I had with other commitments but the coursework opportunity was very good but more time was needed."

- "We're not too fussed about early deadline. Trust us to manage our time. Our fault if we get it wrong."

The response of the module team to comments from the students secured halfway through the semester and well before the deadline for submission of the assignment is provided in Box 1. We have only provided our response to the "negative" comments from the students. We feel that our response was timely, professional and courteous. We accept that not all the students would like or have the maturity to accept or appreciate our firm but direct and evidence-based rebuttal of some of the comments provided.

5. SUMMARY AND CONCLUSIONS

This paper has outlined how academics can address the challenge of simultaneously needing to develop students' employability skills whilst covering core topics required by professional bodies by deliberately incorporating open-ended, real-world industrial activities into teaching and learning activities within assessed modules. It describes and critically evaluates the approaches taken by students undertaking waste-focused activities that involve collaboration with an external organisation. It outlines the results of the scoping reports, by cost benefit analysis, as well as discussing the environmental benefits, utilisation of industrial relationships, potential improvements and limitations of the approaches/processes selected. The benefits to SW, the students and the academics are discussed, together with the outcomes from this activity.

The report arising from this task and associated research has shown clear areas where SW can improve on its wastewater management strategy to reduce their environmental impact, recover nutrients and materials as well as lowering costs and producing new revenue streams. This could be achieved primarily by implementing upstream recovery of nutrients and heat energy which would have the combined effect of producing a revenue stream from the sale of a novel fertiliser, reduce maintenance costs associated with struvite precipitation and help displace fossil fuel derived fertilisers and energy. If implemented, SW could see large economic savings in the operation of their sludge treatment facilities. For example, SW could liaise with Southampton City Council and their local waste management contractor to collect food waste separately and to investigate co-digesting food waste on sludge treatment sites, reducing costs for the council, recovering energy and biomass, and producing a revenue stream for SW.

Targets for increasing nutrient and material recovery, energy usage reduction and energy production could be set and audits carried out periodically to check progress against these targets. Landfill and incineration cannot be seen as zero waste concepts and SW can help other companies in order to comply with the Waste Framework Directive (2008/98/EC) by the co-utilisation of their sludge treatment facilities for organic waste treatment.

There is no doubt that this student-led learning activity stimulated interest, discussion and debate and generally raised both students' and SW's employees' awareness of CE issues. In an educational context, there is considerable merit in prompting action learning of this ilk. Although students' levels of achievement and performance were highly varied, there is little doubt that this task stimulated independent learning and development of professional and employability skills. From the perspective of SW, the students' activities and reports generated suggestions and recommendations that may not have been obvious means to achieve steps towards CE thinking at SW, and may not have otherwise been forthcoming.

As well as describing and evaluating the activity, this paper has showcased some of the learning materials developed, reported on the practical and logistical issues encountered, summarized results from the different activities, evaluated feedback from the students and the commercial organisation, and highlighted potential future developments.

BOX 1: Verbatim response of the module team to students' comments about the assignment (provided halfway through the Semester).

"The comments generally suggest that the coursework is too hard, too complex, contains too much science and engineering and that the deadline is too tight. We are obliged to set challenging coursework at this advanced level of study. We think the coursework mimics exactly what a waste manager / consultant would be required to do by a client and hence we believe that the assignment prepares you well for the "world of work." We think you will start to appreciate the skills and attributes you have developed by tackling this assignment when you've had your feedback, mid-semester pressure has waned and you are feeling more reflective.

We thought we had made it clear in the module's paperwork and via lectures that students could contact us at any time to discuss any aspects of the module. It is pleasing that a large number of students have emailed us to ask a question or to make an appointment to discuss questions relating to the assignment. Students also often use the break between lecture slots to ask questions. We have responded to and met with everyone who has made a request and answered their questions or provided clarifications. We would encourage any students with further questions to contact us immediately – we will be happy to help.

There are a couple of comments about the coursework hand-in date. We gave your assignments out in Week 1, Lecture 1. We outlined the assignments in the lecture and we explained in detail why we set the coursework deadline towards the latter end of November. It is normal for students to be feeling work pressure in mid-semester. The truth of the matter is that no matter when we set the deadline, someone would complain! We set it early so you have the choice when to start your work, according to your own personal schedule.

The coursework weighting is "tried and tested" so we feel it is appropriate. We try and get the right balance between natural sciences, maths and aspects of engineering, social, economic, operational, practical and political issues – Environmental Science is a "broad church" and we need to maintain this tradition on ENVS modules. A second site visit is not available because the site operator cannot schedule it. We'd like to respectfully point out that the coursework is NOT about wastewater – it is about the circular economy and how a waste that has traditionally been normally disposed of by "dumping" – raw sewage – could be turned into resources (including energy, nutrients, aggregates, other raw materials, etc etc).

Thank you for taking the time to provide us with this very useful feedback. We will reflect on all your comments again at the end of the Semester and make changes as necessary."

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