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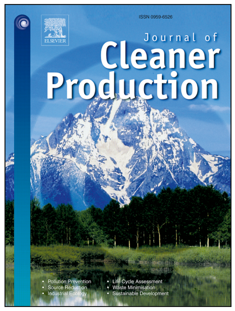

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Managing anaerobic digestate from food waste in the urban environment: evaluating the feasibility from an interdisciplinary perspective

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Abstract

Anaerobic digestion of food waste within urban areas can generate decentralised renewable energy, support community enterprise activities and thereby contribute to closing the waste-energy-food loop. However, widespread uptake of small-scale, urban anaerobic digestion networks is limited by economic costs and the safe disposal of surplus digestate. This paper uses an interdisciplinary approach to assess the feasibility of anaerobic digestate management through the installation of hydroponics or algae cultivation systems, based on a case study of a micro anaerobic digestion system in London, England. Results show that installing a dewatering sifter together with a hydroponics system is a technically and economically feasible option for digestate enhancement in the urban environment. Its installation is, however, not currently justified for the system under consideration due to cost, regulatory, spatial, and contextual constraints identified using actor-network analysis. Nevertheless, if regulatory and wider contextual issues are accommodated, and more than 30 litres of digestate are produced daily, a dewatering and vertical hydroponic system could result in a profit of approximately £100,000 over 10 years. While the microalgal system was also able to upgrade digestate, at present productivity is too low and the capital cost of photobioreactor technology is prohibitively expensive. This underlines the need for technical improvements and low-cost enhancement options to achieve justifiable paybacks until regulatory reforms and the wider economic situation are more favourable to anaerobic digestion treatment within cities.

Keywords:

Micro anaerobic digestion; waste-energy-food loop; circular economy; digestate management; nutrient recycling

1. Introduction

Roughly 1.3 billion tons of food produced for human consumption gets lost or wasted, a major global issue generating negative externalities in both social and environmental terms (Gustavsson et al., 2011). UK households alone discard 7 million tonnes of food waste annually, costing an average family £50/month (WRAP, 2012). The majority of this food waste is produced within cities, implying the need for effective urban food waste management. Food waste management has increasingly been defined as a social topic of interest, with a primary commitment of food waste prevention (Girotto et al., 2015). Reaching this social focus there is a need for community awareness and cooperation, sustainable supply chains and political action. In the European Union, such action was demonstrated thoroughly in the Circular Economy Package 16 Action Plan, which champions 'Reduce, Re-use and Recycle' initiatives (EU, 2016). However, even after implementation of such initiatives, at least 40% of food waste generation is inevitable (WRAP, 2011). Small-scale Anaerobic Digestion (AD)[*] is a favourable way of utilizing this food waste fraction within cities, as it reduces CO_2 emissions from transport and landfills (Appels et al., 2011; Mata-Alvarez et al., 2000). The produced biogas contributes to fossil fuel substitution, while the nutrient-rich AD-effluent can be used as organic fertilizer (Nkoa, 2014).

There has been a wide uptake of AD technologies in the UK since the 1990s, following the introduction of various policy incentives (Edwards et al., 2015). However, this uptake is limited to rural locations treating large amounts of agricultural waste, at scales over 125kWe electrical output (NNFCC, 2016). At smaller scales, AD is predominantly used in developing countries to treat food waste and contribute to urban electricity needs (Lansing et al., 2008). In developed countries such as the UK however, small-scale AD plants are rare despite their potential for urban food waste management (Zhang et al., 2007). A number of authors have addressed the feasibility of such micro-scale AD along with the combustion of biogas in

[*]Abbreviations: AD, Anaerobic Digestion; ANT, Actor-Network Theory; CBA, Cost Benefit Analysis; g, grams; kWe, Kilowatts of electrical output; NPV, Net Present Value; TAN, Total Ammonia Nitrogen.

developed economies (Walker et al., 2017; Stoknes et al., 2016). A common gap in these studies is the effective use of AD-effluent on the small scale. Conventionally, digestate is either landfilled, or directly applied to land. Direct application of AD-effluent as fertilizer is limited due to its nutrient-specific parameters, possible land contamination and the lack of fertile land for application (Xia and Murphy, 2016), which is problematic especially in urban areas. As a consequence, the disposal of digestate is becoming more tightly regulated (Gerardo et al., 2013). Moreover, strict regulations over AD-effluent, such as the UK-specific PAS110 regulation, make its direct disposal problematic (WRAP, 2010). Yet there is real technological potential to recycle the nutrients from AD-effluent through secondary processes and increase the viability of urban small-scale AD plants. As such, the purpose of this paper is to offer and evaluate the economic and operational feasibility of alternative digestate enhancement processes at urban, small-scale levels.

2. Small-scale AD application within cities

Small-scale AD networks have a number of advantages relative to conventional plants. These include decentralised renewable energy generation within cities, reduced waste transport and the potential for community food-growing initiatives. For example, Curry & Pillay (2011) found that small-scale AD plants in urban buildings in Montreal saved transport costs, reduced waste-to-landfill and contributed to urban sustainability. The feasibility of establishing such small-scale AD networks in the urban environment, including cost and benefit analyses of various biogas applications, has been evaluated by WRAP (2013). Increasing methane yield is instrumental for improving the economic feasibility of the AD plant itself, and is in large part determined by the food waste composition. Moreover, technologies can increase the efficiency of AD of food waste, which include co-digestion, addition of micro-nutrients and antifoaming agents, and different process designs (Xu et al., 2018). Li et al. (2017) studied the optimum composition ratios of carbohydrate, protein and lipid to maintain a high methane yield.

While a number of papers address options for improving the methane yield of AD systems, few focus on alternatives to increase profitability of the AD-effluent, especially for small, urban AD systems. One exception is Stoknes et al. (2016), who demonstrate an innovative method where AD-effluent is vermi-composted. Typically, however, the surplus AD-effluent is stored and disposed of in a costly manner (Xia and Murphy, 2016), counteracting the intended benefits of waste reduction. Apart from the transport costs, the ever-increasing digestate production also induces problems related to greenhouse-gas emissions during storage (Monlau et al., 2015). Holm-Nielsen et al. (2009) argue that to unlock the full sustainability potential of AD, nutrients from AD-effluent should be recycled. One method of nutrient recycling is dewatering the AD-effluent and applying the solid and liquid fractions in alternative, innovative ways.

2.1 Dewatering

Techniques to dewater AD-effluent to a solid and a liquid fraction can be divided into mechanical and non-mechanical systems. Mechanical systems include belt presses, decanter centrifuges, screw presses and gyratory sifters, while non-mechanical systems include sedimentation or passive filtration. According to Sheets et al. (2015), non-mechanical dewatering systems are particularly suitable for small-scale projects. However, their overall feasibility is impeded by two key factors: reduced separation efficiency and high odour potential. Firstly, non-mechanical dewatering systems cannot achieve the same separation efficiency as mechanical techniques, a feature that can hinder further enhancement processes (Hjorth et al., 2009). Secondly, non-mechanical dewatering systems are generally not closable, creating odour problems from the hydrogen sulphide gas and gaseous ammonia in the AD-effluent (Turovskiy & Mathai, 2006, p.207). Such odour problems reduce the urban feasibility of the technique, as they are susceptible to complaints from the nearby community. Given these two reasons, only mechanical dewatering systems were considered.

A comparison of the above-mentioned mechanical dewatering technologies (see Table A1) revealed that the gyratory sifter is the most technically and economically suitable option for small-scale dewatering application, mainly due to its low energy demand and its low capital and operational cost compared to belt presses, decanter centrifuges and screw presses. Gyratory sifters use vibratory motion to allow particles from the AD-effluent to penetrate from coarser into finer decks, hence separating particles of similar size and dewatering the AD-effluent (Drosg et al., 2015). Gyratory sifters exist for small volume management, with a throughput of 0.05 m^3/hour, a power of 0.25 kWe, a small footprint of 0.9 m height and 0.6 m diameter, and a separation efficiency of up to 70% dry matter (Drosg et al., 2015).

2.2 AD-effluent enhancement

After dewatering, both the liquid and the solid fraction of AD-effluent can be enhanced. This paper focuses on enhancement of the liquid fraction for two key reasons: 1) the liquid fraction makes up 80-90% of the total mass of AD-effluent and 2) the liquid fraction retains 70-80% of dissolved nutrients such as ammonium, which promote turf growth and food growing (Drosg et al., 2015). As such, this fraction provides greater opportunity for valorisation. Moreover, in the urban, small-scale environment, the solid fraction is negligible, and can be composted (Bustamante et al., 2012) to be used as agricultural biofertiliser (Xia and Murphy, 2016). Sanitation can be achieved as the decomposition of organic matter heats up the compost to up to 70 degrees (WRAP, 2012, A48).

Sheets et al. (2015) provide an overview of emerging technologies for the management of the liquid fraction of AD effluent, which include ANAMMOX, struvite crystallization, ethanol fermentation or use of microbial fuel cells for electricity generation, hydroponics and algae production. These methods were reviewed on a number of criteria, including cost, feasibility in the urban environment, and feasibility for small-scale application (see Table A2). The use of the following digestate enhancement options are not applicable within cities, either due to cost considerations, the need for large-scale infrastructure, or the complexity of the process: ANAMMOX, struvite crystallization, ethanol fermentation or use of microbial fuel cells for electricity generation. Hence, this paper focuses on evaluating biological treatment methods that use AD-effluent as nutrient solution for further cultivation: microalgae cultivation and hydroponic food production. These were chosen because of their potential to produce products suitable for the urban environment, and because they were identified by WRAP (2013) as appropriate for micro-AD networks. Moreover, both methods require little land, with microalgae cultivation using merely 3% of traditional direct land application of digestate (Xia and Murphy, 2016). The steps and materials for each of these processes are shown in Fig.1.

2.2.1 Microalgae cultivation

In this paper, the term algae will refer to microalgae. The high levels of nitrogen, phosphate and trace elements available in the liquid fraction of AD-effluent can be used as nutrient supply for growth of lipid-rich, non-toxic algae biomass (Cai et al., 2013). Microalgae can be cultivated for algae biomass production with a theoretical productivity of between 77 - 96g of dry matter per m^2 per day (at 10% photosynthetic conversion efficiency) (Schenk et al., 2008). The growth rate and productivity however depend on the algae strain and culturing conditions, which are summarized and compared by Monlau et al. (2015). Silkina et al. (2017) document the effective treatment of sludge with algae cultivation to support high value end product generation.

Limitations of microalgae cultivation include less-than optimal growth rates (Tang et al., 2012) due to bacterial contamination, turbidity, ammonia nitrogen inhibition or phosphorus and carbon limitations (Xia and Murphy, 2016). Luo et al. (2017) argue that interactions between bacteria and algae in such systems for microalgae cultivation need to be further studied to improve the technology. Although algal bioreactors have been developed to a commercial scale, few functional photobioreactors for microalgae cultivation exist that treat small quantities of AD-effluent. Additionally, it was noted that concentrations above 50% of digestate may be toxic to microalgae due to the substrate toxicity. Digestate may contain compounds inhibiting microalgal growth such as urea, organic acids, phenols and pesticides (Djelal et al., 2014). Thus an optimal concentration is necessary in order to successfully utilize digestate as a nutrient source for microalgal biomass production. Moreover, the turbidity in AD-effluent could cause inadequate light penetration for algae biomass growth. For example, Wang et al. (2010) showed reduced growth of *Chlorella* sp. in AD-effluent due to turbidity. Moreover, Park et al. (2010) demonstrated that *Scenedesmus* sp. was inhibited by ammonium at levels of 100 mg/litre. Insufficient phosphorus supply can also be a limiting factor in liquid digestate applied to microalgal cultivation (Fuchs and Drosg, 2013). Additionally, carbon sources in digestate may be much lower than required (Ward et al., 2014).

In light of these challenges, Wang et al. (2010) recommended diluting the liquid fraction of AD-effluent to initial total nitrogen concentrations of less than 200 mg/litre to reduce ammonium concentration and lower turbidity for improved light penetration. They also suggested further treatment using filtration or autoclave in order to prevent any contamination in the algae cultivation process. The requirement of metal-tolerant microalgal species is also of importance (Osundeko and Pittman, 2014) when cultivating in anaerobic digester centrate (Guldhe et al., 2017).

In the urban environment, small photobioreactors in vertical tubular or bag systems could be used for algae cultivation due to their relatively small footprint and easy control. Problems with pilot-scale algae cultivation as stated by Cai et al. (2013) include unstable biomass production, contamination and inconsistent wastewater components, and need to be addressed. The algae cultivation process could be carried out using batch or continuous production (Razzak et al., 2013). Algal biomass can be sold for further enhancement, for example to produce energy (Zammalloa, 2011). Given that the AD process also generates heat and CO_2, two main inputs needed to stimulate algae growth, algae production shows promising enhancement potential for AD-effluent, reducing both economic and environmental costs (Vasseur et al., 2012).

2.2.2 Hydroponic food production

The liquid fraction of AD-effluent can alternatively be utilized as nutrient solution for hydroponic food production (Thiyagarajan et al., 2007). Krishnasamy et al. (2012) identified that diluting 1 L of liquid AD-effluent from food waste with 5 L of water resulted in highest foliage yield and plant growth, and can alleviate NH_4^+ toxicity in a small-scale hydroponic system. After dilution, the quality and ecotoxicity of the nutrient solution containing AD-effluent should be assessed regularly, as it depends on the food waste input (Krishnasamy et al., 2012). For example, AD-effluent may contain antibiotic residues (Govasmark et al., 2011), organic pollutants (Hellström et al., 2011) or heavy metals (Kupper et al., 2014). Pathogens can easily spread in hydroponic systems due to high nutrient concentrations which may ruin entire crops through rapid spreading in water circulation (Lee and Lee, 2015). Methods for the examination of AD-effluent include standardized in vitro ecotoxicological tests using aquatic test organisms (e.g. D. magna, V. fischeri), earthworms or soil-based bioassays (Pivato et al., 2016). Moreover, analysis of the soil microbial community response after soil application of AD-effluent gives an indication of potential negative effects and the safety of digestate (Stenberg, 1999). As such, a microbiological analysis of AD-effluent is recommended before application in hydroponic food production. Further limitations of hydroponic food production include the need for specialized management knowledge (Lee and Lee, 2015), suggesting the importance of academia - practitioner relationships.

For urban, small-scale use, a controlled greenhouse structure is recommended, because food production output per hectare is high compared to open farming and nutrients are more easily controlled (Heuvelink et al., 2008). In a hydroponic greenhouse system, cultivation of green vegetables is considered most profitable. In fact, Liedl et al. (2004) suggested that the use of diluted AD-effluent was comparable to a commercial nutrient solution in the production of lettuce. Furthermore, closed pipes directly connected to the outlet of the anaerobic digester are recommended for use in the urban environment.

2.3 Review on methodology

While the above-mentioned review evidences the extensive literature published on the technical possibility to enhance digestate using algae cultivation or hydroponic food production, few papers address the economic feasibility of these processes, and none focuses on the urban environment. Moreover, few studies consider relevant social and operational context in the evaluation of technologies in the field of engineering. These social factors are however critical to the successful implementation of a technology (Valdes-Vasquez, 2011).

To address these gaps, an interdisciplinary, solutions-focussed approach was adopted in this paper to assess the feasibility of the two digestate enhancement options. This approach is illustrated for a small-scale AD system in Camley Street Natural Park in Camden, Central London. The micro AD set-up and process of the case in Camley Street Natural Park, along with cost and revenue information from the associated biogas production, is further described by Walker et al. (2017). This study focuses specifically on the economic and operational feasibility of the digestate enhancement plant as a stand-alone additional system.

Actor-Network Theory (ANT) was used as a tool to understand the context of this case study, for the theory acknowledges that technologies cannot be understood unless they are studied in the context within which they exist. Callon (1986a) defines this idea as 'co-evolution' of society, technology and nature, through three main features: actor-worlds, translation and the actor-networks. Actor-world is the context where different entities interact, which can be either human or technical, with each of these given equal importance (Callon, 1986b). Translation is the process of constructing an actor-world from the different entities. ANT asserts that the removal or addition of any actor, as is the case when a new technology is introduced, affects the functioning of the whole actor world (Doolin & Lowe, 2002). Taking into account that the main obstacle to closed-loop functioning of the small-scale AD plant in Camley Street Natural Park is digestate handling, a search for a context-appropriate urban digestate management solution is warranted. The outcomes of this study can contribute to knowledge on key issues and intervention points for viable urban digestate management. Implementation of recommendations could contribute to closing the waste-energy-food loop and possibly allow further uptake of small-scale AD networks in cities.

3. Materials and Methods

The methodology proposed in this paper provides a logical framework to help decisionmakers and stakeholders involved in small-scale AD development evaluate the feasibility of urban digestate enhancement options. The methodology emphasises the interconnection between technical, economic and social criteria in determining the feasibility of a technology. It consists of two basic elements: (i) a techno-economic analysis (using tools from engineering and economics, including technical criteria, net present value, sensitivity and scenario analysis through automated simulations); and ii) the use of the actor-network theory to understand the social totality in the context of the case study of Camley Street Natural Park, London, UK. Our work draws upon the archives and literature associated with AD, including references to studies by others; interviews and correspondences with technology manufacturers; and visits to the specific project in Camley Street Natural Park (see Table 1).

Table 1: Overview of information collected and its source.

Type of Information Collected		Source of Information
General Information		
	Dewatering system	Correspondences with Russell Finex
Technical Feasibility		
	Technical data gyratory sifter	Russell Finex
	Technical data hydroponics	Article 25
	Technical data algae cultivation	Commercial supplier, literature
Economic Feasibility		
	Cost gyratory sifter	Russell Finex
	Cost hydroponics	Article 25
	Revenue hydroponics	Article 25
	Costs algae cultivation	Commercial supplier
	Revenue algae cultivation	Lizzul et al. (2014)
Operational Feasibility		
	Interview with stakeholders of Camley Street Natural Park	

3.1 Site description

The pilot AD in Camley Street Natural Park converts locally produced food waste collected by a cargo bicycle into biogas for electricity production. The 2 m^3 anaerobic digester is fed with approximately 20kg of food waste daily, to which 2 L of water are added in order to clean the system and ensure the right viscosity feedstock (see Walker et al. (2017) for a detailed description of the system operation). Of this total volume, 90-95% is outputted daily as AD-effluent, with 17 L in the form of liquid AD-effluent. This paper focuses particularly on the business case for the digestate.

3.2. Techno-economic analysis

A Cost Benefit Analysis (CBA) was carried out to determine the economic profitability of the digestate enhancement system, following the method of Zamalloa et al. (2011). For the techno-economic analysis, the lifetime of the enhancement system was set to 10 years. The two digestate enhancement methods, hydroponics and algae cultivation, were compared using the Net Present Value (NPV). A simulation code (see supplementary information) was created for three main purposes: 1) demonstrate how the NPV changes with larger amounts of AD-effluent, 2) test the sensitivity of key parameters to externalities and uncertainties, and evaluate their effects on NPV; and 3) explore the effect of possible scenarios on the feasibility of the enhancement options.

3.2.1 Costs

A gyratory sifter from Russell Finex will be used both for the separation of the solid and liquid AD-fraction and to dewater algae, with a capital cost of £10,500 and yearly operational costs of £3,165, including maintenance and cleaning. The costs for algae cultivation and hydroponics food production (see Table 2) are based on the current volume of AD-effluent available at Camley Street Natural Park. It was assumed that heat, water and CO_2 can be obtained for free from the AD facility, and that AD-effluent storage does not incur a further cost. London Living Wage (£9.50/hour) was used, and a wage rate of £15/hour was applied for the higher skilled labour required for algae cultivation (Coulson & Richardson, 2005). The annual maintenance cost for both algae production and hydroponics was calculated to be 10% of installed capital costs divided equally between labour and materials (Coulson & Richardson, 2005). For calculations of equipment and labour cost with varying production facility size, 95% was assumed to be fixed and 5% variable with increasing volume of AD-effluent. Equipment costs for the photobioreactors are shared between three reactors and a discount of 8% was applied when more than three photobioreactors were purchased, in line with a cost estimate obtained from a commercial supplier. The solid fraction of AD-effluent will be composted on site, and does not constitute an additional cost. Land rental costs in this system are not included, and it is assumed that the digestate enhancement facility is co-located with the AD plant.

Table 2: Capital and operating expenditure for enhancing AD-effluent with a) algae cultivation system (left) based on information from Zamalloa et al. (2011) and commercial suppliers; b) hydroponic system (right) based on information from Article 25. Values are based on AD-effluent volume available in Camley Street Natural Park (17 L/day).

Algae Cultivation		Hydroponics	
Item	Amount (£)	Item	Amount (£)
Capital costs			
Site preparation	2,000	Sensor system	5,750
Instrumentation and machinery (recirculation pump, etc.)	2,500	Instrumentation and machinery (Water tanks, nutrient tanks, water heater, piping, sensor system)	2,327
Photobioreactors (2 *550 L each)	32,510	Growing system	3,265
Equipment costs per 3 photobioreactors	6,771	Equipment costs, e.g. lights	200
Installation/ Commission	10,500	Installation/ Commission	500
Delivery/ Packaging	750	Monitoring	1,000
Total capital costs	*55,031*		*13,042*
Yearly operational costs			
Maintenance	3,251	Maintenance	1,248
Labour	3,375	Labour	6,599
Materials (e.g. flocculants)	200	Materials, (dissolved oxygen, growing media, seeds, supplementary fertilizer)	840

Utilities (electricity)	1,100	Utilities (electricity, heating)	1,624
Total yearly operational costs	*7,726*		*10,311*

For the MATLAB calculations, the amount of variable and fixed CAPEX was based on calculations of different AD sizes and their varying amounts of AD-effluent.

3.2.2 Operational Parameters and Revenue Estimation

Revenue calculations were made for the digestate enhancement system only. Calculations for algae cultivation (see Table 3) are based on parameter values from Lizzul et al. (2014), who also used AD-effluent sourced from Camley Street Natural Park. These include using an illumination of 80 μmol/m^2 with a batch duration of 4 days, an algae biomass yield of 0.32 g/litre and the media being augmented with exhaust gas containing 12% carbon dioxide. While Lizzul et al. (2014) grew *Chlorella sorokiniana* in 1-litre Duran bottles converted into photobioreactors, a scalable manufacturing system based on specialised photobioreactors was considered in this study. Using the Total Nitrogen content (53 mg/litre) of the diluted liquid fraction from Lizzul et al. (2014) as a desired value for optimal algae growth, and the available nitrogen content of 960 mg/litre in the liquid AD-effluent fraction from Camley Street Natural Park, the dilution rate per litre has been calculated to be 18. The algae cultivation calculations were performed under the following assumptions: the metabolism of algae does not switch, algae are ready for harvesting after all nitrogen has been consumed, and all AD-effluent is used.

The revenue calculations for hydroponics were built upon the methodology and parameter values from the charity Article 25. Using the Nutrient Film Technique, the liquid fraction of the AD-effluent was diluted 4 times, and lettuce and oriental greens were grown with an illumination of 16 hours/day at 200 μmol/m^{2}s, at a temperature of 24 °C during the day and 19 °C at night.

Table 3: Revenue parameters for a) algae cultivation (left) based on information from a commercial supplier and EnAlgae (2014); b); hydroponics (right) based on information from Article 25.

Parameter			
Algae Cultivation		Hydroponics	
Amount of liquid digestate per day (L)	17	Liquid digestate in system per day (L)	17
Amount water required per day to dilute to 53 mg/litre total nitrogen (L)	306	Square meters of cultivation (m^2)	21
Volume growth medium per day (L)	323	Number of plants in system	525
Working volume per batch (L)	1,292	Litre recommended in system (L)	1,050
Capacity of 1 PBR (L) [a)]	550	Recirculation rate (L/h)	3,150
Number of PBR's used (L)	2	Recirculation (L/day)	75,600
Amount of culture (algae and wastewater) after one batch (L)	1,100	Productivity per crop (kg)	70.88
Amount of Algae biomass (kg/batch)	0.35		
Number of batches (batch/year)	75	Yield per day (kg)	2.95
Algae biomass yield (kg/year)	26.4	Yield per year (kg)	885.94
Selling price algae biomass in (£/kg) [b)]	27	Selling price lettuce (£)	7.50
TOTAL YEARLY INCOME (£)	713		6,645

3.2.3 Assumptions

To evaluate the profitability of the two digestate enhancement processes with varying AD-effluent volume (using a MATLAB simulation), a number of assumptions were made: construction of the plant finishes after one year and starts to operate at its maximum capacity immediately, the enhancement facility can be built on the existing digester site at Camley Street Natural Park, the plant has no scrap value at the end of its lifetime, and costs of the AD plant set-up are paid back. Moreover, no taxes are charged against the plant's profits given the nature of the community enterprise project and support by governmental organisations such as WRAP and DEFRA. The number of operational days was assumed to be 300 days (Coulson & Richardson, 2005). The dewatering gyratory sifter would be used 30 minutes per day, at a dewatering capacity of 0.5 L/h, an energy use of 0.125 kWh per day and an electricity cost of 0.12 £/kWh.

3.3 Contextual analysis

ANT was used as a framework to identify whether key actors agree that the dewatering system is worth building and defending (Callon, 1986b), and to suggest the necessary steps to best tailor the technology to the community interest (see Table 4). Key stakeholders were interviewed to determine the actors affecting the operational feasibility of the enhancement system. These actors were mapped to assess their interrelations and to understand the embedded complexity. Trade-offs and opportunities of implementing the proposed system were analysed to formulate coherent recommendations of how these problems could be overcome.

Table 4: Applying Actor-Network Theory to the case study in Camley Street Natural Park. Source: Callon (1986b).

Literature	Application Camley Street Natural Park
Actor-world	
Actor-world as context where actors interact	Context is Camley Street Natural Park, Camden, London
Translation	
Translator-spokesman defines actors and their roles, creating the actor-world (Callon, 1986b, p.26)	Researcher acting as primary translator-spokesman and manager of the Camley Street Natural Park as a second translator-spokesman. This allowed the definition of the actor-world to be a participatory and iterative process, as suggested by Teh (2013).
Actor-networks	

Actor-networks identify dynamic relationship between actors and the network of each actor itself.	The network of each actor has been determined together with the manager of Camley Street Natural Park.

4. Results

For urban, small-scale digestate enhancement (between 30 and 250 L of daily AD-effluent volume), hydroponics was found to be more economically feasible compared to algae cultivation. Algae cultivation could become an economically competitive option if algae biomass yield can be increased. Results of this study indicated that technical improvements such as vertical hydroponics or increased algae growth rate had the largest impact on the economic feasibility of the two enhancement options. For successful installation, various operational problems with a future installation of a dewatering and enhancement system need to be overcome. These include dealing with odour, location, financing and regulatory issues regarding the sale of food grown on AD-effluent. Specific findings about the case study are presented in sections 4.1 - 4.3 respectively.

4.1 Case-study specific findings: Techno-economic feasibility

The installation of a dewatering and enhancement facility was found to be technically feasible, but cannot be economically justified given the current liquid AD-effluent volume of 17L/day produced at Camley Street Natural Park. While the economics of hydroponic food production are preferable to that of algae cultivation (see yearly contribution to cover the capital costs in Table 5), the cost-benefit analysis demonstrated that the high investment costs for both enhancement processes would not be repaid in the considered time period of 10 years. The capital costs of algae cultivation are prohibitively expensive, while income from algae biomass is relatively negligible. In the case of hydroponic food production, yearly operational costs are high in relation to possible income from food sales.

Table 5: Cost-Benefit Analysis over 10 years for current AD-effluent quantity of 17 L per day: Algae cultivation and hydroponics with gyratory sifter (24" Eco Separator from Russell Finex with capital costs of £10,500 and yearly operational costs of £3,165 and are included in the total costs for both hydroponics and algae cultivation).

	Algae cultivation costs (£)	Hydroponics costs (£)
Capital costs	65,531	23,542
Yearly operational costs	9,791	12,228
Yearly income	713	6,645
Yearly contribution to cover capital costs	-9,078	-5,583
Payback Period	Never	Never

Operational costs and income shown in Table 5 were scaled in the economic analysis with changing AD-effluent (see supplementary information Matlab Code). This analysis illustrated that hydroponics becomes viable with increasing amounts of AD-effluent produced (break-even at 40 L of AD-effluent produced). Meanwhile, the profitability of algae cultivation remains low within the given system boundaries of computations up to 300 L of daily AD-effluent volume. Moreover, this digestate volume may require a different system for cultivation, with a considerable footprint.

3.1.1 Sensitivity Analysis

A sensitivity analysis re-examined these results under two decisive parameter values: 1) the percentage variable operational cost (using a 'Best Case Scenario' with OPEX distribution of 95% fixed and 5% variable cost; 'Medium Case Scenario' with OPEX distribution 80% fixed and 20% variable cost; and 'Worst Case Scenario' with OPEX distribution of 65% fixed and 35% variable) and 2) the discount rate (0%, 3.5%, 7%).

Given that differences between these scenarios proved significant, the most appropriate scenario for social projects (the 'Medium Case Scenario' and the 3.5% discount rate) was further analysed (Cabinet Office, 2016). In this scenario, the use of a gyratory sifter coupled with a hydroponic system becomes economically feasible (with a profit of £500,000 over 10 years) for Camley Street Natural Park if approximately 150 L of AD-effluent are produced daily.

3.1.2 Scenario Analysis

An analysis of three scenarios constructed for each enhancement option assessed the robustness of the results to externalities and future changes. Scenarios for each option include 1) governmental interventions through subsidies for key capital costs, 2) changes in the macroeconomic environment impacting the price of the sold product, and 3) technical improvements to system operation.

For hydroponic food production, the technical improvement scenario of doubling the plants per square meter in a hydroponics setup (scenario 3) had the largest effect on the profitability of the facility (Fig.3). This scenario could be achieved using a vertical hydroponics system. It could yield a profit of approximately £100,000 over 10 years if double the AD-effluent volume in Camden (approximately 30 L daily) is available. Governmental interventions and changes in the macroeconomic environment had a small impact on NPV. These included scenario 1, funding for the greenhouse structure, and scenario 2, increasing the selling price from £7.50/kg to £10/kg. As such, these factors do not determine the economic feasibility of small-scale hydroponic systems.

For algae cultivation, the technical improvement scenario also had the largest effect on NPV compared to governmental interventions or changes in the macroeconomic environment. In fact, the technical improvement scenario, 'scenario 3', increased algae biomass yield from 0.32 g/litre to a yearly average of 1g/litre, because a higher algae biomass yield was observed in other studies (Sheets et al., 2015). This led to a profit of £5,000 with 250 L of AD-effluent in Camley Street Natural Park (see Fig.4). For scenarios 1 and 2, funding for the photobioreactor and doubling the selling price of algae biomass, NPV remained negative in the given system boundaries.

4.2 Case-study specific findings: Operational feasibility

Mapping the interrelationships between the different human and non-human actors in Camley Street Natural Park revealed the value of using ANT: an understanding of how objects can shape social relationships and determine key decisions (Cresswell et al., 2010). Highlighting the central nodes in the network (see Fig.5), it was possible to identify which actors can further impact other actors and hence shape the feasibility of the dewatering system to a larger extent. The manager of the AD plant in Camley Street Natural Park is a key actor linking various different actors together in her network. Moreover, both the cost of the dewatering system as well as the benefits that can be reaped from enhancement strategies of the liquid AD-effluent fraction directly influence the decision of the AD manager in Camley Street Natural Park. Nevertheless, ANT considers that every actor has the same value (Callon, 1986b). Applying this idea to the operational feasibility study suggests that no actor should be disregarded, especially because the actor worlds and their networks are only temporally stable and are likely to change in the future. This could result in one actor becoming significantly more important and determining whether a digestate enhancement system would become feasible, thus confirming the view of Cresswell et al. (2010, p.4) in the sense that actors "are what they are depending on the context in which they are embedded and used".

The deployment of actor-network theory suggested that even if an economic benefit could be obtained, a dewatering technology would still have to meet certain criteria to be considered worth implementing in Camley Street Natural Park, London. Firstly, the energy consumed by the proposed mechanical equipment would have to be outweighed by the benefits to be gained in order to align with the vision of model viability at Camley Street Natural Park. Secondly, possible regulatory restraints on the sale of food or algae biomass grown on AD-effluent need to be identified and addressed. Thirdly, odour proofing is necessary to eliminate the possibility of odour problems related with the transport of AD-effluent, which can reduce possible public antagonism. However, the manager of Camley Street Natural Park, as a central actor, identified the economic viability as the main barrier currently hindering the installation of the proposed system.

5. Discussion

The research resulted in a variety of economic and regulatory indications showing that small quantities (<250 L) of liquid AD-effluent can be enhanced using hydroponics or algae cultivation in the urban environment. Most authors have summarized or evaluated treatment and reuse of AD-effluent from large-scale AD (Sheets et al., 2015; Frischmann, 2012, WRAP, 2015). The technical potential of emerging digestate enhancement methods has also been reviewed, including algae production (Cai et al., 2013) and hydroponics (Krishnasamy et al., 2012). However, no study to date has specifically evaluated treatment of liquid AD-effluent within urban AD networks, or studied the economic or operational feasibility of these options on smaller scales.

Results from this study focus on the digestate enhancement plant as a stand-alone economic and operational system, and are dependent on the considered case study. While for most of the presented processes there are still great uncertainties and gaps regarding investment and running costs, this study nevertheless provides evidence of how nutrients from liquid digestate could be enhanced in the urban environment. Algae cultivation and hydroponics are both odour-proof processes and could reliably make use of the liquid AD-effluent fraction. At scales between 30 and 250 L of daily AD-effluent volume, hydroponics was found to be more economically feasible at enhancing liquid AD-effluent compared to algae cultivation.

These results are sensitive to biomass yield of algae cultivation, and emerging, low-cost photobioreactors may change the economics in favour of algae cultivation. Alongside economic analyses, it is equally important to perform adequate operational feasibility analyses to ensure effective and context-dependent implementation of digestate enhancement systems. These results are relevant to: 1) managers of existing urban, small-scale AD systems by providing research on options for digestate enhancement on this scale, 2) for managers of future small-scale, urban AD-systems by giving additional financial information to potentially improve the economics of the whole small AD-system process, and 3) to the academic community to indicate the potential for further research.

5.1 Economic feasibility of small-scale AD plants

Profits from small, urban AD-effluent enhancement are linearly related to AD-effluent quantity, suggesting the capital-intensive nature of AD systems documented elsewhere (Xu et al., 2017). This implies both the scale effect in the urban environment, and the importance of additional research into low-cost options for digestate enhancement systems. Within the system boundaries of this research, i.e. 300 L of AD-effluent quantity, a number of specific discussion points emerge.

Installation of a gyratory sifter coupled with hydroponics could yield a profit of £100,000 over 10 years for digestate enhancement of urban AD-networks if: 1) >30 L of AD-effluent volume are available daily, and 2) a vertical hydroponic setup is implemented (see section 3.1.1). The latter scenario is likely in light of the proven technical feasibility of a vertical hydroponics setup. A larger profit (up to £200,000 over 10 years) could be made from hydroponics with larger AD-effluent volumes (300 L per day). Hence, an economic benefit can be made from sharing one digestate enhancement facility within a small-scale AD network. In such a case, digestate enhancement may become central to the economic feasibility of the AD plant itself. This would reject findings from publications arguing that methane yield is the key determinant of the economic feasibility of small-scale AD plants (WRAP, 2013).

Algae cultivation could yield a profit of £5,000 over 10 years for urban digestate enhancement with: 1) a daily AD-effluent volume of >250 litre, and 2) use of an algae strain with biomass yield of 1g/litre. Sheets et al. (2015) present a biomass density of up to 0.75g/litre for *Chlorella sorokiana*, indicating that process optimisation could improve productivity. Moreover, the experimental study by Lizzul et al. (2014) on which the algae cultivation parameters of this study are based did not use a photobioreactor optimised for algae cultivation. Hence, the growth rate of algae might be significantly faster, which increases the NPV.

Results of this study indicate factors of particular importance in the economic feasibility of an urban digestate enhancement facility, which can be useful for managers of small-scale AD plants, funding bodies and universities alike. Economic feasibility is least affected by changes in the selling price of the final product sold, the food grown or the algae biomass produced. This can be attributed to the large CAPEX costs and low productivity of both hydroponics and algae cultivation. Funding for key capital costs of the digestate enhancement facility was also found to have little impact on economic feasibility. Meanwhile, the technical improvements such as vertical hydroponics or increased algae growth rate had the largest impact on the economic feasibility of the enhancement options, implying the need to support further research and practical applications in this area.

Close partnerships between small-scale AD plants, universities, governmental organisations and businesses are pivotal to implement these technical improvements. Edwards et al. (2015) highlighted the importance of incentives such as feed-in tariffs in the initial uptake of AD in the UK. This research suggests that in the case of small-scale AD uptake, and particularly urban digestate enhancement systems, such governmental support could be provided in two forms: 1) funding and support to universities, research institutions and start-ups to create, construct, and test the technical suggestions considered most impactful; and 2) subsidies or funding for the capital costs of digestate enhancement plants. This study further supports findings by Luo et al. (2017) who highlight the need for more collaboration between algal biologists and engineers to improve the sustainability of waste treatment processes.

5.2 Regulatory, operational feasibility of small-scale AD plants

Economic profitability of the digestate enhancement plant must be met in conjunction with providing recommendations for how restrictive regulatory issues might be overcome and odour issues addressed. For urban, small-scale AD plants, the daily AD-effluent should be transported to the centralised plant in sealed containers to minimize potential odour problems. With regard to hydroponics, regulations at EU level include the European Nitrate Directive 91/676/EEC, which limits the annual load of nitrogen to be applied to land as well as national environmental regulations which restrict the period of application (Drosg et al., 2015). These regulations might be moderated if the food grown is not sold commercially, but rather used for in-house cafés, as could be implemented in Camley Street Natural Park. Testing for odour proofing could be achieved by trialling the project to identify such issues. Potential odour problems from the use of hydroponics can be mitigated using granular activated carbon filters, double door systems, extractor fans, and hydroponic substrates to screen off AD-effluent from the open air, such as clay pebbies.

Additionally, conditions in the economic and regulatory environment need to be favourable to assure that the project would be feasible overall. Economic incentives such as grants or significant subsidies from local or national initiatives could cover the initial capital costs of the project. Favourable loan conditions including longer payback periods or lower interest rates for green community energy projects such as the pilot AD-network in Camden could largely improve the financial viability and security of the project. For example, the use of community-owned shares or green energy bonds may be a method well suited to raise money to finance the AD-effluent treatment plant. The first step to achieve this is bringing together community members in urban areas interested to form a community-based energy charity with specific focus on the AD plants. From these members, funding could be sought to pay the initial cost of the AD-effluent. In return, these community members obtain dividends from the profit of selling food or algae biomass throughout the lifetime of the project.

5.3 Recommendations for the small-scale AD in Camley Street Natural Park

For Camley Street Natural Park, the volume of available AD-effluent is low (<20 L per day), and it is unlikely that significantly larger volumes of AD-effluent will be produced in the near future. Hence, use of a shared hydroponics system is recommended, as it is likely that the requirement of more than 30 L of daily AD-effluent is met in light of the close proximity of two further small-scale AD plants to Camley Street Natural Park from which AD-effluent could be sought. This would not only lead to economic viability of the project, but also fully make use of the capacity of the dewatering system.

Implementation of the suggested changes in regard to economic viability and regulatory issues would allow for successful integration of a digestate enhancement facility to the small-scale AD plant in Camley Street Natural Park. This would solve the problem of urban digestate use, and simultaneously add value to the process, thereby contributing to proof-of-concept of small-scale AD networks in the urban environment. This is a key step in incentivising further uptake of such networks in the UK and beyond, as suggested by Walker et al. (2017).

The involvement of further actors through the implementation of a digestate enhancement plant is likely to increase knowledge of circular economy practices given the large emphasis of such practices at Camley Street Natural Park. This may then incentive a larger number of people to get involved in further community waste reduction and reuse initiatives advertised on the site, in turn contributing to the circular economy. Such a case is particularly likely if a closed-loop can be demonstrated on site by using hydroponic grown food in the in-house café of Camley Street Natural Park.

5.4 Further research

The feasibility analysis presented in this paper is part of a larger feasibility analysis of micro-scale AD, further discussed by Walker et al. (2017). Costs associated with micro-scale AD networks beyond the digestate enhancement system, such as micro-scale biogas plants and combined heat and power systems, need to be met and considered alongside the digestate enhancement system to understand potential synergies when taking up small-scale, urban

AD. Further research should identify other providers of small-scale dewatering machines to compare results. For future context assessment, a stakeholder analysis and decision matrix could be used to verify results of the actor-network analysis. Further studies should assess the feasibility of installing low-cost, non-mechanical enhancement systems, which could improve economic viability of small-scale, urban AD networks. Cost and regulatory information must be continuously updated, given the emerging and constantly-changing nature of urban algae cultivation and hydroponics.

6. Conclusions

A digestate enhancement facility consisting of a dewatering, gyratory sifter coupled with a vertical hydroponic system could be an economically feasible option to recycle nutrients of urban small-scale AD plants (with >30 L per day of digestate). If community energy AD projects such as the considered case study in Camley Street Natural Park are to flourish, wider support from governmental, regulatory and financial bodies is required. This includes changes to current regulations enabling AD-effluent to be classified as a product rather than waste, which would facilitate AD-effluent enhancement. Research exploring such local projects may further help gain support for sustainable, affordable and community-integrative living. New forms of community financing for such schemes need also to be canvassed. These include re-examining payback periods and discount rates, uses of community investment bonds, a resurgence of social enterprise, and a responsive approach from regulatory authorities in energy and waste management and community wellbeing from all levels of government.

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6. References

Appels, L., Lauwersa, J., Degrèvea, J., Helsen, L., Lievens, B., Willems, K., Van Impe, J., Dewil, R., 2011. Anaerobic digestion in global bio-energy production: potential and research challenges. Renew. *Sustain. Energy Rev.* **15** (9), 4295–4301.

Arthurson, V., 2009. Closing the global energy and nutrient cycles through application of biogas residues to agricultural land – potential benefits and drawbacks. *Energies* **2**, 226–242.

Bustamante, M.A., Alburquerque, J.A., Restrepo, A.P., de la Fuente, C., Paredes, C., Moral, R., et al., 2012. Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. *Biomass Bioenergy* **43**, 26-35.

Cabinet Office, 2016. Discount Rates and Net Present Value. https://data.gov.uk/sib_knowledge_box/discount-rates-and-net-present-value [accessed 18 Apr 2016].

Cai, T., Park, S.Y. & Li, Y., 2013. Nutrient recovery from wastewater streams by microalgae: Status and prospects. *Renewable and Sustainable Energy Reviews* **19**, 360–369.

Cresswell, L; Worth, A.; Sheikh, A., 2010. Actor-Network Theory and its role in understanding the implementation of information technology developments in healthcare. *BMC Medical Informatics and Decision Making* **10** (67).

Callon, M., 1986a. Some elements of a sociology of translation: domestication of the scallops and the fishermen of St Brieuc Bay. In: Law. Power, action and belief: a new sociology of knowledge? London: Routledge & Kegan Paul.

Callon, M., 1986b. The Sociology of an Actor-Network: The Case of the Electric Vehicle. In Mapping the dynamics of science and technology. London: The Macmillan Press Ltd.

Curry, N.; Pillay, P., 2012. Biogas prediction and design of a food waste to energy system for the urban environment. *Renewable Energy* **41**, 200-209.

Coulson & Richardson, 2005. Chemical Engineering Volume 6 Chemical Engineering Design (4th Edition). Elsevier.

Djelal, H., Tahrani, L., Fathallah, S., Cabrol, A., Mansour, H., 2014. Treatment process and toxicities assessment of wastewater issued from anaerobic digestion of household wastes. Environ. *Sci. Pollut. Res.* **21**, 2437e2447.

Doolin B.; Lowe A. 2002. To reveal is to critique: actor-network theory and critical information systems research. *Journal of Information Technology* **17**, 69–78.

Drosg, B.; Linke, B.; Fuchs, W., 2015. Nutrient Recovery by Biogas Digestate Processing. http://www.iea-biogas.net/files/daten-redaktion/download/Technical Brochures/NUTRIENT_RECOVERY_RZ_web1.pdf [accessed 30 Sep 2015].

Edwards, J., Othman, M., Burn, S., 2015. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. *Renew. Sustain. Energy Rev.* **52**, 815–828.

EU, 2016. The Circular Economy Package Action Plan <http://ec.europa.eu/ priorities/jobs-growth-and-investment/towards-circulareconomy_en> [accessed 20 Apr 2016].

Fuchs, W. and Drosg, B. (2013) Assessment of the state of the art of technologies for the processing of digestate residue from anaerobic digesters. *Water Sci. Technol.* **67**, 1984–1993.

Frischmann, P. (2012). Enhancement and treatment of digestates from anaerobic digestion. Waste and Resources Action Programme, 1-38.

Gerardo, M.L., Zacharof, M.-P., Lovitt, R.W., 2013. Strategies for the recovery of nutrients and metals from anaerobically digested from dairy farm sludge using cross-flow microfiltration. *Water Res.* **47**, 4833–4842.

Girotto, F., Alibardi, L. & Cossu, R., 2015. Food waste generation and industrial uses: A review. *Waste Management.* **45,** 32–41.

Govasmark, E., Stäb, J., Holen, B., Hoornstra, D., Nesbakk, T., Salkinoja-Salonen, M., 2011. Chemical and microbiological hazards associated with recycling of anaerobic digested residue intended for agricultural use. Waste Manage. 31, 2577–2583.

Guldhe, A., Kumari, S., Ramanna, L., Ramsundar, P., Singh, P., Rawat, I., Bux, F., 2017. Prospects, recent advancements and challenges of different wastewater streams for microalgal cultivation. J. Environ. Manage. 203, 299–315. doi:10.1016/j.jenvman.2017.08.012.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., Meybeck, A., 2011. Global Food Losses and Food Waste. FAO, Rome.

Hellström, A., Nilsson, M.-L., Kylin, H., 2011. Current-use and organochlorine pesticides and polychlorinated biphenyls in the biodegradable fraction of source separated household waste, compost, and anaerobic digestion. Bull. Environ. Contam. Toxicol. 86, 60–64.

Heuvelink, E., Bakker, M.J., Marcelis, L.F.M., Raaphorst, M., 2008. Climate and yield in a closed greenhouse. Acta Horticulturae 801, 1083–1092.

Hjorth, M. et al., 2009. Solid—liquid separation of animal slurry in theory and practice. A review. Agronomy for Sustainable Development, 30 (1), 153–180.

Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresour. Technol. 100, 5478–5484.

Keller, R., Perin, K., Souza, W. G., Cruz, L. S., Zandonade, E., Cassini, S. T. A.&Goncalves, R. F., 2008. Use of polishing pond effluents to cultivate lettuce (Lactuca sativa) in a hydroponic system. Water Science and Technology, 58 (10), 2051–2057.

Kupper, T., Bürge, D., Bachmann, H.J., Güsewell, S., Mayer, J., 2014. Heavy metals in source-separated compost and digestates. Waste Manage. 34, 867–874.

Krishnasamy, K; Nair, J.: Bäuml, B., 2012. Hydroponic system for the treatment of anaerobic liquid. Water Science and Technology, 65 (7), 1164–71.

Lansing, S., Botero, R.B., Martin, J.F., 2008. Waste treatment and biogas quality in small-scale agricultural digesters. *Bioresour. Technol.* **99**, 5881–5890.

Lee, S., Lee, J., 2015. Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of hydroponic food production methods. *Sci. Hortic.* **195**, 206–215. doi:10.1016/j.scienta.2015.09.011.

Li, Y., Jin, Y., Borrion, A., Li, H., Li, J., 2017. Effects of organic composition on mesophilic anaerobic digestion of food waste. *Bioresour. Technol*. **244**, 213–224. doi:10.1016/j.biortech.2017.07.006.

Liedl, B.E., Cummins, M., Young, A., Williams, M.L., Chatfield, J.M., 2004. Hydroponic lettuce production using liquid effluent from poultry waste bioremediation as a nutrient source. In: Cantliffe, D.J., Stoffella, P.J., Shaw, N. (Eds.), Proc. VII IS on Prot. Cult. Mild Winter Climates, Acta Horticulturae, 659. ISHS, 721–728.

Lizzul, A.M. et al., 2014. Combined remediation and lipid production using Chlorella sorokiniana grown on wastewater and exhaust gases. *Bioresource Technology* **151**, 12–18.

Luo, S., Berges, J.A., He, Z., Young, E.B., 2017. Algal-microbial community collaboration for energy recovery and nutrient remediation from wastewater in integrated photobioelectrochemical systems. *Algal Res.* **24**, 527–539. doi:10.1016/j.algal.2016.10.006.

Mata-Alvarez, J., Macé, S., Llabrés, P., 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresour. Technol.* **74** (1), 3–16.

Monlau, F., Sambusiti, C., Ficara, E., Aboulkas, A., Barakat, A., Carrère, H., 2015. New opportunities for agricultural digestate valorization: current situation and perspectives. *Energy Environ. Sci.* **8**, 2600–2621. doi:10.1039/C5EE01633A.

Nkoa, R., 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A review. *Agronomy for Sustainable Development* **34**, 473–492.

NNFCC, 2016. Biogas Map [Online]. Available: <http://www.biogas-info.co.uk/resources/biogas-map/> (Accessed 15th August 2016).

Osundeko, O., Pittman, J.K., 2014. Implications of sludge liquor addition for wastewater-based open pond cultivation of microalgae for biofuel generation and pollutant remediation. Bioresour. Technol. 152, 355e363.

Pivato, A., Vanin, S., Raga, R., Lavagnolo, M.C., Barausse, A., Rieple, A., Laurent, A., Cossu, R., 2016. Use of digestate from a decentralized on-farm biogas plant as fertilizer in soils: an ecotoxicological study for future indicators in risk and life cycle assessment. Waste Manage. 49, 378–389.

Razzak, S.A. et al., 2013. Integrated CO2 capture, wastewater treatment and biofuel production by microalgae culturing—A review. Renewable and Sustainable Energy Reviews, 27, 622–653.

Schenk, P.M., Thomas-Hall, S.R., Stephens, E., Marx, U.C., Mussgnug, J.H., Posten, C., Kruse, O., Hankamer, B., 2008. Second generation biofuels: high-efficiency microalgae for biodiesel production. Bioenergy Res. 1, 20–43.

Sheets et al., 2015. Beyond land application: Emerging technologies for the treatment and reuse of anaerobically digested agricultural and food waste. Waste Management, 44, 94–115.

Silkina, A., Zacharof, M.P., Hery, G., Nouvel, T., Lovitt, R.W., 2017. Formulation and utilisation of spent anaerobic digestate fluids for the growth and product formation of single cell algal cultures in heterotrophic and autotrophic conditions. Bioresour. Technol. 244, 1445–1455. doi:10.1016/j.biortech.2017.05.133.

Stenberg, B., 1999. Monitoring soil quality of arable land: microbiological indicators. Acta Agric. Scand., Sect. B, Soil Plant Sci. 49, 1–24.

Stephenson, P.G., Moore, C.M., Terry, M.J., Zubkov, M.V., Bibby, T.S., 2011. Improving photosynthesis for algal biofuels: toward a green revolution. *Trends Biotechnology*, **29**, pp.615-623.

Stoknes, K.; Scholwin, F.; Krzesinski, W.; Wojciechowska, E.; Jasinska, A., 2016. Efficiency of a novel ‘‘Food to waste to food” system including anaerobic digestion of food waste and cultivation of vegetables on digestate in a bubble-insulated greenhouse.

Tang, H., Chen, M., Simon Ng, K.Y., Salley, S.O., 2012. Continuous microalgae cultivation in a photobioreactor. *Biotechnol. Bioeng.* **109**, 2468–2474. doi:10.1002/bit.24516.

Teh, T., 2013. Bypassing the flush, creating new resources: analysing alternative sanitation futures in London. *Local Environment* **20**(3), 335-349.

Thiyagarajan, G., Umadevi, R., Ramesh, K., 2007. Hydroponics Science Tech Entrepreneur, (January 2007). Water Technology Centre, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu 641 003, India.

Vasseur, C., Bougaran, G., Garnier, M., Hamelin, J., Leboulanger, C., Chevanton, M. Le, Mostajir, B., Sialve, B., Steyer, J.-P., Fouilland, E., 2012. Carbon conversion efficiency and population dynamics of a marine algae–bacteria consortium growing on simplified synthetic digestate: First step in a bioprocess coupling algal production and anaerobic digestion. *Bioresour. Technol.* **119**, 79–87.

Walker, M.; Theaker, H.; Yaman, R.; Poggio, D.; Nimmo, W.; Bywater, A.; Blanch, G.; Pourkashanian, M., 2017. Assessment of micro-scale anaerobic digestion for management of urban organic waste: A case study in London, UK. *Waste Management* **61**, 258-268.

Wang, L., Li, Y., Chen, P., Min, M., Chen, Y., Zhu, J., Ruan, R.R., 2010. Anaerobic digested dairy manure as a nutrient supplement for cultivation of oil-rich green microalgae Chlorella sp. *Bioresour. Technol.* **101**, 2623–2628. doi:10.1016/j.biortech.2009.10.062.

Ward, A.J. et al. (2014) Anaerobic digestion of algae biomass: a review. *Algal Res.* **5**, 204–214.

WRAP, 2010. PAS 110: 2014 Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials. The British Standards Institution 2014. ISBN 978 0 580 82661 0.

WRAP, 2011. Estimates for household food and drink waste in the UK 2011. http://www.wrap.org.uk/content/estimates-household-food-and-drink-waste-uk-2011 [accessed 06 Oct 2016].

WRAP, 2012. Household food and drink waste in the UK 2012. http://www.wrap.org.uk/content/household-food-and-drink-waste-uk-2012 [accessed 06 Jun 2017].

WRAP, 2013. Optimising Urban Micro AD Networks. http://impactbioenergy.com/wp-content/uploads/2013/09/WRAP-microscale-AD-systems-report.pdf [accessed 12 Sep 2015].

WRAP, 2015. WRAP, 2015. Optimising the value of digestate and digestion systems. http://www.WRAP.org.uk/sites/files/WRAP/Optimising the value of digestate and digestion systems_0.pdf [accessed 05 Aug 2015].

Xia, A., Murphy, J.D., 2016. Microalgal Cultivation in Treating Liquid Digestate from Biogas Systems. *Trends Biotechnol*. **34**, 264–275. doi:10.1016/j.tibtech.2015.12.010

Xu, F., Li, Y., Ge, X., Yang, L., Li, Y., 2017. Anaerobic digestion of food waste - Challenges and opportunities. *Bioresour. Technol.* **247**, 1047–1058. doi:10.1016/j.biortech.2017.09.020.

Zacharof, M.P., Lovitt, R.W., 2013. Complex effluent streams as a potential source of volatile fatty acids. *Waste Biomass Valorisation*, **4**, pp. 557–581.

Zamalloa, C.; Vulsteke, E.; Albrecht, J; Verstraete.W., 2011. The techno-economic Potential of Renewable Energy through the Anaerobic Digestion of Microalgae. *Bioresource Technology* **102** (2), 1149-158.

Zhang, R.; El-Mashad, H.; Hartman, K.; Wang, F.; Lui, G.; Choate, C.; Gamble, P., 2007. Characterization of food waste as feedstock for anaerobic digestion. *Bioresource Technology* **98** (4), 929-935.

Figure Captions

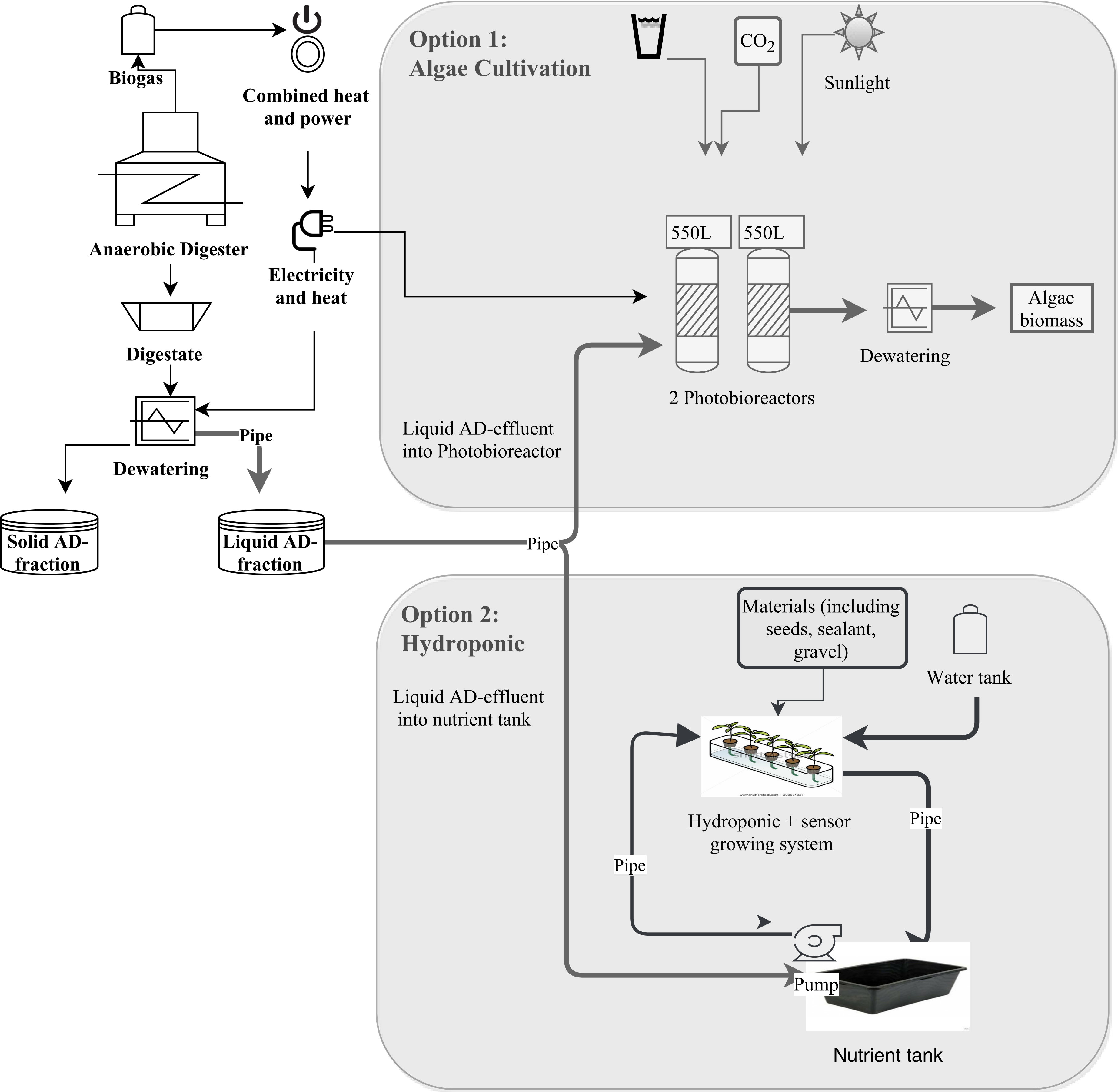
Fig.1: Process flow chart for enhancement of the liquid AD-effluent fraction, with option 1: algae cultivation (top) or option 2: hydroponics (bottom).

Fig.2: Process of small-scale AD at Camley Street Natural Park with this study's system boundaries denoted by the dashed lines.

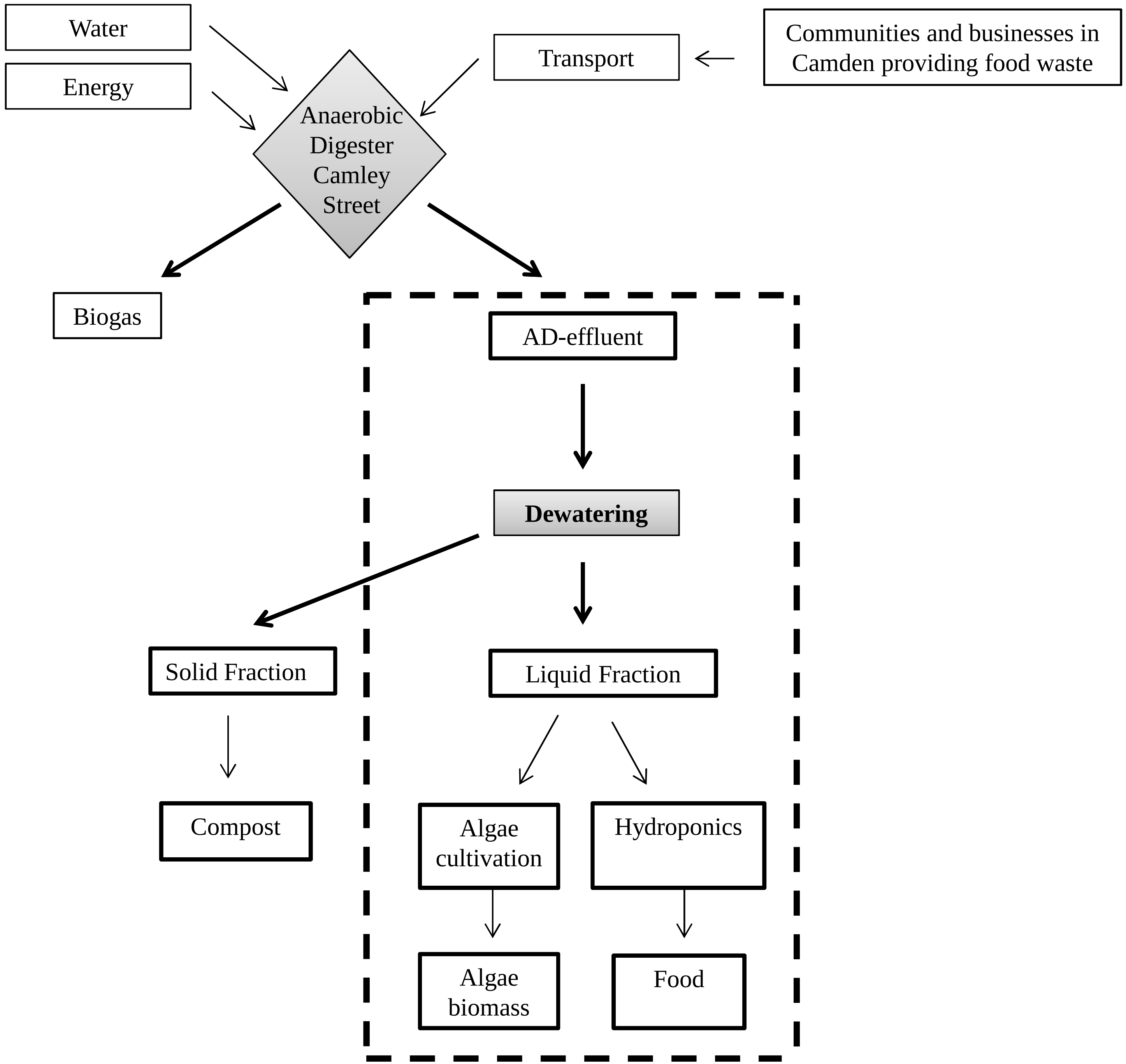
Fig.3: Hydroponics: Comparing NPV (Net Present Value) in £ over varying amounts of anaerobic digestion effluent with different scenarios. Discount rate=0 and a best-case value for percentage distribution of fixed and variable OPEX (95% fixed and 5% variable cost).

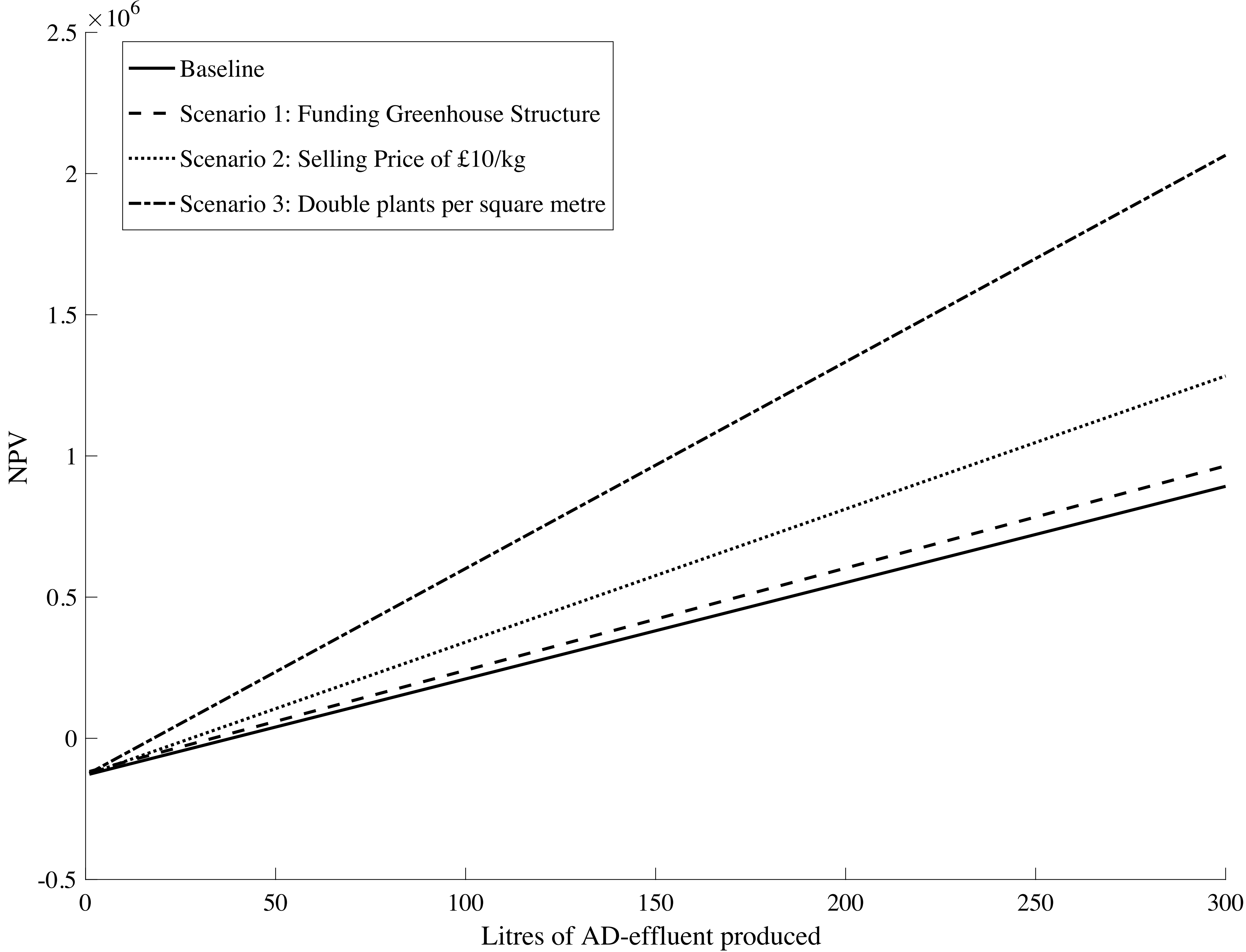
Fig.4: Algae Cultivation: Comparing NPV (Net Present Value) in £ over varying amount of anaerobic digestion effluent available with different scenarios. Discount Rate=0 and best-case value for fixed and variable OPEX (95% fixed and 5% variable cost).

Fig.5: Visualising human and non-human actors in Camley Street Natural Park.

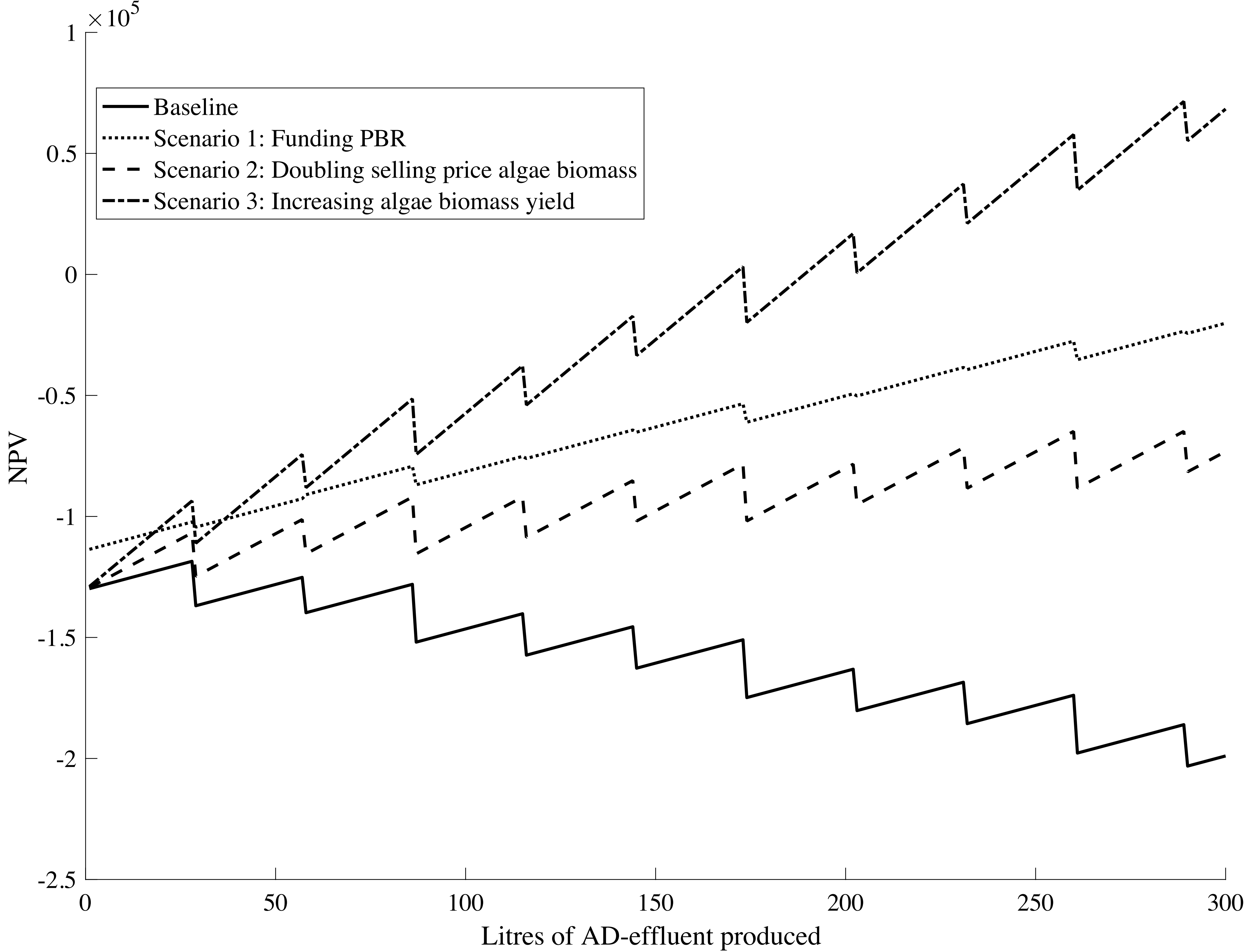


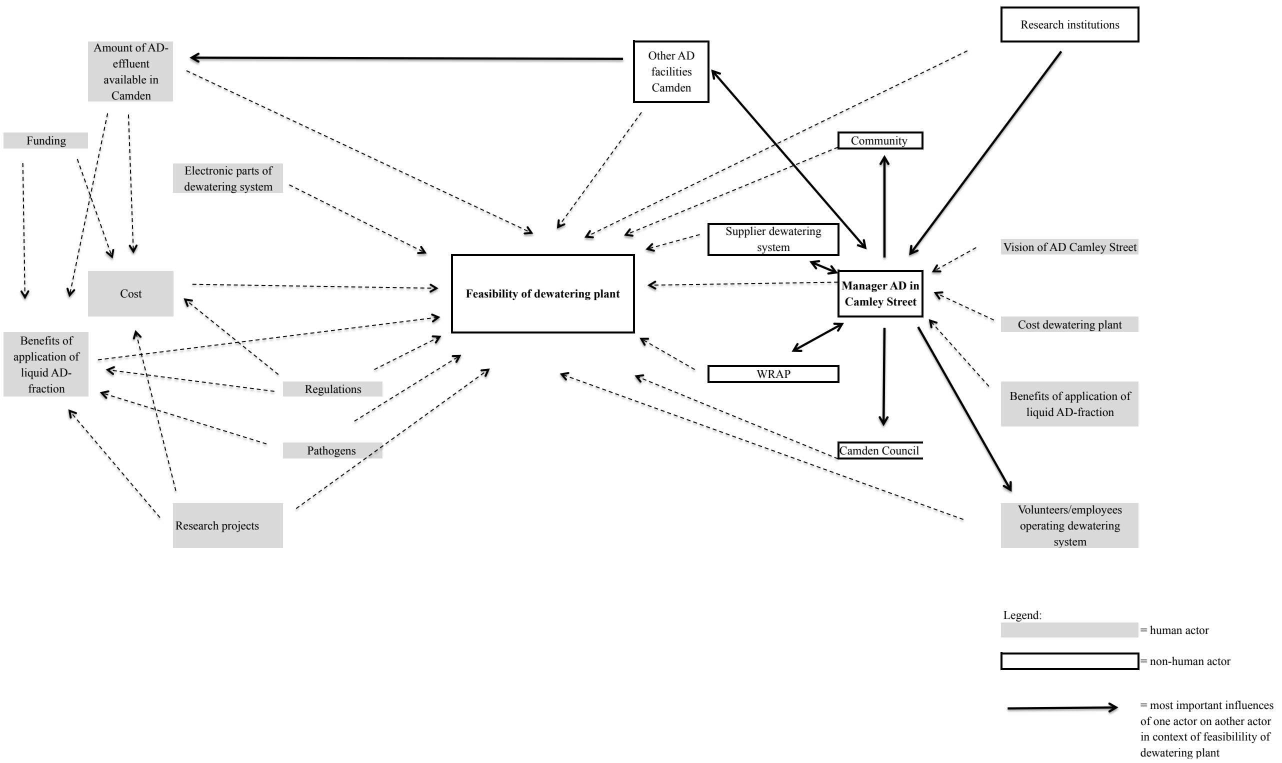
Biogas
Combined heat and power
Anaerobic Digester
Electricity and heat
Digestate
Dewatering
Pipe
Solid AD-fraction
Liquid AD-fraction
Pipe
Option 1: Algae Cultivation
CO_2
Sunlight
550L
550L
Dewatering
Algae biomass
2 Photobioreactors
Liquid AD-effluent into Photobioreactor
Option 2: Hydroponic
Liquid AD-effluent into nutrient tank
Materials (including seeds, sealant, gravel)
Water tank
Hydroponic + sensor growing system
Pipe
Pipe
Pump
Nutrient tank


Water
Energy
Transport
Communities and businesses in Camden providing food waste
Anaerobic Digester Camley Street
Biogas
AD-effluent
Dewatering
Solid Fraction
Liquid Fraction
Compost
Algae cultivation
Hydroponics
Algae biomass
Food



×10^6
2.5
2
1.5
1
0.5
0
-0.5
NPV
0
50
100
150
200
250
300
Litres of AD-effluent produced
Baseline
Scenario 1: Funding Greenhouse Structure
Scenario 2: Selling Price of £10/kg
Scenario 3: Double plants per square metre


×10^5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
NPV
0
50
100
150
200
250
300
Litres of AD-effluent produced
Baseline
Scenario 1: Funding PBR
Scenario 2: Doubling selling price algae biomass
Scenario 3: Increasing algae biomass yield


Research institutions
Amount of AD-effluent available in Camden
Other AD facilities Camden
Funding
Community
Electronic parts of dewatering system
Supplier dewatering system
Vision of AD Camley Street
Cost
Feasibility of dewatering plant
Manager AD in Camley Street
Benefits of application of liquid AD-fraction
Cost dewatering plant
Regulations
WRAP
Benefits of application of liquid AD-fraction
Pathogens
Camden Council
Research projects
Volunteers/employees operating dewatering system
Legend:
= human actor
= non-human actor
= most important influences of one actor on aother actor in context of feasibilility of dewatering plant

Highlights:

Closing waste-energy-food loop within cities requires anaerobic digestate management

Algae cultivation and hydroponics can technically enhance urban anaerobic digestate

Combining techno-economic and actor-network analysis improves project feasibility

Urban, vertical hydroponics economical at volumes of >30 litres/day of digestate

Need for regulatory changes to increase feasibility of small-scale urban digesters