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Influence of UK energy policy on the deployment of anaerobic digestion

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ABSTRACT

Anaerobic digestion (AD) has the potential to contribute to greenhouse gas emissions reductions, improve energy security, increase generation of decentralised renewable electrical and thermal energy, produce low-impact fertiliser and enhance adherence to the principles of proximity as well as self-sufficiency in waste treatment, in energy generation and in resource use. Financial viability is scrutinised investigating optimal logistic pre-conditions such as catchment area or plant size. Given that a breakthrough in deployment does not only depend on technical aspects, the relative importance and magnitude of the necessary incentives is discussed. The influence of policy instruments is studied by devising different incentive scenarios for the United Kingdom. Substantial and predictable rewards for renewable electricity and heat are essential to harness the full potential of AD in addition to the current emphasis on landfill tax. A possible configuration of energy supply companies as a crucial vehicle to bring anaerobic digestion to market is highlighted.

1. Introduction

There is a need for a pronounced increase in the deployment of low-carbon, resource-efficient technologies driven by increasing energy insecurity and the ambitious greenhouse gas (GHG) emissions reduction targets set by the UK government.

The Kyoto Protocol stipulated a 12.5% reduction in GHG emissions based on 1990 levels in the commitment period 2008–2012. The UK government committed to achieving 60% reductions by 2050 (BERR & DEFRA, 2003). In conjunction with the target reduction of GHG emissions of 80% by 2050 proposed by the Department for Energy and Climate Change (DECC), over the next 15 years, the UK must overcome the impending energy gap resulting from the closure of coal and nuclear power plants covering approximately 30% of current electricity supply (Shah, 2006). Electricity represents 18% of total energy consumption (DECC, 2009), while the future domestic energy supply in the UK will likely be insufficient (Rickett, 2007), requiring imports of various energy carriers. Gas accounts currently for 32% of total energy supply and this proportion is expected to grow to approximately 50% by 2020. Of all electricity supplied, gas is expected to account for 80% of fuel feedstock by 2020 compared with 40% currently (DECC, 2009). Also by 2020, up to 90% of the UK gas requirements will rely on imports from the so-called resource triangle, encompassing the former Soviet Union, North Africa and the Middle East, which illustrate the geopolitical implications of the current trend (Remme et al., 2008). Increasing dependence on gas imports could lead to high energy price volatility and possible exposure to political instability, therefore, a shift from a position of import dependence towards efficient utilisation of domestic energy sources will be a requirement of resilient UK energy policy.

Concurrently, the UK faces several waste management challenges. The European Union (EU) Landfill Directive (1999/31/EC), requires EU member states to achieve 65% reduction of the biodegradable municipal waste (BMW) disposed to landfill by 2020, relative to 1995 levels. At current disposal rates, the available landfill capacity in England and Wales is sufficient only for the next 5 years (Environment Agency, 2008). To facilitate diversion of BMW from landfill the UK government set up the Landfill Allowance Trading Scheme (LATS), a scheme designed to benefit local authorities that reduce their disposal of BMW to landfill to a level below their allowance and then trade their excess allowance to lower-performance authorities (Defra, 2007). The benefits from simultaneous diversion of BMW from landfill and production of renewable energy are evidenced by the gradual increase in deployment of waste-to-energy technologies. Anaerobic digestion (AD), as a means of treating biodegradable waste and diverting it from landfill, has been discussed in the UK for many years but with limited investments thus far to bring installations to market. AD controls the decomposition of organic materials in the absence of oxygen in a closed reactor and captures the ensuing biogas for energy generation (Speece, 1996).

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The biogas, comprising methane and carbon dioxide, can be either (i) burned in the combined heat and power (CHP) engine, (ii) upgraded and injected into the gas grid or (iii) cleaned and used in a gas engine vehicle (Börjesson and Berglund, 2006). In the UK, AD is widely used in wastewater treatment facilities; however, despite the widespread and successful application of the technology for electricity generation in countries such as Denmark, Germany, Sweden and Austria, the application has not been exploited in the UK (Lukehurst, 2007).

The Waste Strategy for England 2007 identified the role AD could play in waste management. The UK Biomass Strategy 2007 outlined measures to accelerate deployment of the AD technology, including higher levels of support via the banding of renewable obligation certificates (ROCs) or classification into levels of support for different technology categories according to maturity. This instrument is aimed at supporting the development of local infrastructure and supply chains for AD and supporting its use for treating commercial and municipal food waste.

Four general system configurations exist for AD processes, which have been described in detail elsewhere: a one-stage wet system, with total solids content between 15% and 20% and comprising a main reactor to which feedstock is periodically added in stages and digestate is removed gradually and periodically; a one-stage dry system (Mata-Alvarez, 2002), where dry matter content in the feedstock or total solids (TS) is between 25% and 45%; a two-stage process (Andersson and Björnsson, 2002; Cooney et al., 2007; Zhu et al., 2008), where hydrolysis, acetogenesis and acidogenesis occur within the first reaction vessel or first stage and methanogenesis occurs at the required temperature, either mesophilic or thermophilic, within the second reactor, and a batch configuration (Misi and Foster, 2001), where, unlike the other systems, the reactor is sealed for the duration of the single-stage digestion of the load. Methane emissions reduction is a key benefit of AD compared with disposal to landfill (Börjesson and Berglund, 2006, 2007; Silsoe Research Institute, 2004). AD-derived digestate can potentially be used as natural fertiliser replacing energy-intensive chemical fertilisers, thereby reducing the risk of surface and ground water pollution. Co-digesting different organic wastes has the potential to increase energy yields and the ability to help address challenges posed by waste streams, such as animal manures, slurries and garden waste (Al-Masri, 2001; Banks et al., 2007; Callaghan et al., 2002; Zhu et al., 2008). Research of co-digestion of the organic fraction of municipal solid waste (MSW), with sewage sludge (Gavala et al., 1996; Sosnowski et al., 2003; Stroot et al., 2001) and with energy crops (Amon et al., 2007; Lindorfer et al., 2007), however, has shown that methane savings are achieved only when co-digestion does not involve transport of waste over long distances, which would affect the net GHG emissions balance.

Implementation of AD induces synergistic effects by addressing multiple environmental and political challenges simultaneously while conventional alternatives tackle essentially one challenge. Deployment of AD (i) enhances diversion from landfill; (ii) increases the practicality of recycling schemes relying on source-separation; (iii) generates decentralised, renewable energy, thus assisting the abatement of greenhouse gas emissions; (iv) improves energy security at national and regional level; (v) produces low-impact fertiliser and (vi) facilitates adherence to the European policy principles of proximity of treatment, self-sufficiency in resource use and in waste disposal. In addition, challenges of limited gas capture and gas cleaning requirements common in landfill sites do not apply to AD. Encapsulating these benefits in the justification for a single investment presents difficulties because it is known that multi-issue solutions require multi-department collaboration. In most cases that collaboration needs to be set up in the absence of precedents. Furthermore, bridging the void between environmental and energy strategy at ministerial and local authority execution level is another pre-condition to successful project development.

Despite its advantages, wider deployment of AD in the UK has been slow for the reasons below, some of which are inherent to AD and therefore not exclusive to the UK:

- Historical record of failure of AD plants, with only 25% of installations in the 1990s still in operation, due to poor maintenance and operational problems (Lukehurst, 2007).
- Lack of confidence in the quality of digestate as fertiliser coupled with bad public image of digestate as fertiliser (Donovan, 2008).
- Complexity of achieving source-separated collection schemes, whose development is both time-consuming and costly (Kidson, 2008; Monson et al., 2007), although this is not a problem unique to AD. Also, implementing such schemes, either significantly earlier or later than plant construction, can create further difficulties:
  - Implementation of separation scheme, with high participation, prior to plant build may result in disposal of organic waste to landfill (with potential long-distance transport) and loss of public confidence in the scheme (Kidson, 2008).
  - Implementation of separation scheme after plant build can lead to the risk of contaminated digestate (Monson et al., 2007).
- Source-separated food waste collection is addressed in the draft PAS 110 standard and related Quality Protocol to qualify digestate as a non-waste product (Environment Agency, 2009). This requirement provides clarity on the nature of input materials, which implies that the solid residues are no longer subject to waste management controls. The norm is also aimed at increasing confidence of farmers in digestate as a quality fertiliser.
- Need for process-specific chemical composition of feedstock to ensure consistency of output and uptake route for local authorities (Kidson, 2008).
- Influence of policies originating from different government departments, such as Defra, Department for Business Innovation and Skills, the Office of Gas and Electricity Markets and the Department for Transport, each of which has its own objectives regarding the product end-use.
- The relatively long retention time in the process leading to a throughput time of around 30 days including process and maturation for technology offered commercially in the UK at time of writing. This period is significant commercially because of land take, site costs, rental charges and physical impact implications compared to other processes where dwell times are a day or less.
- Reliance on cooperation between stakeholders from a legislative and monitoring perspective.

The complexity of technology options compounded with the lack of understanding of the relation between technology potential and policy goals are factors contributing to the current reticence to invest in installations.

Profitability of waste-to-energy technologies is influenced significantly by the UK Renewables Obligation, which requires energy suppliers to source a minimum amount of energy from renewable sources (Diaz-Rainey and Ashton, 2008). For each MWh of renewable electrical energy, the supplier is issued a Renewable Obligation Certificate (ROC). Energy suppliers who cannot meet their target can buy ROCs, via auction, from suppliers who exceed the level of their obligation. Effective 1 April 2009, the Renewable Obligation Order 2009 provides a system of banded

ROCs, whereby AD is eligible for two ROCs per MWh. The Energy Act 2008 provides enabling powers for the introduction of feed-in tariffs (FITs) for small-scale, low-carbon electricity generation, up to a maximum limit of 5 MW capacity, while the Renewables Obligation regulation continues to be the main vehicle from which ROCs emerge and are traded as support mechanism for large-scale renewable energy projects. The concept of FITs is used to foster renewable energy deployment in over a dozen EU member states among which Austria, Spain, Germany and Denmark are notable examples.

The EU target to source 20% of energy from renewable sources in primary energy consumption by 2020 is shared between the electricity, heat and transport sector (Burger et al., 2008). Developments in the heat sector in several member states, notably the UK, have fallen behind those in the electricity sector mainly because of the lack of infrastructure and policy support instruments. Renewable heat in the UK accounting for only 1% of the heat in residential, industrial and commercial sectors (Ernst and Young, 2007); hence the government is consulting upon implementation of a heat incentive, with a supporting mechanism of either tradeable green certificates (TGC) similar to the renewable obligations for electricity, or feed-in tariffs.

This paper presents some policy and economic measures to encourage greater uptake of AD. An existing framework for investment analysis with an additional assessment of optimum capacity of the plant, traditionally used for bioenergy ventures, has been applied to this waste-to-energy concept. The study considers investment in AD under several fiscal policy scenarios with implications of both electricity and heat incentives. The likelihood of increased deployment of anaerobic digestion in the UK is discussed in the context of international experience in mitigating risks of investment in the technology.

2. Methodology

The aim of the paper is to analyse the pre-conditions to achieve viability of anaerobic digestion in light of existing waste management policy and possible upcoming renewable energy incentives. The analysis involved the following five methodological steps: (i) technology parameter setting; (ii) criteria for plant capacity selection; (iii) identification of policy scenarios; (iv) economic model for scenario assessment and (v) heat incentive modelling.

Step 1 (*Technology parameter setting*): This step describes the system design and the mass and energy balance profile.

The outline system design is based on the configuration of the Greenfinch plant (Ludlow, Shropshire, UK), which has been operating since 2004. Fig. 1 encompasses the phases, outputs and system boundaries of the system analysed.

The current feedstock for the plant, comprising 90% food waste, source-separated from households and food producers, and 10% grass cuttings, is digested, at 37 °C, in a wet, continuous, single-stage mesophilic process. The plant operates at 85% of its theoretical load, is compliant with the UK Animal By-Product Regulations 2005, and involves a pre-treatment step in which feedstock is macerated to a maximum particle size of 12 mm and mixed with recycled digestate in the conditioning tank, without using fresh water, obtaining a 12% total solids (TS) content. The digestate is mixed through the process of gas recirculation, heated using an external concentric tube heat exchanger and retained in the reactor for 25 days. The biogas produced is then burned in the CHP engine for production of heat and electricity, which is used on site, with any surplus being sold to the grid.

The mass and energy balance profile was configured by characterising key variables such as feedstock composition. Seasonality and country of origin can have a significant impact in performance and require country-specific interpretation of data. In the UK, total solids content per tonne of kitchen and green waste is 0.229 and 0.337 tonnes, respectively, which, according to biochemical methane potential (BMP) tests, equates to 324 and 60 m^3 of biogas per tonne, respectively (Trzcinski, 2006). Similar yields have been reported for the commercial scale in various system configurations (Cecchi et al., 1992). The amount of digestate produced is calculated using the total solids (total solid matter) and volatile solids content in the feedstock. Volatile solids are a part of the total solid matter contained in feedstock that will be transformed into methane in the AD process. According to Trzcinski (2006), 50% of the volatile solids in feedstock is removed in the process; the remaining 50% of mass at the end of the process is available to form digestate as shown in Table 1.

To calculate the energy balance, the total biogas yield was obtained assuming a methane:carbon dioxide ratio of 60:40, as reported by Greenfinch Ltd. (2008). The energy conversion stage comprises biogas being burned in a combined-heat-and-power (CHP) engine with 85% efficiency (Greenfinch Ltd., 2008; Lübken et al., 2007), which is in line with those of ignition engines for co-generation, between 65% and 92% (Verbruggen, 2008). Total

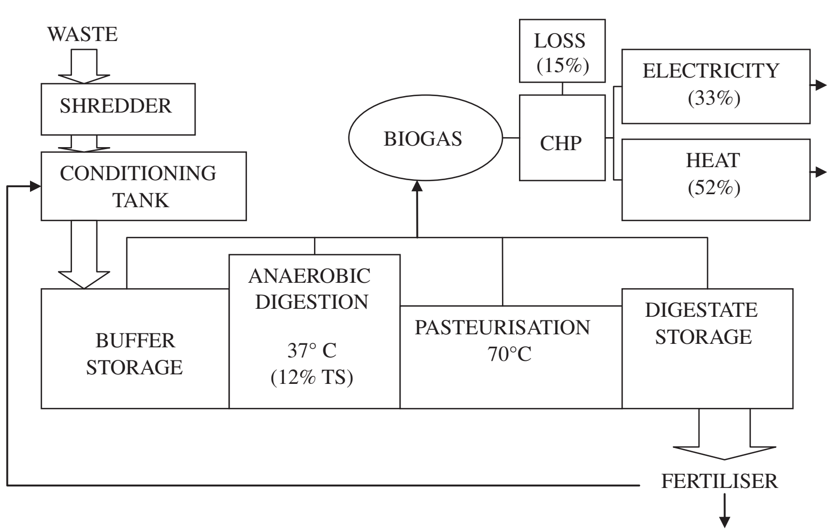

Fig. 1. Schematic of the single-stage wet system plant operation.

Table 1
Biomass characteristics.

1 tonne of	Total solids (tonne)	Volatile solids (tonne)	VS removal (%)	BMP (m^3/tonne VS)
Kitchen waste	0.229	0.218	50	324
Green waste	0.337	0.224	50	60

energy output typically consists of 52% heat and 33% electricity, which normally apply to low-quality CHP engines with a power-to-heat ratio of approximately 0.55 (Verbruggen, 2008). The energy content of biogas used in this study is 21.4 MJ/m^3, according to the simplified volumetric reaction represented in Eq. (1.1) adopted from Greenfinch Ltd. (2008) showing volumes in litres and energy in Megajoules after conversion to useful energy:

$$600\,\mathrm{l}\ CH_4 + 400\,\mathrm{l}\ CO_2 + 1\,\mathrm{l}\ H_2S + 1201.5\,\mathrm{l}\ O_2 \rightarrow 1000\,\mathrm{l}\ CO_2 + 1201\,\mathrm{l}\ H_2O + 1\,\mathrm{l}\ SO_2 + 21.4\,\mathrm{MJ} \tag{1.1}$$

The parasitic load of the plant is 40% of heat and 15% of electricity of the initial energy content of the biogas (Greenfinch Ltd., 2008). The net electricity surplus is exported to the national grid. The model assumes that heat is delivered to local heat demand, e.g. district heating, leisure facilities.

Step 2 (*Criteria for plant capacity selection*): The choice of plant capacity is influenced by the amount of available feedstock, its proximity to the plant and its transport cost. To calculate logistics costs it is necessary to know the mean radius of the area from which the feedstock is planned to be sourced as in Eq. (1.2):

$$C_l = C_f + C_v\overline{R} \tag{1.2}$$

where C_l is the total logistics costs; C_f the fixed costs of material transport; C_v the variable costs of materials transport and $\overline{R}$ the mean transport radius which provides the relationship between the total logistics costs and the plant capacity as in Eq. (1.3). This relation has been derived following the methodology in Dunnett (2008), Nguyen and Prince (1996) and Wright and Brown (2007):

$$\overline{R} = \sqrt{\frac{F}{2\pi Y\partial}} \tag{1.3}$$

where F is the plant capacity (tonnes), Y the yield of feedstocks (tonnes/ha); δ the fraction of land from which the required biomass can be sourced (ha/km^2), for biomass collections from the circular area surrounding the plant ($A=\pi R^2$) the mean transport radius is calculated assuming two concentric circles as in Eq. (1.4):

$$\left(\overline{R} = \frac{R}{\sqrt{2}}\right) \tag{1.4}$$

Logistics costs were determined assuming that food wastes are collected from urban and suburban areas. The population of the UK is 60.6 million (National Statistics, 2008). Assuming 60% capture across the UK, total arisings of 5,375,000 tonnes of food waste per year are available for energy generation (Eunomia, 2007), which represents 89 kg/capita/annum. With urban and suburban areas accounting for 1,138,968 and 475,331 ha, respectively (Dunnet, 2008) and assuming an urban:suburban population density ratio of 4.7:1, the yield of household food waste is 4.334 tonnes/ha for urban and 0.922 tonnes/ha for rural areas with an average yield of 2.628 tonnes/ha.

Fixed and variable costs of food waste transportation were calculated as £10 and £7/tonne/km, respectively, based on costs reported by Hogg (2001) and the proportion of fixed to variable costs supplied by Kidson (2008).

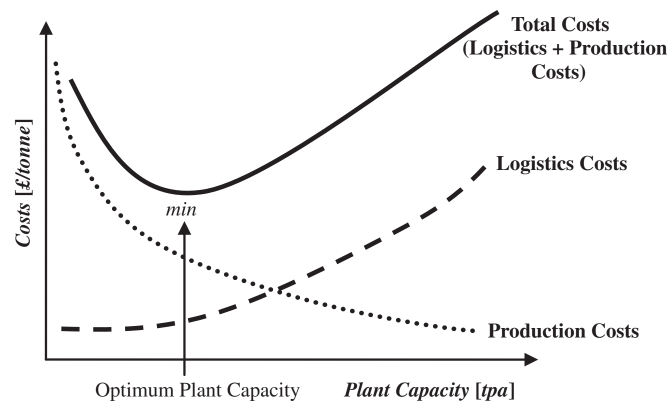

Fig. 2. Optimum plant capacity.

Production costs represent the sum of all annual costs of electricity production, calculated per 1 MWh of electricity produced.

Capital costs of various plant capacities were scaled up from an initial cost of £1,200,000 for 5000 tonnes/year throughput (Arnolds, 2008) according to Eq. (1.5), to the capacities obtained in the logistics calculations for the scales of 26.50, 32 and 38.4 ktpa (see also Section 3.1):

$$\mathrm{Cp} = \mathrm{Cp}_0\left(\frac{M}{M_0}\right)^n \tag{1.5}$$

where Cp_0 is the capital costs for a plant of capacity M_0, n the power law exponent (scale-up factor), M_0 the plant capacity, M the capacity of the new plant and Cp the capital costs of the new plant.

A scale-up factor of 0.7 was used for the assessment (Marbe et al., 2004). The calculated Cp values were adjusted to take account of enabling costs such as grid connection. Operational and maintenance (O&M) costs assumed to be 10% of the capital costs per year, as derived from the original data set for the plant in Shropshire. O&M costs were calculated for further plant capacities obtained through the logistics assessment using the scale-up formula in equation (1.5), from an initial £200,000/year for a 5000 tonnes/annum plant. Capital costs have been annualised using the annuity method. The annuity factor has been calculated according to the formula in Eq. (1.6):

$$r = i(1+i)^n/(1+i)^n - 1 \tag{1.6}$$

where r is the annuity factor, i the interest rate and n the plant lifetime.

The optimum plant capacity is the point of lowest total cost as the sum of production and logistics costs depicted in Fig. 2.

The difference between the optimum capacity of the plant in the urban and suburban areas has also been calculated.

Step 3 (*Identification of policy scenarios*): Four scenarios were selected to determine the influence of policy and scale on investments decisions, using as benchmark a "business-as-usual" scenario (Scenario 1), which was based on policies in force in 2008. Scenarios were configured to explore the varying profitability achieved by altering the degree of application of policy instruments aimed at fostering new technology deployment. The basis of the policy analysis consists of rewards for renewable heat and electricity. For each scenario, a sensitivity to plant capacity of 20% higher and 20% lower than optimum was applied in the economic model. Following is a description of the specific parameters for each scenarios. Note that analysis of changes in yield or efficiency was not an objective of this paper, as the main purpose is to examine the impacts of policy. Changes in yields would rather provide insight into the impact of technological refinements of some installations.

Scenario 1: Business-as-usual scenario (single ROC without heat sales):

- Consider only the climate change levy and the renewable obligation certificate (ROC) as economic incentives for renewable energy generation.
- Allocate a single ROC per MWh, at a price of £53.27/MWh, which is the level achieved at ROCs' auctions in April 2008 (E-Roc, 2008).
- Assume that no heat is sold and there is no policy mechanism to support generation of the renewable heat.

Scenario 2: Moderate policy scenario (double ROCs without heat sales):

- Consider the effects of the reform (2009) to the renewables obligation.
- Allocate double ROCs per MWh of electricity generated, equivalent to a price of £106.54/MWh.
- Assume that no heat is sold off-site.

Scenario 3: Moderate policy scenario (double ROCs with heat sales):

- Consider the effects of the reform (2009) to the renewables obligation.
- Allocate double ROCs per MWh of electricity generated, equivalent to a price of £106.54/MWh.
- Assume that heat is sold off-site.

This scenario investigates the influence of heat utilisation on overall economic performance.

Scenario 4: High Incentives scenario (double ROCs with heat sales and heat incentive):

- Allocate double ROCs per MWh of electricity generated, equivalent to a price of £106.54/MWh.
- Consider income from heat sales and renewable heat incentive.
- Assume a potential value for renewable heat based on the CHP energy production ratio of 1 unit of electricity to 2 units of heat (Jablonski, 2008), since, at the time of writing, there is no established value for renewable heat.
- Posit a price of heat at £20/MWh and a heat incentive at £25/MWh of renewable heat used off-site (Jablonski, 2008).
- Model and account for sensitivity to the value of heat, based on different heat prices of £5, £10 and £40/MWh.
- Model and account for the influence of heat incentive, based on different heat incentives of £10, £20 and £50/MWh of heat.

This scenario is expected to illustrate and inform decisions on the level of support required as reward for low-carbon energy generation that would encourage further investments in anaerobic digestion in the UK.

2.1. Step 4 economic model for scenario assessment

For the purpose of investigating the profitability of anaerobic digestion under different policy scenarios, the economic model applied:

- considers capital, operational and maintenance costs and interests paid on loan;
- predicts future cash flows assuming 25 years of plant lifetime discounted to the present value;
- includes income from gate fees, electricity and heat sales recognising that future sources of revenues vary depending on policy scenario and
- excludes sale of digestate as a fertiliser because, in the short term, possible income from this source would be negligible.

Cash flows were discounted using a discount rate specifically calculated for this analysis. Assuming the installation is fully financed from its revenues, it is possible to calculate the discount factor using a capital asset pricing model (Brealey et al., 2008) as in Eq. (1.7):

$$E(\mathrm{Ri}) = \mathrm{Rf} + \beta i(E(\mathrm{Rm}) - \mathrm{Rf}) \tag{1.7}$$

where $E(R_i)$ is the expected return on the capital asset (discount rate), Rf the risk-free rate of interest, βi the sensitivity of the asset returns (beta coefficient), *E* (Rm) the expected return of the market, *E* (Rm)-Rf the market premium (risk premium).

A risk-free rate of interest was adopted at the level of 4.67%, which is the 10-year nominal par yield of Bank of England annual average yield from British Government Securities (Bank of England, no date). The beta coefficient, adopted from Damodaran (2008), was chosen for the 'Energy: Alternate Source', which is the unlevered beta coefficient corrected for cash and adopted at the level of 1.23. The total risk premium was assumed at 4.91%, which is a UK specific value (standard and poors in Damodaran, 2008). Solving Eq. (1.7), a discount rate of 10.7% was used throughout.

Net present values (NPV) and internal rates of return (IRR) were used as the main financial indicators. The investment is viable when $\mathrm{NPV} > 0$ (Brealey et al., 2008). The internal rate of return (IRR) is defined as a discount rate at which the NPV of the project is equal to zero (Brealey et al., 2008). In general, projects with IRR higher than the opportunity cost of capital are accepted. In this analysis, the opportunity cost of capital is equal to the discount rate.

Levelised costs express a unit cost of electricity generation over the lifetime of the plant, using the present value of all future costs and revenues (Gross et al., 2007). Levelised costs were calculated using the annuity method, which converts the present value of total costs over the lifetime of the plant into equivalent annual cost (EAC) and divides them by the annual net energy output to obtain the levelised unitary value sought (Gross et al., 2007). Costs were calculated, first, excluding any revenues and then including all potential revenues (gate fees, electricity sales, heat sales, ROCs and heat incentive) to illustrate the multi-dimensional character of anaerobic digestion investment.

Step 5 (*Heat incentive modelling*): There is currently no actual value for heat but assuming a price of heat at £20/MWh and a heat incentive at £25/MWh of renewable heat (Jablonski, 2008), the impact of implementation of a heat incentive has been modelled using heat prices of 1, 2 and 4 p/kWh, for a plant of optimum capacity, with additional support of a heat incentive at levels of zero, 1 penny (1 p), 2.5 pence (2.5 p) and 5 pence/kWh.

3. Results

Analysis of the four policy scenarios is presented in terms of determination of the optimum capacity and economic assessment of the AD plant using NPV, IRR, levelised cost calculations and impact assessment of heat incentive.

3.1. Determination of the optimum capacity of the plant

Fig. 3 shows the costs of electricity production for anaerobic digestion plants of different capacities with the optimum plant capacity at 32,000 tonnes/year, which is where unit costs of electricity are at a minimum.

Logistics costs are represented by the equation $y=3.6038x+165.18$ deployed in Fig. 3, which was used over a range of capacities from 1 to 150,000 tonnes, while the production costs, calculated as the cost per unit of electrical output in £/MWh, are represented by the equation $y=941.45x^{-0.7}$.

The observed trend is that, at lower capacity levels, marginal costs are driven by production costs and decrease with increasing capacity, while at higher capacity levels, where the supply of sufficient quantities of feedstock requires larger catchment areas, logistics costs drive marginal costs.

The optimum capacity of 32 ktpa was derived from national average data as opposed to data specifically on urban or suburban areas. This optimum was used in economic modelling of policy scenarios. Optimum capacities for the urban and suburban areas were calculated separately. As illustrated in Figs. 4 and 5, logistics costs in high density urban areas are lower when compared to suburban areas. This difference shifts the optimum capacity of the plant located in urban areas to 40 ktpa, while smaller plant with capacity of 18 ktpa is optimum for less populated suburban regions.

3.2. Economic assessment of anaerobic digestion

Assessment at three different capacities of 25.6 ktpa (20% lower than the average optimum), 32 ktpa (average optimum capacity) and 38.4 ktpa (20% higher than the average optimum) was performed for the four scenarios using NPV, IRR and levelised costs calculations and heat incentive modelling.

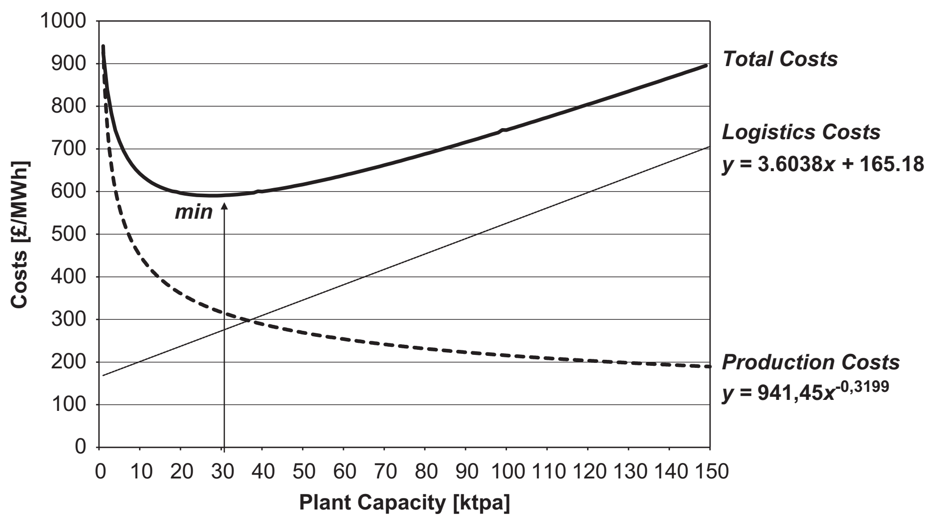

Fig. 3. Estimation of the optimum capacity of anaerobic digestion plant.

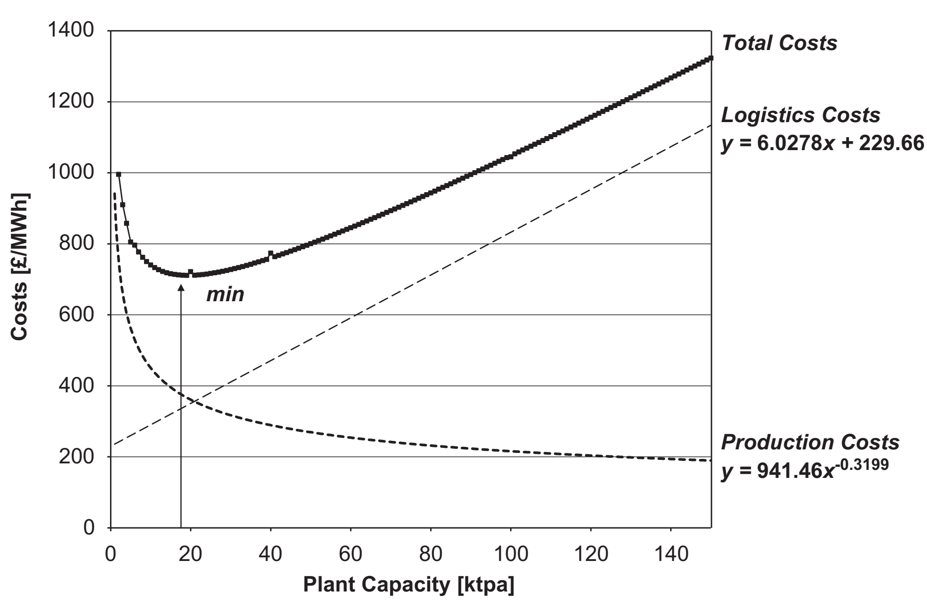

Fig. 4. Optimum capacity of anaerobic digestion in suburban areas.

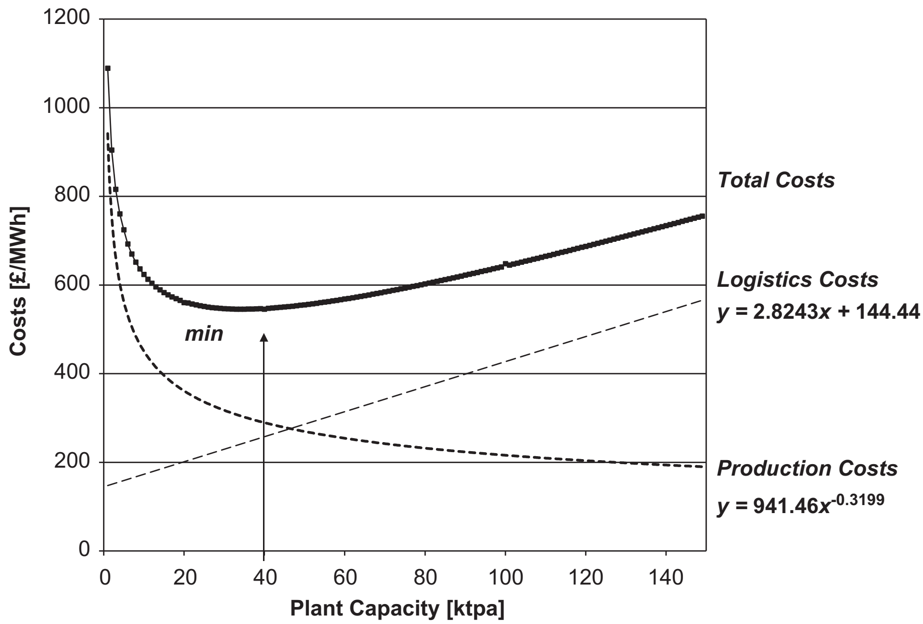

Fig. 5. Optimum capacity of anaerobic digestion in urban areas.

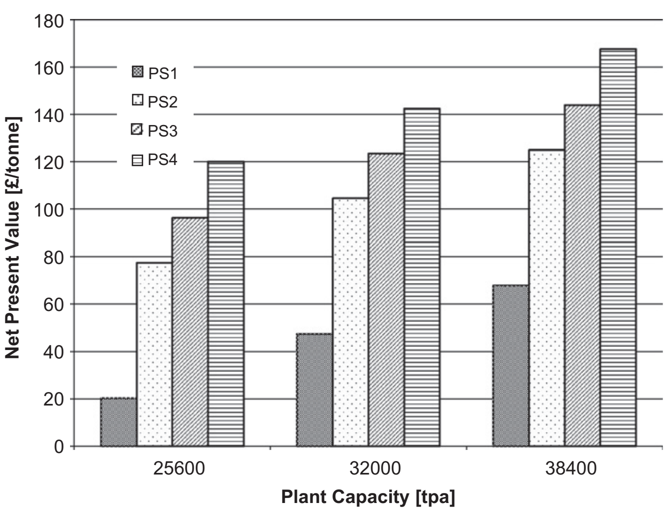

Fig. 6. NPV values for different policy scenarios.

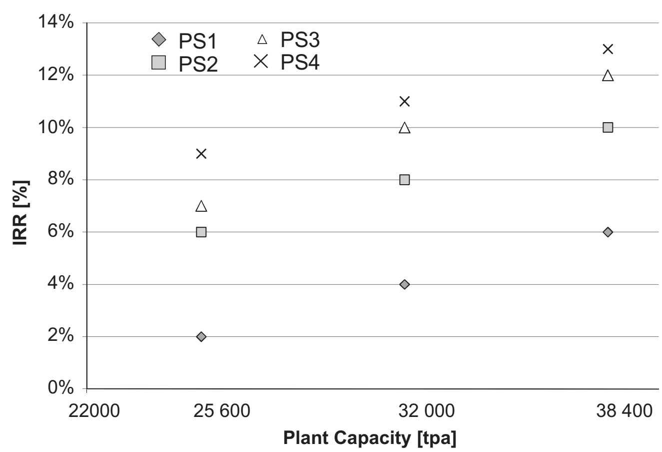

Fig. 7. IRR values for different policy scenarios.

Net present values (NPV) and internal rates of return (IRR): As shown in Fig. 6, for all four scenarios, NPV values are positive. Although the business-as-usual scenario performs the worst, with NPVs of £20.32/tonne for the lower capacity, £47.45/tonne for the optimum and £67.91/tonne for the higher capacity, decisions based upon the NPV figures alone suggest all four scenarios would yield positive returns.

For internal rates of return, Fig. 7 shows a linear relationship between IRR and plant capacity for the four policy scenarios. For the business-as-usual scenario and for scenario 2 (double ROCs without heat sales) all three capacities have an IRR lower than the discount rate of 10.7% applied in the study. In scenario 3 (double ROCs with heat sales) the IRR is above the discount rate only for a plant with a throughput of 38.4 ktpa, while, in the high incentives scenario, which includes the additional heat incentive, the investment becomes feasible also for the optimum plant capacity. There is evidence that selling excess heat improves the profitability for capacities up to 35 ktpa, while for greater capacities, which have the highest capital cost, the hypothesis that returns will be higher for capital-intensive facilities is confirmed. This relationship underlines the effects of scale economies for AD, with an increase in marginal profits with increasing plant capacity.

At a lower discount rate, e.g. 5%, for scenarios allocating at least double ROCs, all capacities would be attractive, regardless of heat sales. Furthermore, any revenues from the additional heat incentive would contribute to profit. However, for plants below the optimum capacity with a greater IRR incremental change, any investment decision considering the additional heat incentive would need to account for marginal revenue derived from this income source.

Application of double ROCs alone increases the NPV for all plants by £60/tonne while incorporating both heat sales and a heat incentive into the model increases the NPVs of all plants by a further £40/tonne.

This difference can be explained by the composition of revenue flows illustrated in Fig. 8 where undiscounted annual income for the anaerobic digestion plant, at the optimum capacity of 32 ktpa, is shown under varying policy regimes. With approximately 12% of the revenue stream originating from electricity sales

(£ 18,730,572), it is evident that increasing the number of ROCs for anaerobic digestion increases revenue significantly. Heat sales and potential heat incentives, although representing a smaller fraction of revenues, could further increase viability.

Levelised costs and revenues The costs and revenues have been calculated as unit cost of electricity production (Table 2), before and after accounting for revenue streams such as gate fees and heat sales. Presenting results per MWh produced emphasises the electricity generation capability of AD, although it can also provide desirable benefits through renewable heat, organic fertiliser and a means of organic waste treatment. Furthermore, it reinforces the symbiotic effect between different technologies that enable good material and energy recovery through the infrastructure and supply chain for separated fractions of the waste stream.

Revenue streams such as electricity and heat sales, income from ROCs and gate fees reduce costs significantly, thus enabling anaerobic digestion installations to achieve levelised costs of electricity competitive with other technologies as shown in Fig. 9. For comparison, levelised costs for AD were calculated for a plant capacity of 25.6 ktpa, with revenues from gate fees of £45/tonne and a conservative assumption of a single ROC at £53.27 MWh^{-1}.

Considering the potential revenue per electric MWh from each capacity level under different policy scenarios, Fig. 10 shows that, for the high incentives scenario with double ROCs, heat sales and heat incentive, revenues can reach £160/tonne of waste assuming electricity sales at £47/MWh_e (Prior, 2008) and heat sales at £20/MWh_{th} (Jablonski, 2008) at a plant capacity 20% above optimum. Moreover, it can be observed that if the plant is located where appropriate feedstocks and a demand for heat are accessible, any electricity produced is highly profitable and revenues from other outputs directly increase competitiveness.

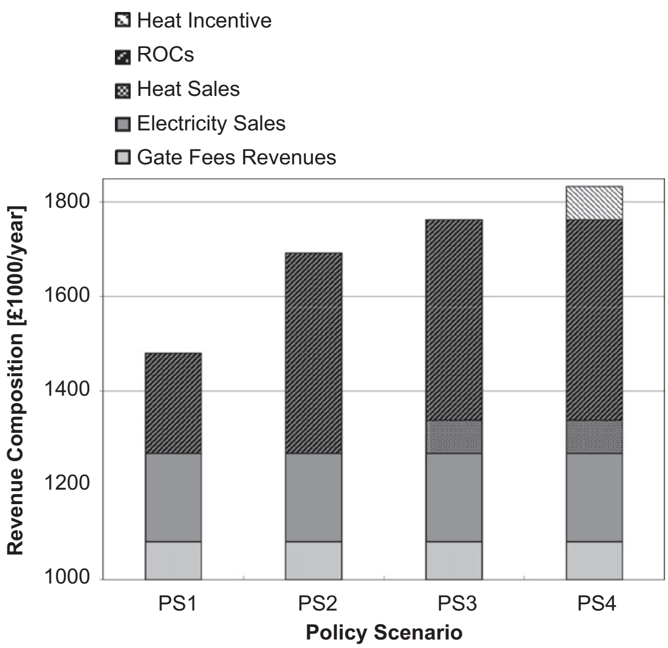

Fig. 8. Anaerobic digestion revenue at optimum capacity.

Table 2
Levelised costs of electricity with additional revenue streams.

Plant capacity (tpa)	Unit production cost (£/MWh_e) without additional revenue streams	Unit production cost (£/MWh_e) with additional revenue streams
25,600	−352.32	−28.00
32,000	−327.02	−2.70
38,400	−307.94	16.00

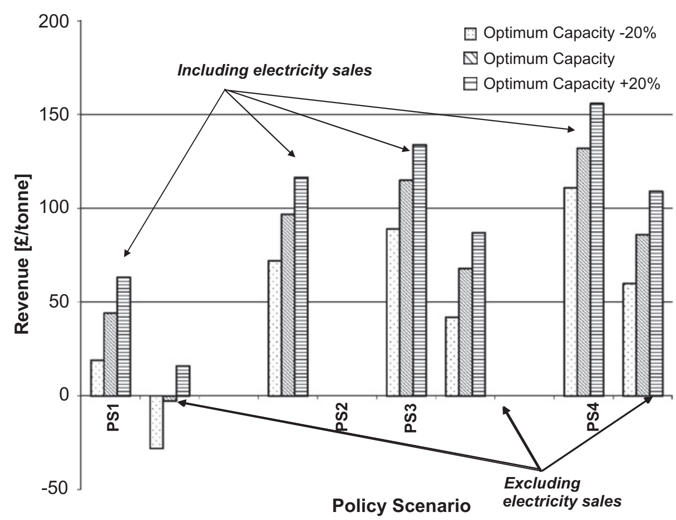

Fig. 10. Revenues per tonne with and without electricity income.

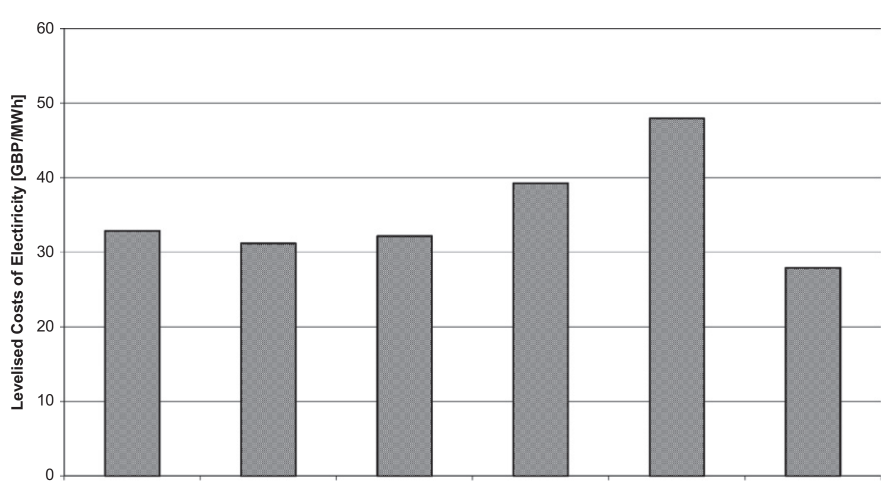

Fig. 9. Levelised cost of electricity generation for different technologies.
Source: Gross et al., 2007.

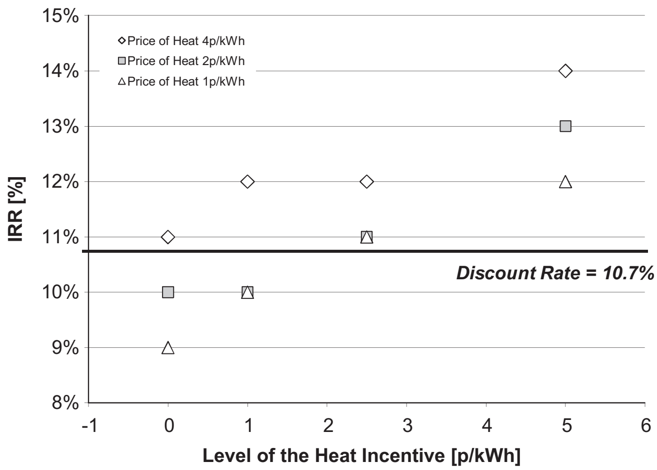

Fig. 11. Effect of the heat incentive.

3.3. *Impact assessment of heat incentive modelling*

Results presented thus far assume that the value of renewable heat is £20/MWh_{th} and that this could be as high as £25/MWh_{th}, by adding a heat incentive. Since there is currently no actual value for heat, the prices modelled at values of 1 p, 2 p and 4 p/kWh_{th} are hypothetical. Fig. 11 presents the impact on performance in terms of IRR at a plant of optimum capacity (32,000 tonnes) of the implementation of a heat incentive at levels of zero, 1 p, 2.5 p and 5 p/kWh_{th}.

Without heat incentive, an AD plant at optimum capacity will achieve an IRR higher than the discount rate only if the price of heat reaches 4 p/kWh_{th}. Heat prices of 1 p and 2 p/kWh_{th} would require a heat incentive of at least 2.5 p/kWh_{th}. In general, a heat incentive will encourage operators to find off-site demand for heat. Early successful examples have emerged from the collaboration between biogas technology proponents, food producers and supermarkets in the UK. Agricultural residues and rejects, out-of-date and out-of-specification food wastes are returned from supermarkets in empty delivery lorries. These feedstocks are digested to generate electricity and heat used in food production and packaging steps (Biogengreenfinch, 2008). Any policy to encourage the uptake of such an incentive and support the use of renewable heat from AD has significant potential to instil increased use of renewable heat in the UK energy portfolio.

4. Discussion

4.1. *Implementation of the heat incentive*

The first years following the introduction of ROCs induced investment growth in renewable energy for well established waste-to-energy technologies, but modestly fostering technology in the pre-commercial stage, such as anaerobic digestion. When devising a sustainable heat policy, it is necessary to consider implications of incentives. Renewable Obligation Certificates for instance, provided a significant thrust to more mature technologies, often described as low-hanging fruit, to the detriment of more promising but less market-ready technology.

Results indicate that the level of support required for waste-to-energy technologies depends largely upon the future value of renewable heat. Although it is common practice to adopt a value for heat at the same level as the cost of heat generation from fossil fuels, the probable values of heat in this study were estimated using a practicable CHP power-to-heat ratio. The results suggest that, if the value of heat ever reached a level similar to the price of electricity, anaerobic digestion would not require additional support. It is important to recognise that the commercial price of electricity is not represented by the value of electricity alone, which covers costs of generation, distribution and supply, but includes the influence of trading between generators, distributors and suppliers. Although sourcing heat from anaerobic digestion to satisfy local demand should be more attractive than generating heat from several fuels and energy vectors, an approximation to a similar value for heat and electricity is unlikely because, in decentralised generation, the price is not influenced by a market for trading. Policy makers must consider implementing meaningful incentives if more renewable heat is to contribute to UK commitments on landfill diversion, best use of resource, energy security and GHG emissions abatement. Current volatility of world stocks, commodity markets and the severe economic downturn illustrate the pitfalls of attempting to predict energy prices. The pronounced rise in oil prices in summer 2008 which more than halved in autumn of that year reflects the risk and uncertainty of investments in energy-related projects. Ofgem (2009) has pointed out the possibility of domestic energy price rises by 2020 of between 14% and 25% with likely blips of up to 60% due to increased investment needs and possible delays in plant replacement. The heat incentive represents an attractive means to mitigate uncertainty associated with future prices for renewable heat and alleviate the cost discrepancy between heat generation from fossil and renewable technologies.

There are four categories of policy for supporting renewable heat: (i) fiscal instruments; (ii) purchase, sale, and remuneration obligation; (iii) use obligations and (iv) other regulatory approaches (Burger et al., 2008). Following the Heat Call for Evidence in 2008, the UK government commissioned research on the barriers and constraints on the supply and demand sides to renewable heat (Enviros, 2008) and the most suitable financial tools for promotion of renewable heat between feed-in tariffs (FITs) and tradable green certificates (TGC) (BERR & NERA, 2008). FITs were initially ruled out from policy design for renewable electricity because they did not involve maximum competition (Toke and Lauber, 2007). It has been argued that setting the level of support centrally is less economically efficient than trading green certificates on the artificial market (Morthorst, 2000). There is a subtle difference between the aim of implementing the renewable obligation for electricity to achieve targets at the lowest possible cost and the aim of developing a technology portfolio to both increase energy security and meet targets in the long term (Toke and Lauber, 2007). Thus far, the renewable obligation has failed to facilitate deployment of emerging technologies that require certainty on the levels of future support.

In Europe, the introduction of FITs has fostered investments in near-commercial technologies creating a wider energy market portfolio, as evidenced by the market participation of small and medium generators enabled by the FIT system rather than a concentration on established electricity suppliers. Within the FITs framework, according to the UK Energy Act 2008, renewable electricity prices are set by the government rather than market trends thus minimising the price volatility exposure for investors and small project developers, thereby leading to higher deployment of long-term-oriented renewable technologies (Toke and Lauber, 2007).

Because of the localised nature of heat, new renewable heat policy must be adjusted to address specific problems, including lack of regulatory structure, similar to the one for the electricity market. To date implementing FITs is considered difficult, since there is currently no market for heat and no infrastructure into which the tariff could be introduced (BERR & NERA, 2008). The alternative of issuing tradable certificates confirming the amount of renewable heat produced, for which generators would be guaranteed a fixed payment over an agreed number of years, would likely render management of the incentive substantially complex. Implementation of heat incentives based on TGC requires banding by type of heat generation technology, which poses a potential difficulty since significant differences can exist between the costs of generation within one type of technology, for example, by using different fuels (BERR & NERA, 2008). Assuming that AD of agricultural waste is less profitable, and requires higher support, it is worth considering banding the new heat policy based on type of feedstock rather than on the type of technology. This analysis recommends that the government would foster investment in infrastructure treating specific feedstocks that, for environmental reasons, are most urgent, with a regular 5-year review. In principle each food-waste-derived MWh of heat used off-site would be rewarded with an additional payment. This payment creates a mutual benefit through AD intertwining waste and energy operations by diverting waste from landfill, enhancing the national renewables portfolio and reducing GHG emissions. This policy may also instigate investments at an accelerated rate; nevertheless, additional research is required to examine investor response to such specifically targeted measures perhaps through international experience.

The first challenge is ascertaining the basis on which the reward should be granted. Unlike electricity policy, the underlying objective of heat policy should be in *using*, rather than *producing* renewable heat. A mechanism for tracking the use of heat stemming from the waste treatment facility could ensure that heat payments only accrue to the utilisation of renewable heat. In addition to local waste generation profiles, plant capacities must be suited to the local demand or uptake for energy outputs to prevent excessive generation and misallocation of resources.

Another challenge is associated with monitoring and the fact that heat is usually not metered. Three approaches that could be used include (i) direct heat monitoring, (ii) metering of biomass inputs and (iii) estimating the possible heat production (BERR & NERA, 2008). Quantification of heat production and utilisation rates are essential for introducing new policy and thus merits a high research and political priority, not least because the absence of heat metering would render fraudulent activity more likely.

4.2. Investment in anaerobic digestion

Even if renewable heat policy made AD-derived heat competitive with fossil-fuel-derived heat, four additional aspects must be considered: (i) choice of optimum plant capacity, (ii) plant location, (iii) logistics infrastructure and (iv) spread of investment risk.

4.2.1. Choice of the optimum capacity of the plant

Results conclude that choice of optimum plant capacity is crucial to the viability of investments. The choice, however, is not solely based on capacity but also on throughput, nature of feedstock and quality of output. For example, a plant in Devon, designed to treat 140 ktpa, is currently treating 40 ktpa (Prior, 2008) due to a switch in feedstocks from agricultural waste to commercial food waste, blood and abattoir waste (Prior, 2008). This feedstock switch was driven by the fact that although digestion of agricultural waste brings high net GHG savings, it achieves low methane yields, due to high moisture content or the presence of digestion inhibitors such as lignin in cattle manure, and attracts no gate fees. The methodology used in this study can be applied to facilitate such investment decisions.

4.2.2. Plant location

The crucial criteria when choosing location are as follows: (i) composition of local waste arisings; (ii) predicted transport distances from feedstock source to plant; (iii) existing waste management practice; (iv) considerable local demand for renewable electricity and (v) proximity of heat demand.

Since inexpensive landfill is the main barrier for new waste management technology, it is crucial for any investment to address these points. Landfill taxes are redressing this disparity, but their gradual escalation implies that infrastructure is only likely to develop when they reach a significantly high level. Assuming non-hazardous landfill gate fees at £25/tonne and landfill tax at £40/tonne, increasing by £8/tonne/year would lead to a cost of landfill in excess of £70/tonne in 2010. Although higher costs might create optimism among technology proponents, infrastructure seems unlikely to be developed in advance to secure disposal routes on time. Thus, developers should locate plants in areas with little or no landfill capacity. This reality differs from the expectation of policy makers designing the landfill tax and landfill allowance trading scheme (LATS), who believed that high long-term landfill costs, would bring investment forward to the medium or near-term.

Another key consideration is that plants should have a good grid connection or high demand for direct electricity and heat supply. None of the existing biological treatment waste-to-energy plants in the UK makes off-site use of the heat produced. Although using heat from co-generation with power would increase profits significantly, the difficulty is to secure uptake at the appropriate price, which is decisive for location decisions. In Scandinavia, the heat from most plants is used for district heating enabling investors to benefit from the full potential of waste-to-energy technology. High heat requirements exist in residential, commercial, institutional and manufacturing. Potential also exists for combined cooling and power (CCP) engines which could supply residential and commercial buildings. Actual project design must reconcile the potential for a viable operation with municipal planning hurdles such as sensible siting to preclude odour nuisance or anticipated opposition to it, thus enhancing public acceptance.

4.2.3. Logistics infrastructure

Fundamental to well operated waste management systems is a sound logistics infrastructure, with varying complexity depending on scale and the stage within the supply chain (Fig. 12). Scrutiny of the waste stream in volume and composition is vital to ascertain the scale and number of plants in the catchment area to be served.

Each part of the waste management system operates at a different scale. For waste managers it is important to dispose of waste; waste processing plants must secure enough waste in their

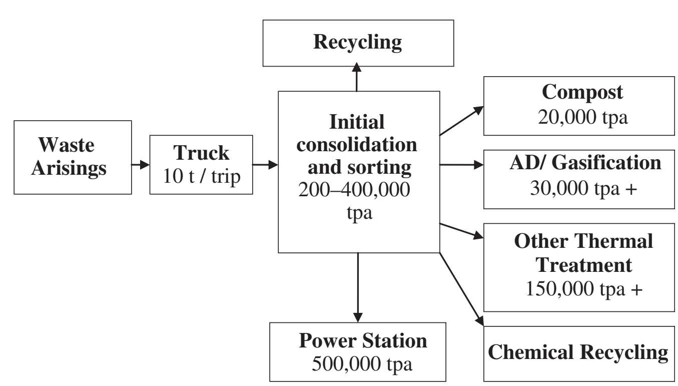

Fig. 12. Logistics and scales within the waste-to-energy supply chain.

proximity for appropriate capacity utilisation. In practice, as shown in Fig. 12, only rarely will a suitable feedstock represent a fraction of the main waste stream that is a multiple of the appropriate scale of the different treatment techniques. An integrated management system, harmonised in terms of scale, transport distance and feedstock type, needs to cope with the surplus perhaps in a co-mingled sub-stream.

4.2.4. Spread of investment risk

Increasing landfill tax and revenues from trading landfill allowances should theoretically raise finance for investments by local authorities but evidence suggests that earnings from LATS have not been substantial enough to increase the budget for new developments and relevant infrastructure (Kidson, 2008). For example, despite complying with its Landfill Allowance, achieving recycling rates of 50% and realising significant results from previous waste minimisation efforts, Somerset County Council has insufficient revenue to develop a new infrastructure without external funds. Funding must come either from the private sector, regional development agencies (RDA) or both. RDAs, responsible for increasing regional economic prosperity and opportunity (Regional Development Agencies (RDA), 2008), are allocated significant resources from central government (Kidson, 2008).

It is unlikely that individual, unilateral investments in anaerobic digestion would happen due to feedstock insecurity, high investment risk and capital expenditure. With cross-sector cooperation uncommon in the UK, there has been slow deployment of new waste-to-energy technologies. Addressing the funding shortages for local authorities can be met by Energy Security Companies (ESCOs), which can be established by private entities, the public or both. They would integrate local authorities, energy companies, technology suppliers and other parties that individually are unable to take the full investment risk. The ESCO can be created as a collaborative, financial vehicle referred to as special purpose vehicle (SPV) that locks up the investment risk, thereby removing liability on the main income stream of the investing parties. In this arrangement, technology providers would be obliged to cover the risk of technology failure, while local authorities could be obliged to cover the risk of adequate feedstock supplies.

Technology proponents are already interested in engaging with energy suppliers, local authorities and waste producers in the private sector such as supermarkets and food producers. The private sector has yet to respond. Using the ESCO concept and stimulating behavioural change towards higher responsibility for waste arising from household, industrial and commercial streams, current investment paradigms could be changed.

5. Conclusions

5.1. Implications of model results

The analysis illustrated that policy instruments that reward renewable energy can make a significant contribution towards guiding investment decisions and to addressing policy objectives in waste disposal, energy security and climate change mitigation. The role for strategic policy support has been reiterated, as it is evident that new, low-carbon energy technology and near-commercial waste treatment technology seem less profitable than conventional waste treatment as well as fossil-fuelled generation of heat and power. Calculations showed how double ROCs in conjunction with a renewable heat incentive would make a significant difference for AD plants at small scales. Larger scales already become attractive when granted double ROCs for their electrical output.

5.2. Strategic and policy implications

Given the identified barriers concerning multi-issue and multi-department solutions, the main breakthrough required is clearly not technical but of administrative, financial and risk management nature. Without improvements facilitated by policy instruments such as double ROCs, feed-in tariffs and renewable heat incentives, the market would likely preserve its unsustainable status quo. The ESCO arrangement proposed addresses the lack of connectivity among stakeholders offering a vehicle to spread benefits and risks. This arrangement, combined with policy consistency over the near and medium term and the lifetime of new projects as well as instruments rewarding low-carbon energy, can decisively enhance the viability of AD and other waste-to-energy technology.

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