Communications in Waste and Resource Management, Volume 10, Issue 1, February 2010, pp. 4-12

# Renewable Energy, Landfill Gas and EfW: Now, Next and Future

K A Adu-Gyamfi[a], R Villa[a] and F Coulon[a,*]

[a]Cranfield University, Centre for Resource Management and Efficiency, Sustainable Systems Department, School of Applied Sciences, Cranfield, MK43 0AL, UK

*Corresponding author: Email: f.coulon@cranfield.ac.uk

Tel: +44 (0)1234 754 981; Fax: +44 (0)1234 751 671

## ABSTRACT

The United Kingdom (UK) has traditionally used landfill disposal as the predominant method of waste management. However, landfilling is unsustainable due to its harmful effects on the environment and public health. Under the European Union (EU) Landfill Directive, member nations are now required to divert biodegradable municipal waste (BMW) from landfills. The UK has also committed to the EU Renewable Energy Directive, which binds it to sourcing at least 15% of its energy mix from renewables by 2020. To meet these targets, the UK has to support alternative waste management options whilst achieving considerable deployment of renewables. This research considers the development of energy from waste (EfW) technologies and their potential contribution to UK's renewable energy targets.

This study identifies the use of biomethane as road transport fuel and small-scale EfW deployment at community level as applications with huge potential benefits for the UK. These two options are easily implementable and could provide substantial savings in greenhouse gas (GHG) emissions. This study concludes that, depending on the pace of investment and availability of suitable feedstock, EfW technologies can contribute up to 50% of UK renewables target by 2020.

## KEYWORDS

Renewable energy, climate change, landfill gas, EfW, biomethane

# 1. INTRODUCTION

The United Kingdom (UK) has historically disposed of most of its wastes in landfills. This is due to the prevalence of non-porous sub-strata and the requirement to fill holes left by mineral extraction activities (Brown and Maunder, 1994). Although a comparatively inexpensive option, landfilling is unsustainable due to its harmful impacts on the environment. For example, landfill gas (LFG) emissions contribute about 40% of UK methane ($CH_4$) emissions and 3% of all UK greenhouse gas (GHG) emissions (Defra, 2007a). GHGs cause global warming, with $CH_4$ about 23 times more potent than carbon dioxide ($CO_2$) (IPCC, 2001). To reduce the negative environmental effects of landfills, LFG is now recovered and used to produce renewable energy. At the same time, policies have been introduced to encourage diversion of biodegradable wastes from landfills, as required by the European Union (EU) Waste Landfill Directive (LFD) (1999/31/EC) (Defra, 2007a; Williams, 2005).

Today, UK waste management is evolving from a disposal problem to a resource optimisation opportunity. Wherever reuse or recycling of waste is not viable, energy recovery is recommended, with disposal used only as a last resort (Defra, 2007a). In addition to LFG utilisation, the rollout of various energy from waste (EfW) technologies is being supported in the UK. The growing use of EfW and other renewables globally has been underpinned by three main factors: i) energy supply security, ii) climate change mitigation and iii) resource efficiency.

The uptake of renewable energy technologies displaces the reliance on fossil fuels. Global reserves of fossil fuels are declining at a time of increasing energy demand mainly attributable to the so-called BRIICS countries namely Brazil, Russia, India, Indonesia, China and South Africa (IEA, 2008). With fossil fuel production mostly concentrated in politically unstable regions, dependent countries are exposed to price fluctuations and future supply uncertainties. The UK has been a net importer of energy since 2004 (Eurostat, 2009) and would also lose some of its nuclear power generation capacity over the next decade through decommissioning. Therefore, it is crucial for the UK to invest in alternatives to fossil fuels.

Fossil fuel use is also the foremost source of carbon dioxide ($CO_2$) emissions, the principal cause of global warming (OECD, 2008). In his “Economics of Climate Change” Review, Lord Stern (2007) cautions that unless decisive action is taken to reduce GHG emissions, atmospheric levels may reach double the pre-industrial amount by 2035. This would result in an average global temperature rise of between 2 and 5 $^{o}$C with serious environmental and economic consequences (Defra, 2009a). By contrast, renewable and EfW technologies typically achieve reductions in $CO_2$ emissions or carbon neutrality.

To facilitate the adoption of low-carbon energy technologies, the EU has promulgated the Renewable Energy Directive (RED) (2009/28/EC). This binds the EU to deriving at least 20% of total energy consumption from renewables by 2020 (Council of the European Union, 2009).

## 2. RENEWABLE ENERGY DEVELOPMENT IN UK

The UK Government is a signatory to the EU RED and has therefore committed itself to contributing its share of sourcing 15% of total energy from renewables by 2020 (House of Lords, 2008). To meet this ambitious target would require a seven-fold increase on the contribution of 2.25% that renewables currently make to overall UK energy mix (DECC, 2009a). To incentivize uptake of renewables, the UK Government has been introducing a range of policies. Renewables Obligation Certificates (ROCs) have been issued as the main support mechanism for UK renewables since 2002 (Bogner et al, 2007). To encourage a shift from a landfill-dominated waste management regime, the Government has raised landfill tax by an annual escalator since 2008 and established the Landfill Allowance Trading Scheme (LATS). The Renewable Transport Fuels Obligation (RTFO) has also been introduced to promote the use of renewable transport fuels. From 2010, feed-in tariffs (FITs) would be provided for small-scale electricity generation (Pöyry, 2009) whilst Renewable Heat Incentives (RHI) would be available from 2011 (OPSI, 2009).

The UK Renewable Energy Strategy (RES) was published in July 2009, providing the framework for increasing the use of renewables. The RES identifies EfW technologies as important contributors to UK’s future energy security, a fact that is also highlighted in the UK’s Biomass Strategy (Defra, 2007b) and the UK Energy White Paper (DTI, 2007). The RES contends that, in addition to providing clean energy, deployment of renewable technologies in UK can also create up to 500,000 new jobs by 2020 (DECC, 2009a).

## 3. ENERGY FROM WASTE (EFW) TECHNOLOGIES IN UK

EfW technologies can be grouped into two main categories (Figure 1).

**Figure 1**: Energy from Waste technologies

Biological technologies consist of mainly anaerobic digestion (AD) (Balat and Balat, 2009; Defra, 2009b) and LFG (Stegmann, 1996), as well as hydrogen ($H_2$) (Sperrey, 2008; Yolcular, 2009) and biofuels (Davies, 2009). Thermal processes involve conventional mass-burn incineration (Cheremisinoff, 2003; Niessen, 2002) and advanced thermal processes (Mullis, 2007; Williams, 2005). The latter includes gasification, pyrolysis and plasma arc technology. Table 1 compares the EfW technologies deployable in the UK.

**Table 1: Comparison of EfW Technologies**

| EfW Technology | Waste Input | Useful Outputs | Applications | Advantages | Disadvantages/Barriers |
|---|---|---|---|---|---|
| **Landfill Gas (LFG)** | All biodegradable wastes. | Landfill gas<br>Biomethane | Combined heat and power (CHP)<br>Electricity<br>Transport fuel<br>Chemical feedstock | • Climate change mitigation from $CH_4$ recovery.<br>• Versatile and easy to adopt.<br>• Established in UK. | • Output to decline because of Landfill Directive.<br>• More viable for larger landfills due to high cost of gas scrubbing. |
| **Anaerobic Digestion (AD)** | Biodegradable waste.<br>Agricultural slurry.<br>Sewage sludge.<br>Food and drink industry waste. | Biogas<br>Biomethane | CHP<br>Electricity<br>Transport fuel<br>Chemical feedstock | • Lowest carbon footprint of all residual waste treatment technologies (EDS, 2008).<br>• Established for wastewater sludge digestion in UK.<br>• Can be deployed at various scales. | • Not fully established for MSW in UK.<br>• Limited availability of land for digestate application (EDS, 2009). |
| | | Digestate | Soil improvement | | |
| **Hydrogen ($H_2$)** | Biomass/ Organic Waste. | Hydrogen gas | Transport fuel cells<br>Portable or fixed electricity generators. | • Combustion emits only water.<br>• Fuel cells have few moving parts and require little maintenance (Sperrey, 2008).<br>• High efficiency. | • High cost of hydrogen production from renewable sources.<br>• Technical difficulties with low density of hydrogen gas (Sperrey, 2008).<br>• Lack of refuelling infrastructure.<br>• Not established worldwide. |

| | | | | | |
|---|---|---|---|---|---|
| **Biofuels** | Biomass waste<br>Waste cooking oils. | Bio-ethanol<br>Bio-diesel<br>Bio-methanol | Transport<br>Chemical feedstock | • Easy to handle/store because of liquid form (Evans, 2001).<br>• More efficient method of biomass conversion than combustion (Davies, 2009). | • Existing vehicles may not be able to run on high content of biofuels (DECC, 2009a).<br>• Production from waste biomass not fully commercialised. |
| **Thermal EfW** | High calorific value wastes.<br>MSW<br>Secondary recovered fuels (SRF). | Heat | CHP<br>Electricity | • High reduction in waste volume and weight (Cheremisinoff, 2003).<br>• Best option for some waste streams e.g. volatile, highly flammable and infectious wastes (Niessen, 2002). | • Negative public perception over health impacts (Guisti, 2009; Mullis, 2007).<br>• Does not allow much flexibility with other technology choices (Cheremisinoff, 2003). |
| **Advanced Thermal EfW** | MSW<br>SRF<br>High calorific value wastes. | Syngas<br>Char<br>Combustible oils | CHP<br>Electricity<br>Chemical feedstock. | • Smaller environmental footprint/land requirement compared with incineration (Mullis, 2007).<br>• Process parameters can be optimised for different energetic products (Williams, 2005). | • Not established in UK.<br>• More expensive than conventional incineration (Mullis, 2007). |

## 4. CURRENT TRENDS IN UK EFW AND RENEWABLES DEPLOYMENT

### 4.1 UK Municipal Solid Waste (MSW) Management

Landfilling is still the predominant management option for UK waste (Figure 2). Incineration with energy recovery accounted for only 8% out of the 35.1 million tonnes of MSW arisings in 2005/06. These EfW facilities generated nearly 0.8 Mtoe, enough energy for 250,000 UK households (ESA, 2008). Although planning consents for thermal EfW and AD facilities have increased in recent years, a combination of factors including public opposition and lengthy implementation timelines, have hampered the uptake of EfW options. The widespread use of landfilling explains the significant contribution of landfill gas utilisation to the UK's renewable energy output.

**Figure 2:** UK Municipal Solid Waste management in 2005/06 (Defra, 2006)

### 4.3 Landfill Gas

Landfill Gas (LFG) is currently the most important source of renewable energy in UK, providing nearly one-thirds of all renewables (Figure 3) (Jamasb et al, 2008). It has been used for production of energy on a commercial scale since 1975 (Bogner et al, 2007). Calorific values for undiluted landfill gas range between 15 and 21 MJ/m$^3$, compared with about 37 MJ/m$^3$ for natural gas. A typical MSW landfill would produce between 6 and 8 m$^3$ of LFG per tonne of waste per year (Williams, 2005). However, the actual amount and composition of LFG output depends on the composition of waste and site-specific conditions.

**Figure 3:** UK renewable energy sources in 2007 (BERR, 2008a)

LFG can be used directly to generate electricity or in CHP systems. It can also be upgraded into biomethane, for gas grid injection or transport fuel. Table 2 gives the typical composition of LFG and the required standards for use as vehicular fuel or grid injection. Apart from providing energy, LFG utilisation provides operators with an additional income stream, which may be used to offset the cost of regulatory compliance and landfill aftercare (Brown and Maunder, 1994). UK LFG output doubled from 731.2 Mtoe in 2000 to 1464.7 Mtoe in 2006. Between 2006 and 2008, output increased by a more modest average rate of 3.7% per year (DECC, 2009b). Inevitably, the importance of LFG as a renewable energy source would decline in future due to the impact of LFD. Therefore support for other EfW and renewable technologies should be increased so they can make up for any energy supply deficits.

**Table 2**: **Composition of LFG and requirements for grid injection**

| **Constituent Gas** | **Average concentration in LFG** | **Required level for use in vehicles/grid injection*** |
|---|---|---|
| Methane ($CH_4$) | 50 % | 97± 1 % |
| Carbon dioxide ($CO_2$) | 45 % | $[CO_2 + O_2 + N_2] < 4\%$ |
| Nitrogen ($N_2$) | 5 % | 20 mg/m$^3$ (max.)** |
| Oxygen ($O_2$) | < 1 % | 1% (max.) |
| Hydrogen Sulphide ($H_2S$) | 21 mg/m$^3$ | 23 mg/m$^3$ (max.)*** |
| Halides | 132 mg/m$^3$ | NA |
| Water vapour ($H_2O$) | NA | 32 mg/m$^3$ (max.) |
| NMOCs | 2,700 mg/m$^3$ | NA |

Notes: NA = data not available

NMOCs = non-methane organic compounds (assorted contaminants)

* Based on Swedish Biogas Standard SS 15 54 38 (Requirement A)

** Calculated as ammonia ($NH_3$); *** Total sulphur

Sources: (Cheremisinoff, 2003) and (Cenex, 2008)

# 5. NEXT: OPPORTUNITIES FOR EfW EXPANSION

## 5.1 Biomethane as Transport Fuel

The use of renewable transport fuels, especially those derived from wastes, would help reduce anthropogenic climate change impacts. The UK transport sector accounts for 70% of national oil demand (BERR, 2008b) and a quarter of $CO_2$ emissions (DTI, 2007; DECC, 2009c). Although renewable fuels and hybrid vehicles are expected to penetrate the transportation sector in coming decades, the global car fleet is also predicted to increase from 650 million in 2005 to 1.4 billion by 2030. This means fossil fuels may still account for about 80% of global energy supply in 2030 (IEA, 2008).

Biomethane, from upgraded LFG and biogas from AD, can be used as fuel in road vehicles (Persson et al, 2007). According to the latest data compiled by the Natural Gas Vehicle Association Europe (NGVA Europe), in terms of biomethane use for road transport, the top four countries i.e. Pakistan, Argentina, Brazil and Iran command over 65% of global market share. In Europe, Italy maintains its dominant position as market leader, followed by Germany and Sweden. The UK has not yet experienced any significant penetration of NGV technology (Figure 4). The reasons for this include lack of refuelling infrastructure and consumer uncertainty about the safety and reliability of this technology within the UK.

**Figure 4:** Natural Gas Vehicle (NGV) adoption in selected countries as of July 2009
Data: Natural Gas Vehicle Association Europe

Nonetheless, the use of biomethane as road transport fuel confers several advantages. Biomethane has higher energy content and emits less $CO_2$ than fossil fuels (Table 3). Biomethane also emits less particulates, nitrogen oxides and dioxins than fossil fuels. Additionally, engines running on biomethane are quieter than those utilising conventional fuels, a desirable feature for urban environments (Eriksson and Olsson, 2007). When fitted according to approved standards, the use of biomethane in vehicles can be safer than petrol. This is due to the higher flammability limits, higher diffusion coefficient and auto-ignition temperature of biomethane (Cenex, 2009). Biomethane vehicles are also 40% cheaper to run than diesel and 55% more economical than equivalent petrol engines (Sustainable Transport Solutions Limited, 2006).

**Table 3**: **Comparison of Energy Content and $CO_2$ Emissions from Different Fuels**

| **Fuel** | **% $H_2$** | **LHV* (MJ/ kg)** | **LHV (KWh/ kg)** | **$CO_2$ Emitted per KWh (g)** |
|---|---|---|---|---|
| **Biomethane** | 25.0 | 50.0 | 13.89 | 198.0 |
| **Propane** | 18.2 | 45.6 | 12.67 | 236.8 |

| | | | | |
|---|---|---|---|---|
| **Butane** | 17.2 | 45.3 | 12.58 | 241.2 |
| **Diesel** | 13.5 | 42.7 | 11.86 | 267.5 |
| **Petrol** | 13.5 | 42.4 | 11.77 | 279.5 |
| Notes: * LHV = Lower Heating Value [Heating Value refers to the amount of energy released when a fuel is completely burned]; MJ= mega joules; KWh = kilowatt-hour; kg = kilogram; g = gram. | | | | |

Source: (Natural Gas Vehicle Association Europe, 2009)

NGV technology is easy to adopt and existing vehicles can be retrofitted at a cost of between £1000 and £2000 (based on quotations from some licensed converters). Biomethane can be produced from a wide range of biomass feedstock available within the EU and can also be produced through gasification of organic materials. Biogas can be upgraded into biomethane for as little as between 0.11 and 0.22 eurocents per normal cubic metre (Nm$^3$), depending on the size of plant (Biogasmax, 2009). 1 Nm$^3$ of biomethane is equivalent to 1 litre of petrol or diesel. In the event of shortfalls in biomethane production, supplies can be augmented with natural gas because they are chemically identical. As a further incentive to investors, biomethane produced for transport fuel is eligible for RTFO credits. There is a substantial commercial gap within the UK automotive market for the introduction of NGVs. This study estimates that UK NGVs could be increased from the present number of about 294 to 30,000 units by 2020 through a combination of new gas vehicle introduction and retrofitting.

## 5.2 Small-Scale Community Level Power Generation

Distributed energy production would also help to de-carbonise the UK’s economy (BERR, 2008c). Mullis et al (2009) identified AD, pyrolysis and gasification as the EfW options best suited to community scale deployment. Although small-scale EfW facilities are constrained by diseconomies of reduced scale, the potential benefits of adopting them within communities make them a viable option. Such schemes have a more benign environmental footprint compared with large-scale deployment and also encourage local ownership. Community level power generation may avoid grid connection and planning obstacles that pose barriers to larger facilities. The efficiencies of community EfW systems are increased by the availability of a consumer base for heat utilisation. According to Porteus (2005), incineration of 1 tonne of MSW is equivalent to 500 KWh of energy or 30 tonnes of hot water. The UK Government's eco-towns project presents a great opportunity to demonstrate the viability of community level EfW schemes (Mullis et al, 2009). EfW technologies are integral components of eco-cities such as Masdar (UAE), Dongtan (China) and Treasure Island (USA) (Biello, 2008).

# 6. FUTURE DEVELOPMENTS

## 6.1 Future Trends and Technologies

By 2020, both AD and thermal EfW are expected to become established MSW conversion technologies in the UK (Defra, 2007a; Defra, 2009b). Meanwhile, recent advances in cellulose degradation would increase the production of biomass-derived or 'second generation' biofuels (Davies, 2009). Waste-derived biofuels do not have the negative indirect land use impacts often associated with biofuels produced from primary crops (RFA, 2008). However, technical and financial barriers (Briner, 2008; Niessen, 2002) may continue to limit commercialisation of hydrogen fuel and plasma technologies.

## 6.2 Potential Contribution of EfW to UK Renewables Targets in 2020

Research carried out by Sustainable Transport Solutions Limited (2006) found that AD has the potential to produce a theoretical maximum of about 6 Mtoe in biogas. According to the Waste Strategy for England (Defra, 2007a), thermal EfW could be used for 25% of MSW by 2020. Based on current figures, this would generate about 2.1 Mtoe of renewable energy. Projecting from existing trends (BERR, 2008b), LFG output would still contribute around 2 Mtoe in energy by 2020. Meanwhile, industrial waste conversion and 'second generation' biofuels can contribute about 1.3 Mtoe.

Summing up all these outputs shows that EfW can contribute around 11 Mtoe, which would be 50% of the required contribution of renewables by 2020 (RAB, 2008). The other half, i.e. 7.5% of total energy, can be sourced from other renewables such as wind, hydro and the proposed Severn Estuary tidal project. Figure 5 illustrates how UK's energy mix could look like in 2020. Comparing with the UK's recent energy mix (BERR, 2008b) indicates that EfW and renewables could displace about 13% of current fossil fuel consumption. However, actual results would depend on the pace of investment in renewables over the next decade. The availability of suitable feedstock for EfW processes would also be critical in determining how much displacement of fossil fuel use occurs.

**Figure 5:** Potential UK energy mix in 2020

## 6.3 Future Uses of Landfills

Whilst LFG output will fall in coming decades, landfills may be 'mined' for valuable raw materials, depending on favourable cost-benefit analyses. An estimated 200 million tonnes of plastics, worth around £40 billion, have been dumped in UK landfills over the past 20 years (Smith and Sherman, 2008). Recovered materials could be used for manufacturing or combusted for energy production. Ground source heating from landfills would also become more common.

## 6.4 Planning for Uncertain Outcomes

The UK EfW sector is undergoing unprecedented changes, with stakeholders having to constantly adapt to new legislation and evolving market forces. The concepts of "eco-design" and "zero waste" are gaining prominence as the Government seeks to encourage waste prevention. Meanwhile, existing treatment technologies are being updated continually to increase efficiency whilst novel methods are developed. These changes require waste management plans to be adaptable. Unfortunately, many EfW projects are funded through private finance initiative (PFI) contracts, typically spanning 25 years (Friedhoff, 2009).

This means any failure to forecast future changes in legislation, technology or waste composition, may lead to redundant facilities and thus huge financial losses for investors (Adamson, 2008). There is also potential for over-capacity of treatment technologies such as AD and thermal EfW, leading to shortage or increased cost of feedstock. It is, therefore, imperative that investment in technology is done in parallel with feedstock availability analyses. The full long-term impacts of changing legislation and market forces on waste firms are uncertain. However, the likely winners are the bigger firms with more diversified technology portfolio and greater financial clout.

## 7. RECOMMENDATIONS AND CONCLUSION

The uptake of renewables and EfW technologies in UK requires considerable support and political will from Government. In Sweden, where biomethane use for transport is thriving, incentives include free city-centre parking for NGVs and tax relief for businesses. When biomethane-powered cars become widely available on the UK market, they are expected to cost about £2,500 more than equivalent models (Cenex, 2009). To encourage patronage, the Government could subsidise this premium. Similarly, incentives such as discounted energy tariffs and free domestic hot water for people living near EfW plants could assuage lingering public opposition to incinerators in UK.

Greater cooperation among Government, industry, research institutions and local authorities would be required to hasten the adoption of low-carbon technologies (OECD, 2008). Biogas production and scrubbing ‘rings’ have been suggested for small-scale operators (Fuller, 2009). Local authorities could also benefit from waste management partnerships (Greenfield, 2009). Similarly, to achieve targets the UK public will need to be engaged as strategic partners. The successful planning application for the £4 billion Greater Manchester Waste PFI contract, the largest of its kind tendered in Europe, underscores the importance of effective stakeholder involvement (Kevan, 2009). With the target year of 2020 only a decade away, the benefits of EfW and renewables need better media coverage in order to encourage buy-in from the public. The 2012 London Olympics (Jeffries, 2009; MRW, 2008) would be an excellent platform to demonstrate the usefulness of EfW and renewable technologies.

By anticipating future policy trends and acting early, the UK can capitalise on ‘first mover’ advantages. The global market for renewable technologies is worth an estimated £3 trillion and is growing by 5% annually (Reeves, 2009a). Many countries including USA, China, South Korea and Germany are now investing heavily in low-carbon technologies in order to capture sizeable market shares and stimulate economic growth. For the UK economy to remain competitive, much more investment in renewable and low-carbon technologies is needed (Reeves, 2009b).

In conclusion, EfW technologies can make significant contributions towards achievement of the UK's renewable energy and GHG reduction targets. However, if these targets are to be met, concerted and sustained action is required from all stakeholders. The use of biomethane for road transport and community-level EfW should be given more support because they would provide much-needed energy and help to combat climate change. Small-scale EfW facilities deployed within communities would also help to overcome some of the challenges faced by larger installations. Although UK Government policies have encouraged renewable technology development (DECC, 2009a), innovators require greater support in bringing technologies to market (CIWEM, 2009). It is also recommended that detailed studies of reliable sources of EfW feedstock should be undertaken to inform investment decision-making.

## ACKNOWLEDGEMENTS

The authors would like to thank Geotechnical Instruments (UK) Limited and The Chartered Institution of Wastes Management (CIWM) for sponsoring this research.

## REFERENCES

Adamson, T (2008) Will EfW Facilities be left in the Cold? Materials Recycling Week, Emap, London, 192 (11), 81

Balat, M, and Balat, H (2009) Biogas as a Renewable Energy Source- A Review, Energy Source, Part A: Recovery, Utilization, and Environmental Effects, 31 (14), 1280-1293

Biogasmax (2008) Biomethane Business Model, available from: http://www.biogasmax.co.uk/media/7_biomethane_in_business__050081100_1523_12122008.pdf (accessed 01 September 2009)

Department for Business Enterprise and Regulatory Reform (BERR) (2008a) Digest of United Kingdom Energy Statistics 2008, available from: http://stats.berr.gov.uk/energystats/dukes08.pdf (accessed 08 September 2009)

BERR (2008b) UK Energy in Brief July 2008, available from: http://www.berr.gov.uk/files/file46983.pdf (accessed 01 July 2009)

BERR (2008c) UK Renewable Energy Strategy Consultation, available from: http://www.decc.gov.uk/en/content/cms/consultations/cons_res/cons_res.aspx (accessed 01 June 2009)

Biello, D (2008) Eco-Cities: Urban Planning for the Future, Scientific American, October, available online from: http://www.scientificamerican.com/article.cfm?id=eco-cities-urban-planning (accessed 01 June 2009)

Bogner, J, Ahmed, M A, Diaz, C, Faaij, A, Gao, Q, Hashimoto, S, Mareckova, K, Pipatti, R, and Zhang, T (2007) Waste Management, in: Metz, B, Davidson, O R, Bosch, P R, Dave, R, and Meyer, L A (eds) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK

Briner, G (2008) A Monumental Challenge: The Transition to a Hydrogen Economy, Environmentalist, Institute of Environmental Management and Assessment (IEMA), Lincoln, UK, 20 October

Brown, K A, and Maunder, D H (1994) Using Landfill Gas: A UK Perspective, Renewable Energy, 5 (II), 774-781

Cenex (2009) Biomethane Toolkit: A Guide to the Production and Use of Biomethane as a Road Transport Fuel, Cenex, Loughborough, UK

Chartered Institution of Water and Environmental Management (CIWEM) (2009) Green Innovators Struggle For Finance, Business Briefing 4 (7), CIWEM, London, UK

Cheremisinoff, N P (2003) Handbook of Solid Waste Management and Waste Minimisation Technologies, Butterworth Heinemann, London, UK

Council of the European Union (2009) Renewable Energy Directive 2009/28/EC, Official Journal of the European Union, L 140 (52), 16-62

Davies, E (2009) The Biofuel Future? ChemistryWorld, Royal Society of Chemistry, 6 (4), 40-43

Department of Energy and Climate Change (DECC) (2009a) UK Renewable Energy Strategy, TSO, Norwich, UK

DECC (2009b) UK Energy in Brief 2009, available from: http://www.decc.gov.uk/en/content/cms/statistics/publications/brief/brief.aspx (accessed 10 September 2009)

DECC (2009c) Energy Trends: March 2009, National Statistics, available from: http://www.berr.gov.uk/files/file50354.pdf (accessed 10 September 2009)

Department for Environment, Food and Rural Affairs (Defra) (2006) Key Facts about: Waste and Recycling, available from: http://www.defra.gov.uk/environment/statistics/waste/kf/wrkf02.htm (accessed 01 July 2009)

Defra (2007a) Waste Strategy for England 2007, HMSO, London, UK

Defra (2007b) UK Biomass Strategy, Defra, London, UK

Defra (2009a) Adapting to Climate Change, UK Climate Projections 2009, available from: http://www.defra.gov.uk/environment/climatechange/adapt/pdf/uk-climate-projections.pdf (accessed 22 June 2009)

Defra (2009b) Anaerobic Digestion- Shared Goals, available from: http://www.defra.gov.uk/environment/waste/ad/pdf/ad-sharedgoals-090217.pdf (accessed 10 July 2009)

Department of Trade and Industry (DTI) (2007) Meeting the Energy Challenge: A White Paper on Energy, HMSO, London, UK

Environmental Data Services (EDS) (2008) Carbon Analysis Favours MBT waste Treatment Using Anaerobic Digestion, The Ends Report no. 397

EDS (2009) Waste Companies Face Digestate Disposal Hurdle, The Ends Report no. 410

Environmental Services Association (ESA) (2008) Briefings: Energy from Waste, available from: http://www.esauk.org/publications/briefings/energy_from_waste.asp (accessed 01 July 2009)

Eriksson, P, and Olsson, M (2007) The Potential of Biogas as Vehicle Fuel in Europe- A Technological Innovations Systems Analysis of the Emerging Bio-Methane Technology, Master’s Thesis, Chalmers University of Technology, Göteborg, Sweden

Eurostat (2009) http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home (accessed 20 September 2009)

Evans, G (2001) Biowaste and Biological Waste Treatment, James and James, London, UK

Friedhoff, S (2009) Does PFI Work in Waste? Materials Recycling Week, Emap, London, 193 (21), 25

Fuller, S (2009) Waste: Fuels of the Future, Futuresource 2009, Excel, London, UK, 09-11 June

Giusti, L (2009) A Review of Waste Management Practices and their Impact on Human Health, Waste Management, 29 (8), 2227-2239

Greenfield, D (2009) Partnership Working, Futuresource 2009, Excel, London, UK, 09-11 June

House of Lords (2008) The EU's Target for Renewable Energy: 20% by 2020, TSO, Norwich, UK

Inter-governmental Panel on Climate Change (IPPC) Working Group 1 (2001) Climate Change 2001: The Scientific Basis, Cambridge University Press, Cambridge, UK

International Energy Agency (IEA) (2008) World Energy Outlook 2008, IEA, Paris, France

Jamasb, T, Kiamil, H, and Nepal, R (2008) Hot Issue and Burning Options in Waste Management: A Social Cost Benefit Analysis of Waste-to-Energy in the UK, Environmental Policy Research Group (EPRG) Working Paper 0802, Cambridge University, Cambridge, UK

Jeffries, E (2009) An Olympic Effort, CIWM, Chartered Institution of Wastes Management, Northampton, UK, August, 46-47

Kevan, R (2009) The Planning Challenge, CIWM, Chartered Institution of Wastes Management, Northampton, UK, June, 54-55

Materials Recycling Week (MRW) (2008) London Grabs the Green Games Baton, Emap, London, UK, 192 (11), 20-22

Mullis, E (2007) Energy From Waste, Environmental Knowledge Transfer Network (KTN) Publications, Kidlington, UK

Mullis, E, Kay, M, Morrall, A, and Drew, G (2009) Micro & Community Scale Domestic Waste & Wastewater Treatment Technologies, Environmental Knowledge Transfer Network (KTN) Publications, Kidlington, UK

Natural Gas Vehicle Association Europe (NGVA Europe) (2009) Natural Gas Vehicles Markets and Statistics, available from: http://www.ngvaeurope.eu/ (accessed 10 August 2009)

Niessen, W R (2002) Combustion and Incineration Processes, 3rd Edition, Marcel Dekker, New York, USA

Office of Public Sector Information (OPSI) (2009) Energy Act 2009, available from: www.statutelaw.gov.uk (accessed 13 July 2009)

Organisation for Economic Cooperation and Development (OECD) (2008) Environmental Outlook to 2030, OECD, Paris, France

Persson, M, Jönsson, O and Wellinger, A (2007) Biogas Upgrading to Vehicle Fuel Standards and Grid Injection, IEA Bioenergy Task 37, available from:

http://www.biogasmax.co.uk/media/1_biogas_upgrading__075624200_1207_19042007.pdf (accessed 02 May 2009)

Porteus, A (2005) Why Energy from Waste Incineration is an Essential Component of Environmentally Responsible Waste Management, Waste Management, 25 (4), 451-459

Pöyry (2009) Design of Feed-in Tariffs for Sub-5MW Electricity in Great Britain, Element Energy Limited, London, UK

Reeves, N (2009a) The Technology Race, WEM, The Chartered Institution of Water and Environmental Management (CIWEM), 14 (6), 13-16

Reeves, N (2009b) Lets Hear About a Vision of Britain as a Low Carbon Society, WEM, The Chartered Institution of Water and Environmental Management (CIWEM), 14 (7), 4-6

Renewables Advisory Board (RAB) (2008) 2020 Vision- How the UK can Meet its Target of 15% Renewable Energy, available from: http://www.renewables-advisory-board.org.uk/vBulletin/showthread.php?t=136 (accessed 20 August 2009)

Renewable Fuels Agency (RFA) (2008) The Gallagher Review of Indirect Effects of Biofuels Production, available from: http://www.dft.gov.uk/rfa/_db/_documents/Report_of_the_Gallagher_review.pdf (accessed 01 May 2009)

Smith, L and Sherman, J (2008) High Price of Plastics Raises Prospect of Rubbish Mining in Dumps, The Times, 12th August, available from: http://www.timesonline.co.uk/tol/news/environment/article4510201.ece (accessed 01 May 2009)

Sperrey, T (2008) Hydrogen Set to Clean up, Engineering and Technology, Institute of Engineering and Technology, Stevenage, UK, 3 (18), 54-55

Stegmann, R (1996) Landfill Gas Utilization: An Overview, in: Christensen, T H, Cossu, R, and Stegmann, R (eds) Landfilling of Waste: Biogas, E & FN Spon, London, UK, pp 9-17

Stern, N (2007) The Economics of Climate Change- The Stern Review, Cambridge University Press, Cambridge, UK

Sustainable Transport Solutions Limited (2006) Biogas as Road Transport Fuel, National Society for Clean Air and Environmental Protection, Brighton, UK

Williams, P T (2005) Waste Treatment and Disposal, 2nd Edition, Wiley, Chichester, UK

Yolcular, S (2009) Hydrogen Production for Energy Use in European Union Countries and Turkey, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 31 (15), 1329-1337