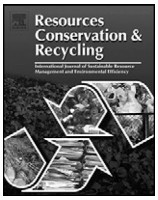
Resources, Conservation and Recycling 53 (2009) 624–630

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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



Bioethanol from waste: Life cycle estimation of the greenhouse gas saving potential

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ARTICLE INFO

Article history:
Received 5 October 2008
Received in revised form 2 April 2009
Accepted 21 April 2009
Available online 22 May 2009

Keywords:
Bioethanol
Greenhouse gas emissions
Waste management
LCA
Transport fuels
Recycling

ABSTRACT

This paper considers two alternative feedstocks for bioethanol production, both derived from household waste—Refuse Derived Fuel (RDF) and Biodegradable Municipal Waste (BMW). Life Cycle Assessment (LCA) has been carried out to estimate the GHG emissions from bioethanol using these two feedstocks. An integrated waste management system has been considered, taking into account recycling of materials and production of bioethanol in a combined gasification/bio-catalytic process. For the functional unit defined as the 'total amount of waste treated in the integrated waste management system', the best option is to produce bioethanol from RDF—this saves up to 196 kg CO_2 equiv. per tonne of MSW, compared to the current waste management practice in the UK.

However, if the functional unit is defined as 'MJ of fuel equiv.' and bioethanol is compared with petrol on an equivalent energy basis, the results show that bioethanol from RDF offers no saving of GHG emissions compared to petrol. For example, for a typical biogenic carbon content in RDF of around 60%, the life cycle GHG emissions from bioethanol are 87 g CO_2 equiv./MJ while for petrol they are 85 g CO_2 equiv./MJ. On the other hand, bioethanol from BMW offers a significant GHG saving potential over petrol. For a biogenic carbon content of 95%, the life cycle GHG emissions from bioethanol are 6.1 g CO_2 equiv./MJ which represents a saving of 92.5% compared to petrol. In comparison, bioethanol from UK wheat saves 28% of GHG while that from Brazilian sugar cane – the best performing bioethanol with respect to GHG emissions – saves 70%. If the biogenic carbon of the BMW feedstock exceeds 97%, the bioethanol system becomes a carbon sequester. For instance, if waste paper with the biogenic carbon content of almost 100% and a calorific value of 18 MJ/kg is converted into bioethanol, a saving of 107% compared to petrol could be achieved. Compared to paper recycling, converting waste paper into bioethanol saves 460 kg CO_2 equiv./t waste paper or eight times more than recycling.

1. Introduction

Transport is a significant contributor to greenhouse gas (GHG) emission, accounting for about 20% of global carbon dioxide emissions and 25% of emissions in the United Kingdom (UK); these figures are growing faster than for any other sector (The Royal Society, 2008). Therefore, reducing the emissions from this sector could contribute significantly to reaching the EU targets on climate change. Currently, the European Commission's non-binding target is to have 5.75% of biofuels used for transport by 2010 (Frondel and Peters, 2007). In the future, it is expected that these targets will be increased to 10% and will become mandatory.

It is thus important as well as timely to identify sustainable options for integration of biofuels into the transport sector. Currently, the majority of the biofuels are produced from food crops, including wheat, corn, sugar beet and soy. This has already led to undesirable socio-economic effects with respect to food production, including increases in food prices, shortage of fodder, and growing competition for land (Cramer, 2007; Mol, 2007; Thompson, 2008). Furthermore, the environmental advantages of biofuels derived from food crops are not clear and in some cases the impacts can be higher than that of petrol due to the cultivation of the feedstock (Crutzen et al., 2007; Zah, 2007).

In contrast, biofuels derived from waste do not pose similar risks; on the contrary, using non-recyclable waste as a resource would save the landfill disposal capacity, support the re-use of resources and lead to a reduction of GHG emissions from disposal sites, thus helping to fulfil the requirements of various legislation, including the European Waste Framework Directive (European Commission, 2006).

This paper considers the use of Municipal Solid Waste as a potentially sustainable source of bioethanol and discusses the potential for GHG savings on a life cycle basis compared to petrol and bioethanol derived from food crops.

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doi:10.1016/j.resconrec.2009.04.012

2. Biethanol from MSW: system definition

The bioethanol production system is evaluated in this work as part of an integrated waste management system. Two feedstocks for bioethanol production are investigated: Refuse Derived Fuel (RDF) and Biodegradable Municipal Waste (BMW). As shown in Figs. 1 and 2 this leads to different integrated waste management systems, as follows:

(i) RDF (Fig. 1): Municipal Solid Waste (MSW) is pre-sorted into the recyclables and the remaining waste. The former is collected and sent to a materials recovery facility and subsequently to recycling. The remaining MSW is collected and routed via a transfer station to a Mechanical and Biological Treatment (MBT) plant. The recyclable and non-combustible fractions are separated in the MBT plant and the remainder is stabilised, shredded and processed into RDF, which is then treated in the bioethanol production plant to produce ethanol. The recyclable fraction is sent to recycling while the remaining waste from the MBT plant is landfilled.

(ii) BMW (Fig. 2): MSW is pre-sorted into recyclables, BMW (including garden and food waste and forest residue) and remaining waste. The recyclables are treated in the same manner as in the previous waste management option. BMW is transferred directly to the bioethanol production plant without any pre-treatment. The remaining waste is incinerated.

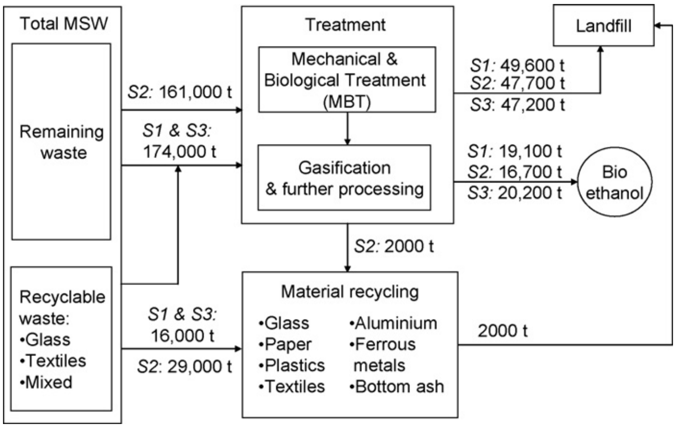

Fig. 1. A life cycle model of bioethanol production from RDF within an integrated MSW management system (Scenarios 1–3) (S1, S2 and S3: flows for Scenarios 1, 2 and 3, respectively).

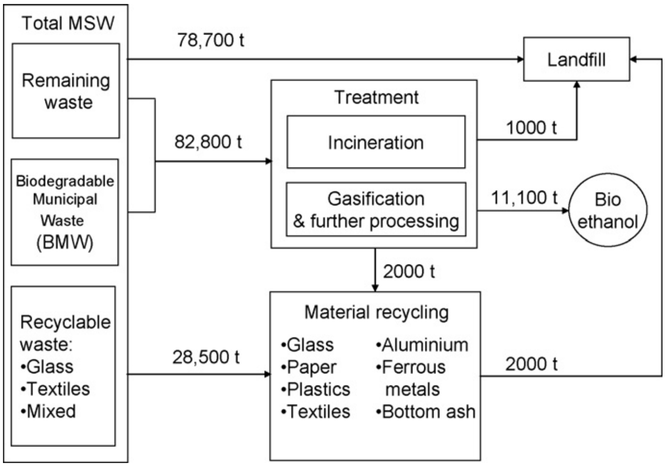

Fig. 2. A life cycle model of bioethanol production from BMW within an integrated MSW management system (Scenario 4).

In the bioethanol plant, the RDF or BMW are fed through a gasifier to produce synthesis gas (CO and H_2) and heat. Synthesis gas is then routed to a bio-catalytic fermenter to generate ethanol, which is then purified by distillation. Molecular sieves are used to remove the remaining water in ethanol and to obtain anhydrous ethanol that can be used as transport fuel. In addition to ethanol, butanol and other co-products are also produced. The heat from the gasifier is utilised to generate electricity and pre-heat the waste as well as for ethanol distillation.

3. Methodology for calculating the life cycle emissions of GHG

A life cycle approach has been used to calculate the GHG emissions from the bioethanol production systems outlined in Figs. 1 and 2. The ISO 14044 methodology for Life Cycle Assessment (LCA) has been used for these purposes (ISO, 2006). The aim of the study is twofold:

- to compare the GHG emissions for bioethanol derived from RDF and BMW in an integrated waste management system, considering different waste management scenarios; and
- to compare the GHG emissions from bioethanol produced from RDF and BMW with petrol and bioethanol derived from food crops.

Therefore, two functional units have been defined. For the comparison of different waste management scenarios, the functional unit is defined as the 'treatment of 190,000 t of MSW/year'. The comparison of bioethanol from waste with petrol and other bioethanols is based on the functional unit defined as 'MJ of fuel equivalent'.

The following five integrated waste management scenarios have been considered:

- Baseline scenario (Fig. 3): based on the waste management situation in the UK in 2004 (DEFRA, 2006);
- Scenario 1 (Fig. 1): As Baseline scenario, but with the addition of the MBT plant and the bioethanol production process; in this scenario, plastic and paper are converted into RDF in the MBT plant instead of being recycled; RDF is then used as feedstock in the bioethanol plant;

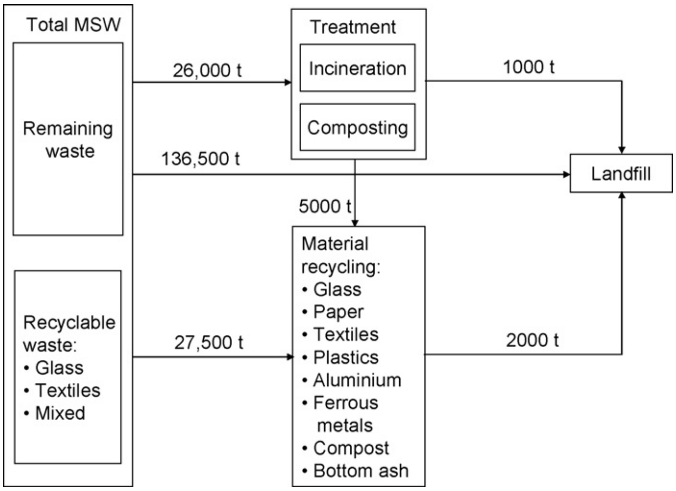

Fig. 3. Baseline scenario: based on the waste management situation in the UK in 2004 (DEFRA, 2006).

Table 1
Material flows in different scenarios.

	Baseline scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total waste (t/year)	190,000	190,000	190,000	190,000	190,000
Waste to recycling[a] (t/year)	27,500	16,000	29,000	16,000	28,500
Waste to treatment[b] (t/year)	26,000	174,000	161,000	174,000	82,800
Waste to landfill[c] (t/year)	136,500	0	0	0	78,700
Ethanol produced (t/year)	N/A	19,100	16,700	20,200	11,100

[a] Waste to recycling shows only the amount of recyclable materials going directly to recycling; the total amount of recycled materials may be higher depending on the amount of recyclables recovered in other stages of the integrated waste management system (see Figs. 1, 2 and 4 for more detail).

[b] Treatment includes incineration, composting, mechanical & biological treatment, and gasification & further processing (see Figs. 1, 2 and 4 and the corresponding scenarios).

[c] Waste to landfill represents waste going directly to landfill, without any treatment or recycling; the total waste landfilled is higher due to the solid residue from various treatment process (e.g. bottom ash and waste remaining after recycling). The total waste landfilled for each scenario can be seen in Figs. 1, 2 and 4.

- Scenario 2 (Fig. 1): As Scenario 1, except that here all waste materials are recycled and the remaining waste is converted into RDF and subsequently into bioethanol;
- Scenario 3 (Fig. 1): As Scenario 1, except that the remaining household waste is converted into RDF and then to bioethanol while the paper and plastic are used in the bioethanol plant directly (note that the difference between this and Scenario 1 is that the quantity of the feedstock in the bioethanol plant is higher here thus producing more bioethanol than in Scenario 1 (see Table 1); and
- Scenario 4 (Fig. 2): BMW, comprising 80% of the organic waste and 40% of paper originally present in the collected waste (assuming maximum amount of organic waste and recycling rates in the UK), is transferred directly to the bioethanol plant. The recycling rates for the recyclables are the same as in Baseline scenario; the remaining waste is sent to landfill (90%) and incineration (10%).

Scenarios 2–4 have been chosen to represent a range of different plausible possibilities for diverting MSW and particularly BMW waste from landfills, as stipulated by the Landfill Directive (European Commission, 1999).

The material flows in the different scenarios are shown in Table 1. The composition of MSW which is assumed the same for all scenarios is based on the waste situation in the UK in 2004 (DEFRA, 2006); the breakdown of different waste fractions is given in Table 2. In the same year, 72% of MSW was landfilled, 9% incinerated and 19% recycled/composted; this has been used as the basis for Baseline scenario (as shown in Table 1 and Fig. 3).

For the purposes of this analysis, it has been assumed that MSW enters the system with no up-stream environmental burdens. This is justified because waste is common to all scenarios considered, with the same initial composition assumed throughout.

The composition of RDF and the content of biogenic and fossil carbon assumed in the calculations are shown in Table 3 (Marsh et al., 2007). Biogenic carbon is that derived from biomass, i.e. from a renewable source, while the fossil carbon is related to fossil-derived materials. Only the emissions of fossil-derived carbon have been included in the calculations of the total GHG emissions; as biogenic carbon is derived from the biomass present in the waste which had adsorbed that amount of carbon while growing, it has not been included in the overall calculations. However, methane emissions from the biogenic carbon sources have been considered.

Table 2
Composition of waste assumed in this work (DEFRA, 2006).

Waste composition	Quantity (t/year)	Contribution (%)
Organic	69,350	36.5
Paper and card	34,200	18.0
Non-combustibles	23,370	12.3
Glass	12,540	6.6
Waste electrical and electronic equipment	8,550	4.5
Fine material (<10 mm)	7,600	4.0
Dense plastic	6,650	3.5
Wood	6,080	3.2
Plastic film	5,130	2.7
Textiles	4,560	2.4
Absorbent hygiene products	4,180	2.2
Ferrous metals	3,040	1.6
Combustibles	2,850	1.5
Household hazardous waste	1,140	0.6
Non-ferrous metals	760	0.4
Total	190,000	100.0

Based on the RDF composition in Table 3, the lower heating value (LHV) of RDF has been calculated using data from three different data sources: the UK Waste and Resource Assessment Tool for the Environment (WRATE) (The Environment Agency, 2007), the Dutch Energy Centre database (ECN, 2008) and a Danish LCA tool EASEWASTE (2008). These different values are shown in Table 4. The LHV for RDF used in this study is 18 MJ/kg. Although this value is higher than that in WRATE (15.6 MJ/kg), it is closer to the values calculated using the Dutch and Danish data. The LHV used in WRATE appears to be underestimated, mainly because of the low LHV assumed for plastics and paper (Biffaward, 2003). For simplicity, the constant LHV has been assumed for all scenarios as MBT operators can tailor the composition of RDF as required.

Compared to RDF, the water content in BMW is usually between 30 and 60% so that its LHG is relatively low; the value of 7.8 MJ/kg has been assumed in this work.

All transport distances within the integrated MSW management system have been assumed at 50 km.

Table 3
The composition of RDF and the carbon content assumed in the study.

	RDF (dry) (%) [A]	Total carbon in individual waste fraction (%) [B]	Biogenic carbon in individual waste fraction (%) [C]	Total biogenic carbon in waste fraction (%) [D = (A × B × C/10000]	Fossil carbon in waste fraction (%) [E = (A × B/100) − D]
Paper/cardboard	49.9	49	100	24.4	0
Plastics	18.0	80	0	0	14.4
Textile	12.0	56.8	36.8	2.5	4.3
Wood/miscell.	6.0	49	100	2.9	0
Water	14.0	0	0	0	0
Total	100			29.8	18.7

Table 4
Lower heating values (LHV) for different waste fractions (DEFRA, 2006; ECN, 2008; EASEWASTE, 2008).

	RDF (dry) (%)	WRATE (MJ/kg)	NL data (MJ/kg)	DK data (MJ/kg)	NL (calc.) (MJ/kg)	DK (calc.) (MJ/kg)	WRATE (calc.) (MJ/kg)
Paper	49.9	14.5	17.1	15.6	8.5	7.8	7.2
Plastics	18.0	28.7	36.9	36.3	6.9	6.8	5.4
Textile	12.0	17.7	14	19.8	1.7	2.4	2.1
Wood/miscell.	6.0	18.6/14.5	16	16.0	0.8	0.8	0.9
Water	14.0	0	0	0	0	0	0
Total	100				17.9	17.8	15.6

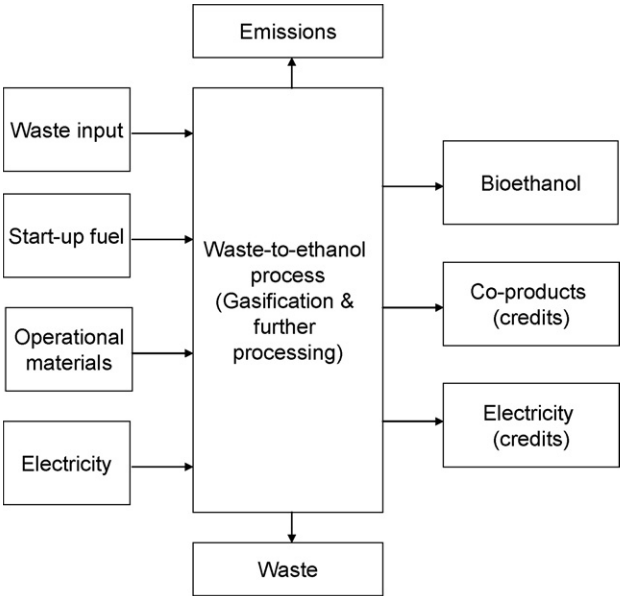

Fig. 4. The life cycle model of the bioethanol process.

WRATE has been used to model the integrated waste management systems as defined above and to estimate the GHG emissions. Due to the lack of data in WRATE, the bioethanol process has been modelled in GaBi (PE Europe, 2003) and imported into WRATE. The LCA model for the bioethanol process is shown in Fig. 4.

As shown in Fig. 4, the bioethanol production system has been credited for electricity generation and for the production of butanol. The credits have been implemented by subtracting the GHG emissions from the life cycles of the UK electricity mix and butanol production by hydro-formation of propylene, respectively. The integrated waste management system has also been credited for recycling of materials; the credits for different materials used in this study are shown in Table 5.

Finally, a credit has been added to the overall system for producing bioethanol, by subtracting the life cycle GHG emissions of an equivalent amount of petrol. Depending on the system boundary considered, the crediting has been carried out as follows:

- for the 'cradle-to-gate' system boundary, the 'cradle-to-gate' GHG emissions from petrol (i.e. up to the production of petrol) have been subtracted; and
- for the 'cradle-to-grave' system boundary, the GHG emissions from the whole life cycle of petrol, including its use in vehicles, have been subtracted from the system.

This is discussed further in the next section.

4. LCA results

As mentioned in the previous section, the LCA results are analysed for two systems:

1. integrated waste management; and
2. transport fuels.

The first set of results compares the GHG emission from the current waste management scenario in the UK (Baseline scenario, Fig. 3) with Scenarios 1–4 which produce bioethanol in an integrated waste management system (Figs. 1 and 2). The second set compares the GHG emissions saving potential from bioethanol from waste with petrol and bioethanol from different food crops. These results are discussed below.

4.1. Comparison of different waste management scenarios

The comparison of the GHG emissions for the five waste management scenarios is shown in Fig. 5. The results are based on the GHG emission estimates for petrol and bioethanol given in Table 6,

Table 5
GHG emissions saved by using recycled materials (DEFRA, 2006).

Material	GHG credit (kg CO_2 equiv. saved/t material)
Aluminium	10,365
Steel	995
Glass	24
Paper	200
Plastic (film)	534
Plastic (rigid)	685
Textiles	4,288
Bottom ash	72
Compost	88

Table 6
GHG emissions and savings from bioethanol compared to petrol (only fossil CO_2 equiv. shown).

GWP	Production (kg CO_2 equiv./kg) [A]	Use (kg CO_2 equiv./kg) [B]	Energy-equivalent factor (LHV equiv.) [C]	Total (kg CO_2 equiv./kg petrol equiv.) [$D = (A + B) \times C$]
Petrol (LHV = 43.2 MJ/kg)	0.57	3.50[a]	1	4.07
Bioethanol from RDF (LHV = 26.8 MJ/kg)	1.60	0.72	1.61	3.74
Bioethanol from BMW (LHV = 26.8 MJ/kg)	0.07	0.10	1.61	0.27
GHG savings[b] from replacing petrol by biofuel from:			RDF	0.33
			BMW	3.80

[a] Based on current efficiency of internal combustion engine.

[b] Excluding waste collection and any other transportation stages.

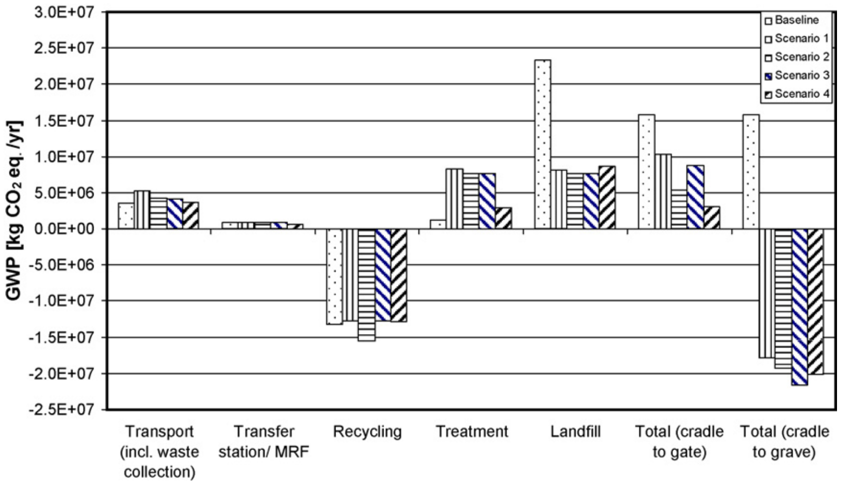

Fig. 5. Global Warming Potential (GWP) for all scenarios in the integrated waste management system (treatment comprises incineration, composting, mechanical & biological treatment, and gasification & further processing; total (cradle-to-gate)—excludes the use of bioethanol; total (cradle-to-grave)—includes the use of bioethanol).

Table 7
Cradle-to-grave GHG emissions savings from different types of ethanol compared to petrol (at 100% ethanol replacement).

Fuel	GHG emissions (g CO_2 equiv./MJ)	GHG saving (current vehicles) (%)	GHG saving (future vehicles) (%)	Reference
Petrol (current vehicles)	94.2	–	–	This work; Table 6
Petrol (future vehicles)	84.8	–	–	DfT (2008)
Bioethanol from RDF	86.5	8.2	−2.0	This work; Scenario 3
Bioethanol from BMW	6.3	93.3	92.5	This work; Scenario 4
Bioethanol from wheat (UK)	61	35.2	28.1	DfT (2008)
Bioethanol from sugar beet	50	46.9	41.0	DfT (2008)
Bioethanol from sugar cane (Brazil)	25	73.5	70.5	DfT (2008)

showing the contribution of the production and use (combustion) of fuels to the total GHG emissions (note that the emissions from waste collection and transport are not included in the results shown in Table 6, to enable an equivalent comparison with petrol). The emission factors from the use of petrol have been estimated using the current efficiency of internal combustion engines. The results show that bioethanol from RDF offers a modest GHG saving potential of 0.33 kg CO_2 equiv./kg petrol equiv. and BMW a much larger saving of 3.80 kg CO_2 equiv./kg petrol equiv. These emission factors have been used to estimate the total cradle-to-gate saving of GHG emissions for the scenarios, based on different flows of waste and quantities of ethanol produced (see Fig. 5).

The results reveal that bioethanol from RDF (Scenarios 1–3) and BMW (Scenario 4) offer a considerable potential for reducing GHG emissions compared to the current waste management situation in England (Baseline scenario).

Considering the 'cradle-to-gate' system boundary (i.e. the use of ethanol is not considered), for RDF as a feedstock for bioethanol (Scenarios 1–3) the best option is Scenario 2, offering the GHG saving of 69% compared to the Baseline scenario (see Fig. 5). This is mainly due to the highest quantity of materials being recycled in this scenario and the associated GHG credits for recycling.

However, for the same system boundary, Scenario 4 (BMW) is the best option overall, offering a saving over the Baseline scenario of 81%; however, this is assuming that the process produces sufficient excess heat to dry the BMW before processing. Scenario 4 also assumes 95% biogenic carbon in the feedstock. This reduces the amount of biodegradable waste going to landfill and consequently leads to considerable GHG savings from landfill. Note that the biogenic carbon content of the produced bioethanol correlates with the biogenic carbon content of the feedstock: the higher the biogenic carbon content in the bioethanol, the greater the GHG savings from its use as transport fuel.

If on the other hand the system boundary is from 'cradle to grave' (i.e. the use of ethanol is considered), all scenarios are better than the Baseline, because the integrated waste management system has been credited for displacing petrol (Fig. 5). The total GHG savings range between 177 and 196 kg CO_2 equiv. per tonne of MSW. Scenario 3 (RDF) is the best option for this system boundary, leading to a factor two reduction of GHG emissions compared to the Baseline scenario (Fig. 5). The main reason is that in this scenario the amount of waste treated in the bioethanol plant is the highest and therefore the amount of ethanol produced is the largest (see Table 1). The next best is Scenario 4 (BMW),

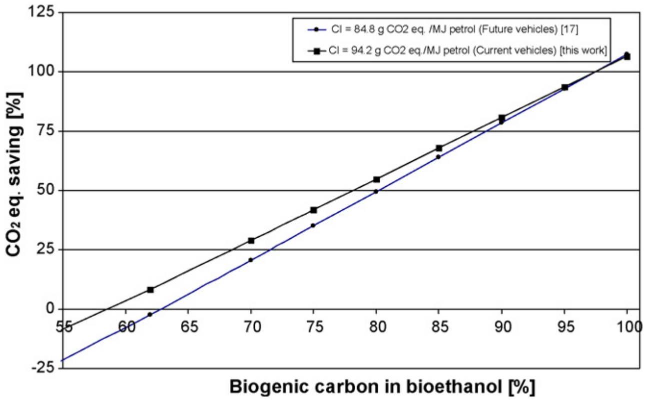

Fig. 6. GHG savings from bioethanol related to the biogenic content in bioethanol.

Table 8
GHG emission and savings from bioethanol from waste paper (only fossil CO_2 equiv. shown).

GWP	Production (kg CO_2 equiv./kg) [A]	Use (kg CO_2 equiv./kg) [B]	Energy-equivalent factor (LHV equiv.) [C]	Total (kg CO_2 equiv./kg petrol equiv.) [D = (A + B) × C]
Petrol (43.2 MJ/kg)	0.57	3.50	1	4.07
Bioethanol from waste paper (26.8 MJ/kg)	−0.16	0.00	1.61	−0.26
GHG savings from replacing petrol by bioethanol from paper[a]				4.33

[a] Excluding waste collection and any other transportation stage.

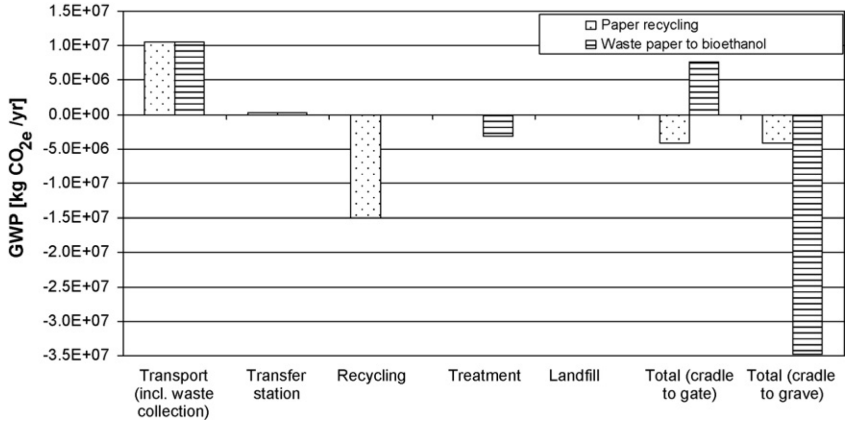

Fig. 7. Comparison of GHG emissions from paper recycling and bioethanol from waste paper.

mainly because of the highest biogenic carbon content in the feedstock.

4.2. Comparison of bioethanol from waste with other transport fuels

It is now interesting to compare the GHG emissions from the best scenarios for RDF and BMW (Scenarios 3 and 4, respectively) with the GHG emissions from petrol and ethanol produced from food crops. In all cases, the 'cradle to grave' system boundary has been considered and the comparison is based on MJ of fuel equivalent. The assumed biogenic carbon content for bioethanol from different feedstocks is as follows:

- RDF: 61% (taking the ratio of the biogenic and fossil fuel in RDF shown in Table 3 and accounting for the fossil fuel needed for gasification start-up);
- BMW: 95% (assuming some residual plastic is likely to be present); and
- food crops: 100% (the fossil carbon is accounted via the life cycle calculations of the total GHG emissions).

The GHG emissions per MJ of petrol and bioethanol from different feedstocks are shown in Table 7. As can be seen from the table, the GHG emissions saving from bioethanol compared to petrol depends on the assumed carbon intensity (CI) or life cycle GHG emissions from petrol. Two different GHG CIs have been considered in this work: the UK Renewable Fuels Transport Obligation (RTFO) value of 84.8 g CO_2 equiv./MJ petrol (DfT, 2008) and the value of 94.2 g CO_2 equiv./MJ estimated in this work (see Tables 6 and 7). The former figure is based on future internal combustion engines (ICE) with improved efficiency and the corresponding CO_2 emission factors, while the latter is based on the current ICE.[2]

The results in Table 7 show that, for the estimated current CI of petrol of 94.2 g CO_2 equiv./MJ, there are some GHG savings from the RDF-derived bioethanol (8.2%) and significant savings for the BMW-derived bioethanol (93.3%). However, if the CI of petrol for future ICE is considered (84.8 g CO_2 equiv./MJ petrol), bioethanol from RDF does not offer any GHG savings compared to petrol—in fact, its life cycle emissions are 2.3% higher than for petrol. Bioethanol from BMW in this case provides up to 92.5% GHG saving over petrol.

The results are sensitive to the content of biogenic carbon in the feedstock and thus in the bioethanol. Therefore, a sensitivity analysis has been carried out to find out how the savings in the GHG emissions change with the biogenic carbon content, compared to petrol using the two CIs. These results are shown in Fig. 6. For example, to achieve a 50% saving in GHG emissions compared to petrol with the CI of 84.8 kg CO_2 equiv./MJ, the biogenic carbon in bioethanol has to be 80%. For the same CI of petrol, bioethanol containing 95% of biogenic carbon would save 92.5% CO_2 equiv. and 100% biogenic carbon would save 107% CO_2 equiv. compared to petrol. Thus, at 100% biogenic carbon, the bioethanol system becomes a carbon sequester. As can also be seen from Fig. 6, the results are similar for both CIs for high but differ for lower biogenic carbon contents.

One of the possible bioethanol feedstocks which would have nearly 100% biogenic content is waste paper. It is thus interesting to investigate the GHG saving potential from using waste paper for bioethanol production, compared to the GHG savings from paper recycling. These results are shown in Table 8. Similar to the analysis presented in Table 6, these results take into account the production and combustion of bioethanol but not the collection and transport of waste paper. As shown in the table, bioethanol produced from waste paper would save 4.33 kg CO_2 equiv./kg petrol equiv.

To investigate these results further, an additional scenario has been modelled in WRATE taking into account the whole life cycle

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[2] As shown in Table 7, the calculated CI for current vehicles (using an assumed mix of 75% Euro I–IV cars and 25% of Light Goods Vehicles (LGV) and their respective CO_2 emission factors) is 4.07 kg CO_2 equiv./kg petrol. This figure divided by the LHV of petrol of 43.2 MJ/kg gives the CI of 94.2 g CO_2 equiv./MJ. This compares with 3.66 kg CO_2 equiv./kg petrol used in DfT (2008) for future vehicles, leading to the CI of 84.8 g CO_2 equiv./MJ.

of converting waste paper into bioethanol, including the production of bioethanol and its use (as shown in Table 8) but also the waste collection and other transport stages. A total of 75,000 t/year of waste paper has been assumed for these purposes (slightly more than double the amount of 34,000 t/year used in all previous scenarios; for comparison, the total amount of waste paper generated in the UK is 13.8 million t/year, DEFRA, 2006). The assumed collection of paper is by bring-banks, whereby the waste paper is brought to paper recycling banks by consumers, from where it is collected and transported to a transfer station and then either transferred to a paper recycling or the bioethanol plant. The assumed total distance travelled between the households and the paper treatment/conversion plant is 160 km. It has also been assumed that waste paper enters the system with no up-stream environmental burdens (the same assumption as in the previous scenarios).

The results of this analysis are shown in Fig. 7, which compares the life cycle emissions of GHG from paper recycling and bioethanol from waste paper. Note that, for simplicity, the results do not include the whole integrated waste management system, but consider the waste paper as the only waste material in the system. As shown in Fig. 7 for the 'cradle-to-gate' system boundary, recycling of paper is better than producing bioethanol as it saves 55 kg CO_2 equiv./t waste paper compared to bioethanol which generates additional 102 kg CO_2 equiv./t waste paper.

However, when the use of bioethanol is considered, i.e. the system boundary is from 'cradle to grave', it is much better to produce bioethanol from waste paper than to recycle it, as the saving is 464 kg CO_2 equiv./t waste paper compared to 55 kg CO_2 equiv./t waste paper for recycling. Thus conversion of waste paper into bioethanol saves eight times more GHG than recycling. However, these results should be interpreted with care, as GHG emissions is just one criterion—other criteria should also be considered, including a potential increase in the demand for virgin paper pulp and the related land use for the trees as well as whether the trees are sourced from sustainable forests.

5. Conclusions

Production of bioethanol from MSW provides significant GHG emissions savings compared to the current waste management options in the UK; in an integrated waste management system, including materials recycling, the savings range between 177 and 196 kg CO_2 equiv. per tonne of MSW, with the best performing feedstock being RDF.

However, comparison of bioethanol with petrol on an energy-equivalent basis reveals that bioethanol from RDF offers little or no advantage with respect to GHG emissions for a typical biogenic carbon content in RDF of 60%: for the current efficiency of petrol vehicles, there is only an 8% saving compared to petrol; considering an improved efficiency of vehicles in the future, the life cycle GHG emissions from RDF-derived bioethanol are higher than from petrol. On the other hand, bioethanol derived from BMW has a potential to save up to 92.5% of GHG emissions; by comparison, bioethanol from Brazilian sugar cane saves 70% of GHG compared to petrol.

If waste paper is used as a feedstock, the bioethanol system becomes a net carbon sequester. Waste paper with the lower heating value of 18 MJ/kg converted into bioethanol provides the saving of 464 kg CO_2 equiv./kg waste paper—this represents a factor of 8 saving compared to recycling the equivalent amount of waste paper.

In addition to the GHG savings, ethanol from waste offers other advantages such as avoiding the use of food crops; furthermore, its supply is relatively constant and independent of the season and weather conditions. It also saves the landfill disposal capacity and leads to GHG emission reduction from landfills and thus helps to fulfil the requirements set by various legislation, including the European Waste Framework Directive (European Commission, 2006).

However, the presented results are solely based on the GHG emissions; the overall environmental sustainability of bioethanol from waste cannot be assessed without investigating other environmental and socio-economic impacts. Furthermore, the production of ethanol from waste might compete with other recycling or material recovery options which should also be analysed by using a full life cycle approach.

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