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Technical/economic/environmental analysis of biogas utilisation

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Abstract

Biogas may be utilised for Combined Heat and Power (CHP) production or for transport fuel production (CH_4-enriched biogas). When used to produce transport fuel either electricity is imported to power the plant or some of the biogas is used in a small CHP unit to meet electricity demand on site. The potential revenue from CH_4-enriched biogas when replacing petrol is higher than that for replacing diesel (Irish prices). Transport fuel production when replacing petrol requires the least gate fee. The production of greenhouse-gas is generated with cognisance of greenhouse-gas production with the scheme not in place; landfill of the Organic Fraction of Municipal Solid Waste (OFMSW) (20% of biomass) with and without combustion of landfill gas is investigated. The transport scenario with importation of brown electricity generates more greenhouse-gas than petrol or diesel, when the 'do-nothing' case involves combustion of landfill gas. The preferred solution involves transport fuel production with the production of CHP to meet electricity demand on site. A shortfall of this solution is that only 53% of biogas is available for export.

Keywords: Biogas; CHP; CH_4-enriched biogas; OFMSW; Pig slurry; Gate fee; Greenhouse-gas; Sustainable

1. Introduction

Denmark has a significant number of Centralised Anaerobic Digestion (CAD) facilities [1–7]; the biogas generated is used in CHP plants. In the larger plants (circa

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1 MWe), an electrical efficiency of 35% is achieved; the thermal product (circa 40% efficiency) is distributed via a district-heating infrastructure [3,5,8]. In many countries, a district-heating infrastructure is not available; heat may not be sold in summer months unless the thermal demand is industrial. In Sweden and Switzerland, biogas is scrubbed of carbon dioxide and impurities to generate a CH_4-enriched biogas (95–98% CH_4). This CH_4-enriched biogas may be used as vehicle fuel [9–12]. There is potential to discharge the CH_4-enriched biogas to the national gas-grid to allow a series of biogas service stations. Volvo, among others, has developed a bi-fuel car, which runs on petrol and biogas [13]; this allows flexibility to the consumer and allows maximum utilisation of the biogas.

The aim of this paper is to ascertain the most beneficial use of biogas. A decision support software package has been developed which models the technical/economic/environmental conditions of a biogas system. This paper outlines an example of its use at 1 MWe scale.

2. Asset value of 1 m^3 of biogas

With reference to Fig. 1, the asset value of 1 m^3 of biogas when used in a CHP system may be noted. The rate applied for electricity is in accordance with AER VI (alternative energy rate competition number 6 year 2003 in Ireland) [14]. The rate applied for thermal energy is just less that the cheapest fossil-fuel alternative in Ireland. Box 1 outlines the asset value of biogas when used to substitute for petrol or diesel. This technology will become more widespread and will benefit in terms of economics due to two proposed European Directives [15]:

- One proposes that biofuels make up a minimum of 5.75% of petrol and diesel used in cars in 2010.
- The other allows member states to reduce excise duty on biofuels, a value of 25% tax is used in this example.

It may be noted that biogas has the potential to earn €0.39/Nm^3 as a petrol substitute, €0.28/Nm^3 as a diesel substitute, €0.19/Nm^3 in a CHP plant, €0.143/Nm^3 for electricity-only production. This would suggest that biogas use as a transport

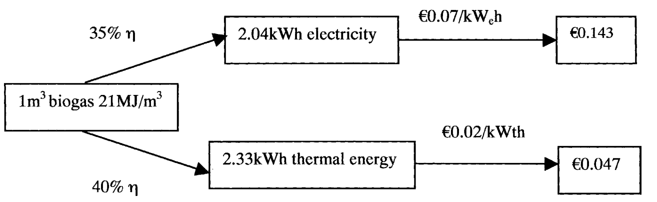

Fig. 1. Asset value of 1 m^3 of biogas producing CHP.

Box 1. Asset value of 1 m^3 of biogas

Fuels
Energy value of oil 47.89 GJ/T, density of petrol 673 kg/m^3, energy value of petrol 32.23 MJ/l, density of diesel 850 kg/m^3, energy value of diesel = 40.7 MJ/l CH_4-enriched biogas (95%CH_4): energy value 0.95 (37.78 MJ/Nm^3) = 35.9 MJ/Nm^3

Efficiencies [13,16]

Petrol:	Volvo V70 bi-fuel:	9.8 km/l = 0.3 km/MJ
CH_4-enriched biogas:	Volvo V70 bi-fuel:	9.6 km/Nm^3 = 0.267 km/MJ
Diesel:	Volvo S60:	13.17 km/l = 0.32 km/MJ
CH_4-enriched biogas:	Volvo S60 bi-fuel:	10 km/Nm^3 = 0.29 km/MJ

Asset value as petrol substitute
Petrol €0.89/l in Ireland = €0.0276/MJ, Biogas has 90% efficiency of petrol = €0.025/MJ, 1 m^3 CH_4-enriched biogas = €0.89 equates to €0.52 m^3 biogas @ 55.5% CH_4 (21 MJ/Nm^3)

Asset value of 1 m^3 biogas = €0.39 allowing for 25% tax

Asset value as diesel substitute
Diesel €0.8/l in Ireland = €0.020/MJ, Biogas has 90% efficiency of diesel = €0.018/MJ, 1 m^3 CH_4-enriched biogas = €0.635 equates to €0.37 m^3 biogas @ 55.5% CH_4 (21 MJ/Nm^3)
Asset value of 1 m^3 biogas = €0.28 allowing for 25% tax

fuel has an economic advantage over use in a CHP plant. However all biogas is not available for export; biogas is required for heating the digester, for provision of electricity in a sustainable system and for transport of slurries in a transport system. A more detailed analysis is required.

3. Greenhouse-gas production from utilisation of 1 m^3 of biogas

Box 2 outlines the derivation of greenhouse-gas emissions in combustion of 1 m^3 of biogas and utilisation in electricity production and as a transport fuel. The direct production of greenhouse-gas is not promising when compared with coal (0.89 t CO_2/MWh) and a petrol-fueled car (150 g CO_2/km @ 40 mpg). A more detailed analysis is required which allows for biogas losses in the system and greenhouse-gas production if the scheme is not in place.

Box 2. Greenhouse-gas production from biogas (55% CH_4 and 44% CO_2).

Combustion of CH_4: $CH_4 + 2O_2$	to	$CO_2 + 2H_2O$
1 mole methane	to	1 mol carbon dioxide
16 molecular weight	to	44 molecular weight
1 kg CH_4	to	2.75 kg CO_2
1 m^3 CH_4	to	1.96 kg CO_2 (CH_4 0.714 kg/m^3)
0.55 m^3 CH_4	to	1.078 kg CO_2
0.45 m^3 CO_2	to	0.88 kg CO_2 (CO_2 1.96 kg/m^3)
Combustion of 1 m^3 biogas	to	1.96 kg CO_2

Greenhouse-gas production: electricity (1 MWe scale) from 1 m^3 of biogas @ 35%ηe

1 m^3 Biogas (21MJ)	to	1.96 kg CO_2
2.04 kWh	to	1.96 kg CO_2
Equivalent to 0.96 T CO_2/MW_eh		

Greenhouse-gas production: utilisation of 1 m^3 of biogas as a transport fuel

1 m^3 of biogas produces 0.579 m^3 CH_4-enriched biogas (95% CH_4, 35.9 MJ/Nm^3)
Petrol 32.23 MJ/l: 40 mpg = 14.16 km/l = 0.44 km/MJ petrol CH_4-enriched biogas: 0.395 km/MJ = 14.18 km/Nm^3 CH_4-enriched biogas = 8.2 km/Nm^3 biogas
Greenhouse-gas production: 8.2 km/1.96 kgCO_2 equiv = 239 g CO_2/km

4. Scenarios investigated

Five main scenarios are analysed in detail in the program (Box 3). Scenario 1 is a model of the typical Danish system; diesel is imported into the system to power the transport fleet. Scenario 2 produces a CH_4-enriched transport fuel with the surplus biogas (a quantity of biogas is burned in a boiler to heat the digester); importation of electricity is required. Brown electricity was chosen as Ireland has a limited supply of green electricity; its use here would reduce its use elsewhere. Scenario 3 differs from Scenario 2 in that a small CHP plant is provided which supplies electricity to power the digester and the scrubbing system. In effect, sustainability is obtained only in Scenario 3.

5. Biogas plant

For the purpose of the analysis a biogas plant is proposed as set out in Box 4. Allowing 4 l per pig per day [17–19] and 200 kg OFMSW per person equivalent per annum [20], the waste material is generated by 5600 sows (1 sow = 10 pigs) [21] and 70 000 person equivalents. Pig slurry (6% dry solids) generates 26 m^3 biogas/T; OFMSW (35% dry solids) generates 120 m^3 biogas/T [22]. Electrical energy input is based on 10 kWh/t of waste [5,23]. Thermal-energy input is based on the specific heat capacity of water = 3.77 kJ/kg/°C.

6. Technical details Scenario 1

The technical details of the CHP plant may be summarised as in Box 5. Typically this system can power 2500 houses and heat 240 houses. All biogas is sent to a CHP plant; 12% of electricity is used on site, 52% of thermal energy is used on site. Fig. 2 outlines the energy available for export. Fig. 3 outlines the relationship between the average distance from the biogas plant to the source of waste. This is based on the usage of diesel in a HGV with a capacity of 32 m^3.

7. Technical details Scenario 2

In Scenario 2, electricity is taken from the national grid to power the biogas plant and the scrubber. Box 6 outlines CH_4-enriched biogas production and electricity

Box 3. Biogas scenarios investigated.

1: Production of CHP. Importation of diesel for transport of slurries
2A: Production of transport fuel (displacement of diesel in HGV) with importation of electricity.
2B: Production of transport fuel (displacement of petrol in cars) with importation of electricity.
3A: Production of transport fuel (displacement of diesel in HGV). Generation of CHP with biogas to cover parasitic energy requirements
3B: Production of transport fuel (displacement of petrol in cars). Generation of CHP with biogas to cover parasitic energy-requirements.

Box 4. Technical details of biogas plant.

Biomass treated	87 000 tpa (73 000 t pa pig slurry, 14 000 tpa OFMSW)
Biogas production	3 648 000 m^3 pa (42 m^3/tpa)
Temperature mode	Pasteurisation of OFMSW, thermophilic digestion
Primary digester volume	5 608 m^3 (20 days HRT)
Secondary digester volume	2 804 m^3 (10 days HRT)
Hours of operation	7 446 pa
Electrical energy required	10 kWh/m^3 biomass, 870 000 kWh pa, 117 kW
Thermal energy required	170 MJ/t biomass, 4 108 333 kWh pa

Box 5. Technical details of Scenario 1.

Energy in biogas	3 648 000 m^3 pa @ 21 MJ/Nm^3, 76 608 GJ pa, 2856 kW
Electricity production	1 MW (35%ηe) = 7 443 315 kWh pa
Excess-electricity production	7 443 315–870 000 = 6 573 315 kWh pa
Houses powered (2628 kWhpa/house)	2501
Thermal production	1.142 MW (40%ηt) = 8 506 646 kWh pa
Excess heat production	8 506 646 − 4 108 333 = 4 398 312 kWh pa
Houses heated (66 GJpa/house)	240
Transport-energy required	13.5 kWh/t biomass (103 578 lpa of diesel imported)

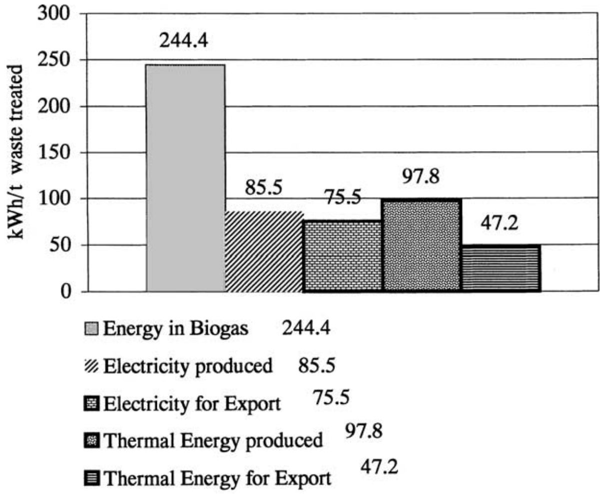

Fig. 2. Energy balance Scenario 1.

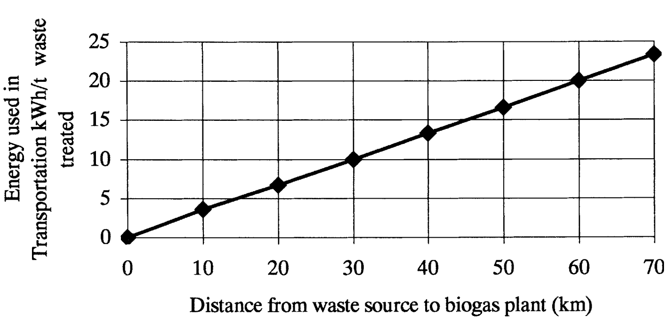

Fig. 3. Relationship between distance from biogas plant to source of waste and energy used.

imported to the system. The biogas available for export is outlined in Fig. 4; 28.8% of all biogas is required in the system. Scenarios 2A and 2B differ only in the use of biogas (Box. 7). Both scenarios save about 1 000 000 tpa of diesel/petrol. Of the order of 1000 cars, or 50 HGVs, may be powered by the biogas.

8. Technical details Scenario 3

Scenario 3 requires a CHP plant to provide sufficient electricity to power the biogas plant and the scrubber. The electrical efficiency of a CHP plant is typically 25% at scales of 200 kWe [8]. Burning biogas in a boiler makes up the shortfall in thermal energy. Box 8 outlines the reduced quantity of CH_4-enriched biogas available; 1 262

Box 6. Technical details Scenario 2

CH_4-enriched biogas production	
Biogas Produced	3 648 000 m^3 pa
Thermal demand of digester	4 108 333 kWh pa = 17 400 GJ pa @ 85%η in boiler = 829 097 m^3 pa
Net biogas production	3 648 000−829 097 = 2 818 903 m^3 pa
CH_4-enriched biogas production	2 818 903 m^3 pa × 0.555/0.95 = 1 648 316 m^3 pa
CH_4-enriched biogas used in transport	4681 GJ pa@0.047 km/MJ = 130 419 m^3pa of CH_4-enriched biogas
CH_4-enriched biogas for export	1 517 898 m^3 pa (54 477 GJ pa)
Electricity import required for Scenario 2	
Electricity demand of scrubber	0.75 kWh/m^3 CH_4-enriched biogas [11] × 1 648 316 m^3 pa = 1 236 237 kWh pa
Electricity demand of digester	870 000 kWh pa
Total electricity demand	2 106 237 kWh pa

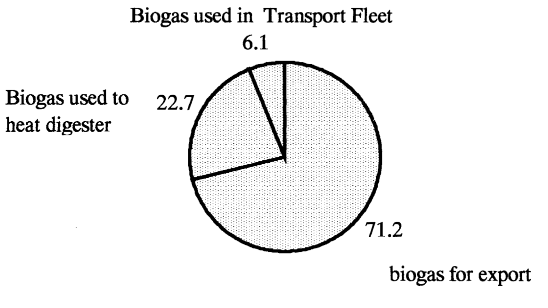

Fig. 4. Percentage biogas available for export: Scenario 2.

410 m^3 pa compared to 1 648 316 m^3 pa in Scenario 2, a drop of 23.4%. This is the cost of sustainability. The biogas availability in Scenario 3 is outlined in Fig. 5; 46.9% of all biogas is required in the system as compared to 28.8% in Scenario 2. Scenarios 3A and 3B differ only in the use of biogas (Box 9). It is of interest to know that, for both scenarios, about 760 000 T pa of diesel/petrol is replaced. Of the order of 760 cars, or 38 HGVs, may be powered by the biogas.

Box 7. Replacement of petrol/diesel in Scenario 2.

Scenario 2A: Replacement of diesel in HGVs (operating at 6 mpg on diesel 0.052 km/MJ)

HGV operating on CH_4-enriched biogas, 90% efficiency of diesel	= 0.047 km/MJ
Potential travel distance powered by biogas	= 256 0507 km
HGVs powered @ 50 000 kmpa	= 51
Diesel substituted 54 477 GJ pa × 0.9 = 49 029 GJ pa	= 1 209 841 l pa

Scenario 2B: Replacement of petrol in cars (operating at 40 mpg on petrol 0.439 km/MJ)

Car operating on CH_4-enriched biogas, 90% efficiency of petrol	= 0.396 km/MJ
Potential travel distance powered by biogas	= 21 560 852 km
Cars powered @ 20 000 km pa	= 1 078
Petrol substituted 54 477 GJ pa × 0.9 = 49 029 GJ pa	= 1 527 634 l pa

Box 8. Reduced CH_4-enriched biogas production in Scenario 3.

Electricity required in digester	= 870 000 kWh pa
Electrical demand of scrubber 0.75 kWh/m^3 CH_4-enriched biogas × 1 262 410 m^3 pa	= 946 808 kWh pa
Total electrical demand 244 kW × 7 446 h	= 1 816 808 kWh pa
Biogas required to supply electricity, 25%ηe	= 1 246 601 m^3 pa
Thermal energy required	= 4 108 333 kWh pa
Thermal energy produced, 40%η	= 2 906 892 kWh pa
Thermal shortfall	= 1 201 441 kWh pa
Biogas required in boiler @ 85%η	= 242 461 m^3 pa
Total biogas required in plant	= 1 489 062 m^3 pa
CH_4-enriched biogas production (3 648 000−1 489 062) × 0.555/0.95	= 1 262 410 m^3 pa
CH_4-enriched biogas used in transport	= 130 419 m^3 pa
CH_4-enriched biogas available for export	= 1 131 992 m^3 pa

9. Economic analysis of scenarios

An analysis of various case studies and a literature review [2,3,5,8–11,24,25] modified to the year 2003 using 3.5% inflation per annum lead to the following data being used in the decision-support software:

• Capital cost of biogas plant	€74/t waste treated per annum
• Operating cost of biogas plant	10% of capital cost
• Capital cost of transport fleet	€4.8/t waste treated per annum
• Operating cost of transport fleet	€2.3/t
• Capital cost of CHP plant	Fig. 6
• Operating cost of CHP plant	€0.01/kWh
• Capital cost of scrubber	€7860/m^3 CH_4-enriched biogas/h
• Operating cost of scrubber	€0.03/m^3 CH_4-enriched biogas

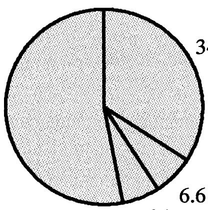

Fig. 5. Percentage biogas available for export Scenario 3.

Box 9. Replacement of petrol/diesel in Scenario 3.

Scenario 3A: Replacement of diesel in HGVs (operating at 6 mpg on diesel 0.052 km/MJ)

HGV operating on CH_4-enriched biogas 90% efficiency of diesel	= 0.047 km/MJ
Potential travel distance powered by biogas	= 1 909 671 km
HGVs powered @ 50 000 km pa	= 38
Diesel substituted 40 628 GJ pa × 0.047/0.052 = 36 721 GJ pa	= 902 254 l pa

Scenario 3B: Replacement of petrol in cars (operating at 40 mpg on petrol 0.439 km/L)

Car operating on CH_4-enriched biogas 90% efficiency of petrol	= 0.396 km/MJ
Potential travel distance powered by biogas	= 16 074 286 km
Cars powered @ 20 000 km pa	= 803
Petrol substituted 40 628 GJ pa × 0.396/0.439 = 36 648 GJ pa	= 1 134 517 l pa

Table 1 outlines the cost of the various scenarios. It is assumed that the pig farmers provide storage. Tax on vehicle fuel is assumed to be 25%. A 5% return on investment is utilised with a 20-year payback for non-mechanical works and a 10-year payback period for mechanical plant. The asset value of energy is as outlined in Section 2. It may be noted in Table 1 that Scenario 2B requires the least gate fee. From a sustainability point of view, Scenario 3B is preferred, as electricity is not imported and the gate fee difference is small. The following sections investigate the scenarios in more detail.

10. Sensitivity analysis of gate fee

Fig. 7 highlights the effect of the return offered per unit of produced electricity on the gate fee of the non-agricultural biomass. Scenario 1 is the only scenario affected by the rate change. Scenario 1 becomes the cheapest at revenues in excess of €0.115/kWh. No gate fee is required for Scenario 1 at rates in excess of €0.234/kWh. The AER rate offered in Ireland is one of the lowest in Europe [28]; increasing the rate for electricity has a strong effect on the viability of a CHP plant.

Fig. 8 highlights the effect of the unit rate of purchased electricity on the gate fee of the non-agricultural biomass. Scenarios 2A and 2B are the only scenarios affected by the rate change. Scenario 3B becomes the cheapest at rates in excess of €0.119/kWh.

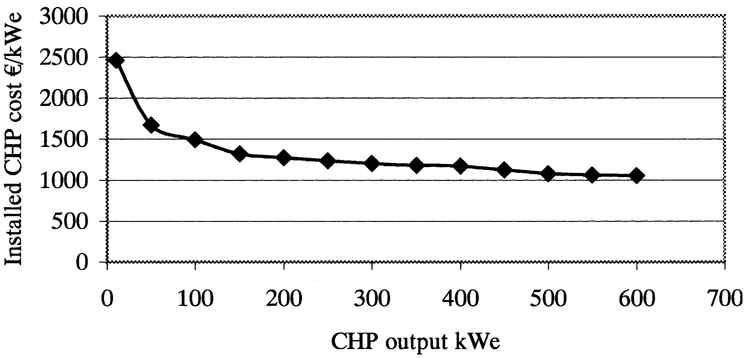

Fig. 6. Typical installed costs for small-scale packaged CHP Units, adapted from [26,27].

Table 1
Summary of the economics of the various scenarios

Scenario number	Description	Capital cost (€)	Gate fee €/t biomass	Gate fee €/t OFMSW
1	CHP	7 905 221	12.38	76.92
2A	Fuel to HGVs, import electricity	8 595 563	12.40	77.06
2B	Fuel to cars, import electricity	8 595 563	9.00	55.92
3A	Fuel to HGVs	8 488 806	12.23	76.03
3B	Fuel to cars	8 488 806	9.70	60.26

Fig. 9 highlights the effect of the unit rate of thermal energy sold on the Gate Fee of the non-agricultural biomass. Scenario 1 is the only option affected by the rate change. Scenario 1 is the most expensive option with the revenue from thermal energy being less than €0.0195/kWh. Scenarios 2B and 3B remain cheaper for the rates investigated.

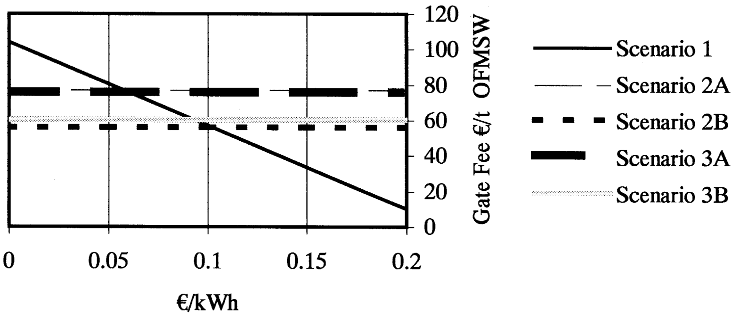

Fig. 7. Relationship between gate fee and revenue from electricity.

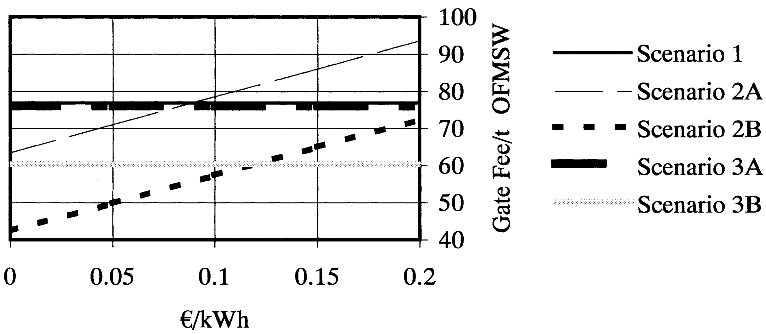

Fig. 8. Relationship between gate fee and cost of electricity.

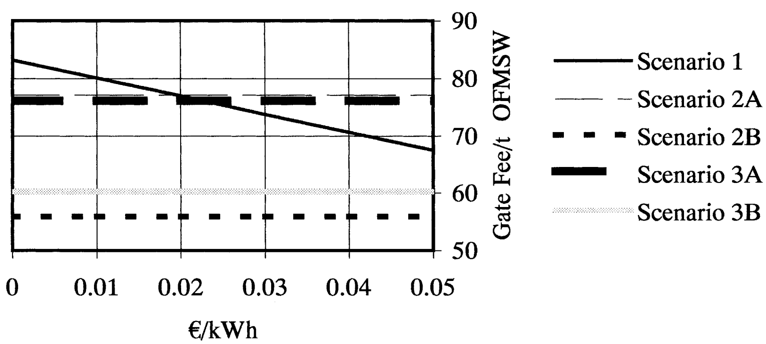

Fig. 9. Relationship between gate fee and revenue from heat.

Fig. 10 highlights the effect of fuel tax (excise duty and VAT combined) on the Gate Fee of the non-agricultural biomass. Scenario 1 is the only scenario not influenced by the rate change. Scenario 1 is the most expensive scenario if the tax on fuel is less than 25.7%. Scenario 1 is the least expensive scenario if tax on the fuel is greater than 48.3%. The less tax imposed on the fuel, the greater economic advantage associated with Scenario 2: Scenario 2 has more CH_4-enriched biogas for export than Scenario 3.

With reference to Table 1, it may be noted that the capital costs of all scenarios are of the same order, with the capital cost of Scenario 1 slightly less than Scenario 3, which in turn is slightly less than Scenario 2. Thus the return on investment does little to change the relative economic merits of the scenarios (Fig. 11). The effect of a capital grant is to reduce the gate fee by a similar percentage as the capital grant (Fig. 12). It also reduces the relative economic merits of Scenario 1 due to its slightly lower capital cost. Initially Danish CAD plants received 40% grants, but this has now reduced to 20% [2]. Examining Scenario 3B, the effect of the grant is to reduce the gate fee to 81% of the original with a 20% capital grant and to 62.7% of the original for a 40% capital grant.

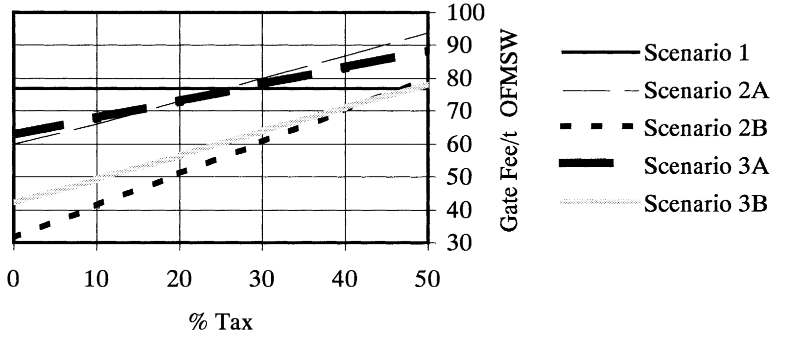

Fig. 10. Relationship between gate fee and % tax on transport fuel.

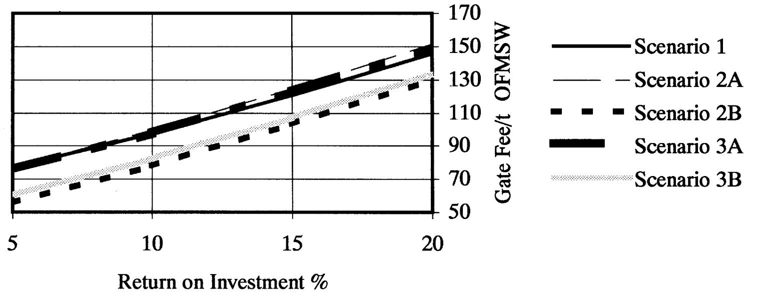

Fig. 11. Relationship between gate fee and return on investment.

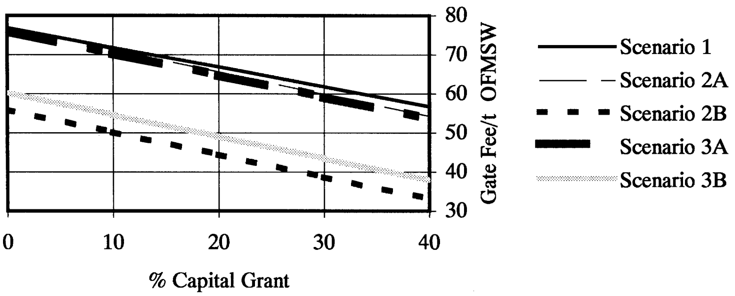

Fig. 12. Relationship between gate fee and capital grant expressed as a % of capital cost.

11. Greenhouse-gas analysis of CAD scale plants

In terms of greenhouse-gas production, there are three scenarios; the A and B transport scenarios differ in that the market for the biogas is different, but the quantity of displaced fuel is the same. The analysis is carried out under two headings: net greenhouse-gas produced and greenhouse-gas savings. The net greenhouse-gas production is based on an assessment with the scheme not in place compared with the scheme in place. Greenhouse-gas savings include the displacement of electricity/thermal power/transport fuel.

If the scheme is not in place, then the agriculture slurry is stored for a period of time (winter months) and is then land applied. An OECD report [29] outlines an approach to calculate greenhouse-gas emissions as follows:

- 10% of potential biogas production for 1-month's storage;
- 20% of potential biogas production for 2-month's storage;
- 10% of remaining biogas potential for land application in moist climates.

Maximum biogas potential is taken as 65% destruction of volatile solids [30,31]. This approach is outlined in Table 2.

Municipal waste is generally landfilled in Ireland. In a landfill, maximum destruction of volatile solids (65%) will be achieved over a long time [30,31].

It may be shown in a similar manner as outlined in Box 2, allowing for a Global-Warming Potential (GWP) of CH_4 of 21, that the emission of biogas (55%CH_4 45%CO_2) generates 9.2 kgCO_{2equiv}.

In the scenarios studied, the storage and land application of the waste are outlined in Table 2. Of immediate note is the fact that the landfill of OFMSW is a very large generator of greenhouse-gas. In the base year in Ireland for the Kyoto Protocol (1990), OFMSW was landfilled and the landfill gas was not burned.

The net greenhouse-gas production from Scenario 1 includes:

- Escape of biogas during digestion through fugitive losses and incomplete burning. It is assumed that 7.5% of the remaining biogas potential is generated in the secondary digester and that 6.3% of the total biogas escapes,

Table 2
Greenhouse-gas production from storage/landspread/landfill of wastes (scheme not in operation)

Feedstock	Quantity (T pa)	Max potential production of biogas (m^3 pa)	Production of biogas in storage [m^3 pa (%)]	Production of biogas in landspread [m^3 pa (%)]	Production of biogas in landfill [m^3 pa (%)]	TCO_2 pa[a]
Pig slurry[b]	73 000	213 5250	427 050 (20%)	170 820 (10%)		5500
OFMSW[c]	14 000	207 0250			2 070 250 (100%)	19 046
Total	87 000					24 547

[a] 9.2 $kgCO_2/m^3$ biogas emitted.

[b] 73 000 tpa × 6% DS × 75% VDS × 65% maximum destruction = 2135 TVDS destroyed = 44 840 GJ pa (21 GJ/TVDS) = 2 135 250 m^3 pa. 20% emission for 2 months storage = 4 27 050 m^3 pa. 10% emission of remaining for land application = 1/10 (2 135 250–427 050) = 170 820 m^3 pa.

[c] 14 000 tpa × 35% DS × 65% VDS × 65% maximum destruction = 2070 TVDS destroyed = 43 475 GJ pa = 2 070 250 m^3 pa. 100% emission for landfill = 2 070 250 m^3 pa.

typically biogas generated in the secondary digester equates to escaped biogas [30,32].
- Combustion of biogas.
- Utilisation of diesel in transportation of slurry and digestate.
- Storage and land application of digestate less storage, land application landfill of waste material in the ‘‘do-nothing’’ scenario.

The greenhouse-gas savings from Scenario 1 include:

- Saved greenhouse-gas production from brown electricity production (in the year 2000, the Irish electricity supply board, the ESB, produced 0.734TCO_2/MWh [33])
- Saved greenhouse-gas production from thermal-energy production from natural gas.

Box 10 outlines greenhouse-gas production/savings from Scenario 1. It may be noted that the greenhouse-gas production per unit of biogas production is negative.

The net greenhouse-gas production from Scenario 2 includes:

- Escape of biogas during digestion through fugitive losses and incomplete burning.
- Electricity import.
- Combustion of biogas
- Land application of digestate less storage, land application and landfill of waste material in the ‘‘do-nothing’’ scenario.

The greenhouse-gas savings from Scenario 2 include:

- Saved greenhouse-gas production from displaced diesel/petrol.

Box 10. Scenario 1 greenhouse-gas production/savings.

Net greenhouse-gas production		
Escape of biogas 243 115 m^3 biogas pa @ 9.2 $kgCO_2/m^3$		2 237 t CO_2 pa
Combustion of biogas equates to	3 615 856 m^3 pa × 1.96 kg CO_2/m^3	7 087 t CO_2 pa
Combustion of diesel equates to	103 578 l pa × 2.688 kg CO_2/l	278 t CO_2 pa
Storage and landspread of digestate 65 841 m^3 biogas pa × 9.2 kg $CO_2/m^3/1000$		606 t CO_2 pa
Total CO_2 production		10 208 t CO_2 pa
Net CO_2 production (do nothing less scheme in place) (24 547−10 208)		−14 339 t CO_2 pa
TCO_2/MWh		−2.181
kg CO_2/m^3 biogas produced		−3.966
Greenhouse-gas savings		
Electricity production 6 573 315 kWh pa × 0.734 t CO_2/MWh		4 825 tCO_2 pa
Thermal production 4 398 312 kWh pa × 0.24 t CO_2/MWh natural gas		1 056 tCO_2 pa
Total savings from CHP		5 881 tCO_2 pa
Total savings by Scenario 1		20 219 tCO_2 pa

Box 11 outlines greenhouse-gas production/savings from Scenario 2. It may be noted that the greenhouse-gas production per unit of biogas production is negative.

The net greenhouse-gas production from Scenario 3 includes:

- Escape of biogas during digestion through fugitive losses and incomplete burning.
- Combustion of biogas
- Land application of digestate less storage, land application and landfill of waste material in the "do-nothing" scenario.

The greenhouse-gas savings from Scenario 3 include:

- Greenhouse-gas production from displaced diesel/petrol.

Box 12 outlines greenhouse-gas production/savings from Scenario 3. It may be noted that the greenhouse-gas production per unit of biogas production is negative.

Table 3 summarises the greenhouse-gas production/savings for the three scenarios. Scenario 1 (CHP scenario) saves more greenhouse-gas production than Scenarios 2

Box 11. Scenario 2 greenhouse-gas production/savings.

Net greenhouse-gas production		
Importation of electricity	6 573 315 kWh pa × 0.734 t CO_2/MWh	4 825 t CO_2 pa
Escape of biogas equates to		2 237 t CO_2 pa
Combustion of biogas equates to		7 087 t CO_2 pa
Storage and landspread of digestate equates to		606 t CO_2 pa
Total CO_2 production due to Scenario 2		14 754 t CO_2 pa
Net CO_2 production (do-nothing less scheme in place) (24 547−14 754)		−9 792 t CO_2 pa
kg CO_2/m^3 biogas produced		−2.708
Greenhouse-gas savings		
1 209 841 l pa diesel saved × 2.688 kg CO_2/l		3 252 t CO_2 pa
Total savings by Scenario 2		13 044 t CO_2 pa

Box 12. Scenario 3 greenhouse-gas production.

Net greenhouse-gas production	
Escape of Biogas equates to	2 237 t CO_2 pa
Combustion of Biogas equates to	7 087 t CO_2 pa
Storage and landspread of digestate equates to	606 t CO_2 pa
Total CO_2 production due to scenario 3	9 929 t CO_2 pa
Net CO_2 production (do-nothing less scheme in place) (24 547−9 929)	−14 617 t CO_2 pa
kg CO_2/m^3 biogas produced	−4.043
Greenhouse-gas savings	
902 254 l pa diesel saved × 2.688 kg CO_2/l	2 425 t CO_2 pa
Total savings by Scenario 3	17 042 t CO_2 pa

Table 3
Summary of greenhouse-gas production/savings by different scenarios

Scenario	CO_2 production (T CO_2 pa)	kg CO_2/m^3 biogas	(T CO_2/MWh) g CO_2/km	Total savings (T CO_2 pa)
1	−14 339	−3.966	(−2.181)	20 219
2A	−9 792	−2.708	−3824	13 044
2B	−9 792	−2.708	−454	13 044
3A	−14 617	−4.043	−7564	17 042
3B	−14 617	−4.043	−909	17 042

and 3 (transport scenarios). Scenario 2 (transport with imported electricity) saves less greenhouse-gas production than Scenario 3 (transport with electricity produced with biogas).

Scenario 3 actually has a greenhouse-gas production lower than Scenario 1, as diesel is not combusted for transport of slurries and digestate. However Scenario 1 saves more greenhouse-gas production as the savings in greenhouse-gas from displaced electricity and thermal production is greater than that from displaced diesel-combustion.

All scenarios save greenhouse-gas; in effect the more CHP used or the more distance travelled in a biogas vehicle, the better the greenhouse-gas balance sheet will be. This is primarily due to the detrimental effect of landfilling OFMSW.

The next section deals with a comparison with combustion of landfill gas in the ‘‘do-nothing’’ scenario.

12. Direct burning of landfill gas in the ‘‘do-nothing’’ scenario

The conversion of landfill gas (biogas) to carbon dioxide through direct burning reduces significantly greenhouse-gas production as compared to the emission of landfill gas to the atmosphere. This may be noted in Table 4.

The ‘‘do-nothing’’ Scenario (landspread/landfill of biomass/waste) greenhouse-gas production is reduced by 61% by burning landfill gas (24 547 t CO_2 pa to 9 558 t CO_2 pa). Table 5 outlines the greenhouse-gas production/savings with direct burning of landfill gas. The change is significant. This may be considered more applicable to countries with a history of good environmental practice (Kyoto Base Year 1990).

Table 4
Effect of landfill-gas combustion on greenhouse-gas production

	Quantity of OFMSW (pa)	Production of landfill gas (m^3 pa)	kgCO_2/m^3 biogas	TCO_2 pa
No landfill-gas burning	14 000	2 070 250	9.2	19 046
Landfill-gas burning	14 000	2 070 250	1.96	4 058

Table 5
Summary of greenhouse-gas production/savings by different scenarios with burning of landfill gas on site

Scenario	CO_2 production (T CO_2 pa)	kg CO_2/m^3 biogas	(T CO_2/MWh) g CO_2/km	Total savings (TCO_2 pa)
1	650	0.18	(−0.0989)	5231
2A	5196	1.437	3733	−1944
2B	5196	1.437	443	−1944
3A	371	0.103	194	2054
3B	371	0.103	23	2054

The transport scenarios all produce greenhouse-gas rather than being CO_2 neutral or better as in the analysis summarised in Table 3.

13. Comparison of greenhouse-gas production with energy from fossil fuel

Tables 6–8 outline a comparison of the scenarios analysed with energy derived from a fossil fuel. In Table 6, it may be noted that CHP from biogas is better than CO_2 neutral. It may therefore be considered "*more green*" than wind power for example.

Table 7 compares greenhouse-gas production from a Heavy Goods Vehicle (HGV) powered by a diesel operating at 6 mpg with a HGV powered by biogas. Table 8 compares greenhouse-gas production from a car powered by petrol

Table 6
Greenhouse-gas production per unit of electrical power from different sources

Source of electricity	TCO_2/MWh
Coal	0.89
Oil	0.72
Natural gas	0.48
Wind	0
Biogas (no burning of landfill gas in "do-nothing" scenario)	−2.18
Biogas (burning of landfill gas in "do-nothing" scenario)	−0.0989

Table 7
Greenhouse-gas emissions from a HGV powered by various fuels

	Fuel efficiency	gCO_2/km
Diesel	6 mpg, 2.124 km/l, 0.052 km/MJ	1266
Biogas Scenario 2A (no burning of landfill gas)	0.0468 km/MJ	−3824
Biogas Scenario 3A (no burning of landfill gas)	0.0468 km/MJ	−7564
Biogas Scenario 2A (burning of landfill gas)	0.0468 km/MJ	3733
Biogas Scenario 3A (burning of landfill gas)	0.0468 km/MJ	194

Table 8
Greenhouse-gas emissions from a car powered by various fuels

	Fuel efficiency	gCO_2/km
Petrol	40 mpg, 14.16 km/l, 0.439 km/MJ	150
Biogas Scenario 2B (no burning of landfill gas)	0.395 km/MJ	−454
Biogas Scenario 3B (no burning of landfill gas)	0.395 km/MJ	−909
Biogas Scenario 2B (burning of landfill gas)	0.395 km/MJ	443
Biogas Scenario 3B (burning of landfill gas)	0.395 km/MJ	23

operating at 40 mpg with a car powered by biogas. The "do-nothing" scenario with landfill-gas emission to the atmosphere yields a great benefit to the biogas-powered vehicles. From an Irish perspective, this is valid, however it may be stated that a waste problem is inflating the benefit of biogas powered vehicles. Thus if the "do-nothing" scenario with the burning of landfill gas is considered, the following points may be made:

- Scenario 2 (importation of brown electricity) is less favourable from a greenhouse-gas emission perspective than petrol or diesel powered vehicles.
- Biogas powered vehicles (Scenario 3) generate of the order of 15% of the greenhouse-gas of petrol and diesel powered vehicles.

14. Conclusions

- The potential for a centralised anaerobic-digestion industry is very favourable in an Irish context. Typically the biomass digested is 80% agricultural and 20% municipal/industrial [2]. A gate fee is only charged on the non-agricultural waste. In the example analysed in this paper, 20% of the biomass is OFMSW. Landfill charges in Ireland in 2003 are of the order of €200/t. Gate fees for OFMSW are estimated to be of the order of €55–77/t. Furthermore, the implementation of the landfill directive [34] will necessitate an alternative treatment method for MSW.
- The production of transport fuel is more economic than the utilisation of biogas in a CHP plant for all scenarios if tax on transport fuel is less than 26%. The proposed EU directives on biofuels [15] will facilitate this.
- The cost of diesel per unit of energy is less than that of petrol. Basing the cost of CH_4-enriched biogas on the revenue per unit of energy of petrol offers an even greater economic advantage to transport fuel production over CHP production.
- Scenario 2B (production of transport fuel to displace petrol with the importation of electricity) has the lowest gate-fee.
- In the analysis of greenhouse-gas production two situations were investigated: combustion of landfill gas and dissipation of landfill gas to the atmosphere in the "do-nothing" scenario. Scenario 2 creates more greenhouse-gas than petrol or diesel as a transport fuel when the "do-nothing" scenario allows for the combustion of landfill gas.
- Scenario 3 (production of transport fuel with the generation of CHP on site using biogas) is the only sustainable scenario. Only 53% of biogas is available for export. However in terms of greenhouse-gas production, this option is far more favourable than Scenario 2. In the worse case investigated, the greenhouse-gas production was 15% that of a petrol or diesel powered vehicle. The gate fees are of the order of €60/t.

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