Modeling and Analysis

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Can grass biomethane be an economically viable biofuel for the farmer and the consumer?

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Abstract: Farm incomes in Ireland are in decline and many farmers would operate at a loss in the absence of subsidies. Agriculture is responsible for 27% of Ireland's greenhouse gas emissions and is the largest contributing sector. Penetration of renewable energy in the heat and transport sectors is falling short of targets, and there is no clear plan for achieving them. The anaerobic digestion of grass to produce biogas or biomethane is put forward as a multifaceted solution, which could help meet energy and emissions targets, reduce dependence on imported energy, and provide additional farm income. This paper addresses the economic viability of such a system. Grass biogas/biomethane fares poorly under the current combined heat and power tariff structure, which is geared toward feedstock that attracts a gate fee. Tariff structures similar to those used in other countries are necessary for the industry to develop. Equally, regulation should be implemented to allow injection of biomethane into the gas grid in Ireland. Blends of natural gas and biomethane can be sold, offering a cost-competitive green fuel. Sale as a renewable transport fuel could allow profitability for the farmer and savings for the consumer, but suffers due to the lack of a market. Under current conditions, the most economically viable outlet for grass biomethane is sale as a renewable heating fuel. The key to competitiveness is the existing natural gas infrastructure that enables distribution of grass biomethane, and the renewable energy targets that allow renewable fuels to compete against each other. © 2010 Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction

Farming in crisis

Farm incomes in Ireland are in decline. When inflation is taken into account, the average family farm income (FFI) for all farming systems decreased by 22% in real terms from 1995 to 2008.[1] There is a growing dependence on grants and subsidies in all farming sectors and without them beef and sheep farms would operate at a loss. Low FFIs mean that many farmers are seeking opportunities for farm diversification and alternative sources of income, and the National Development Plan[2] recognizes as a key task the promotion of

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the diversification of the rural economy. A move away from conventional farming can be further supported by the fact that all grass-based farming systems (beef, dairy, and sheep) produce large quantities for the export market. This is especially true in the beef sector, which had self-sufficiency values of over 600% for each year in the period 2000 to 2008.[3,4]

Greenhouse gas emissions in agriculture

Agriculture was responsible for 27.3% (18.4 Mt CO_{2eq}) of Ireland's greenhouse gas (GHG) emissions in 2008 and was the single largest contributing sector, followed by energy industries (21.8%), transport (21.1%), industry and commercial (16.9%), residential (11.2%), and waste (1.6%).[5] Enteric fermentation in non-dairy (i.e. beef) cattle is the largest contributor to agricultural emissions and is one of the biggest GHG emission sources in the country.[6] Ireland has the highest ratio of cattle to human population in the European Union (from Eurostat data[7,8]) and the importance of the agricultural sector is largely responsible for the country's relatively high per capita GHG emissions; in 2007 per capita emissions were 15.9 t CO_{2eq} compared with 10.2 t CO_{2eq} for the EU27.[9] The National Climate Change Strategy has put forward a decrease in herd size as a potential measure for reducing GHG emissions in the agricultural sector.[10]

Energy in crisis

Ireland is over 89% dependent on imported energy, with imported oil and gas accounting for 81% of energy supply.[11] This has significant implications for security of supply, emissions agreements under the Kyoto Protocol, and national and EU targets for renewable energy. Targets have been set in Ireland for renewable energy penetration by 2020 in each of the three energy sectors: 40% renewable electricity,[12] 12% renewable heat, and 10% renewable transport fuels.[13] Renewable energy in the electricity sector is expected to be provided largely by wind, but significant challenges are predicted in the heat and transport sectors. Ireland is currently over 99% dependent on oil and oil products for transport energy, all of which are imported,[14] while 96% of thermal energy is from non-renewable sources.[11] Renewable energy sources need to be found.

Grass for biogas, biomethane, bioNG, and bioCNG

Grass biogas/biomethane has been put forward as a renewable energy solution.[15] Anaerobic digestion (AD) is used to produce biogas from grass. Biogas can be burned directly for heat or electricity generation or can be upgraded to the same standard as natural gas, i.e. biomethane (~97% CH_4, ~3% CO_2 and some minor constituents). Biomethane and natural gas are mixable and interchangeable; mixtures of biomethane and natural gas are termed bioNG. BioNG can be sold from the gas grid in a similar manner to renewable electricity as long as an accounting system is in place to ensure that the quantity of biomethane injected into the grid matches the quantity sold. Different mixtures of bioNG could be sold for different purposes. To help meet the target for 12% renewable heat, a blend of 12% biomethane and 88% natural gas could be sold (12/88). A 10/90 blend could be sold as a transport fuel (bioCNG, or biocompressed natural gas) to aid in meeting the target for 10% renewable energy in transport.

At present, there are four farm digesters in Ireland: three generate thermal energy on site and one sells electricity to the grid. These digesters are predominately slurry digesters and do not employ energy crops. The potential for energy from grass in Ireland is huge, however, as grass covers around 90%[16] of the country's agricultural land. The expertise, knowledge, and equipment for growing, harvesting, and storing grass and grass silage already exist on Irish farms. The energy balance of grass biomethane is better than other temperate energy crop biofuels and compares favorably with tropical biofuels.[17] The GHG savings of grass biomethane used as a transport fuel meet the requirements of the EU Directive.[18] In terms of the constraints imposed by agricultural and biofuels policy, grass biomethane is the best energy crop for meeting the 2020 renewable transport energy target in Ireland.[19] An indigenous grass biogas industry could also provide employment and aid in developing the 'greentech' sector.

Focus of paper

Grass biogas/biomethane is a viable solution for meeting renewable energy targets in Ireland in terms of available technology, energy balance, GHG savings, and policy constraints. An issue that has not yet been addressed, however, is financial return. The aim of this paper is to investigate the economic viability of a grass biogas/biomethane industry in Ireland. While there is a significant body of work on the economics of AD, much of this is concentrated on wastes/residues for CHP (combined heat and power)[20-26] and there is limited information on the economics of grass digestion, either for CHP or for grid injection. Work by Murphy and Power[15] found the cost of grass biomethane used as a biofuel to be competitive with wheat bioethanol. A UK study found that a grass biogas CHP plant would struggle to break even, even when income is maximized through the sale of electricity, heat, and compost,[27] while German studies have found that grass biogas can be profitable under certain conditions; for example, for larger plants, for plants in receipt of agricultural subsidies, and for plants with lower feedstock costs and a year-round heat market.[28-31] There has been little research into the potential markets for biogas/biomethane and nothing of this kind has been done for Ireland. The results of this analysis are particular to grass biomethane in Ireland, but the approach adopted can be used for other countries and for other renewable energy resources.

Methodology and description of grass biomethane system

Boundary conditions

This paper is intended to act as a sister paper to previous work on grass AD, including an energy balance[17] and a GHG analysis,[18] and as such uses the same farm and AD plant size and output (Table 1). The plant is based on an operational facility, visited by the authors in Austria, which processed 1650 tDS y^{-1} of grass silage. In an Irish context, this is equivalent to 137.5 ha. Specialist beef production is the dominant type of farming in Ireland, with an average farm size of 27.5 ha.[32] A farmers co-op is therefore envisaged, whereby a number of farmers produce the grass silage, own and manage the AD facility, and sell the energy product (electricity/heat/biomethane).

Methodology

A simple economic analysis is carried out on the system by calculating annual costs and incomes, and then determining the tariff required to break even (i.e. to yield a return of 5% over 15 years). The values used for costs and incomes are relevant to the Irish context and are taken from the literature and from discussions with industry in Ireland and abroad. Annualized capital costs are calculated from the equation in Box 1. Land is assumed to already be in the ownership of the farmers' co-op and the cost of land acquisition and rent are excluded from the analysis.

Table 1. Farm and AD plant size and output.

	Value[a]	Comments
Annual feedstock (tDS y^{-1})	1650	
Grass silage yield (tDS ha^{-1})	12	Typical yield in Ireland
Area under grass (ha)	137.5	
Yield of volatile dry solids (tVS y^{-1})	1485	0.9 tVS tDS^{-1}
Methane yield (m^3 y^{-1})	445 500	300 m^3 CH_4 tVS_{added}^{-1}
Biogas yield (m^3 y^{-1})	810 000	55% CH_4 in grass biogas
Biogas energy yield (GJ y^{-1})	16 831	CH_4 energy content 37.78 MJ m^{-3}
Losses in upgrading (%)	1.5	
Biomethane yield (m^3 y^{-1})	452 389	97% CH_4 in biomethane
Biomethane energy yield (GJ y^{-1})	16 579	

[a]Grass and energy yields from previous work.[17,18]
DS = total dry solids; VS = volatile dry solids; VS_{added} = volatile dry solids added to digester.

Box 1. Annual capital cost

Annual capital cost (€ y^{-1}) =

$$R = [P(1 + r)^N r] / [(1+r)^N - 1]$$

where r = rate of return (5%)
P = principal (€)
N = lifetime of project (15 years)

The calculated break-even tariffs are compared with existing tariffs where appropriate (i.e. for CHP) and the effectiveness of the tariff system is assessed. The results also compare profitability under the current tariff structure with existing farm incomes. It is not expected that grass biogas will offer a solution to the economic crises in farming. Diverting grass to AD and decreasing livestock numbers, however, results in a decreased workload (due to the absence of a herd) and, if similar or better economic return can be achieved, this will be attractive to farmers. Where no existing tariff structure is in place, i.e. for grid injection, the markets (heat and transport) are examined to assess the potential for profitability as well as the competitiveness of the product from the consumer's perspective.

Potential pathways for the use of grass biogas/biomethane

The use of biogas for energy can follow a number of different pathways (Fig. 1). Two main scenarios are considered in this paper:

- Scenario 1: biogas for on-site CHP
- Scenario 2: upgrading to biomethane standard and injection into the gas grid

On-site heat production is not considered as there are limited markets for heat in Ireland. Sale as a vehicle fuel on site is excluded as there is unlikely to be a market in the vicinity of a rural farm plant, while container transport is not considered due to logistical difficulties. It is assumed that biomethane injected into the gas grid is purchased by a shipper for sale elsewhere on the grid. The calculation of shipping charges is beyond the scope of this study, which looks instead at potential markets for biomethane from the grid and the price these markets would be willing to pay.

Capital costs

Silage storage and AD plant

Silage is to be stored in a horizontal silo (silage pit); 21 silage pits are required (Table 2). If we consider 5 farms of average size (27.5 ha) then 4 pits are required per farm. In practice the farms would already have pits, thus the estimated construction cost of €456 250 (Table 2) must be viewed as conservative. The capital cost of an AD plant depends on a number of factors, including plant size and type, with larger plants generally having lower capital costs per m^3 of biogas produced. The capital cost of a plant visited by the authors in Austria, which was a continuously stirred tank reactor (CSTR) of the same size as the one in this analysis, was €745 000. As AD is a relatively new technology to Ireland, 10% is added to this value to give €819 500 (approximately €110 t^{-1} feedstock). This is assumed to include the cost of *in situ* hydrogen sulphide (H_2S) removal.

CHP plant and connection to electricity grid

From discussions with industry and values in the literature,[20,22,33] the cost of the CHP plant is conservatively taken as €1500 kW_e^{-1}, which is the fully installed cost including

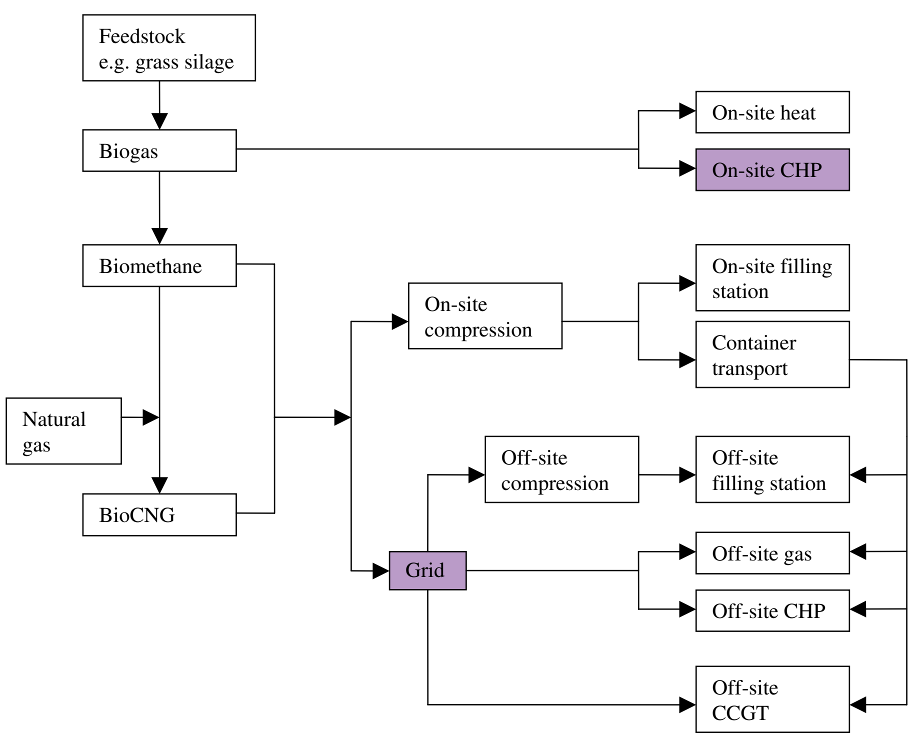

Figure 1. Pathways for the use of biogas.

Table 2. Cost of silage pit.

Component	Quantity[a]	Unit cost[b 36]	Total cost
Silo wall	22 walls x 25 m long	€400 m^{-1}	€220 000
Silage base	21 pits x 25 m long x 10 m wide	€42 m^{-2}	€220 500
Effluent channel	Assume 250 m	€63 m^{-1}	€ 15 750
Total			€456 250

[a]Pit silage typically has a dry solids content of 22%;[17] thus total silage production is 7500 t y^{-1}. Typical dimensions for a full silage pit are 25 m long, 10 m wide and 2.1 m high, with a capacity of 360 t silage.[72] Therefore 21 such pits would be required (this is a conservative value as silage will be used between harvests).
[b]Costs for silo wall and effluent channel are per linear metre.

civil works and electrical and piping installations. Assuming 85% operational efficiency, the cost of a 220 kW_e CHP plant is €330 000. The cost of connection to the electricity grid is very site-specific and depends on the location of the new generator in relation to the existing loads and generation on the network, as well as the distance from the grid. A survey of a number of developers puts the typical cost for a 200–250 kW_e facility as €80 000 for connection equipment, €10 000 for a connection study, and €10 000 for the substation (if required). Underground lines cost around €50 000 km^{-1}; 400-meter lines costing €20 000 are assumed in this analysis, giving a total cost of €120 000.

Upgrading plant and connection to gas grid

The capital cost of an upgrading facility is highly dependent on plant size, with smaller plants having higher costs per m^3 of upgraded gas. A membrane plant with a capital cost of €500 000 (€0.10 kWh^{-1} y^{-1}) is assumed, which includes gas metering and quality monitoring, and is similar to values in the literature.[15,34] The cost of connection to the gas grid can vary widely and depends on distance to the network, ground conditions, and the type of pipes, grid connection, and compressor. Contractual costs can form a significant part of the overall cost. There are currently no biomethane plants with grid injection in Ireland and a full pricing scheme has yet to be developed. It is assumed that the upgrading plant is located within 0.5 km of the distribution network, which has a pressure of about 4.2 bar. The cost of installing distribution pipes is very site specific; values between €150 000 km^{-1} and €400 000 km^{-1} have been estimated in the literature[35] and in discussions with Bord Gáis (the Irish Gas Board). Bearing in mind the variability associated with this item, the total capital cost of connection to the gas grid is estimated at €200 000. Upgrading plants typically pressurize gas up to 7 bar, so no additional compressor is required.

Operating costs

Silage harvesting

Yield per hectare has the biggest influence on the cost of silage. Other factors include the cost of machinery and labor. The volatility in oil prices, which directly affects fuel and fertilizer costs, results in considerable fluctuations in the cost of producing silage. Two-cut silage with an annual yield of 12 tDS ha^{-1} is used in this analysis. The cost of getting a hectare of grass into the pit is €950 ha^{-1} (€17 t^{-1}), which includes fertilizer, reseeding, lime, plastic, and contractor charges (calculated from data in Teagasc[36]). According to Korres *et al.*,[18] an application of 300 kg N ha^{-1} y^{-1} is required in establishment years and 225 kg N ha^{-1} y^{-1} in subsequent years. As the market price of silage is around 40% higher, it is important that grass silage is produced on-farm and not purchased at market prices. In order to maintain high biogas yields, silage losses in the field and in the silage pit should be kept to a minimum and effluent from the pit should be collected and added to the digester.

AD plant

The operational cost of an AD plant is made up of the cost of labor, electricity (for mixing and pumping), heating fuel (either biogas or imported fuel to meet the parasitic heat demand), and maintenance, and depends on the type of process used. Previous work suggests annual operational costs of an AD plant (excluding feedstock) to be of the order of 10–12% of the unsubsidized capital costs.[37,38] Work in the UK[27] and Sweden[39] used values of 4% and 15%, respectively. A value of 10% is used in this analysis. An additional allowance of 6.67% of the unsubsidized capital costs is made for depreciation of the AD, CHP, and upgrading plants. This allows for a fund equal to the initial investment to be available after the 15-year lifetime of the facility. The inclusion of a depreciation fund results in a relatively conservative analysis, as not all developers allow for such a fund.

CHP and upgrading plants

Typical running costs for a CHP plant are given as €0.01 kWh_e^{-1}.[15,20,33] The operating cost of the upgrading plant is taken as €0.02 kWh^{-1} (€0.20 m^{-3}) of upgraded gas, which equates to around €92 000 y^{-1}, and gives a total (capital + operating) cost of €0.03 kWh^{-1} (€0.30 m^{-3}) for upgraded gas. This is at the lower end of the range quoted by the Swedish Gas Centre[40] for plants of this size. The plant in this analysis upgrades around 110 m^3 h^{-1} of raw gas (assuming an operational efficiency of 85%) and is relatively small compared with operational plants in Germany and Sweden. Membrane plants have lower maintenance and energy requirements leading to lower operating costs than for other technologies.[41]

Connection to electricity grid and gas grid

It is assumed that the renewable energy tariff received for electricity is the net revenue to the renewable energy provider; additional costs have not been included in the analysis for this item. The operating costs of the compression plant for injection into the gas grid are assumed to be included in the upgrading costs. The operating costs for metering and quality monitoring are also included in the cost of the upgrading plant.

Finance and subsidies

Capital

There is a national scheme in place offering capital grants for biogas CHP plants of up to 30% of the eligible capital costs.[42] The maximum grant is assumed in this analysis. There are no specific grants for biomethane plants injecting into the gas grid, although there are a number of national and EU schemes that could potentially provide funding. Three subscenarios are investigated: 30% grant toward capital costs, 50% grant, and no grant.

Operational

The Common Agricultural Policy (CAP) is a system of subsidies and support programs for agriculture operated by the EU. In addition to standard farm payments, there are a number of schemes under CAP which could provide additional support for a grass biogas/biomethane system, such as the Energy Crops Scheme and the Rural Environmental Protection Scheme (REPS). This paper carries out the economic analysis with and without agricultural subsidies. The average direct payment received by cattle rearing farms is €461 ha^{-1} (from 2006, 2007, and 2008 farm survey data[1,43]).

Income

Biogas

Biogas can be used on site to generate end products which can then be sold, i.e. heat, electricity, and biomethane. The price paid for heat depends on what it is replacing or what the alternative is. Examples of average commercial fuel costs[44] are: oil at €0.058–0.069 kWh_{th}^{-1} (depending on grade); wood pellets at €0.036 kWh_{th}^{-1} (bulk) or €0.061 kWh_{th}^{-1} (bagged); wood chips at €0.034 kWh_{th}^{-1}; and natural gas at €0.04 kWh_{th}^{-1} (based on a medium-sized business and including standing charges). It is assumed that €0.06 kWh_{th}^{-1} is paid for heat in this analysis. Subtracting value added tax (VAT) of 13.5%, the income to the biogas plant is €0.053 kWh_{th}^{-1}. The tariff for electricity from biogas CHP in Ireland is €0.12 kWh_e^{-1}.

There is currently no tariff structure for biomethane injected into the gas grid. There is considerable volatility in the wholesale price of natural gas, which varies depending on the season and on international markets. A figure of €0.02–0.03 kWh^{-1} is assumed and this is considered the minimum tariff for biomethane injected into the grid and is used for comparison in the initial analysis. A biomethane tariff system should incentivize renewable gas and offer a higher return than for fossil gas. Biomethane injected into the grid can be used in the heat, electricity, or transport sectors, and the existing market conditions will influence the price paid. Potential markets and market prices are discussed in the section on improving the viability.

Digestate

For farm-based AD plants, it is common practice for the digestate to be returned to the land serving the plant, thus replacing chemical fertilizer and offering financial savings. The amount of fertilizer replaced depends on the nutrient content of the digestate, but there is limited information on grass digestate[17] and it is difficult to estimate its value. In addition, the available nutrient content is highly dependent on the method and time of spreading. Further difficulties arise as the price of chemical fertilizers, and hence the savings achieved through their replacement, varies considerably from year to year. The digestion of 137.5 ha of grass results in 46.5 t of digestate at 2.1 kg N t^{-1} or 102 kg N. Thus, mineral fertilizer is reduced from 300 to 198 kg N ha^{-1} in the establishment year and from 225 to 123 kg N ha^{-1} y^{-1} in subsequent years.[18] Discussions with the AD industry in Ireland resulted in a conservative estimate for the net value of digestate of €4 t^{-1}. The digestate quantity is assumed to be 90% of the silage input[18,45] and the value of digestate is therefore 4 x 0.9 x 7500 = €27,000, or €196 ha^{-1}.

Economic analysis of grass biogas and biomethane under current conditions

Scenario 1: Biogas to on-site CHP

Base-case economic analysis

The plant produces biogas and CHP on site. The base-case analysis considers three different cases (Table 3, Box 2):

1. The sale of heat (€0.053 kWh_{th}^{-1}) and electricity (€0.12 kWh_e^{-1}) with no capital grant (E+H)

Table 3. Scenario 1: Gras s to biogas to CHP base-case economic analysis.

	Total cost (€)	Annual (€ y^{-1})	E+H (€ y^{-1})	G+E (€ y^{-1})	G+E+H (€ y^{-1})
Capital costs					
Silage pit	456 250	43 956			
AD plant	819 500	78 953			
CHP plant[a]	330 000	31 793			
Connection to electricity grid	120 000	11 561			
Total capital costs	1 725 750	166 263	166 263		
Capital finance[b]	263 714				
Total capital cost includig grant	1 462 036	140 856		140 856	140 856
Operating costs					
Depreciation[c]		76 672			
Silage production[d]		130 625			
AD plant[e]		81 950			
CHP plant[f]		16 363			
Total operating cost		305 610	305 610	305 610	305 610
Capital + operating costs			471 873	446 466	446 466
Income	**(€ kWh^{-1})**				
Heat	0.053	99 116			
Electricity	0.12	196 362			
Fertilizer savings[g]		27 000			
Total income		322 477	322 477	223 362	322 477
Income – costs			-149 395	-223 104	-123 989
Profit (€ ha^{-1})			-1087	-1623	-902
Profit (€ m^{-3} biogas)			-0.184	-0.275	-0.153
Profit (€ kWh_e^{-1})			-0.091	-0.136	-0.076
Elec price for break even (€ kWh_e^{-1})			0.211	0.256	0.196
Subsidy for break even (€ ha^{-1})			1087	1623	902

G = grant included; H = heat included; E = electricity included.
[a]The capital cost of the CHP plant is €1500 kW_e^{-1}.
[b]The maximum grant of €1200 kW_e^{-1} is assumed.
[c]Depreciation is 6.67% of capital costs.
[d]The cost of producing silage is €950 ha^{-1}.
[e]The operating cost of the AD plant is 10% of capital costs.
[f]The operating cost of the CHP plant is €0.01 kWh_e^{-1}.
[g]The savings from the use of digestate as fertilizer are estimated at €4 t^{-1}.

Box 2. Scenario 1: Grass to biogas to CHP base-case system boundaries

System boundaries	Assumptions		
Biogas yield (m^3 y^{-1})	810 000		
Energy yield (GJ y^{-1})	16 831		
Electricity output (GJ y^{-1})	5891	35	% electrical efficiency
Electricity output (MWh_e)	1636		
Electricity output (kW_e)	220	85	% operational efficiency
Heat output (GJ y^{-1})	6732	40	% thermal efficiency
Heat output (MWh_t)	1870		

2. The sale of electricity only with capital grant (G+E)
3. The sale of electricity and heat with capital grant (G+E+H)

The proposed facility is not profitable and would require an electricity tariff of between €0.196 and €0.256 kWh_e^{-1} to break even, which is significantly higher than the current tariff of €0.12 kWh_e^{-1}. Even when the average farming subsidy of €461 ha^{-1} is included, the plant still operates at a loss (Table 4).

Reduced operating costs and depreciation

A relatively high value for operating costs is used in the base-case analysis (10% of unsubsidized capital costs) and an additional allowance is made for depreciation (6.67%) of the AD and CHP plants, which results in a fairly conservative analysis. Using a less onerous value of 10%, to cover both operating costs and depreciation, lowers the break-even prices (Table 4), but they are still higher than the current tariff of €0.12 kWh_e^{-1}. Inclusion of the farming subsidy (€461 ha^{-1}) brings the best-case scenario (G+E+H) into profit and results in an annual return of €117 ha^{-1}. However, this is lower than the average FFI for cattle rearing farms (€279 ha^{-1} for 2006 to 2008 inclusive [1,43]) and therefore not competitive with current farming practice.

Increased size of digester

As plant size increases, investment costs per kW decrease; therefore, increasing the quantity of grass silage could increase profits. The relationship has been investigated by a number of authors for AD and CHP plants,[33,46] as well as for upgrading facilities.[40,47] To assess the impact of increasing plant size on the grass digestion facility, the break-even electricity price is determined for a plant twice the size of that in the base-case analysis, i.e. for 275 ha of grass and 440 kW_e CHP. Using data in Murphy and McCarthy,[33] the capital cost of the larger AD facility, in € t^{-1} feedstock, is estimated to be 81% that of the base-case facility, while the capital cost of the CHP plant

Table 4. Tariff required for break even.

	Scenario 1[a,c] (€c kWh_e^{-1})			Scenario 2[b,c] (€c kWh^{-1})		
	E+H	G+E	G+E+H	50%G	30%G	NG
Base case						
– No subsidy	21.1	25.6	19.6	10.0	10.8	12.1
– With subsidy (€461 ha^{-1})	17.3	21.8	15.7	8.6	9.5	10.7
Reduced operating costs and depreciation						
– No subsidy	16.4	20.9	14.9	8.1	8.9	10.2
– With subsidy (€461 ha^{-1})	12.6	17.1	**11.0**	6.7	7.5	8.8
Co-digestion[d]						
– No subsidy	**10.0**	14.5	**8.4**	5.9	6.4	7.1
– With subsidy (€461 ha^{-1})	**8.4**	12.9	**6.8**	5.3	5.8	6.6
Co-digestion[d] (reduced operating costs and depreciation)						
– No subsidy	**5.9**	**10.4**	**4.3**	4.5	5.0	5.8
– With subsidy (€461 ha^{-1})	**4.3**	**8.8**	**2.7**	4.0	4.5	5.2

[a]Scenario 1: grass to biogas to CHP.
[b]Scenario 2: grass to biogas to biomethane.
[c]Figures in bold indicate profitability under current conditions:
– €0.12 kWh_e^{-1} is paid for electricity from biogas CHP;
– €0.02 – 0.03 kWh^{-1} is the wholesale price of natural gas.
[d]Co-digestion of 7500 t y^{-1} grass and 7500 t y^{-1} belly grass.

(in € kW_e^{-1}) is 87% that of the smaller plant. This results in a break-even electricity price of €0.166 kWh_e^{-1} (G+E+H), which, although 15% lower than the base-case value of €0.196 kWh_e^{-1}, is still higher than the current tariff of €0.12 kWh_e^{-1}. The size-cost relationship developed by Walla and Schneeberger[46] suggests the per kWh cost of the 440 kW_e facility is only 5% lower than that of the 220 kW_e facility, indicating little benefit from increasing plant size. Their analysis also showed that the highest cost savings are achievable when moving from small plants to plants of around 200 kW_e in size; above this, costs continue to decline at a much lower rate and few further cost benefits are achieved in plants over 1000 kW_e.[46]

Increasing the quantity of grass silage would also result in increased transport distances for silage delivery and digestate disposal, as well as in more traffic movements. Ideally, transport distances and the number of journeys should be kept to a minimum because of associated costs, emissions, and nuisance on rural roads, and the related planning permission requirements. Average haul distance is dependent on silage yields and silage availability (Box 3). The high silage yields in Ireland and the high percentage of land under grass (50% total land area) mean that haul distance is very much dependent on the percentage of land contracted to the plant in a given area. For a plant using silage from 137.5 ha, the average haul distance, assuming 10% of grassland is contracted, is 2.8 km; for a 275 ha plant, the distance is 3.9 km. These distances are within the range used in the literature (e.g. 10 km for grass;[48] 6 km for slurry in a large centralized plant;[33] and 5–8 km for operational plants in Denmark[49]). If only 1% of grassland is contracted to the plant, the average haul distance rises to 12.5 km for the 275 ha plant; for a 1 MW_e plant, requiring around 625 ha of grass silage, the average haul distance is 18.8 km. Therefore, as plant size increases, particular attention needs to be paid to silage availability.

Suggested measures for profitability

Under current conditions, profitability of grass biogas CHP is possible, but difficult, and relies on:

- keeping operational costs to a minimum;
- finding a year round market for heat, although this may prove challenging due to limited heat markets in Ireland; and
- maintaining current farming subsidies.

Scenario 2: Biogas to biomethane to grid

Base-case economic analysis

The plant produces biomethane on site and the biomethane is injected into the gas grid. The boundary of the analysis is at injection into the grid and the break-even price of biomethane sold to the grid is calculated. Three different scenarios are considered:

1. Receipt of grant for 50% of capital cost (50G)
2. Receipt of grant for 30% of capital cost (30G)
3. No grant (NG)

The break-even price of gas is found to be €0.10, €0.108 and €0.121 kWh^{-1}, assuming 50%, 30%, and 0% capital grant respectively (Table 4). If the farming subsidy of €461 ha^{-1} is included, the break-even price falls to between €0.086 and €0.107 kWh^{-1}. This is uncompetitive with the wholesale price of natural gas, which is around €0.02–€0.03 kWh^{-1}.

Improving the economics

Reducing the operating costs and depreciation (as for the CHP plant) brings the break-even gas price down to €0.081–€0.102 kWh^{-1} excluding the farming subsidy, and €0.067–€0.088 if the subsidy is included (Table 4). Even in the best-case scenario, the break-even price is still more than double the wholesale price of natural gas.

Co-digestion

Pros and cons of co-digestion

It is common practice to digest the main substrate with a co-substrate, as this frequently improves the performance of

Box 3. Average haul distance

Average haul distance (km)[a] = $\bar{x} = 2/3x\tau$

where x = radius of area of supply (km) = $\sqrt{Q / ya\pi}$

τ = tortuosity factor ($\sqrt{2}$ for rural roads)

y = silage yield (t km^{-2})

Q = required amount of silage (t)

a = factor of silage availability [b]

[a]Average haul distance is calculated following the methodology given by Walla and Schneeberger.[46]

[b]On average in Ireland, silage, hay and pasture make up 50% of the total land area (calculated from national data on land and grassland areas [16,71]). Assuming that 10% of the grass in a given area is used for AD, the factor of silage availability, a, is 0.1 x 0.5 = 0.05.

the digester and increases the amount of biogas produced. Examples of co-substrates include manure, food remains, animal blood, rumen contents, fermentation slops, and the organic fraction of municipal solid waste (OFMSW). Another advantage of co-digestion is that a gate fee can often be charged for the co-substrates, generating additional revenue for the plant. Larger plants can also take advantage of economies of scale, and tend to have lower capital and operational costs per tonne of feedstock. On the downside, current legislation restricts the use of substrates from certain sources and may lead to higher AD processing and digestate disposal costs. There is also ongoing uncertainty in the waste sector in Ireland, over issues such as waste collection rights, planning permission, and preferred technologies.

Animal byproducts

Many materials suitable for AD, either on their own or as a co-substrate, are animal byproducts (ABPs). ABPs can pose a threat to animal and human health via the environment if not properly disposed of, potentially causing disease and contamination of the food and feed chain. Because agriculture is such an important part of the Irish economy, accounting for 8.1%, 8.1% and 9.8% of GDP, employment, and exports respectively,[50] problems associated with the incorrect handling of ABPs can have wide-reaching impacts. The collection, transport, storage, handling, processing, and use or disposal of all ABPs are therefore tightly controlled by the ABP regulations.

The regulations[51] divide ABPs into three categories based on their potential risk to animals, the public or to the environment, and set out how each category must or may be disposed of. Category 1 is high-risk material and may not be used in an anaerobic digester. Provided requirements for process parameters (e.g. temperature treatment) and the plant location (e.g. in relation to animal access) are met, Categories 2 and 3 may be used as feedstock for AD, as follows:

- Category 2 material comprising milk, manure, digestive tract content.
- Category 3 material comprising former foodstuffs, catering waste (including cooking oil), feathers, milk, certain fish and fish products, shells, hatchery byproducts, egg byproducts, processed animal protein.

The ABP regulations lay down requirements for processing (i.e. hygenization) of ABPs and for disposal of digestate (e.g. grazing restrictions and the type of crops that can be grown on land fertilized with digestate). The level of treatment required and the restrictions regarding digestate disposal depend on plant size, the type and quantity of ABPs, the source of ABPs (on-farm or imported), and the end use of the digestate. Compliance with the regulations can add significant cost and must be weighed against the gate fees received for the ABPs. While the regulations are obviously needed to protect human and animal health and the environment, the strict requirements pose challenges for the development of AD in Ireland and have been a stumbling block for the industry. The Department of Agriculture, Fisheries and Food has recognized this and is currently in consultation with industry with the aim of facilitating the growth of AD.[52]

Cattle slurry

This paper considers a cooperative AD plant among a group of livestock farmers; the most obvious co-substrate is therefore cattle slurry. From a microbiological perspective, cattle slurry is a recommended co-substrate for grass silage.[53] Other benefits of digesting cattle slurry include improved nutrient management, reduced odors, and less risk of pollution. However, these benefits are not translated into financial incentives in Ireland. Previous studies[26,45] have found that, if the non-market co-benefits are excluded, the AD of farm wastes is generally not financially viable. This is exacerbated by the dilute nature of cattle slurry and its low methane yield (10% DS, 140 m^3 CH_4 tVS_{added}^{-1} [54]), meaning that larger digestion tanks and operational energy demands (heating and mixing) are required than for grass silage (22% DS, 300 m^3 tVS_{added}^{-1}), but with much lower energy return. With reference to Box 4, a simplified economic analysis of a slurry biomethane system is presented. It may be noted that 29 700 t y^{-1} of slurry is needed to produce the same biomethane as 137.5 ha of grassland. This requires the slurry of 5690 cattle or 24 400 pigs. The capital cost is larger due to the larger volumes associated with the dilute slurry. Allowing for reduced operating costs (6.67% y^{-1}), the cost of slurry biomethane with no grants added is €1.47 m^{-3}. This may be compared with €1.02 m^{-3} for grass biomethane under similar conditions (Table 4). In the absence of financial incentives, co-digestion of cattle slurry with grass does not improve the economic viability of the plant.

Other co-substrates

Greater economic benefit could be achieved by digesting co-substrates that attract a gate fee. For the CSTR considered in this analysis, a low solids content substrate such as slaughter waste (belly grass) would be appropriate. Discussions with the slaughter waste industry in Ireland suggest that gate fees of around €20 t^{-1} could be attracted. Equal quantities (7500 t y^{-1} of each) of grass silage and belly grass are used and it is conservatively assumed that there are no financial savings from the digestate. The same per unit capital and operating costs are assumed as for the grass digester. Substantial profits are achievable with the CHP plant (Table 4), showing that the current tariff system works well for feedstock that attracts a gate fee. For grid injection, however, even the best-case scenario has a higher break-even price than the wholesale price of natural gas.

Farmers' co-op versus private developer

The farmers' co-op model is likely to be the cheapest option, as silage can be produced on farm; however, the case of a developer owning and operating the plant should also be considered. Operating costs will be higher as silage must now be purchased at market prices of about €23 t^{-1}, compared to the farmers' production cost of around €17 t^{-1}. In addition, the rate of return required by investors is likely to be higher than for the farmers' co-op. Assuming market prices for silage and a rate of return of 7%, the estimated

Box 4. Cost of slurry biomethane

Capital costs			
Capital cost of AD facility	€110 t^{-1} y^{-1} feedstock		
Capital cost of upgrading plant	€1.00 m^{-3} y^{-1} biomethane		
Operating costs			
Running costs of AD facility	6.67% capital costs = €7.4 t^{-1} slurry		
Operating costs of upgrading plant	€0.20 m^{-3} biomethane		
Biogas production			
Biogas yield	25 m^3 t^{-1} slurry		
Biomethane is 97% CH_4 and 3% CO_2.			
Analysis of slurry digester			
Annual slurry	29,700 t y^{-1}		
This is equivalent to slurry from 5689 cattle (100 cattle produce 522 m^3 slurry in 18 weeks) or 24 400 pigs (300 pigs produce 1 tonne of slurry day^{-1}).			
Biogas yield	742 500 m^3 y^{-1}		
Methane yield	445 500 m^3 y^{-1}		
Losses in upgrading	1.5%		
Biomethane yield	452 389 m^3 y^{-1} (97% CH_4 in biomethane)		
Capital costs			
Capital cost of AD facility	€3 267 000		
Capital cost of upgrading plant	€452 839		
Total capital costs	€3 719 839		
Annual costs		**€ y^{-1}**	
Cost of capital		358 378	
Running costs of AD facility		217 909	
Operating costs of upgrading plant		90 478	
Total annual costs		666 766	
Cost of biomethane		666 766	**€1.47 m^{-3}**

break-even electricity and biomethane prices (assuming reduced operating costs and depreciation, and no farming subsidy) are €0.187 kWh_e^{-1} (G+E+H) and €0.102 kWh^{-1} (30%G), respectively.

Viability of grass biogas and biomethane under current conditions

Under present conditions, the only financially viable option for grass biogas/biomethane in Ireland is use in an on-site CHP plant, and viability is heavily dependent on heat markets and farming subsidies. Profits are low and there is little incentive to switch from current farming practice. There is currently no tariff structure in place for grid injection, although the development of such a structure is underway. This analysis shows that grass biomethane injected into the grid is not competitive with natural gas. Co-digestion can improve the economics, but the ABP regulations pose challenges for the industry. The question is therefore how grass biogas/biomethane can offer a competitive return for farmers, while at the same time offering a competitive alternative to consumers. The next section addresses this issue.

Improving the viability of grass biogas and biomethane for the farmer and the consumer

Argument for subsidies and financial incentives

Energy security, national targets, and farm diversification

Grassland agriculture in Ireland is effectively subsidized for export, while at the same time almost 90% of energy is imported and non-renewable fossil fuels account for 96% of all energy used in the country.[11] It is suggested that a better balance could be achieved by diverting some grassland to AD. As grass is a lignocellulosic feedstock, grass biomethane used as a biofuel earns the country double credits[55] for meeting the 2020 targets for renewable energy in transport. Injecting biomethane into the gas grid is an effective means of getting renewable energy to a large number of consumers without any change in existing infrastructure. In addition, grass AD provides an opportunity for farm diversification, leading to a strong case for subsidizing for grass biogas/biomethane and AD plants in general.

Environmental benefits

Through the replacement of fossil fuels, the use of biogas/biomethane reduces GHG emissions. The extent of the reduction depends on the feedstock used and the fuel being replaced. GHG savings of 82% for cattle slurry biomethane compared with diesel have been reported,[56] while savings of 75 to 150% are achieved for grass biomethane compared to diesel (depending on the level of carbon sequestration[18]). Methane is also a much cleaner burning fuel in terms of local pollutants (e.g. nitrogen oxides (NO_x) and particulate matter (PM)) than coal or oil, improving air quality and benefiting health,[57-59] especially if used in urban areas. In addition, the digestion of wastes is a proven waste treatment option that decreases GHG emissions from uncontrolled fermentation and reduces pollution from poor waste-management practices.[26]

Monetary value of environmental benefits

Improvements in the environment benefit both biodiversity and the human population, but assigning a value to the non-market co-benefits of an AD plant is open to debate; there is considerable uncertainty and values are likely to change in the future as concerns over environmental issues heighten.[26] At the end of pipe, savings from methane through avoiding emissions like CO_2, NO_x, and PM have been estimated as €0.43 L^{-1} of diesel replaced for a passenger car in an urban area,[35] which equates to €1387 ha^{-1} of grass digested. In city centres, this rises to €0.89 L^{-1} diesel replaced [35] or €2870 ha^{-1} of grass. If a waste feedstock is used, the benefit from avoided methane leakage is €0.26 L^{-1} of diesel replaced and the total benefit, including improved end-of-pipe emissions, is €1.15 L^{-1} of diesel replaced.[35] This equates to €17.1 t^{-1} of cattle slurry digested (based on a biogas yield of 25 m^3 t^{-1} of slurry at 60% CH_4).

Competitive advantage of biomethane

Renewable energy targets

When non-market benefits are excluded, grass biomethane is not competitive with natural gas. However, renewable energy targets in each of the three energy sectors (heat, transport and electricity) mean that biomethane (renewable gas) is in competition, not with fossil fuels, but with other renewables. The competitive advantage of biomethane is that it can be transported via the natural gas network, and could potentially go a long way toward achieving renewable energy targets without investing in new infrastructure.

Gas grid and existing customer base

The natural gas grid in Ireland is quite extensive and reaches 23 out of the 32 counties. There has been significant investment in the grid in recent years, with the construction of a new pipeline in the west, and the connection of many new towns is ongoing. A program has also been completed replacing all of the old cast-iron pipes with polyethylene pipes, resulting in a more efficient network. In 2004, losses from the distribution network were so small they could not be measured.[6] In a country of ca. 4 million people with 1.46 million houses,[60] there are currently around 619 100 domestic connections and 24 000 industrial and commercial connections to the gas grid in the Republic of Ireland. In Northern Ireland, there are a further 118 800 domestic customers and 8400 industrial and commercial customers.[61] Unlike other renewable energy technologies which must develop a customer base from scratch, biomethane plants injecting into the gas grid have an existing market which requires only a change in the billing system.

Space requirements

For new installations, bioNG has the edge over other renewable technologies in areas on the gas grid, especially in urban areas where space may be at a premium. Significant space is required for many renewable energy solutions, such as wood chips (fuel storage areas) or horizontal geothermal installations; such space may be costly or unavailable in cities and towns (e.g. in apartment blocks).

Finding the right market – electricity, transport, or heat?

There are clearly competitive advantages of grass biomethane; the issue is now to find the right market so as the exploit these advantages. The potential of the electricity, transport and heat markets are discussed in the following section.

Grass biomethane in the renewable electricity market

Meeting the targets

Ireland's 40% renewable electricity target for 2020[12] is expected to be provided largely by wind. Ireland has one of the best wind resources in Europe and wind electricity can be generated relatively cheaply compared with other renewable sources. There are also targets for electricity from ocean energy (500 MW of installed capacity by 2020) and for 30% biomass co-firing in existing peat-fired power plants.[13] The presence of viable alternatives for renewable electricity means that there is not expected to be a large market for electricity from grass biogas; however, there may be some scope in the CHP market and in existing power plants running on natural gas. The market size is considerable as 62% of primary natural gas energy is used for electricity generation.[62]

Cost competitiveness of CHP plants

There is a government target to achieve at least 800 MW from CHP by 2020, with emphasis on biomass-fueled CHP.[13] The use of grass biogas in an on-site CHP plant struggles economically, due largely to the current tariff structure and the lack of heat markets in Ireland. However, there is potential for existing natural-gas-fueled CHP plants to purchase renewable gas from the grid, with the advantages that the capital investment has already been made and there is generally a market for heat at existing plants. As 93% of the installed CHP capacity in Ireland runs on gas fuels,[63] there is significant market potential; however, the renewable bonus of €0.12 kWh_e^{-1} for biomethane does not make financial sense, as CHP plants typically displace electricity purchased from the grid and have a return of about €0.10–0.11 kWh_e^{-1}.

Suggested financial incentives

It is suggested that a revised system of tariffs be introduced. Currently, a flat rate of €0.12 kWh_e^{-1} is paid for biogas CHP. The same electricity tariff is paid regardless of whether a gate fee is received or the feedstock is purchased, and there is no allowance for the non-monetary benefits of AD; for example, to encourage use of cattle slurry. The German tariff structure[64] uses graded tariffs, which depend on feedstock type, plant size, and AD technology type, among other factors. The International Energy Agency (IEA) has stated[65] that the high investor security provided by the German feed-in tariff has been a success, resulting in a rapid deployment of renewables, the entrance of many new actors to the market, and a subsequent reduction in costs. Using the German tariffs for the grass plant in this analysis, the electricity tariff rises to €0.1718 kWh_e^{-1} for an on-site CHP plant and €0.1818 kWh_e^{-1} for an off-site CHP plant using biomethane tapped from the grid (Table 5).

Potential for profitability

Such a tariff structure would bring the on-site CHP plant into profit as long as there is a market for the heat (Table 6). The annual income for E+H and G+E+H is 2 to 2.6 times the average FFI for cattle-rearing farms (€279 ha^{-1}) when reduced operating costs and depreciation are considered. In the case of the off-site CHP plant, a return of €0.085 kWh^{-1} biomethane can be achieved, assuming 40% thermal and 35% electrical efficiency (€0.1818 kWh_e^{-1} + €0.053 kWh_{th}^{-1}). This is over 25% higher than the best-case break-even price for grass biomethane (from Table 4). The viability of off-site CHP plants can only be assessed on a case-by-case basis. Determining factors include the plant size, the proportion of biomethane/natural gas in the mix, and the individual circumstances of the plant; for example, if capital costs have already been paid.

CCGT plants

There is potential for the use of biomethane in combined cycle gas turbine (CCGT) plants. An economic analysis of biomethane in CCGT plants is outside the scope of this study; however, initial advantages of biomethane used in a CCGT facility include:

- an electrical efficiency of around 55% compared to 35% in a small scale CHP;
- increasing the priority listing of the CCGT plant as it is now seen as a renewable source of electricity as opposed to a fossil fuel electricity generating plant; and
- use of electricity from CCGT to power electric cars and provide renewable fuel in transport.

Table 5. Potential tariffs with German tariff structure (simplified).

Tariff	On-site CHP (€c kWh_e^{-1})	Off-site CHP (€c kWh_e^{-1})
Basic compensation	9.18	9.18
Emission minimization bonus	1	–
Grass as a feedstock	7	7
Upgrading	–	2
Total	17.18	18.18

Problems with the market

The lack of a comprehensive tariff structure is a stumbling block for the industry. There is also a disparity between AD plant output and the demand of off-site electricity generators. Three-quarters of CHP plants in Ireland are in the size range 0.5–1 MW_e.[63] Assuming 30% co-firing (which is the target for biomass co-firing in peat plants) in 0.75 MW_e CHP plants, the grass biomethane facility in this analysis would serve only 2.7 such plants. Being reliant on such a small customer base puts the biomethane supplier at risk of failure from small changes in demand. An obligation for CHP plants to meet renewable energy targets would improve the viability through providing greater market stability for the developing industry, and by putting biomethane in competition with other renewables, as opposed to cheap natural gas.

Table 6. Profitability of on-site CHP from grass biogas with farming subsidies and German tariff structure.

	Base case			Reduced operating costs and depreciation		
	E+H	G+E	G+E+H	E+H	G+E	G+E+H
Total income[a] (€ y^{-1})	407,240	308,124	407,240	407,240	308,124	407,240
Total costs (€ y^{-1})	471,873	446,466	446,466	395,201	369,794	369,794
Income – costs (€ y^{-1})	–64,633	–138,342	–39,266	12,039	–61,670	37,446
Income – costs (€ ha^{-1})	–470	–1,006	–285	88	–449	272
Average annual subsidy (€ ha^{-1})	461	461	461	461	461	461
Return including subsidy (€ ha^{-1})	-9	–545	176	549	12	733

[a]€0.1718 kWh_e^{-1} received for electricity, €0.053 kWh_{th}^{-1} received for heat.

Grass biomethane in the renewable transport market

Meeting the targets

There is a target for 10% renewable energy in transport 2020.[13] Unlike the electricity sector where significant progress is being made toward meeting the target, there are significant challenges in the transport sector. Penetration of renewables in transport currently stands at less than 1.2%,[11] and there is no clear national roadmap for reaching the target. The problem is further compounded by policy constraints in biofuels (sustainability criteria) and agriculture (land use) which restrict the type of biofuels that can be used and the type of energy crops that can be grown. Work by Smyth *et al.* [19] investigated Ireland's options for meeting the 2020 target (including imported biofuels, electric vehicles, waste/residue-derived biofuels, and indigenous energy crop biofuels) and found that the largest potential lies with grass biomethane.

Cost competitiveness

The break-even price of compressed biomethane from grass varies between €0.078 and €0.132 kWh^{-1} (Table 7). Excise duty is not charged on gas used as a propellant, but VAT at 21% has to be added,[66] giving a minimum selling price (i.e. break-even price) of between €0.096 and €0.163 kWh^{-1}. The sale prices of petrol and diesel lie within this range (Table 8). The price of CNG is significantly lower than that of petrol and diesel, meaning that considerable savings can be achieved if bioCNG is sold. If a 10% biomethane/90% CNG blend is used, the break-even price is between €0.0199 and €0.0217 MJ^{-1} (based on UK CNG prices). At 53% of the price of petrol and 71% of the price of diesel (for the higher price of €0.0217 MJ^{-1}), this is competitive.

Problems with the market

The obvious stumbling block for the sale of biomethane as a transport fuel in Ireland is the absence of a market; there are currently only two natural gas vehicles in the country.[67] However, there are over 10 million CNG vehicles worldwide [67] and the use of compressed biomethane, either on its own or mixed with natural gas (bioCNG), is growing. Sweden has around 17 000 natural gas vehicles, and over 55% of the gas used in transport is biomethane.[68] The development of biomethane for transport in other countries has generally been based on an existing CNG market, and the development of CNG is often based on the introduction of CNG to captive fleets (e.g. buses, waste collection lorries, taxis) followed by private cars. The sale of biomethane for transport in other countries has been found to be profitable, offering higher returns than heat or electricity. The CNG market may develop in Ireland as it has done elsewhere, but would require regulation and incentives from government to do so.

Grass biomethane in the renewable heat market

Meeting the targets

The government has set a target for 12% renewable heat by 2020 and has also stated that the public sector will lead the way with the deployment of bioenergy heating.[13] The residential sector is responsible for the largest share of natural gas final energy consumption, at 40.7%.[62] Twenty-eight per cent of houses have gas central heating,[69] with the highest proportion in Dublin, where there are almost 375 000 natural gas customers or about 60% of total national customers. Average residential natural gas demand (weather corrected) in 2008 was 14.4 MWh (51.8 GJ) per household. The grass biomethane plant in this analysis could fuel about 320

Table 7. Break even of compressed biomethane from grass silage as a vehicle fuel.

	Base case (€c kWh^{-1})[a]			Reduced operating costs and depreciation (€c kWh^{-1})[b]		
	50%G	30%G	NG	50%G	30%G	NG
Break-even price of biomethane injected to grid	10.0	10.8	12.1	6.7	7.5	8.8
Cost of compression to 250 bar + filling station[c]	1.1	1.1	1.1	1.1	1.1	1.1
Break-even price of compressed biomethane	11.1	11.9	13.2	7.8	8.6	9.9
- including 21% VAT	13.4	14.4	16.0	9.4	10.4	12.0
- including 21% VAT (€ m^{-3})	1.37	1.47	1.63	0.96	1.06	1.22

[a]Excludes farming subsidy.
[b]Includes farming subsidy (€461 ha^{-1}).
[c]Estimated from values in the literature[15] and discussions with industry.

Table 8. Comparison of vevhicle fuel costs.

Fuel	Unit cost	Energy value	Cost per unit energy (€c MJ^{-1})
Petrol[a]	€1.224 L^{-1}	30 MJ L^{-1}	4.08
Diesel[a]	€1.150 L^{-1}	37.4 MJ L^{-1}	3.07
Compressed biomethane (high)[b]	€1.63 m^{-3}	37 MJ m^{-3}	4.41
Compressed biomethane (low)[b]	€0.96 m^{-3}	37 MJ m^{-3}	2.59
CNG – Austria[c]	€0.89 m^{-3}	37 MJ m^{-3}	2.41
CNG – UK[c]	€0.71 m^{-3}	37 MJ m^{-3}	1.92
CNG – Germany[c]	€0.70 m^{-3}	37 MJ m^{-3}	1.89
BioCNG (high)[d]	€0.80 m^{-3}	37 MJ m^{-3}	2.17
BioCNG (low)[d]	€0.74 m^{-3}	37 MJ m^{-3}	1.99

[a]Price of petrol and diesel is the price at the pumps.[73]
[b]Price of compressed biomethane is the minimum selling price of grass biomethane. The highest and lowest prices from Table 7 are used.
[c]In the absence of Irish CNG prices, the prices in Austria, Germany and the UK[67] are shown for comparison.
[d]BioCNG price calculated using UK CNG prices and a blend of 10% biomethane, 90% CNG.

houses solely on biomethane or 2665 houses on bioNG containing 12% renewable gas. The potential for a large number of customers offers more flexibility than the electricity market.

Cost competitiveness

Obviously, alternatives such as wood chips or wood pellets could also be employed; however, the installation of these systems requires significant capital investment in both the boiler and biomass storage areas, as well as changes in practice. Figure 2 compares heating costs based on an existing building remaining on the gas grid (fuel and running costs only for natural gas, grass biomethane and bioNG) and new wood chip and pellet heating systems (fuel, running, and annualized capital costs). While grass biomethane is uncompetitive, a 12/88 bioNG fuel is competitive with the renew-

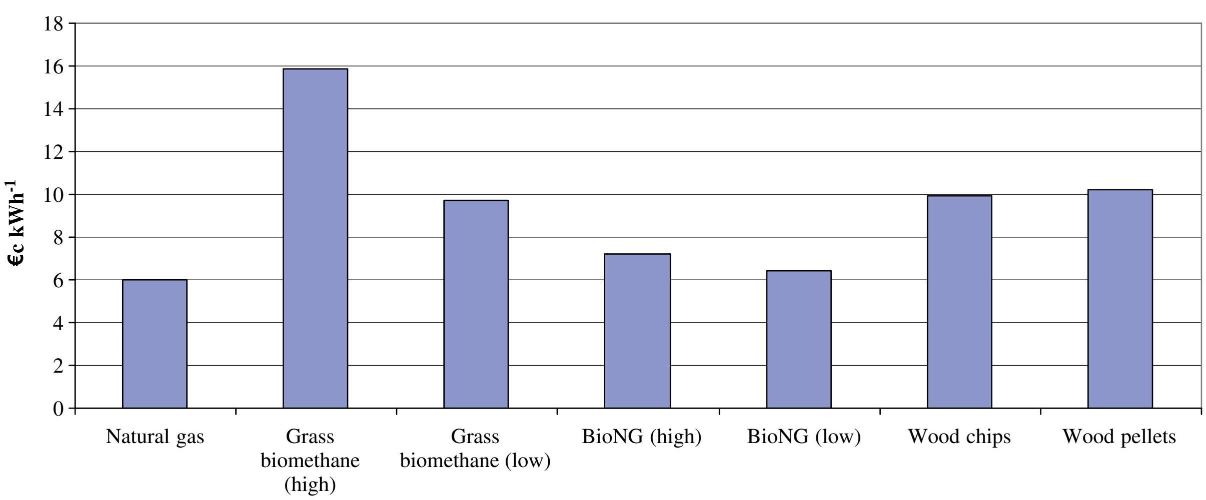

Figure 2. Comparison of heating costs for various systems. The cost of grass biomethane is the break-even price (highest and lowest values are taken from Table 4 and 13.5% VAT is added). The cost of bioNG is based on a blend of 12% biomethane and 88% natural gas. For the gas systems, estimated running costs are added to the fuel costs to give the heating cost. The heating cost of wood chips and wood pellets includes capital and operational costs. Total wood chip, wood pellet and natural gas heating costs were calculated using a heat cost comparison spreadsheet,[74] current commercial fuel costs [4] and work undertaken as part of a Master's thesis.[75] A 570 kW boiler with 900 h y^{-1} operation is assumed.

able energy alternatives. The analysis assumes biomethane is produced from grass only; biomethane produced from feedstock with a gate fee, such as slaughter waste, would be considerably more competitive.

Problems with the market

Although Directive 2009/73/EC on the natural gas market[70] states that biogas should be granted non-discriminatory access to the gas system, and biomethane is injected into the grid in other countries, as yet there is no system for this in Ireland. Gaslink (the Irish gas network operator) and Bord Gáis are currently investigating a quality standard for biomethane injection into the grid.

Conclusions

The key to the competitiveness of biogas/biomethane is the renewable energy targets, which place it in competition, not with cheap natural gas, but with other renewables. The principal advantage of biomethane over other renewables is that it can be distributed through the gas grid to a large existing customer base.

The renewable electricity market is largely dominated by wind and it is the view of the authors that electricity is not the most advantageous avenue for biogas. If a biogas electricity industry were to develop from grass, a revised tariff structure would be necessary. The existing tariff structure works well for feedstock that attracts a gate fee but, in spite of this, the industry is faltering, largely due to the strict interpretation of the ABP regulations and uncertainty in the waste sector.

The transport market offers the potential for profitability and provides a cheaper alternative to petrol and diesel for the consumer. There is currently no market for CNG in Ireland, therefore the transport market is not a practical option at present.

Unlike other renewable technologies in the heat sector, grass biomethane has a large, easily accessible customer base. Existing natural gas customers would not require the installation of a new renewable heating system or any changes in practice, and their gas supplier would need only a change in their billing system; thus the higher cost of renewable gas can be offset against avoided capital investment. Injecting grass biomethane into the grid for sale as a heating fuel is the path of least resistance. However, there is currently no legislation in place in Ireland to allow grid injection.

Under certain conditions, grass biogas/biomethane has the potential to be an economically viable alternative for farmers and for the consumer. Its cost competitiveness can be further improved by co-digestion with gate-fee feedstock and by taking account of the associated non-monetary co-benefits. A recurring theme, however, is the lack of consistent legislation regarding anaerobic digestion and the use of biogas/biomethane, and this is acting as a barrier to the development and economic success of the industry. For the industry to succeed economically, the implementation of cohesive legislation is required.

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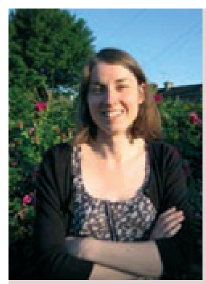

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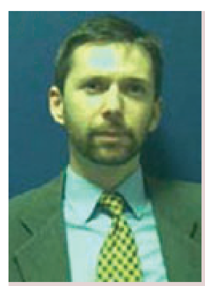

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