EPA Climate Change Research Programme 2007–2013

The Potential for Grass Biomethane as a Biofuel

Compressed Biomethane Generated from Grass, Utilised as a Transport Biofuel

CCRP Report

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Prepared for the Environmental Protection Agency

by

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The EPA Climate Change Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Grass is an excellent energy crop due to long persistence of high yields accompanied by low energy inputs. Approximately 91% of Irish agricultural land is under grass. The national herd has decreased and will continue to do so. Cross compliance does not encourage the conversion of permanent pastureland to arable land; thus we have and will continue to have increased quantities of excess grassland. Therefore, grass must be considered a significant source of biomass. Current grass species and cultivation practices are favourable for anaerobic digestion (AD), which is a mature technology. Upgrading biogas to biomethane, injecting into the gas grid, leads to an effective bioenergy system complete with distribution to all major cities and 620,000 houses.

The Renewable Energy Directive allows a double credit for biofuels derived from residues and lignocellulosic material (such as grass). It is shown that 100,000 ha of grass (2.3% of agricultural land) will allow compliance with the 10% renewable energy in transport target for 2010. Alternatively, this would substitute for 35% of residential gas consumption. Reactor design must take account of the specific feedstock or combinations of feedstock; the reactor must be suited to the feedstock. This is not technically difficult. Of significant concern in the sustainability of the biofuel produced is the parasitic energy demand of the process and the vehicle efficiency. Emission reductions are optimised by the use of green electricity and the use of biomass for thermal energy input. On a field-to-wheel basis, it is essential that the vehicle operating on biomethane has an equivalent efficiency (expressed as MJ/km) as the displaced fossil fuel. The Renewable Energy Directive requires an emission savings of 60% compared with the displaced fuel for new facilities constructed after 2017. This is readily achieved for grass biomethane through optimisation of the system. Allowing for carbon (C) sequestration in grassland of 0.6 t C ha/year will lead to emissions savings of 89%. This would suggest that grass biomethane is one of the most sustainable indigenous, non-residue-based transport biofuels. The economics of biomethane are shown to be difficult. There is a requirement for innovative policy and marketing of the industry. A compressed natural gas transport fuel market is an essential prerequisite to using biomethane as a transport fuel. Mandating a certain percentage of biomethane in natural gas sales is of benefit to biomethane as both a transport and a thermal biofuel. Government policy is required to support a biomethane industry.

Further research is required in the following areas:

- **Bioresource mapping:** This includes the creation of a Geographical Information System to highlight sources of the organic fraction of municipal solid waste (OFMSW), slurry, slaughter waste and areas of high-yielding silage production. The system would include distribution systems (natural gas grid, electricity grid) and demand nodes (e.g. transport fleets, district heating, new towns) to propose areas with significant potential for biomethane production.

- **Assessment of biomethane facilities:** This includes full life-cycle analysis of different biomethane facilities, including co-digestion of slurries and grass silage, mono-digestion of OFMSW, and mono-digestion of slaughter wastes. The research should allow assessment of the cost of the produced biomethane.

- **Digester design:** This basic research should assess optimal digester systems for different feedstocks.

- **Agricultural impact of AD:** This research includes monitoring carbon sequestration in grasslands where silage is cut and digestate is applied. This should be compared with carbon sequestration on grazed pastures. The fertiliser value of different digestates needs to be assessed along with the emissions associated with application of digestate. The research should also assess the effect on biodiversity.

1 Why Grass and Why Biomethane?

1.1 Overarching Policy and Strategy

The deployment of biofuels is affected by policy in energy and agriculture. In the agricultural sector, policy enforces environmentally friendly production systems that will affect agricultural status quo and production chains. In the energy sector, concerns regarding the sustainability of biofuel systems and their impact on food prices led to a set of sustainability criteria in the Renewable Energy Directive (EC, 2009a). In addition, the site specificity of biofuel feedstock production, agricultural practices, and indirect land-use change will significantly affect growth trends in biofuel usage and the ability of an EU Member State to reach a 10% renewable energy in transport target by 2020.

1.2 Ireland: The Food Island

The agri-food sector is one of the most important and dynamic indigenous manufacturing elements in the Irish economy and accounts for an estimated 8.1%, 8.1% and 9.8% of gross domestic product (GDP), employment and exports, respectively (DAFF, undated). Irish agriculture, influenced by the wet and mild climate, has traditionally been characterised by extensive grass-based farming systems and relies heavily on grassland-based livestock farming. Grass and grass crops cover around 91% (i.e. 3.9 million ha) of all agricultural land (O'Mara, 2008). Livestock and livestock products account for most of total agricultural output (Jensen et al., 2003). About 53% of farms are classified as beef and they account for 40% of the agricultural area used (AAU), while they contribute to over a third (€1.3 billion) of agricultural export earnings (Anonymous, 2008a). Farm profitability associated with beef production is not competitive (Anonymous, 2008a). Projections estimate a decline in cattle numbers (Donnellan and Hanrahan, 2008; CSO, undated), particularly those of suckler cows (Binfield et al., 2008) by possible trade and policy reform scenarios.

1.3 Agricultural Legislation

The 2003 *Mid-Term Review of the Common Agricultural Policy* (CAP) made agricultural support payments conditional upon compliance with environmental standards and 'good farming practice'. Community initiatives, amongst others, aim to limit agricultural pollution, to promote the production and use of biofuels, and to protect biodiversity (Osterburg et al., 2005). Attaching conditions to the receipt of agricultural subsidies is a policy mandatory tool known as cross compliance (EC, 2003). It consists of two strands (i.e. Good Agricultural and Environmental Condition and the Statutory Management Requirements) (Mussner et al., 2006) and aims to improve standards in modern farming practices (Farmer and Swales, 2004). Cross-compliance regulations (Article 5) require that the land declared as under permanent pasture in 2003 is maintained under permanent pasture. It also requires that the ratio of land under permanent pasture to the total agricultural area of each Member State must not decrease by 10% or more from the 2003 reference ratio. Ireland is therefore under obligation not to allow any significant reduction in the total area of permanent pasture; this restricts the type of energy crops that can be grown. In the same CAP reforms, a special aid for energy crops grown on non-set-aside land was introduced. Energy crops (crops grown for the production of biofuels including biogas or for use as biomass in the production of electric and thermal energy) are eligible for a premium of €45/ha. An additional top-up of €80/ha, funded by the National Exchequer, is also paid. Major reform of the CAP is expected in 2013 and this may have implications for energy crops and biofuels.

1.4 Agri-Environmental Schemes

The Rural Environment Protection Scheme (REPS) was introduced under Council Regulation EEC/2078/1992 in order to encourage farmers to carry out their activities in a more extensive and environmentally friendly manner (Hynes et al., 2008).

This was introduced due to the realisation of the severe ecological and environmental impacts of agricultural intensification under previous EU agricultural support mechanisms (Clergue et al., 2005). The Sixth Environment Action Programme (EC, 2001), the Water Framework Directive (EC, 2000) and the Nitrate Directive (EEC, 1991) introduce a series of measures that should lead to an overall reduction in greenhouse gas (GHG) emissions at farm level through lower stocking rates. This, in turn, could free up grassland for other purposes, such as grass biomethane. The adoption of batch storage for slurry has also been suggested (Chardon and Schoumans, 2008), which could make it amenable to anaerobic digestion (AD) and biofuel production. Biofuels are also influenced by the *Biodiversity Action Plan* (Caslin, 2009), which aims to improve or maintain biodiversity and prevent further biodiversity loss due to agricultural activities. Priorities include restricting intensive farming and establishing sustainable resource management. Most grassland in the EU is devoted to meat production, where profitability is low and farmers often rely on EU single-farm payments to survive; thus, grassland farming can face considerable challenges in implementing new environmental measures without financial supports (Boyle, 2008).

1.5 Renewable Energy in Transport

Renewable energy originates from energy resources that are continuously replenished through the cycles of nature, and their supply is unlikely, compared with fossil fuels, to be exhausted. The use of biofuels as a means of greening the transport sector is strongly supported by European policy (EEA, 2004). EU Directive 2009/28/EC on renewable energy sets a mandatory target for each EU Member State for 10% of transport energy (road and rail) to be met by renewable sources by 2020 (EC, 2009a). Liquid biofuels (i.e. biodiesel from rapeseed, soybean and palm oil and bioethanol from maize, wheat, sugar beet and sugar cane) are the main renewable fuels produced and consumed in the EU (USDA, 2006). The use of biogas as a transport fuel after its upgrading to biomethane has started gaining attention in many European countries, such as Sweden, Austria, France and Switzerland (Mathiasson, 2008). Additional to the production of biofuels from wastes, residues and lignocellulosic material, the use of electricity in transport is encouraged in the EU by Directives 2009/28/EC and 2009/33/EC (EC, 2009a,b).

1.6 Biofuels in Ireland – Targets and Options

The share of biofuels in Ireland in 2008 (as a percentage of energy content in petrol and diesel) was 1.2%, although significant increases from 1 ktoe[1] in 2005 to 56 ktoe in 2008 were recorded (Howley et al., 2009a). Biodiesel was the dominant biofuel in 2007 followed by bioethanol and pure plant oil at 76%, 16% and 8%, respectively, (Foley et al., 2009) whereas the contribution of biomethane is still negligible. The target for biofuels was 4% *by volume* of biofuel (DCENR, 2009) by 2010. For 2020, two approaches to national energy forecasts for Ireland were employed for the quantification of the 10% target for transport energy; these were termed *Baseline* and *White Paper Plus* (Walker et al., 2009). The *White Paper Plus* approach allowed consideration of the energy savings in transport associated with Ireland's *National Energy Efficiency Action Plan*. Estimated values of 24.7 PJ and 23.8 PJ for *Baseline* and *White Paper Plus* were calculated, respectively. In this report, a value of 24 PJ will be used as the renewable energy in transport target for 2020. The *Electric Vehicles Plan* sets an ambition of 10% of private vehicles powered by electricity in combination with the 40% target of electricity from renewable energy (Howley et al., 2008) by 2020. It has been shown that the utilisation of electricity in transport (vehicles, trams and rail) will account for 3.6 PJ by 2020 (Foley et al., 2009; Walker et al., 2009) or 1.5% of energy in transport, leaving a shortfall of 8.5%, which must be filled by biofuels. These biofuels may be sourced from various feedstock sources, which may be imported or indigenous energy crops, wastes and residues, or lignocellulosic biomass. In order to achieve Ireland's renewable energy target, the biofuel system must meet certain sustainability criteria.

1.7 The Renewable Energy Directive

Biofuels eligible to contribute to the mandatory target of 10% as set in the EU Renewable Energy Directive

1. ktoe, kilotonnes of oil equivalent.

2009/28/EC (EC, 2009a) should meet the requirements summarised in Box 1.1. The Directive allows for double credit/counting of biofuels produced from wastes, residues and lignocellulosic materials. Singh et al. (2010b) consider grass as a lignocellulosic source and as such it is liable for a double credit.

1.8 Advantages of Grass Methane

Smyth et al. (2010a) reported on sustainability issues concerning imported biofuels (such as corn ethanol and soybean diesel), which may not allow these imported biofuels count in achieving the 10% target. The issues relate to:

- Poor or negative energy balances;
- Adverse environmental impacts;
- Habitat destruction;
- Low GHG savings;
- High land requirements; and
- Carbon leakage.

Imported biofuels from tropical regions such as Brazil, Malaysia and Indonesia have significant issues with land-use change and deforestation. Higher demand for palm oil leads to significant land-use change, which results in lower GHG emission savings, accompanied by adverse social and environmental impacts. In addition, importing biofuels at the expense of local industry could make it difficult for indigenous producers to find a place in the energy market. This is contrary to the government's goals of accelerating the growth of renewables and creating jobs in the energy sector (DCMNR, 2007). However, the use of grass for biofuel (biomethane) production has been highlighted by Murphy and Power (2009a). The energy balance of the grass biomethane system is significantly better than alternative Irish biofuel crops and compares favourably with tropical biofuels (Fig. 1.1) such as sugar-cane ethanol and palm-oil biodiesel (Smyth et al., 2009; Korres et al., 2010). In terms of GHG emissions, an analysis by Korres et al (2010) found grass biomethane to be one of the most sustainable indigenous, non-residue-based European transport biofuels. The advantages of perennial grasses over first-generation agro-fuels include long persistency of high dry matter (DM) yield, intercropping potential with legumes and subsequent reduction in fertiliser application rates, lower rates of pesticide application, and the protection of grassland area in the present CAP cross-compliance system (Peeters, 2009). The reduction in the cattle herd will lead to reduced requirements for grazing and for silage production. Cross compliance will limit the ability to convert excess grassland to arable land. Even allowing for the conversion of grassland to forest, significant quantities of high-value grassland will be available for grass biomethane by 2020 (Smyth et al., 2010a). Smyth et al. (2009, 2010a) suggested an excess of 0.39 Mha by 2020 and allowing for grass biomethane from 25% of this area (ca. 100 kha) could produce 11.9 PJ of biomethane. This is equivalent to 5% of energy in transport in 2020 and 10% when the double credit for lignocellulosic material is allowed (Table 1.1).

Box 1.1 Significant Articles in The Renewable Energy Directive (2009/28/EC) relating to sustainable biofuels

- Article 17 (2): From 1 January 2017, the greenhouse gas emissions of biofuels from new facilities must be reduced by 60% compared with the alternative fossil fuel use.
- Article 17 (3): No damage may be done to sensitive or important ecosystems in producing biofuels.
- Article 17 (4): In the production of sustainable biofuels, wetland, forestry or grassland may not be converted to energy crop production.
- Article 21 (2): The contribution from biofuels made from wastes, residues, non-food cellulosic material and lignocellulosic material shall be considered to be twice that made by other biofuels.

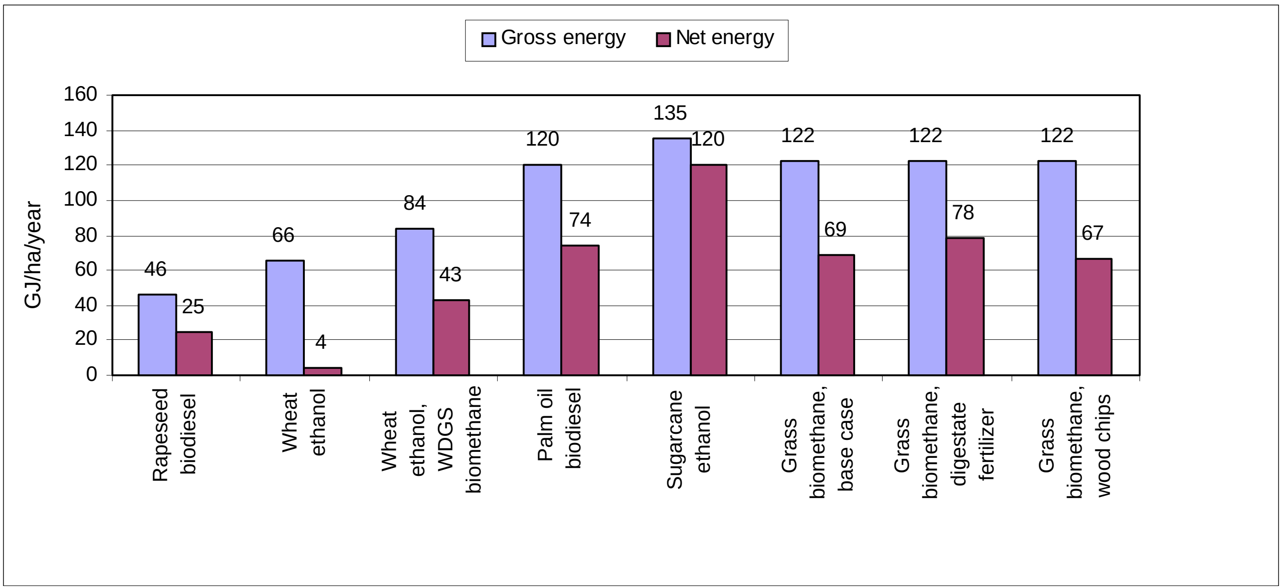

Figure 1.1. Comparison of gross and net energy output of selected energy crop biofuel systems (Smyth et al., 2009; Korres et al., 2010). Gross energy is the energy produced in the form of transport fuel. Net energy is the gross energy less all the energy inputs to the system including for all the steps in the production of the crop and all parasitic energy demands in the production system. WDGS, wet distiller's grains with solubles. 'Grass biomethane, base case' excludes the use of digestate as a fertiliser and uses gas to satisfy thermal parasitic demand. 'Grass biomethane, digestate fertilizer' allows for the use of digestate as a substitute for mineral fertiliser. 'Grass biomethane, wood chips' allows for woodchips to satisfy thermal parasitic demand.

Table 1.1. Strategy for meeting the target of 10% renewable energy in transport by 2020 (adapted from Singh and Murphy, 2009).

Fuel	Feedstock	Practical energy in 2020 (PJ)	Factor	Contribution to target (PJ)	Percentage of energy in transport (2020)
Biodiesel	Tallow	0.715	×2	1.43	0.58%
	Used cooking oil	0.455	×2	0.91	0.38%
	Rapeseed	0.6		0.60	0.25%
Bioethanol	Cheese whey	0.27	×2	0.54	0.23%
Biomethane	Slurry	1.88	×2	3.76	1.57%
	OFMSW	0.57	×2	1.14	0.48%
	Slaughter waste	0.68	×2	1.36	0.57%
	Grass	11.93	×2	23.86	9.94%
Electricity	National grid	1.44	×2.5	3.60	1.5%
Total		**18.54**		**37.20**	**15.5%**

OFMSW, organic fraction of municipal solid waste.

1.9 Waste Management and Residues

Treatment of organic wastes is currently of particular importance in the European Union (Ward et al., 2008) under the EU Landfill Directive (EC, 1999). Recent research for Ireland (Singh and Murphy, 2009) estimated the practical transport energy available from biodiesel (produced from tallow and used cooking oil (UCO)) and biomethane (from cattle slurry, the organic fraction of municipal solid waste (OFMSW) and slaughter waste) to be 4.3 PJ/year in 2020 (Table 1.1). Allowing for double credits, this equates to 3.6% of energy in transport by 2020. This is based on readily achievable collection regimes; for example, 2% of cattle slurry, 5% of pig slurry, and 25% of OFMSW. Significant GHG emissions savings are associated with biomethane from residues. Singh and Murphy (2009) calculated 82% GHG savings for cattle slurry biomethane and 100% for slaughter waste biomethane when compared with diesel.

1.10 Conclusions

The high potential of grassland utilisation as feedstock for biomethane production, given the environmental constraints in agricultural production in conjunction with sustainability issues associated with first-generation biofuels, suggests grass biomethane to be an optimum solution for achieving the 2020 renewable energy in transport target. Diversification of agricultural enterprise to biomethane production will assist rural development through sustainable employment, security of energy supply, and environmental benefits associated with reduced stocking rates.

2 What is Grass?

2.1 Grassland

Grassland is defined as the habitat where the vegetation is either dominated by grasses or is 'grassy' in appearance, with abundant small sedges or rushes and is mainly used for feeding herbivores and ruminants. It also provides an important regulating ecosystem service and supports biodiversity and cultural services, for example by contributing to a region's cultural heritage and to recreational values (Smit et al., 2008). Among its major benefits (i.e. long persistency of high dry matter yield, intercropping potential with legumes and subsequent reduction in fertiliser application rates (Peeters, 2009), protection of soil from erosion, and groundwater formation (Prochnow et al., 2009)), grassland is also an important carbon store and potential carbon sink (Tilman et al., 2006) and a source of feedstock for the production of renewable energy in the form of grass biomethane (Smyth et al., 2009; Korres et al., 2010).

2.2 Grassland Classification

There are various grassland types (based on husbandry practices) and grassland classifications based on botanical composition or phytosociology (Braun-Blanquet, 1932; Feehan, 2003). O'Sullivan (1982) and O'Sullivan and Murphy (1982) distinguished three types of Irish grassland:

1. **High-quality swards:** High-quality swards with *Molinio-Arrhenatheretea* and *Lolio-Cynosuretum* as the prevailing class and association, respectively, are found in high fertile soils, such as those in the east, south and south-east (i.e. Meath, Kildare, Wicklow, Waterford, Wexford and Cork). The dominant species within this class are *Lolium perenne* (perennial ryegrass), *Poa trivialis* (rough meadow grass) and *Trifolium repens* (white clover). High-quality swards include the majority of reseeded pastures found in Ireland.

2. **Moderate-quality swards:** Moderate-quality swards are characterised by the *Molinio-Arrhenatheretea* class and are distinguished from the former type by the *Centaureo-Cynosuretum* association. The dominant species in this type are *Lolium perenne*, *Trifolium repens*, *Holcus lanatus* (Yorkshire fog) and *Agrostis* spp (bentgrass). Three sub-associations are observed within this type of grassland:

    (i) Type A is confined to shallow, well-drained, limestone soils;

    (ii) Type B is found in the better-drained lowlands or deep, well-drained brown earths and grey–brown podzolics; and

    (iii) Type C is common on drumlins in the North Midlands, the Castlecomer Plateau and some soils in the mid-west and is often subjected to poaching under wet conditions.

3. **Low-quality swards:** Low-quality swards include poor-quality wet pastures on soils of low natural fertility and represent around 11% of Irish grassland. Species of the order Molinietalia Caeruleae such as *Juncus* spp. (rushes), *Lythrum salicaria* (purple loosestrife), *Lychnis flos-cuculi* (ragged robin), *Angelica sylvestris* (wild angelica), *Achillea millefolium* (yarrow), *Senecio aquaticus* (marsh ragwort) and *Lotus uliginosus* (marsh trefoil) are dominant in this type of grassland.

2.3 Grassland and Farming Practices

Brockman and Wilkins (2003) classified grassland according to farming practices as rough mountain hill grazing, permanent and rotational or temporary grassland.

- Rough mountain grassland is found in unenclosed or relatively large enclosures on hills, uplands, moorland, heaths and downlands. It is uncultivated grassland and is characterised by high levels of species richness, low stocking rates and low production. The soil is usually acidic or peaty and therefore difficult to cultivate.

- Permanent grassland is grassland in fields or relatively small enclosures not in arable rotation.

It is dominated by perennial grasses and it is more productive and usually more highly stocked than mountain hill grazing grassland.

- Rotational or temporary grassland is grassland within an arable rotation. It is characterised by low abundance and low species richness, high stocking rates and production.

In addition, Lockhart and Wiseman (1988) distinguished two types of grassland, uncultivated and cultivated. The former consists of rough mountain and lowland heaths grassland, whereas the latter includes permanent grassland (over 5 years old) and leys or temporary grassland (less than 5 years old). This, based on perennial ryegrass percentage, can be further distinguished as first- (>30%), second- (20–29%), third-grade (<20%) and poor (usually dominated by bentgrass) grassland. Cultivated grassland according to Fossitt (2000) can be classified as improved grassland that is highly modified, intensively managed and species poor used for heavy grazing and/or silage production. It includes regularly reseeded monoculture grasslands dominated by perennial ryegrass that is planted as part of an arable rotation. The Irish Central Statistics Office (CSO) displays its data on grassland use based on four categories – pasture, rough grazing, silage and hay. Increased production from grassland has arisen from improved understanding of soil and plant nutrition, plant physiology and cultivar improvement, while improved understanding of feed evaluation, ruminant nutrition, grazing management and silage technology have contributed to increased utilisation of grassland under grazing and cutting. In this report, high-quality, improved first-grade grassland (i.e. pasture and silage) is considered for the analysis of energy balance and related GHG emissions for biomethane production.

2.4 Grass in Animal and Biomethane Production Systems

Grass, more than anything else, is what Irish farming is all about (Feehan, 2003) and it evolves as modern scientific approaches to farming are developed. Agronomists and progressive farmers require the cultivation of high productive grass species for high productive pastures (Connolly, 2001) which allows them to receive full benefit from its various uses (e.g. grazing, silage production) (Walker, 1995). This is true for the use of grass and grass silage along with animal feed as a feedstock for the production of biomethane (Nizami et al., 2009).

The attention on different perennial grasses, i.e. *Panicum vigratum* (switchgrass) (McLaughlin and Kszos, 2005), *Miscanthus* × *Giganteus* (miscanthus) (Clifton-Brown et al., 2004), *Phalaris arundinacea* (reed canary grass) and *Phleum pratense* (timothy) (Lewandowski et al., 2003), *Andropogon gerardii* (big bluestem) (Weimer and Springer, 2007), forage grasses (i.e. ryegrass) (Smyth et al., 2009; Korres et al., 2010), as energy crops, mainly in the USA and Europe, was accelerated when it was realised that they offer good energy balances along with several environmental advantages. Species, varieties and seed mixtures should clearly be chosen to suit the purposes for which the sward is to be used and the environment (Feehan, 2003). The physiology of grasses considering, for example, their photosynthetic (PS) pathway, i.e. C-3 (cool or temperate) versus C-4 (warm or tropical) grasses, imposes environmental specificity and, hence, differences in their productivity (Niu et al., 2006) and biomethane yield (Table 2.1). The main characteristics of cool compared with warm grasses that affect their productivity are that the former fix carbon dioxide (CO_2) in a cooler environment, i.e. they respond to nitrogen fertiliser early in the spring, whereas in warm seasons their growth rates are reduced. In contrast, warm species require less nitrogen to achieve the same light-saturated assimilation rate, leading to higher photosynthetic nitrogen use efficiency, are more efficient at gathering carbon dioxide in warm environments and more tolerant at water stress conditions (Winslow et al., 2003; Lunt et al., 2007; Nippert et al., 2007).

However, productivity of animals (i.e. meat, milk, wool) consuming mostly forage is directly related to the quality of the forage and the amount consumed (Buxton, 1996). The quality of forages consumed by animals is accounted for, in large part, by their digestibility (dry matter digestible (DMD)) and the fraction of the DM or energy that remains in the body on passage through the gut tract (dry matter indigestible (DMI)) (Brown, 1999). The lower digestibility of warm grasses due to their higher fibre

Table 2.1. Potential perennial grasses as energy crops in Europe (data adapted from Lewandowski et al. (2003); Prochnow et al. (2009); Braun et al., undated).

Common name	Latin name	PS pathway	Methane (m^3/ha)	Yield (t DM/ha)
Ryegrass	*Lolium perenne*	C-3	2,500–6,150	9–16.7[a]
Miscanthus	*Miscanthus × Giganteus*	C-4	1,432–5,450	5–44
Switchgrass	*Panicum vigratum*	C-4	900–7,820[b]	5–23
Reed canary grass	*Phalaris arundinacea*	C-3	1,700–4,730	7–13
Timothy	*Phleum pratense*	C-3	1,362–5,800	9–18
Meadow foxtail	*Alopecurus pratensis*	C-3	1463	6–13
Big bluestem	*Andropogon gerardii*	C-4	–	8–15
Cocksfoot	*Dactylis glomerata*	C-3	1,480–3,800	8–10
Tall fescue	*Festuca arundinacea*	C-3	1,462	8–14
Napier grass	*Pennisetum purpureum*	C-4	0.19–0.34[c]	27
Sudan grass	*Sorghum × drummondii*	C-4	2,130–6,060	10–20
Cypergrass	*Cyperus longus*	C-4	–	4–19

[a]Yields of early, intermediate and late perennial ryegrass were reported equal to 16.7, 15.3 and 15 t DM/ha/year, respectively (Lockhart and Wiseman, 1988).
[b]Based on 0.18–0.34 m^3 CH_4/kg dry matter (Pettigrew, 2000; Chynoweth et al., 2001; Samson, 2006).
[c]Litres of methane (CH_4) per gram of volatile solids (Wilkie, 2008).
PS, photosynthetic; DM, dry matter.

Table 2.2. Dry matter indigestible (DMI), dry matter digestible (DMD) and acid detergent fibre (ADF) concentration of C-4 and C-3 grasses, adapted from Brown (1999)

Grass type	DMI[a] (g/day/$kg^{0.75}$)	DMD[b] (%)	ADF[c] (% of DM)
C-4 (sheep)	56	62	–
C-3 (sheep)	71	71	–
C-4 (sheep)	65.7	54.5	42.5
C-3 (sheep)	66.2	65.5	35.8
C-4 (cattle)	89.8	60	42.7
C-3 (cattle)	89.5	67	38.3

[a]DMI (dry matter indigestible): dietary fibre (sometimes called roughage) is the indigestible portion of plant food.
[b]DMD (dry matter digestible): the percentage of the feed dry matter actually digested by animals; high-quality feeds have a DMD of over 65%, whilst feeds below 55% DMD are of poor quality.
[c]ADF (acid detergent fibre): estimation of cellulose and lignin content in a feed; the lower the ADF the higher the DMD (and metabolisable energy).

content (Minson, 1981; Reid et al., 1988) (Table 2.2) is indicative for possible lower biomethane yields since digestibility of dry matter may be equated to the potential digestibility of the silage in cattle paunch (Robson et al., 1989). It is therefore imperative that the selection of the appropriate type of grass should consider several characteristics in terms of farming system, environmental conditions, legislative issues (i.e. cross compliance) and biomethane production potential.

2.5 Suitability of Grass Species for Biomethane and Animal Production in Ireland

The use of grass either as feed for livestock or as a feedstock for biomethane production determines the husbandry management and agricultural operations due to differences in environmental factors and the microbiology of AD as opposed to rumen (Nizami et al., 2009). For example, the level of cellulose degradation is up to 80% in biogas plants with retention times of 30–80 days, while it is 40–60% in rumen with retention of about 2 days (Ress et al., 1998). In the temperate grassland region, particularly in Ireland, grass silage of perennial ryegrass is preferred for biomethane production because of its high digestibility values (Robson et al., 1989), water-soluble carbohydrate (WSC) levels (Smith et al., 2002) and reduced quantities of crude fibre (Table 2.3) (Nizami et al., 2009).

Mahnert et al. (2005) reported that perennial ryegrass gave the highest biogas yield (0.83–0.86 m^3/kg volatile dry solids (VDS) added), compared with other grass species, both fresh and ensiled. For example, cocksfoot gave a biogas yield of 0.65–0.72 m^3/kg VDS added. Considering that grass biogas is typically 55% methane (CH_4), these results indicate that ryegrass yielded 0.45–0.47 m^3 CH_4/kg VDS added, while cocksfoot yielded 0.36–0.40 m^3 CH_4/kg VDS added. Perennial ryegrass is one of the most dominant grass species in Irish grassland (Fig. 2.1). Along with Italian ryegrass and white clover, it accounts for nearly all of the grass/clover seed sold for forage production in Ireland (Anonymous, 2008b). Additionally, O'Kiely et al. (2005) stated that the main attractions in favour of perennial ryegrass swards are that they produce high yields in response to fertiliser application, have high digestibility when harvested at the appropriate growth stage, are relatively easy to preserve as silage due to their superior content of sugar and they persist as permanent swards where favourable management practices prevail. Tetraploid ryegrass varieties are recommended due to high sugar levels (Dieterich, 2008). In recent times diploid varieties have tended to dominate mixtures in Ireland, but tetraploid varieties remain an important component of grass seed mixtures because of their higher WSC content, their increased palatability, which determines higher intake by livestock, and their tolerance to drought. However, they tend to have lower tiller densities resulting in more

Table 2.3. Comparison of fresh and ensiled grass characteristics in batch and continuously stirred tank reactor (CSTR) digesters (Nizami et al., 2009).

	Batch digester					CSTR			
	Fresh grasses			Grass silage		Fresh grasses			
	PRG	CF	MF	PRG	CF	PRG	CF	MF	MIX
Total solids (TS) (%FM)	17.6	18.6	15.8	18.7	27.3	25.6	22.9	24.2	24.2
Volatile dry solids (%TS)	90.1	89.1	91.1	88.5	88.8	90.6	88.8	90.6	90
Volatile fatty acids (g/kg FM)	0.5	0.5	0.3	6.9	14.3	0.7	0.5	0.6	0.6
pH	6.5	6.7	6.6	4.6	6.1	6.5	7.1	7.1	6.9
Carbon to nitrogen ratio	16.4	13.7		15.5	14.3	19.8	12	13.5	15.1
Crude protein (%TS)	14.7	18.5		17	18.4	11.8	21.4	18.8	17.4
Crude fibre (%TS)	24.8	24.8	25.3	31.3	30.1	29.1	28	31.5	29.5
Saccharides (%TS)	10.8	9.8	3.3	3.4	3.1	19.3	9.8	9.1	12.7
Crude fat (%TS)	2.1	2.3	2.2	4.9	4.6	2.4	2.6	2.1	2.4

PRG, perennial ryegrass; CF, cocksfoot; MF, meadow foxtail; MIX, mixture; FM, fresh matter.

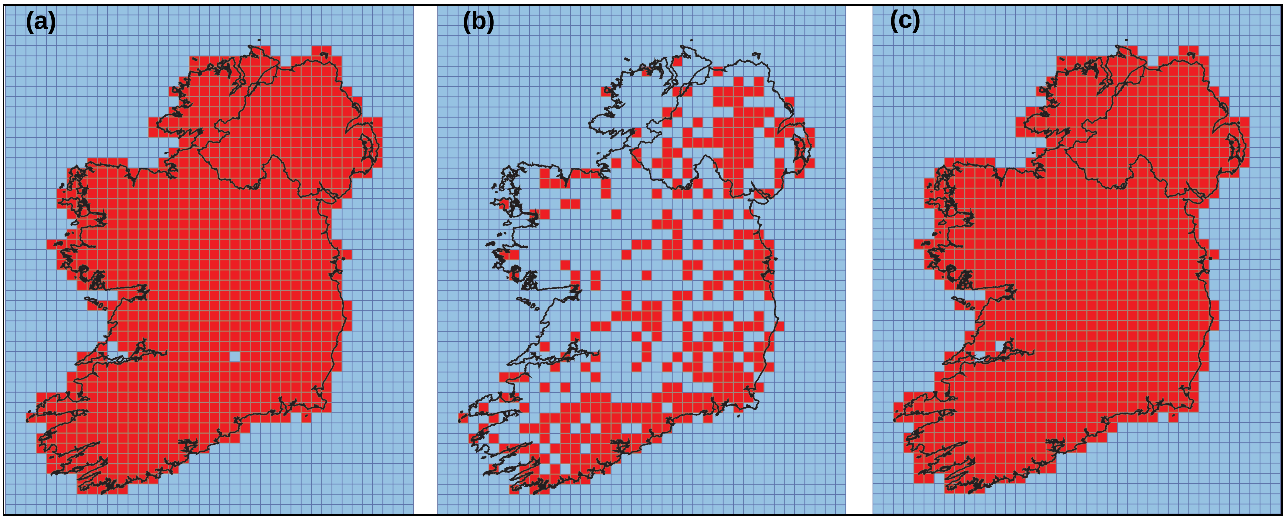

Figure 2.1. Distribution of (a) perennial ryegrass, (b) Italian ryegrass, and (c) white clover in Irish grassland. Maps constructed based on data provided from the National Biodiversity Network Gateway (http://data.nbn.org.uk).

open swards and lower dry matter compared with diploids. Seeding rates for tetraploid grasses will need to be higher because of their larger seed size (Anonymous, 2008b).

Considering the potential of grass and grass silage as a feedstock for biomethane production as a biofuel (Murphy and Power, 2009b) and the need to increase biofuel penetration in line with the European Directive for the use of biofuels (EC/28/2009), this then necessitates the rapprochement of grass and grass silage production and their characteristics that make them suitable for both feed and biofuel. Grass for AD is grown in the same way as high-quality grass for animal feed as, in both cases, the aim is to maximise metabolisable energy (ME) by harvesting the grass as long as it is in a leafy, non-lignified stage (Dieterich, 2008). Nevertheless, certain agronomical management decisions, such as fertilisation, harvesting date and frequency, and ensiling, can affect biomethane yield through mainly changes in chemical and structural composition of cell walls in grasses.

2.6 Fertilisation

Fertilisation of grassland to achieve higher yields is the most important husbandry factor. Nevertheless, Nordheim-Viken and Volden (2009), investigating the effects of husbandry factors such as nitrogen fertilisation of timothy, found that increases in fertilisation rate resulted in increases in neutral detergent fibre (NDF). Such fibre is a measure of cellulose and hemicellulose and is a reflection of the total cell wall content. This is supported by findings of Keady et al. (2000), where increases of nitrogen application rate were accompanied by increases in the cellulose and hemicellulose content of ryegrass (Fig. 2.2). This leads to a decrease in digestibility.

In general, the results of nitrogen fertilisation on fibre digestibility are moderate. As such, Peyraud et al. (1997) found that unfertilised perennial ryegrass was accompanied by decreased fibre digestibility of 0.06 units when provided as a feed to dairy cattle but all NDF, acid detergent fibre (ADF) and acid detergent lignin ((ADL) estimation of lignin content) moderately increased with nitrogen application. Additionally, several authors have reported lower water-soluble carbohydrates in grasses with increased nitrogen fertilisation (Buxton and Fales, 1994; O'Kiely et al., 2002). These evidences suggest that an excess in fertilisation rate could negatively affect biomethane production since increases of the non-easily fermentable content of grasses occur.

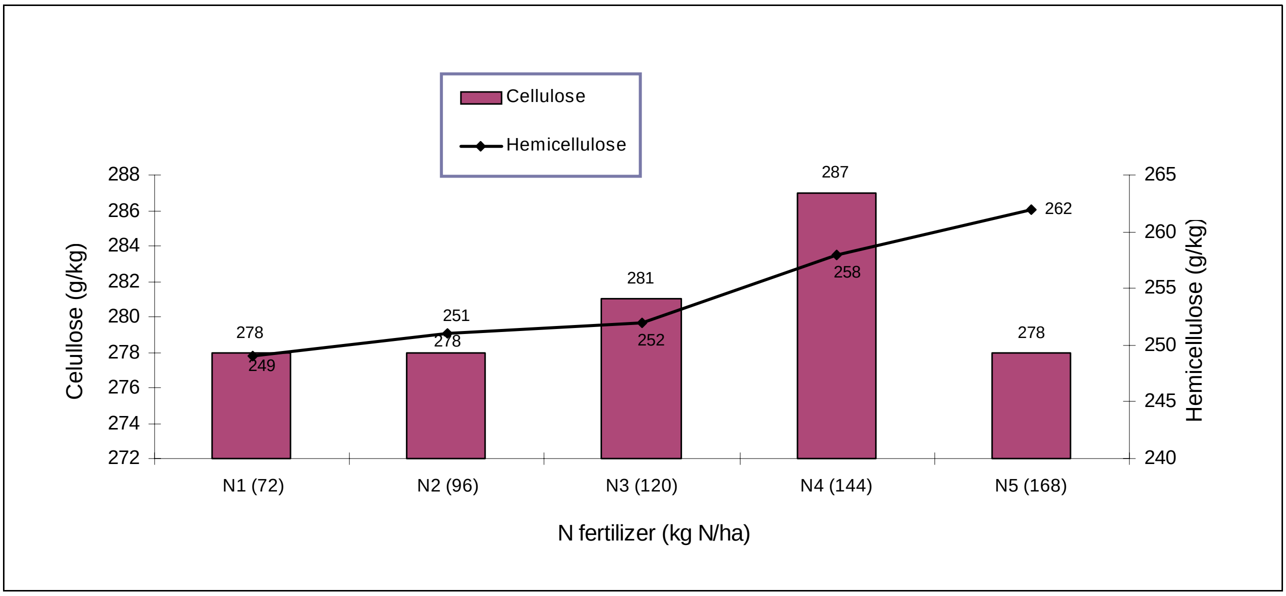

Figure 2.2. Effects of nitrogen fertilisation on the concentration of structural carbohydrates (cellulose and hemicellulose). Based on data from Keady et al. (2000).

2.7 Harvesting Date

Grass for silage is usually harvested at a less mature stage of growth (leafy and non-lignified) (Fig. 2.3), since the aim is to obtain a crop with a relatively high content of fermentable substrate and a low content of fibre as the crop at this stage usually has a high leaf–stem ratio (Woolford, 1984).

Amon et al. (2007), reporting on a multifaceted crop rotation to increase the yield of methane per hectare, found that the first cut at vegetation stage was selected as the optimum option for harvesting. Furthermore, De Boever et al. (1993) found significant increases in structural carbohydrates (i.e. NDF and ADF) and lignin between early and late first cut in a permanent pasture consisting of a 50:50 ratio between diploid and tetraploid varieties of perennial ryegrass. The same was reported by Keady et al. (2000) for perennial ryegrass comprised of intermediate varieties (Fig. 2.4).

Nevertheless, inconsistencies in biomethane production per kilogram VDS and harvesting date have been reported for clover, ryegrass and timothy in mixed swards. Kaparaju et al. (2002) found that clover produced 50% more methane per kilogram VDS at the vegetative stage than at the flowering stage, whereas Pouech et al. (1998), performing the same experiment, obtained different results, where 32% lower methane yield per kilogram VDS was recorded at the vegetative stage than at the flowering stage. Prochnow et al. (2005) described more biogas yield in second-cut than first-cut silage, but, in spite of high dry solids (DS) and VDS contents present in late-cut grass, a lower methane yield was established. The total solids (TS) and VDS contents in grass, hence yield of biomethane production (Nizami and Murphy, 2010), depend on several factors, such as location, origin, climate, cultivation practices, soil type, nutrient content of grass and pretreatment of biomass for AD (Bauer et al., 2007). Additionally, methane production potential can also be increased if grass is cut in the afternoon as it increases the concentration of WSC (White, 1973). Another important factor affecting the qualitative characteristics of grass silage relates to harvesting management (Buxton, 1996) – the methane yield may possibly be affected by harvest frequency. It has been mentioned by various authors that a cutting cycle of grass between 2 and 4 weeks in terms of the carbon/nitrogen ratio (Holliday, 2005) or at cutting intervals of 6 weeks following an early first cut (Murdoch, 1980) can optimise the methane yield in AD through increases in digestibility of grass.

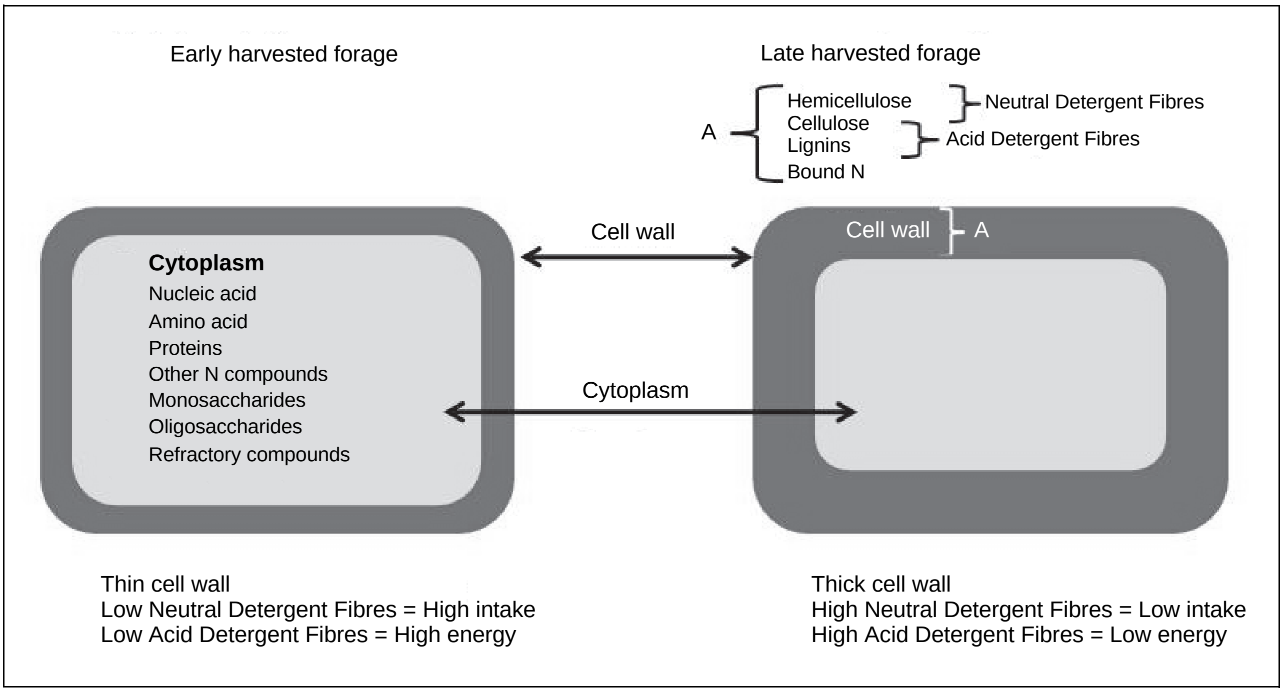

Figure 2.3. Effects of harvesting date on morphological and chemical composition of grass.

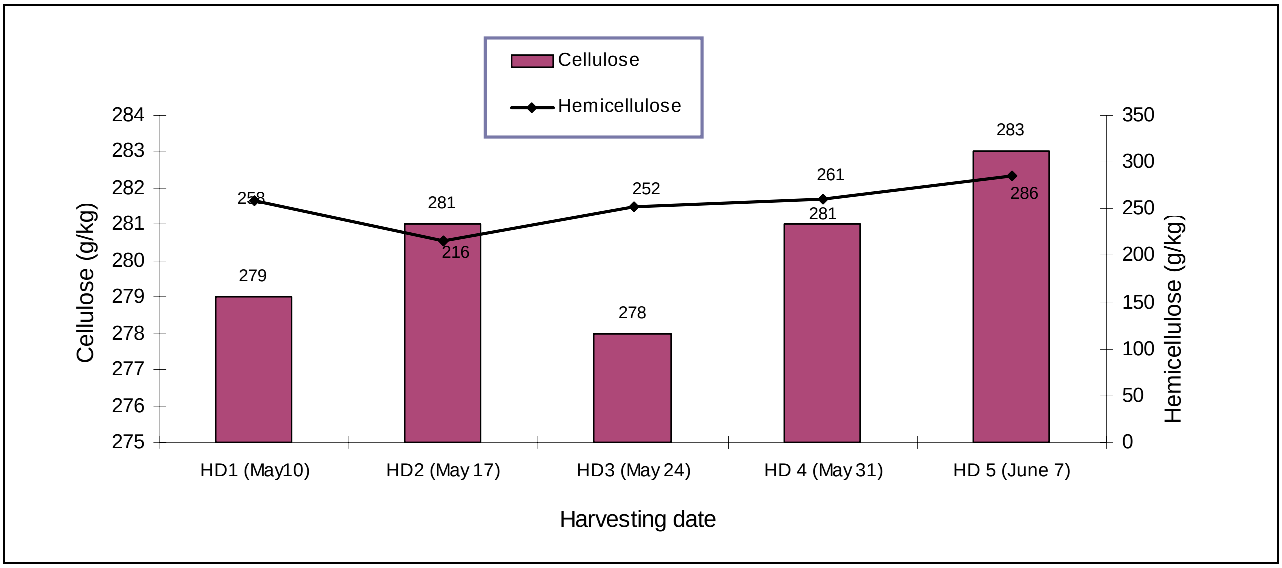

Figure 2.4. Effects of harvesting date on grass fibre components (based on data from Keady et al., 2000).

2.8 Ensiling of Grass

Grass and, in particular, grass silage form the basal diet for the vast majority of ruminants in many parts of the world during the winter feeding period (Charmley, 2001). Additionally, ensiling of grass for AD is preferable compared with fresh grass (Nizami et al., 2009), whilst ensiled grass in comparison with dried and stored grass ensures lower organic matter losses and independency of weather conditions that might cause damage to the dried feedstock. There may be potential to batch digest fresh grass in the summer months and to utilise other energy crops or biomass in the winter months. Grass silage produced higher methane per tonne of organic dry matter (ODM) than fresh grass (Holliday, 2005). During ensiling, the resistive polysaccharides are degraded and intermediates, such as volatile fatty acids (VFAs), for methanogens are produced, which increase methane yield in the digester (Madhukara et al., 1993). Use of additives during ensiling is a common practice. Nevertheless, the use of additives in silage preparation did not increase methane as recorded by Neureiter et al. (2005) and Rani and Nand (2004). Conversely, according to Lehtomaki (2006), formic acid addition resulted in higher methane production, possibly due to improvements in silage fermentation through decreases in pH and ammonia-nitrogen (Keady et al., 2000). Acidic conditions are suggested during the whole ensiling process to produce efficient silage for the digester (Mosier et al., 2005). Another agronomical factor that influences biomethane production from grass silage is the biological pretreatment of feedstock, such as the use of cellulase enzymes during ensiling (Clavero and Razz, 2002). This can result in an increased degradation of cell walls and the breakdown of structural carbohydrates, hence improving the potential of biomethane production (Clavero and Razz, 2002). Considering the use of inoculants, it has been proposed that heterofermentative bacteria (as compared with homofermentative bacteria) could be more beneficial for efficient AD since they facilitate the production of intermediates for methanogens (Idler et al., 2007).

2.9 Mixed Pastures

Mixtures of species are more common than pure stands in grazed pastures, with grasses (i.e. ryegrass) and clover in rotational pastures (Brown, 1999) being most common. Such mixtures have advantages over monospecific pasture because legumes have a higher nutritive value for ruminants and fix atmospheric nitrogen, whereas the different resource requirements or environmental responses between various species in mixed pastures allow for broader resource exploitation (Brown, 1999). Additionally, grass species may vary in terms of their chemical composition – hence methane yields from grassland could possibly depend on the mixture of species within the vegetation (Prochnow et al., 2009).

Mixtures of grasses and grass silage increase methane yield when compared with a single grass type, such as *Cynodon* spp. (Bermuda grass) (Gunaseelan and Nallathambi, 1997). Additionally, Plochl and Heiermann (2006) reported methane production from forage and paddock mixtures of 297–370 m^3/t and 246 m^3/t ODM, respectively. The efficiency of AD can be considerably improved in mixed feedstock such as that of grass with legumes because the NDF concentration of grasses is usually greater than that of legumes, which is caused mostly by differences in the NDF concentration of grass and legume leaves (Buxton, 1996). Hence, increasing the proportion of legumes, particularly clover, and, consequently, the leaf to stem ratio of forage results in lower cell wall concentration, in other words reduced indigestible material and increases in digestibility of feedstock. This improves the efficiency of lignocellulosic decomposers and possibly increases biomethane production (Table 2.4).

2.10 Conclusions

- The most important husbandry factors that could affect the potential biomethane production from grass and grass silage are species selection, fertilisation and harvesting date.
- The selection of suitable grass species (e.g. perennial ryegrass, timothy, cocksfoot and meadow foxtail), based on their chemical composition and dominance in Irish grasslands, can significantly affect biomethane production.
- Excess fertilisation could negatively affect biomethane production due to increases in the structural carbohydrate content of grasses.
- Late harvesting contributes to decreases in the non-structural carbohydrate content of grasses, hence the potential for biomethane production.
- Mixed pastures (e.g. ryegrass and clover) have shown that they might positively affect biomethane production.
- Conservation of grass has been shown to produce higher methane per tonne of organic matter than fresh grass.

Table 2.4. Effects of pasture type on methane production (Prochnow et al., 2005).

Substrate	Biogas yield (l/kg VDS)	Methane yield (l/kg VDS)	Conditions
Intensive grassland (monoculture fresh, silage)	700–720	–	Batch, 35°C, 25 days
Extensive grassland (fresh and silage)	540–580	–	
Extensive grassland (fresh and hay)	500–600	–	Semi-continuous, 35°C, 18–36 days, co-digestion
Extensive grassland (silage)	500–550	–	Continuous, 35°C, 20 days, co-digestion
Mixed pasture grassland (fresh and silage)	650–860	310–360	Batch, 35°C, 28 days, mono-digestion
Mixed pasture grassland (silage)	560–610	300–320	Semi-continuous, 35°C, 28 days, mono-digestion
Grasses and clover (silage)	532, 474, 427[a]	370, 326, 297[a]	Batch, 37–39°C, 58 days, mono-digestion
Intensive grassland (monoculture, silage)	–	390	Semi-continuous, 37°C, 25–60 days, co-digestion
Extensive grassland (silage)	–	220	Semi-continuous, 37°C, 25–60 days, co-digestion

[a]Harvesting mid-May (before anthesis), end of May (anthesis), mid-June (after anthesis), respectively.
VDS, volatile dry solids.

3 How Do We Convert Grass to Biomethane?

3.1 Anaerobic Digestion

Anaerobic digestion is an old technology used for stabilising waste and wastewaters and, more recently, for energy production. The process of AD also occurs in nature when organic matter degrades and decays, for example the cow's digestive system, marshes and swamps, landfills, etc. Biogas, the major end product of the AD process, is either produced naturally or artificially in airtight vessels known as anaerobic digesters (Salminen and Rintala, 2002). The biochemical processes in AD, through which the microbial decomposition of organic matter under anaerobic conditions occurs, are distinguished by the following phases:

- Hydrolysis (complex organic matter is decomposed into smaller units);
- Acidogenesis (products of hydrolysis are converted into VFAs and methanogenic substrates);
- Acetogenesis (products from acidogenesis, which cannot be directly converted to methane by methanogenic bacteria, are converted into methanogenic substrates such as acetic acid); and
- Methanogenesis (the production of methane and carbon dioxide from intermediate products) (Al Seadi et al., 2008).

The process of biogas production is not efficient unless carried out in a controlled environment within an anaerobic digester. The digester technology should be designed so as to optimise the conversion of the specific organic material to gaseous products (Demirbas and Ozturk, 2005). A range of digester types and configurations may be utilised. The configuration chosen (Fig. 3.1) must be based on various process parameters, such as the solids content of the feedstock, the number of phases or stages of digestion activities, the operating temperature, the method of feeding the substrate, the retention time in the digester, and the organic loading rate (Karagiannidis and Perkoulidis, 2009; Nizami and Murphy, 2010).

The history of AD starts with sanitation – septic tanks treating low-strength wastewaters under psychrophilic temperatures (ambient, less than 20°C) (Rebac et al., 1995). The technology has advanced to the thermophilic treatment of solid waste (Vandevivere, 1999) and the production of gaseous transport fuel from high solid content feedstocks such as grass silage (Murphy and Power, 2009b). A significant trend in AD technology is higher treatment efficiency. This is made possible by adequate pre- or post-treatments and by various types of additives or co-substrates that improve nutrient composition, metabolic diversity and resistance towards toxicants (Nizami et al., 2009). The application of AD technology covers a wide range of uses and substrates, for example farm waste, wastewater, industrial organic waste, municipal solid waste, agricultural residues, crops, crop residues, grass and grass silage (Vandevivere, 1999).

3.2 Anaerobic Digesters

A steady and predictable supply of usable biogas can be achieved if anaerobic digesters are designed, operated and maintained properly. Concrete, steel and brick or plastic are the materials with which anaerobic digesters are made. A variety of shapes, such as silos, troughs, basins or ponds, exist. They may be placed underground or on the surface. The same basic components in all designs are a premixing area or tank, a digester vessel, a system for using the biogas, and a system for distributing or spreading the effluent (Demirbas and Ozturk, 2005).

In a one-stage digester, all the AD processes (i.e. hydrolysis, acidification and methanisation) occur in one tank. In a two-stage system, all the reactions occur in each vessel. In a two-phase reactor, microbiological processes are separated: hydrolysis and acidification occur in the first reactor and acetogenesis and methanogenesis in the second reactor. In batch

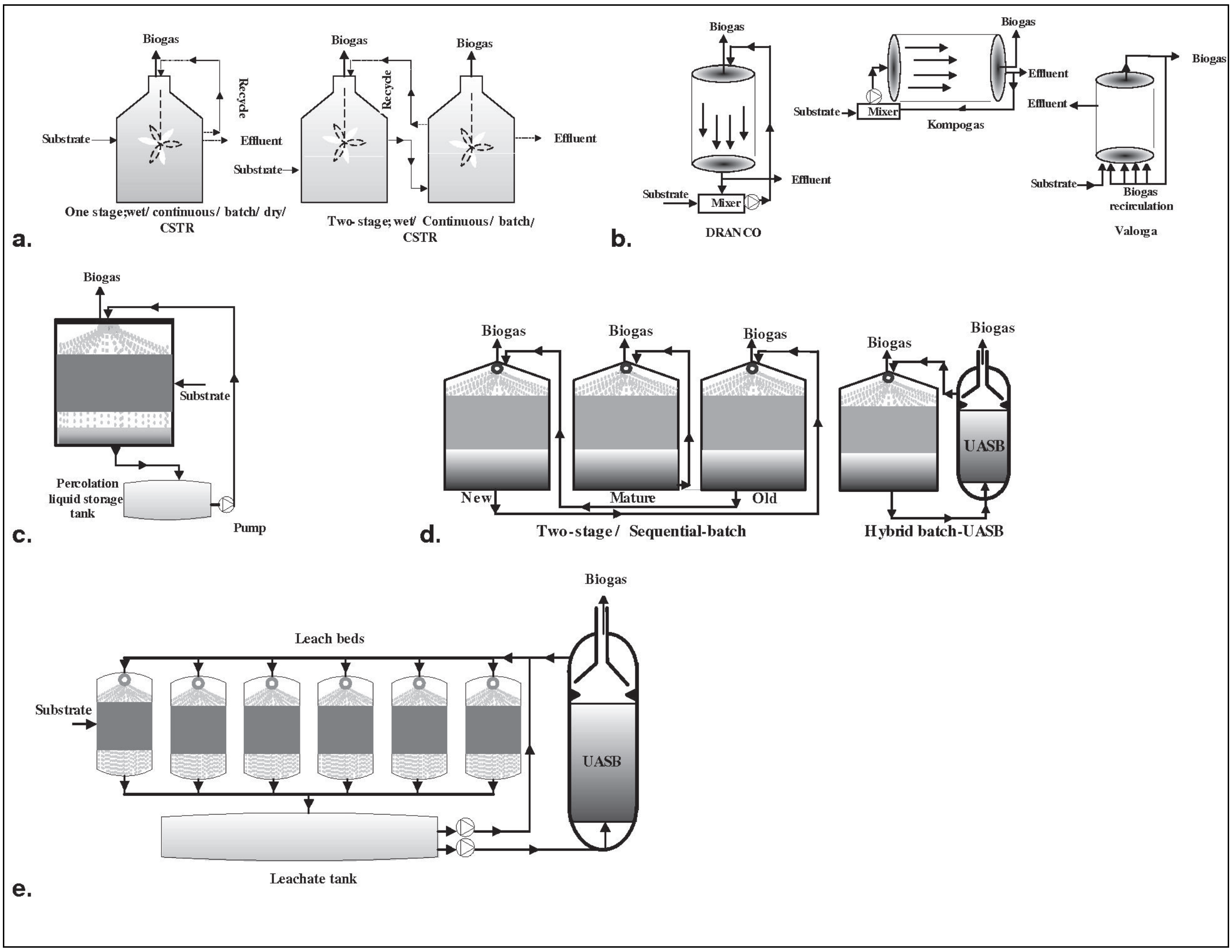

Figure 3.1. (a) Design variation in one- and two-stage digesters, (b) one-stage dry continuous digesters, (c) one-stage dry batch digester, (d) two-stage dry batch digesters, and (e) sequencing fed leach bed digesters coupled with an upflow anaerobic sludge blanket (UASB) (Vandevivere et al., 2003; Nizami and Murphy, 2010). CSTR, continuously stirred tank reactor; DRANCO, DRy ANaerobic COnversion.

digesters, the feedstock is inserted once into the digester for a certain period of time to complete the digestion activity, while in continuous digesters the feedstock is constantly or regularly fed either mechanically or by force of the new feed. In dry digesters, high solid feedstock with dry matter ranging from 20% to 50% is used as substrate. The feedstock is either sprinkled with recirculating water (dry batch digestion) or mixed with digestate (dry continuous). Wet digesters, such as the continuously stirred tank reactor (CSTR), typically operate at less than 12% DS content. High solid content feedstock may be treated in a wet continuous system through homogenisation to liquid state (Nizami and Murphy, 2010), (Fig. 3.1).

The majority of digesters treating OFMSW and biowaste (i.e. 90% of the full-scale plants currently in use in Europe) rely on continuous one-phase systems (Lissens et al., 2001) (Table 3.1). Nevertheless, a considerable amount of information in the literature exists (e.g. Sachs et al., 2003) on anaerobic treatment of wastes in two-phase digestion (i.e. the acid-forming phase followed by the methanogenic phase). Two-phase systems offer more possibilities to control the intermediate steps of the digestion process, although the single-phase system is preferred in industry because of simplicity in design and lower investment cost (Arvanitoyannis and Varzakas, 2008) (Table 3.2). Currently, only 5% of European biogas plants are psychrophilic, 8% are thermophilic, and 87% are

Table 3.1. Five-year development in different digesters types (adapted from De Baere and Mattheeuws, 2008).

Period	One-phase versus two-phase digesters		Wet versus dry digesters	
	One-phase	**Two-phase**	**Wet**	**Dry**
1991–1995	85%	15%	37%	63%
1996–2000	91%	9%	38%	62%
2001–2005	92%	8%	59%	41%
2006–2010 (estimated)	98%	2%	29%	71%

Table 3.2. Comparison of process weaknesses and benefits of various digester types (Nizami and Murphy, 2010).

System		Strengths	Weaknesses
One-stage versus two-stage digesters	**One-stage**	• Simpler design • Less technical failure • Low cost	• Higher retention time • Foam and scum formation
	Two-stage	• Efficient substrate degradation owing to recirculation of digestate • Constant feeding rate to second stage • More robust process • Less susceptible to failure	• Complex and expensive to build and maintain • Solid particles need to be removed from second stage
Dry versus wet digesters	**Dry**	• Higher biomass retention • Controlled feeding • Simpler pretreatment • Lower parasitic energy demands	• Complex handling of feedstock • Mostly structured substrates are used • Material handling and mixing is difficult
	Wet	• Good operating history • Degree of process control is higher	• Scum formation • High consumption of water and energy • Short-circuiting • Sensitive to shock loads
Batch versus continuous digesters	**Batch**	• No mixing, stirring or pumping • Low energy input process and mechanical needs • Cost-effective	• Channelling and clogging • Larger volume • Lower biogas yield
	Continuous	• Simplicity in design and operation • Low capital costs	• Rapid acidification • Larger volatile fatty acid production
High rate bioreactors		• Higher biomass retention • Controlled feeding • Lower investment cost • No support material is needed	• Larger start-up times • Channelling at low feeding rates

mesophilic. In Europe, only Italy and Switzerland use psychrophilic biogas plants, whereas in Denmark there are more thermophilic than mesophilic biogas plants (Poulsen, 2003).

Anaerobic digestion technology due to recent improvements – reduced technology costs and increased process efficiency (Murphy and Power, 2009a) – has become an attractive option as a source for renewable energy production as opposed simply to waste treatment (Durand, 2003). Anaerobic digestion of grass and grass silage has received increased attention in recent years in Europe (Murphy and

Power, 2009a), but its use is modest in comparison with others substrates (Abraham et al., 2007). Most of the work on digestion of grass and grass silage is carried out at laboratory and pilot scales (Murphy and Power, 2009b), using manure and maize silage as co-substrates. Nevertheless, in European biogas plants during 2002–2004, grass and maize silage were the most used co-substrates (Weiland, 2006). The literature regarding the mono-digestion of grass and grass silage is limited. However, some studies have shown a high potential of biogas production (Table 3.3).

3.3 Upgrading and Injection

Utilisation of biogas as a vehicular fuel should have as high as possible a volumetric energy density content as can be achieved. This is affected by removal of carbon dioxide and other gases that exist in the biogas mixture. Apart from methane and carbon dioxide, biogas also contains water, hydrogen sulphide, nitrogen, oxygen, ammonia, siloxanes and particles. These impurities can be removed by cooling, compression, precipitation, absorption or adsorption (Petersson and Wellinger, 2009); collectively this is termed upgrading (Murphy et al., 2004; Persson et al., 2006). de Hullu et al. (2008) compared five techniques for upgrading of biogas (Table 3.4):

1. Chemical absorption
2. High-pressure water scrubbing (HPWS)
3. Pressure swing adsorption
4. Cryogenic separation, and
5. Membrane separation.

They found that membrane separation and HPWS are the simplest processes to operate because they do not need special chemicals or equipment to run. In addition, HPWS provides maximum purity, with up to 98% methane with minimal cost.

Upgraded biogas, biomethane, can either be used directly on the site where it is generated or distributed to customers via pipelines. After upgrading, it may be fed into the distribution grid (Persson et al., 2006). The on-site option for the use of biomethane as a transport fuel is to compress it up to 300 bar and discharge it to the vehicle through cascading pressure reduction to 250 bar. Alternatively, the existing natural gas infrastructure may be used as a distribution system to a service station at a remove from the facility. A European Commission report (EC, 2006) states that the energy required for local distribution of natural gas is zero. This is because the high-pressure trunk lines (typically operating at between 35 and 70 bar) that feed the low-pressure networks (typically operating at 4 bar) provide sufficient energy to supply local distribution. In either case, for use as a transport fuel it is necessary to scrub and to compress to 300 bar.

Intermediate pipelines (8 bar) present an interesting option since pressure is similar to some biogas upgrading processes while injection into the distribution network (4 bar) is the final and most practical solution. However, the gas utility must ensure that the minimal summer load is greater than the projected biomethane flow. Furthermore, for security reasons, the utility may require more stringent monitoring of the gas quality since dilution of biomethane will be low. Technologies such as pressure swing adsorption (PSA) and amine scrubbing are promising candidates for simple injection and monitoring systems, since they often provide an additional assurance that gas quality will meet specification (Electrigaz, 2008).

There are several incentives for using the gas grid for distribution of biogas:

- One important advantage is that the grid connects the production site with more densely populated areas which enables the gas to reach new customers.
- An off-site customer may have a year-round demand for electricity and thermal energy (a brewery for example).
- An off-site customer may achieve far higher energy conversion efficiency due to economy of scale (a combined cycle gas turbine).
- An off-site customer may have a large captive fleet (bus service).
- It is also possible to increase the production at a remote site and still use 100% of the gas.

Table 3.3. Comparison of the optimal anaerobic digesters for grass silage (adapted from Nizami and Murphy, 2010).

	Example	Pretreatment	Process	Quality of digestate	HRT (days)	Solid contents (%)	Operating temperature (°C)	Cost	Destruction of volatile solids (%)	OLR (kg VDS/m^3/day)
Wet continuous one/ two-stage digester	CSTR	• Pulping • Chopping • Slurry • Hydrolysed	Two-stage (can be one-stage)	Juice rich in protein and nutrients, soil conditioner	>60	2–14	35–40	Medium	40–70	< 3.5
Two-stage sequential batch digester connected with high-rate bioreactor	Leach bed with UASB	• Chopping • Pulping	Two or multistage	Soil conditioner, fertiliser, fibrous materials	<40	20–40	35	High	40–70 overall 75–98 from UASB	10–15
One-stage dry continuous digester	DRANCO	• Shredding Chopping	One-stage	Dewatered, good quality, fibrous materials	< 40	20–50	50–58	Medium	40–70	12
One or multistage dry batch digester	BEKON	• Chopping	One-stage	Dewatered, good quality, fibrous materials	<40	30–40	35	Low	40–70	12–15

HRT, hydraulic retention time; OLR, organic loading rate; VDS, volatile dry solids; CSTR, continuously stirred tank reactor; DRANCO, DRy ANaerobic COnversion; UASB, upflow anaerobic sludge blanket.

Table 3.4. Comparison of different biogas upgrading techniques (adapted from de Hullu et al., 2008).

Technique	Maximum achievable		Advantages	Disadvantages
	Yield (%)	Purity (%)		
Chemical absorption	90	98	• Almost complete hydrogen sulphide removal	• Only removal of one component in one column • Expensive catalyst
High-pressure water scrubbing	94	98	• Removes gases and particulate matter • High purity, good yield • Simple technique, no special chemicals or equipment required • Neutralisation of corrosive gases	• Limitation of hydrogen sulphide absorption due to changing pH • Hydrogen sulphide damages equipment • Requires a lot of water, even with the regenerative process
Pressure swing adsorption	91	98	• More than 97% methane enrichment • Low power demand • Low level of emissions • Adsorption of nitrogen and oxygen	• Additional complex hydrogen sulphide removal step needed
Cryogenic separation	98	91	• Can produce large quantities with high purity • Easy scaling up • No chemicals used in the process	• A lot of equipment is required
Membrane separation	78	89.5	• Compact and light in weight • Low maintenance • Low energy requirements • Easy process	• Relatively low methane yield • Hydrogen sulphide removal step needed • Membranes can be expensive

- Furthermore, injecting biogas into the gas grid improves the local security of supply (Persson et al., 2006).

3.4 Conclusions

Selection of the proper digester design for grass biomethane production is an important management/design decision that merits further investigation. The wet continuous two-stage system, the leach bed system with an upflow anaerobic sludge blanket (UASB), the dry continuous system and batch digesters all have potential for biomethanation of grass silage. Nevertheless, comparisons for treating similar quantities of grass silage under similar loading rates and characteristics to evaluate optimal digestion configuration are required. These systems can be further optimised for better and continuous biogas production, based on changing their filling regimes and co-digestion patterns. There is a need to compare the potential of various pretreatment options (including pressure, thermal, enzymatic and chemical pretreatments) for increased efficiency. Upgrading of biogas comprises the removal of carbon dioxide, hydrogen sulphide and other possible pollutants from biogas. Membrane separation and HPWS may be the simplest processes to operate because the use of special chemicals or equipment is not necessary. Also, HPWS provides maximum purity (up to 98% CH_4) with minimal cost. The technology is evolving and better results than those indicated in Table 3.4 have and will be achieved. The produced biomethane can either be used directly on-site as a transport fuel or, after grid injection, may be used off-site where better energy efficiencies and financial returns may be achieved.

4 Life-Cycle Analysis of Grass Biomethane

4.1 Aims and Methodology

Biomass, which includes both energy crops and residues, is a renewable energy resource with significant potential in Ireland. This study proposes to assess the use of grass silage as a feedstock for biomethane production. The advantages according to Murphy and Power (2009b) include:

- Arable land is not needed for growing grass and direct food substitution is not an issue;
- Over 91% of Ireland's agricultural land is under grass;
- Biomethane as a transport fuel is a mature technology;
- Biogas can also be made from wastes and residues, thus increasing the availability of feedstock; and
- Projections for reductions in animal stock will release grassland for biomethane production.

Grassland sequesters carbon into the soil, which is not released on harvesting leading to a potential for sustainable biofuel production from grass (Tillman et al., 2006). The Renewable Energy Directive recognises the potential for biogas as a transport fuel in attributing a GHG saving of 83% to compressed biomethane generated from residues. The aim of this study was to investigate in detail the production of grass biomethane as a transport biofuel in accordance with the Renewable Energy Directive sustainability criteria, in particular GHG emissions savings in comparison with the fossil fuel it replaces (diesel in this instance). To be deemed sustainable according to the Renewable Energy Directive, a reduction in emissions of 35% is required if operated before 2017, 50% after 2017, and 60% for new installations installed after 2017 (EC, 2009a). The methodology employed involves a life-cycle assessment (LCA) of current agricultural practices for reseeded perennial ryegrass pastures for silage production; the process technology includes a two-stage CSTR, and biogas upgrading for biomethane production.

Life-cycle assessment is one of the most appropriate methodologies for the evaluation of the environmental burdens associated with biofuel production, since it allows the identification of opportunities for environmental improvement and is widely used for evaluation of sustainability of biofuel production (Singh et al., 2010a). The scope of the study may be represented by the cradle (grass silage production) to the grave (the utilisation of produced biomethane in the vehicles) analogy (Fig. 4.1). The analysis takes into consideration the energy and emissions (both direct and indirect) associated with all stages of production of silage and biomethane. This facilitates comparison of systems if the boundary conditions are the same. The functional unit is defined as cubic metres of biomethane per year and the environmental impacts are expressed as grams carbon dioxide equivalent (CO_2e) per megajoule energy replaced. This is important; the analysis is a field-to-wheel system rather than a field-to-tank system. The vehicle operating on gaseous transport fuel is assumed to have an efficiency (MJ/km) 18% less than a diesel vehicle (Korres at al., 2010). This thus reduces the efficiency of the whole process. Emissions associated with the manufacture of machinery are not included as per the EU Renewable Energy Directive (EC, 2009a). The global warming potential (GWP) for carbon dioxide, nitrogen dioxide and methane is 1 kg CO_2, 296 kg CO_2 and 23 kg CO_2, respectively.

The basis of the analysis is a grass-based farm-to-biomethane facility visited by the authors in Austria in early 2008. The Austrian facility digests grass from 150 ha, which equates to 1,650 t DM/year based on a typical yield of 11 t DM/ha/year. Yields in Ireland tend to be higher; the assumption in this analysis is that the farms entering the biomethane industry will be from areas with good yields. A production of 12 t DM/ha is assumed. Accordingly, the facility modelled under Irish conditions, assuming that grassland is used exclusively for silage production, requires a farm of

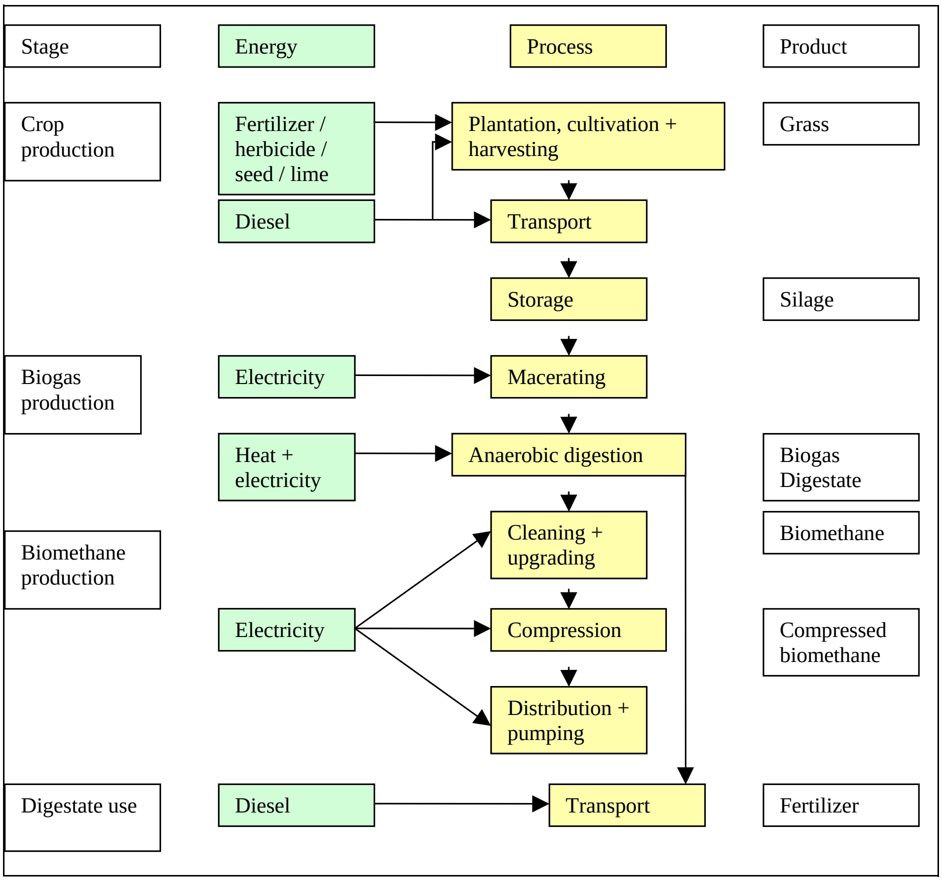

Figure 4.1. Grass-to-biomethane system (Smyth et al., 2009).

137.5 ha. The energy used in the process is split into direct and indirect energy. Direct energy is the energy used in the production process, e.g. fossil fuel used in machinery. Indirect energy is the energy used in producing materials that are subsequently used in the production, e.g. fertiliser, diesel, etc.

4.2 Grass Silage Production

- **Reseeding:**
  Reseeding of grassland is recommended in order to improve grass vigour and growth (Kilroy, 2007). Life-cycle assessments of grass systems in the literature use various reseeding frequencies, from 2 to 8 years (Kelm et al., 2004; Gerin et al., 2008). The *Irish Farmers Journal* recommends reseeding every 4–8 years (Kilroy, 2007). A 2004 survey of 180 silage-making farms (O'Brien et al., 2008) found that 54% of pasture farms were more than 10 years old. The reseeding frequency used in this analysis is once every 8 years and assumes that the traditional method of direct sowing is carried out in the autumn. A seeding rate of 25 kg/ha is used in this study as recommended in the *Irish Farmers Journal* (Kilroy, 2007). It is preferable when reseeding that low or no-till methods are employed to minimise production of GHG emissions.

- **Harvesting:**
  Harvesting is assumed to take place twice per year, i.e. two-cut silage – the first cut is usually at the end of May, the second at the beginning of July. Two cuts are the norm in the Irish livestock sector, as a three-cut system is generally deemed uneconomic due to the high costs of harvesting and lower yields from third (or subsequent) cuts.

- **Fertiliser application rates:**
  Fertiliser application rates for nitrogen (N), phosphorus (P) and potassium (K) used in this

study are as recommended by Teagasc (Table 4.1). Biomethane production results in the generation of digestate that can replace conventional fertilisers. In this study, each hectare produced 12 t of DM, equivalent to 54.5 t of grass silage at 22% DS content. The resultant digestate production is 48.6 t/ha/year (Table 4.2). As digestate contains 2.1 kg/t, 0.087 kg/t and 3.08 kg/t N, P and K, respectively, it can replace 102 kg/ha/year N, 4.2 kg/ha/year P and 149.7 kg/ha/year K.

- **Herbicides:**
  Weeds are not a problem for the majority of Irish pastures, but better weed control has the potential to increase output in some cases (O'Mara, 2008). In the case of continuous silage, weeds (e.g. docks) may become problematic and herbicide spraying is therefore recommended every 3–4 years (Fitzgerald, 2007). The herbicide glyphosate is assumed to be applied once before ploughing and asulam twice during the life cycle of the crop.

- **Lime:**
  Irish soil tends to be slightly acidic. A common practice to restore pH to acceptable levels is through the application of lime. Lime application enhances nutrient availability, increases the activity of micro-organisms and earthworms, and improves the response to fertiliser (Coulter, 2004). The optimum pH for grassland in mineral soils is 6.3 (Culleton et al., 1999; Coulter, 2004) and Teagasc recommends that grassland should be limed at least every 5 years (Coulter, 2004). The application of 10 t/ha over the 8-year crop cycle is assumed.

- **Silage yields:**
  Silage yields in Ireland are typically between 11 and 15 t DM/ha/year; yields are generally higher in the south-west of the country and decrease towards the north-east (Ryan, 1974; Brereton, 1995; Holden and Brereton, 2002). For this study, each hectare is assumed to produce 12 t DM/year, which is somewhat conservative. It is assumed that pit silage has a DS content of 22%, which yields an overall production of 54.5 t/year. Grass when cut may be at 18% DS, thus 67 t of grass may be cut in every hectare. Losses will occur in silage production; 12 t DM/ha/year are taken as the solids remaining in the silage pit.

4.3 Biogas Production

Anaerobic digestion is a ubiquitous technique for converting organic wet biomass into renewable energy in the form of biogas by bacteria in an oxygen-free environment, which may then be upgraded to biomethane (Singh et al., 2010b). It is a well-established process and is widely used in many European countries, although research aiming to optimise the process for biogas yields is still ongoing (Nizami and Murphy, 2010).

A CSTR operating at 10% DS is assumed. Typically slurries with a DS content below 12% are used as a feedstock in a CSTR. The digestion of grass with a higher DS content is achieved through the addition of water and/or recirculated leachate to reduce the DS content below 12%. It is assumed that the digester

Table 4.1. Fertiliser application rates (adapted from Coulter, 2004).

	Nitrogen (kg/ha)[a,b]		Phosphorus (kg/ha)[b,c]		Potassium (kg/ha)[b,d]	
Establishment year	75		70		110	
	First cut	**Second cut**	**First cut**	**Second cut**	**First cut**	**Second cut**
First 4 years after establishment	150	125	20	10	200	95
Subsequent years	125	100	20	10	200	95

[a]In the establishment year, half of the nitrogen is applied at sowing and half 3–4 weeks later.
[b]Values given assume no slurry application.
[c]Phosphorus advice assumes a soil phosphorus index of 2.
[d]Potassium advice assumes a grass only (no clover in the sward), a soil potassium index of 1, and a target yield of 12 t DM/ha.

operates at a mesophilic temperature of 38°C and that the temperature of the incoming feedstock is 10°C, which is typical for the south of Ireland.

The loading rate for wet digestion of grass silage is taken as 1.44 kg VDS/m^3/day. The working volume of each digester for 7,500 t grass silage per year is calculated as 1,413 m^3, assuming that digesters are cylindrical in shape, with a diameter to height ratio of 1:1.5 (CropGen, 2007). The volume of the first digester is 1,766 m^3, assuming an 80% working volume, whereas the volume of the second digester is 3,532 m^3, assuming half of the digester volume is used for storage. Approximately 45.2 m^3 feedstock (at 10% DS) are fed into the first digester every day. The total retention time is 62.5 days, with the substrate remaining about half of the time in each digester. The substrate flows by gravity from the first to the second digester and the liquid is circulated back to the first digester. The recirculation of the liquid digestate reduces the water demand and increases the microbial population, improving the efficiency of the AD facility (Nizami et al., 2009). Maceration of the silage is carried out before insertion of feedstock into the first digester. It reduces the particle size of the feedstock, hence preventing physical obstruction of pipes and pumps by the fibres, and increases the surface area available for microbial attack, thus speeding up the digestion process (Nizami et al., 2009). Mixing may allow better digestion of grass silage by keeping the material homogenous and hindering the settling of silage particles. The optimal DS content for grass silage digestion in a CSTR is reported as 10% (Börjesson and Berglund, 2006). The produced grass silage (7,500 t/year) is mixed with up to 9,000 t of water/liquid digestate to obtain the desired DS level. The water demand is fulfilled by the recirculation of the liquid digestate. Varying the recirculation rate of this liquid digestate can allow control of the relative rate of biogas production in the two vessels and the level of VFA in both vessels.

A methane yield of 186–380 m^3 CH_4/kg VDS is reported in the literature (Steffen et al., 1998; Gerin et al., 2008; Lehtomaki et al., 2008). The destruction of 1 kg VDS produces about 1 m_n^3 of biogas at 55% methane content. Maximum destruction therefore is 550 l CH_4/kg VDS added. A methane yield of 550 m_n^3 biogas per tonne VDS (302 m_n^3 CH_4/t VDS) added to the AD plant is assumed on the basis of 55% destruction of VDS. Total biogas production is 816,750 m_n^3/year (Table 4.2). The daily mass balance for the digester is presented in Fig. 4.2.

4.4 Compressed Biomethane Production

Biogas from the AD of grass consists of approximately 55% methane, 45% carbon dioxide and a small amount of other contaminants. It must be upgraded or scrubbed to natural gas standard (about 97% methane) before being used in vehicles or in the natural gas grid. There are two types of filling operations, slow fill and fast fill. Slow-fill stations have the simpler design, with the dispensing lines connected directly to the compressor, but have longer filling times, typically from 20 min to a number of hours. A fast-fill operation is more complex, but gives filling times of only 3–5 min, and is typically used on a traditional service station forecourt. Fast fill is assumed in this analysis.

4.5 Energy and GHG Emissions Associated with Grass Silage Production

4.5.1 Direct energy consumption and related emissions associated with grass silage production

The primary fuel input into a ryegrass production system is diesel for tractors and trucks. The GHG emissions from diesel consumption are 2.688 kg CO_2e/l (Murphy et al., 2004) and in production are 0.51 kg CO_2e/l (Thamsiriroj and Murphy, 2009). The gross energy of the diesel equals 36 MJ/l (EC, 2009a), thus the GHG emissions equal 88.8 g CO_2e/MJ. The direct energy consumed during field operations was estimated based on Eqn 4.1 (Romanelli and Milan, 2004). The individual values for each component for each field operation were selected among an extensive range of publications suitable for grass production and the highest value to obtain a more conservative interpretation was chosen. Greenhouse gas emissions were then estimated based on Eqn 4.2. The results from the energy consumed during the whole crop cycle and the subsequent GHG emissions are reported in Table 4.3. The average direct energy consumption was estimated as 2.98 GJ/ha/year.

Table 4.2. Size of the digester tanks and biomethane yield (Korres et al., 2010).

Component	Quantity
Farm size (ha)	137.5
Silage production (t DM/ha/year)	12
Silage biomass (t/ha/year)	54.2
Silage yield (t/year)	7,500
Dry solids (DS) (t/year) at 22% DS	1,650
Volatile dry solids (VDS) (t/year) at 90% of DS	1,485
Loading rate (kg VDS m^3/day)	1.44
Working volume of each digester (m^3)	1,413
Volume of Digester 1 (m^3) at 80% working volume	1,766
Volume of Digester 2 (m^3)	3,532
Amount of feedstock added (m^3/day) at 10% DS	45.2
Retention time (days)	62.5
VDS degraded (t/year) at 55% degradation	816.8
Biogas production (m_n^3/year) at 55% VDS destruction	816,750
Biomethane production (m_n^3/year) at 97% methane	463,105
Losses in upgradation and compression process (m_n^3/year) at 2% loss	9262
Net biomethane production (m_n^3/year)	453,843
Energy in net biomethane produced (GJ/year)	16,631
Energy in net biomethane produced (GJ/ha/year)	121
Energy displaced vehicle operating 18% less efficiently on gas than diesel (GJ/ha/year)	99
Digestate yield: (t/year)	6,683
(t/ha/year)	48.6

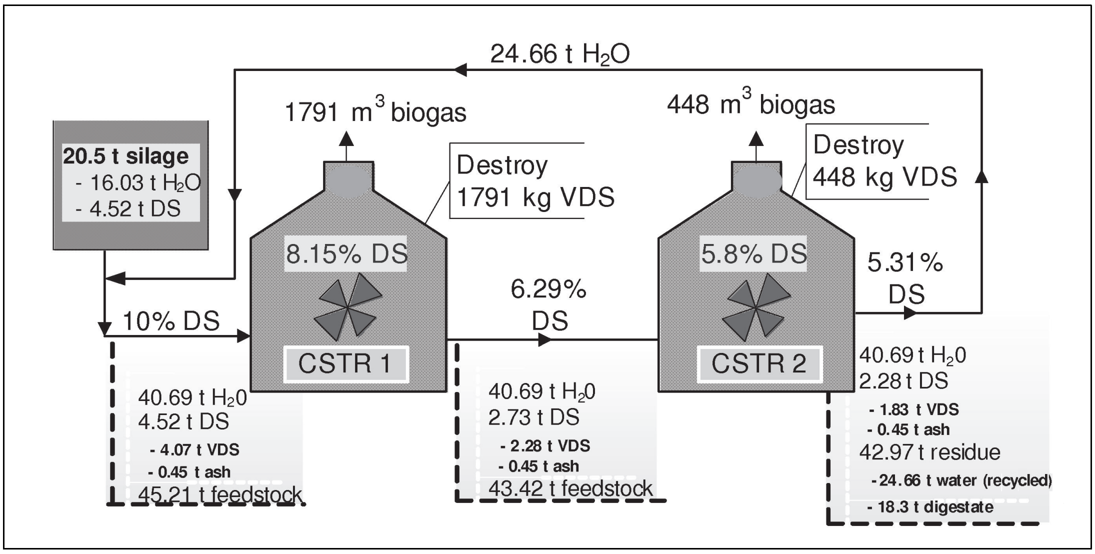

Figure 4.2. Daily mass balance of anaerobic digester (Smyth et al., 2009). DS, dry solids; VDS, volatile dry solids; CSTR, continuous stirred tank reactor.

Harvesting, spreading of digestate, ensiling and ploughing are the operations (in that order) that require the highest energy inputs and thus emit the highest amounts of CO_2e. Direct emissions during the crop cycle equal 2.67 g CO_2e/MJ of energy replaced (Table 4.3).

$$FE = \sum_{1}^{i} (F_{ci} \times f_c) / O_{ci} \qquad \text{(Eqn 4.1)}$$

$$GHG = FE \times 0.0888 \qquad \text{(Eqn 4.2)}$$

where *FE* is the fuel energy consumed (MJ/ha), F_{ci} is the fuel consumption (l/h) for *i* field operations, f_c is the heating value of the fuel, and Oc_i is the work capacity for *i* operation (ha/h) and *GHG* is the GHG emissions (kg CO_2e/ha/year).

Volatilisation of herbicides occurs up to 48 h after their application. Derivation of herbicide emission due to volatilisation was estimated from Eqn 4.3 (Baas and Lekkerkerk, 2003). The energy consumed for the production of 1 kg of active ingredient (a.i.) as proposed by Saunders et al. (2006) and the corresponding emission factors (i.e. kg CO_2e/MJ) was adopted. The final result equated to 5.44 kg CO_2e/ha/year or 0.054 g CO_2e/MJ energy replaced and was insignificant in terms of GHG emissions.

Table 4.3. Direct energy consumption and related carbon dioxide emissions during the 8-year crop cycle (emissions from diesel production are included) (Korres et al., 2010).

Operations	Energy consumed (MJ/ha/year)		Average energy consumed (MJ/ha/year)	CO_2 emissions (kg CO_2/ha/year)		Average emissions (kg CO_2/ha/year)	g CO_2e/MJ energy replaced
	Year 1	Years 2–8		Year 1	Years 2–8		
Ploughing	1,141.7	0	142.7	101.4	0.0	12.7	0.13
Sowing	148.8	0	18.6	13.2	0.0	1.7	0.02
Harrowing	238.1	0	29.7	21.2	0.0	2.6	0.03
Rolling[a]	249.9	0	31.2	22.2	0.0	2.8	0.03
Fertiliser[b]	154.8	77.4	87.1	13.8	6.9	7.7	0.08
Lime[c]	22.5	0 (22.5)	5.6	2.0	0 (2.0)	0.5	0.01
Herbicide[d]	54	0 (27)	13.5	4.8	0 (2.4)	1.2	0.01
Spreading[e]	473.9	947.8	888.6	42.1	84.2	78.9	0.80
Transport[e]	1.9	37.7	33.2	1.7	3.3	3.1	0.03
Harvesting[f]	1,309.0	1,309.0	1,309.0	116.3	116.3	116.3	1.17
Ensiling[a,g]	416.0	416.0	416.0	37.0	37.0	37.0	0.37
Total	**4,210.5**	**2,787.9 (2,814.9, 2810.4)**[h]	**2,975.3**	**375.5**	**247.7 (250.1, 249.7)**[h]	**264.5**	**2.67**

[a]Data on energy consumption for rolling and ensiling from Smyth et al. (2009).
[b]Fertiliser is applied four times during the first year of the crop cycle and twice every subsequent year after each harvesting.
[c]Lime is applied at two intervals during the crop cycle, the first and fifth year after establishment
[d]Herbicides are applied before ploughing and after sowing to favour crop-against-weed competition. Application is in the first year and twice during the rest of the crop cycle in the third and sixth year (corresponding values for energy consumption and related emissions are shown in parentheses).
[e]Transport and spreading were estimated based on the assumption that each load carries 16 t digestate; hence, 418 loads needed per year of which 250 were assumed, excluding empty return. The energy consumption for transport is assumed as 1 and 1.6 MJ/t/km, excluding and including empty return, respectively (Salter and Banks, 2009). Energy required for loading and spreading of digestate is assumed as 2.5 and 17 MJ/t, respectively (Power and Murphy, 2009).
[f]Harvesting includes operations such as cutting, mowing and turning the grass.
[g]Ensiling comprises operations such as silage collection, unloading and inlaying.
[h]The first number in the parentheses represents values for the 3rd and 6th year, and the second number for the 5th year.

$$E_{Herbicide} = \sum_{1}^{i} m_{Herbicide,i} \times EF_{Herbicide,i} \quad \text{(Eqn 4.3)}$$

where $E_{Herbicide}$ is the total emission of pesticide (kg/year) due to volatilisation, $m_{Herbicide,\,i}$ is the mass of the individual herbicide applied (kg/year), and $EF_{Herbicide,\,i}$ is the emission factor for the individual herbicide (kg/kg).

The lime application in the pasture is in the form of crushed limestone ($CaCO_3$). Carbon dioxide emissions from liming are calculated from the amount of crushed limestone applied per year (10 t/ha/year over 8 years = 1,250 kg/year) (Eqn 4.4). The emission factor equals 0.12 t CO_2-C/t of $CaCO_3$ (Baas and Lekkerkerk, 2003). A value of 550 kg CO_2e/ha/year was calculated, which equals 5.55 g CO_2e/MJ energy replaced (see Table 4.8).

$$E_{\text{lime}} = \sum_{1}^{i} m_{\text{lime},\,i} \times EF_{\text{lime},i} \quad \text{(Eqn 4.4)}$$

where E_{lime} is the total emission of carbon or carbon dioxide from liming (t C/year), $m_{\text{lime},i}$ is the mass of the individual liming agent applied (t $CaCO_3$/year), and $EF_{\text{lime},i}$ is the emission factor (carbon conversion factor) for the individual liming agent (t C/t $CaCO_3$).

The fraction of applied nitrogen actually emitted as nitrous oxide (N_2O) varies on a site-specific basis (Thornton, 1996). Coefficients of variation for nitrous oxide emissions typically range from 0.003 to 0.03 (IPCC, 2006). Emissions of nitrous oxide from the use of fertiliser were estimated from Eqn 4.5 (EMEP/CORINAIR, 2004) which includes both direct and indirect nitrous oxide emissions (Eqns 4.6 and 4.7):

$$N_2O\text{ (t)} = 0.0125 \times \text{N applied (t)} + 0.01\,(NH_3 + NO)\text{ emitted (t)} \quad \text{(Eqn 4.5)}$$

$$NH_3\text{ (t)} = \sum_{i} cf_i \times \text{ N fertiliser}_i\text{ applied (t)} \quad \text{(Eqn 4.6)}$$

$$NO\text{ (t)} = 0.0007 \times \text{Total N applied (t)} \quad \text{(Eqn 4.7)}$$

where cf_i values for the most common fertilisers used in Ireland (ammonium nitrate, calcium ammonium nitrate (CAN) and urea) are 0.02, 0.02 and 0.15 t NH_3/t N applied/year, respectively (EMEP/CORINAIR, 2004).

The most common source of nitrogen fertiliser used in Ireland is CAN; thus, a value of 0.02 is chosen. Indirect emissions of nitric oxide (NO) are estimated based on Eqn 4.7. Both ammonia (NH_3) and nitric oxide emissions are summed as indirect emissions (Table 4.4). The total nitrous oxide emission from fertiliser applications is estimated as 525 kg CO_2e/ha/year (Table 4.4). This result is in the lower level of the range observed by Kiely et al. (2009), who reported nitrous oxide emissions in Irish grassland ecosystems of between 2 and 8.4 kg N_2O/ha/year (equivalent to 592–2,486 kg CO_2e/ha/year).

4.5.2 *Indirect inputs and related emissions associated with grass silage production*

Indirect emissions result from the energy (and the associated CO_2) invested for the production of the primary inputs into the crop (i.e. fertilisers and lime, herbicides and seeds), along with the energy required for their transport and application (Table 4.5).

Limestone is transformed into quicklime or calcium oxide (CaO) after heating, and then into hydrated lime ($Ca(OH)_2$). The amount of carbon dioxide released into the atmosphere was estimated as a direct emission.

Nitrogen and potassium have the highest percentages of indirect energy consumed in the silage crop (i.e. 71.4% and 13.3%, respectively) and carbon dioxide

Table 4.4. Direct and indirect nitrous oxide emissions (Korres et al., 2010).

	Direct	Indirect	Total
Year 1 (kg CO_2e/ha/year)	923	19.6	942.6
Years 2–8 (kg CO_2e/ha/year)	456	9.7	465.7
Average (kg CO_2e/ha/year)	514	10.9	525
Emissions (g CO_2e/MJ energy replaced)	5.18	0.11	5.29

Table 4.5. Indirect energy consumption and related carbon dioxide emissions during the 8-year crop cycle (Korres et al., 2010).

Crop production	Dose applied (kg/ha/year)		Energy required (MJ/kg)	Energy consumed (MJ/ha/year)		Average energy consumed (MJ/ha/year)	Emission factor[a] (kg CO_2e/MJ)	CO_2 emissions (kg CO_2e/ha/year)		Average emissions (kg CO_2e/ha/year)	g CO_2 e/MJ energy replaced
	Year 1	Years 2–8		Year 1	Years 2–8			Year 1	Years 2–8		
Fertiliser[a,b,c]											
Nitrogen	249	123	65	16,185	7,995	9,018.7	0.05	809.2	399.7	450.94	4.55
Phosphorus	97.9	26	15	1,468.5	390	524.8	0.06	88.1	23.4	31.49	0.32
Potassium	330.2	145	10	3,302	1,450	1,681.5	0.06	198.1	87	100.89	1.02
Herbicide[a,b]											
Glyphosate[d]	2.016	0	550	1,108.8	0	138.6	0.06	66.5	0	8.32	0.08
Asulam[d]	4.4	0 (4.4)	310	1,364	0 (1,364)[e]	511.5	0.06	81.8	0 (81.8)[f]	30.69	0.31
Lime[a,b,f]	5,000	0 (5,000)	0.6	3,000	0 (3,000)	750.0	–	0	0	0	0
Seed	25[d]			40[d]	0	5	1.98[f,g]	49.5	0	6.19	0.06
Total				**26,468.3**	**9,835 (11,199, 12,835)**	**12,630.2**		**1,293.3**	**510.1 (2,670, 592)**	**628.5**	**6.34**

[a]Saunders et al. (2006).
[b]Kelm et al. (2004).
[c]Styles and Jones (2004).
[d]Smyth et al. (2009).
[e]Energy and emissions in parentheses for the application of herbicide (asulam) in the third and sixth year of the crop cycle.
[f]West and Marland (2002).
[g]kg CO_2e/kg seed.

emissions during the crop production period (i.e. 71.7% and 16%, respectively). Indirect energy consumption and emissions during the crop production cycle equate to 12,630 MJ/ha/year and 6.34 CO_2e/MJ energy replaced, respectively (Table 4.5).

4.5.3 Emissions from transportation

Berglund and Börjesson (2006) reported that transportation of grass by truck requires 0.7 MJ energy per tkm excluding empty return. The transportation of 7,500 t grass/year from field to AD plant (10 km distant) requires 52.5 GJ/year. Total emissions in transportation of grass are calculated as 0.34 g CO_2e/MJ energy replaced.

The summed emissions for lime transport from the UK are 0.5 GJ/t lime (Kongshaug and Jenssen, 2003; Harrison et al., 2006), with subsequent carbon dioxide emissions equal to 0.044 kg CO_2e/kg of limestone (88.8 g CO_2e/MJ diesel). At 10 t of limestone per hectare in an 8-year cycle on 137.5 ha displacing 99.2 GJ/ha/year, this equates to 55 kg CO_2e/ha/year, which equals 0.55 g CO_2e/MJ energy replaced.

4.6 Direct Energy Consumption and Related Emissions Associated with Biomethane Production

4.6.1 Heating digesters

The heat requirement of digestion is calculated by summing the energy lost from the digester tank and energy required to heat the feedstock. Equations 4.8 and 4.9 are used (Salter and Banks, 2009):

$$hl = UA\Delta T \qquad \text{Eqn 4.8}$$

where *hl* is heat loss (J/s), *U* is the overall coefficient of heat transfer (W/m^2/°C), *A* is the cross-sectional area through which heat loss is occurring (m^2), and ΔT is the temperature drop across the surface (°C);

$$q = CQ\Delta T \qquad \text{Eqn 4.9}$$

where *q* is the heat required to raise feedstock to digester temperature (kJ/s), *C* is the specific heat of the feedstock (kJ/kg/°C), and *Q* is the volume to be added (kg).

The coefficient of heat transfer for the wall, floor and roof of the digester is taken as 0.8, 1.7 and 1 W/m^2/°C, respectively (CropGen, 2007). The volume of feedstock added daily is 45.21 m^3 at 10% DS. As the feedstock has a low solids content, its specific heat is assumed to be similar to that of water (4.2 MJ/t/°C). The production of thermal energy is assumed to be by natural gas; an emission factor of 240 g CO_2e/kWh thermal energy (Murphy et al., 2004) is used. This analysis may be considered conservative as temperature drop from the floor of the digester must be less than 28°C and recycled leachate will be warmer than 10°C, also the amount of heat provided by metabolic generation is uncertain and therefore neglected. The annual thermal energy demand is calculated as 3,703 GJ, which emits 248.8 t CO_2e/year, equivalent to 18.25 g CO_2e/MJ energy replaced (Table 4.6). The conservativeness of the approach employed here relates to modest loading rates, effective volumes of only 80% of the tank and the oversizing of the second digester to provide storage. Thus the stored material is also heated.

4.6.2 Biogas losses

Even moderate losses of methane can affect significantly the emissions from the biomethane production process, since methane is 23 times a more potent GHG than carbon dioxide. Methane losses

Table 4.6. Greenhouse gas emissions from digesters (Korres et al., 2010).

	Energy (GJ/year)	Energy (GJ/ha/year)	GHG emission (kg CO_2e/year)	GHG emission (g CO_2e/MJ energy replaced)
Heat loss from Digester 1	681	4.95	45,785	3.36
Heat loss from Digester 2	1,082	7.87	72,679	5.33
Heating of the feedstock Digester 1	1,940	14.11	130,395	9.56
Heating of the feedstock Digester 2	0.00		0.00	0.00
Total	**3,703**	**26.93**	**248,859**	**18.25**

during the upgrading and compression of biogas are taken as 2% of biomethane (Börjesson and Burglund, 2006), whereas losses during the rest of the system are considered negligible. According to Murphy and McKeogh (2004), each cubic metre of biogas that escapes and is not combusted produces 9.16 kg of CO_2e. Thus, this escape equates to 147.5 t CO_2e/year or 10.82 g CO_2e/MJ energy replaced.

4.6.3 Indirect emissions from biomethane production

The energy required for maceration, mixing and water pumping activities is supplied by the electric grid. At the time of writing, 542.8 kg CO_2e/MWh are produced in the Irish Grid (SEI, 2009a). The electrical energy requirement for maceration is taken as 2 kWh/t of silage added (Smyth et al., 2009), for mixing slurry digesters (operating at about 10% DS) 10 kWh/t of slurry digested (Murphy et al., 2004), and for pumping of water from the second digester to the first is taken as 0.2 kWh/m^3 (assuming a 4 kW pump with a capacity of 20 m^3/h). The total energy consumption and emissions from the maceration, mixing and water pumping are calculated as 4,760 MJ/year and 98.68 t CO_2e/year, respectively. These emissions are equivalent to 7.24 g CO_2e/MJ energy replaced (Table 4.7).

The electrical demand for biogas scrubbing and compression ranges between 0.3 and 0.6 kWh/m^3 and 0.35 and 0.63 kWh/m^3 upgraded biomethane, respectively (Persson, 2003; EC, 2006; Murphy and Power, 2009a). A value of 0.35 kWh/m^3 is assumed for each operation, which equates to 317.7 MWh/year (8,318 MJ/ha/year) electricity demand. Approximately 172.4 t CO_2e are emitted during the production of the required electricity. The upgradation and compression of biomethane emits 12.6 g CO_2e/MJ energy replaced.

4.7 Sensitivity Analysis

4.7.1 Base case

Table 4.8 outlines the summary of the energy demand and GHG emissions of biomethane production. The total parasitic energy demand is 56.7 GJ/ha/year and emissions are 6.9 t CO_2e/ha/year, equivalent to 69.7 g CO_2e/MJ energy replaced. The net energy production from each hectare is equal to 64.4 GJ (Fig. 4.3) and emissions savings equal 21.5% in comparison with fossil diesel (88.8 g CO_2e/MJ). Grass silage production, upgrading and compression of biomethane and parasitic energy demand of anaerobic digesters are the main contributors to GHG emissions.

4.7.2 Wind energy for electrical demand

Significant GHG emissions reductions can be achieved by technology substitution or improvement. Using electricity from wind greatly reduces the emissions associated with the grass biomethane system. Assessment of GHG per kW_eh varies greatly (8–46.4 g CO_2e/kW_eh) in the literature (Weisser, 2007; Tremeac and Meunier, 2009). Considering the highest value, biomethane from grass silage effects a 42% reduction in emissions (Fig. 4.3), which would lead to a classification of sustainable biofuel for the years 2010–2017.

4.7.3 Woodchips for thermal demand

The supply of thermal heat demand by utilisation of woodchips in biomethane production can provide significant GHG savings. Eriksson and Gustavsson (2010) reported 3.5–5.5 kg CO_2/MWh energy production from woodchips under various scenarios.

Table 4.7. Emissions in maceration, mixing and pumping activity during biogas production (Korres et al., 2010).

	Quantity (t/year)	Energy required (kWh/t)	Energy required (MJ/ha/year)	GHG emissions (kg CO_2e/year)	GHG emissions (g CO_2e/MJ energy replaced)
Maceration	7,500	2	392	8,142	0.60
Mixing	16,500	10	4,320	89,562	6.57
Water pumping	9,000	0.2	47	977	0.07
Total		**12.20**	**4,759**	**98,681**	**7.24**

GHG, greenhouse gas.

Table 4.8. Energy demand and greenhouse gas (GHG) emissions for biomethane production from grass silage under base-case scenario (adapted from Korres et al., 2010).

Activity	Energy required (MJ/ha/year)	GHG emissions (kg CO_2e/ha/year)	GHG emissions (g CO_2e/MJ energy replaced)
Grass silage production			
Direct			
Agronomic operation	2,975	265	2.67
Herbicide volatilisation	–	5.4	0.054
Lime dissolution	–	550	5.55
Nitrous oxide emissions	–	514	5.18
Indirect			
Production of inputs	12,630	629	6.34
Nitrous oxide emissions	–	10.9	0.11
Transportation			
Grass silage	382	33.9	0.34
Lime	750	55	0.55
Biomethane production			
Direct			
Heating of digesters	26,930	1,809.9	18.25
Biogas loss	–	1,072.7	10.82
Indirect			
Maceration, mixing and pumping	4,760	717.7	7.24
Upgrading and compression	8,318	1,253.8	12.6
Total	**56,745**	**6,917**	**69.70**

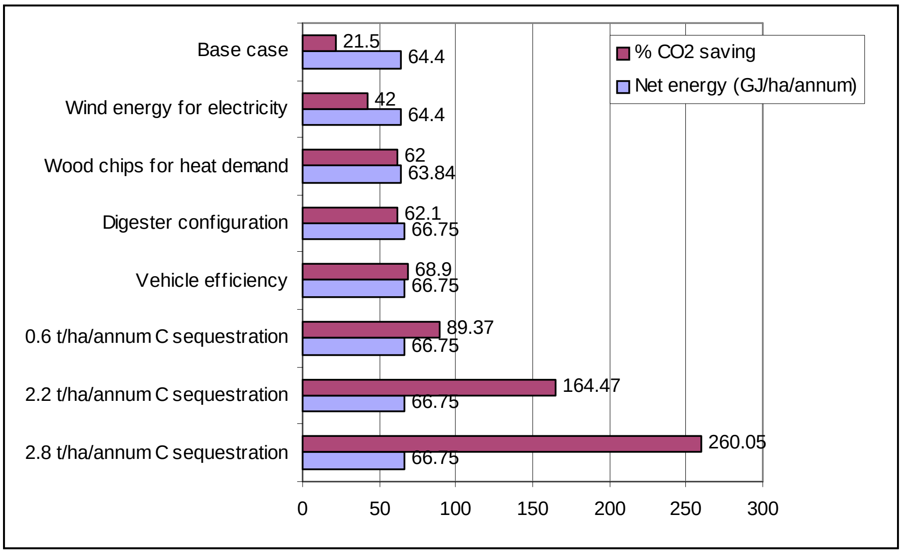

Figure 4.3. Percentage carbon dioxide savings over fossil diesel and net energy production under various scenarios in biomethane production (the scenarios are cumulative top to bottom) (adapted from Korres et al., 2010).

Adopting the highest emission value, biomethane from grass silage results in 62% reduction in emissions (Fig. 4.3), which would lead to a classification of sustainable biofuel for the years after 2017. The net energy of the system is slightly lower (63.84 GJ/ha/year) than other scenarios, as the energy used in the production and transport of woodchips has to be taken into account (0.02 MJ of primary energy per 1 MJ of biomass stored (Gasol et al., 2009)).

4.7.4 Digester configuration

Half of the volume in the second digester is used as a storage tank. The heat requirement to maintain a constant temperature within it for maximum microbial activity can be reduced significantly if the second digester is used only for digestion and the digestate is stored in a separate tank. This leads to a drop of 2.91 GJ/ha/year energy demand and cumulative GHG savings of 62.1% compared with diesel.

4.7.5 Vehicle efficiency

Spark ignition engines converted to use natural gas as a fuel show a power decrease of 18% (used in this study) due to decreases in volumetric efficiency. This power loss can be decreased by utilising a higher compression ratio and advancement in spark timing (Henham and Makkar, 1998). Improvements in engine efficiency to a similar km/MJ as diesel will improve the emissions. This leads to an overall production of 27.63 g CO_2e/MJ instead of 88.8 g CO_2e/MJ for diesel, generating a cumulative saving of 68.9% compared with diesel.

4.7.6 Carbon sequestration

Three scenarios are examined:

1. The amount of carbon sequestered by grassland as recorded by Byrne et al. (2007) is 2 t C/ha/year (0.6 t soil C/ha/year). This is in agreement with Freibauer et al. (2004) and Jones and Donnelly (2004), where a minimum amount of 0.6 t C/ha/year was reported as the potential soil carbon sequestration rate for perennial ryegrass and permanent crops under European agricultural conditions. This yields a cumulative emissions savings in relation to fossil fuel for substitution of 89.4%.
2. The amount of carbon contained in digestate (2.2 t C/ha/year). This yields a savings in relation to fossil fuel for substitution of 164.5%.
3. The sum of carbon contained in the above two cases (2.8 t C/ha/year). This yields a savings in relation to fossil fuel for substitution of 260%.

All scenarios secure sustainability of biomethane production from grass silage after 2017.

4.8 Conclusions

The life-cycle analysis is necessarily detailed. It draws upon data from numerous sources, both agricultural and process engineering. There is potential for variance in many of the figures. The agricultural data in particular are open to discussion – indirect emissions associated with fertiliser, nitrous oxide emissions, and emissions associated with land spreading of digestate. Carbon sequestration is site specific, depends on the land type, and whether the grass is grazed or used for silage production. These topics abound in the scientific literature and are subject to numerous ongoing research studies. Likewise, the process is open to debate. How much gas is lost in the biogas plant? What is the efficiency of the upgrading process? What is the vehicle efficiency?

However, allowing for the above, the analysis presented in this section suggests that parasitic energy demands at the grass biomethane facility are the major source of emissions. Thus, purchase of green electricity and minimisation of thermal energy input are essential. As supported by other researchers, the vehicle must be optimised for biomethane; bi-fuel vehicles may not meet this criterion.

Through process optimisation, an emission reduction of more than 60% may be effected by grass biomethane. Allowing for grassland sequestering carbon (a value of 0.6 t C/ha/year is deemed conservative), a reduction in emissions of 89% is achievable, which would suggest that grass biomethane is one of the most sustainable, indigenous, non-residue, European transport biofuels.

5 What is the Market for Grass Biomethane?

5.1 The Relationship between Grass, Farming and Energy

Farm incomes in Ireland are in decline and many farmers would operate at a loss in the absence of subsidies. When inflation is considered, the average family farm income (FFI) for all farming systems decreased by 22% in real terms from 1995 to 2008 (Connolly et al., 2009). There is a growing dependence on grants and subsidies in all farming sectors. Low FFIs lead farmers to seek opportunities for farm diversification and alternative sources of income. The National Development Plan (NDP, 2007) recognises as a key task the promotion of 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 2000–2008 (DAFF, 2009; CSO, 2010). This means that the cattle industry is effectively subsidised for export.

Ireland is over 89% dependent on imported energy, with imported oil and gas accounting for 81% of energy supply (Howley et al., 2009a). This has significant implications for security of supply, emissions agreements 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:

1. 40% renewable electricity (Howley et al., 2008);
2. 12% renewable heat (DCMNR, 2007); and
3. 10% renewable transport fuels (DCMNR, 2007).

Ireland is currently over 99% dependent on oil and oil products for transport energy (Howley et al., 2009b), while 96% of thermal energy is from non-renewable sources (Howley et al., 2009a). Thus, Ireland imports energy and exports agricultural produce; it could be said that it exports grass as this is the feedstock for cattle.

Grass is used in many operational AD plants throughout Europe, and is the second most important energy crop for AD in Germany (Rösch et al., 2009). Grass covers around 91% of Ireland's agricultural land; thus, as a bioenergy crop, no land-use change is required. The energy balance of grass biomethane is better than that of temperate energy crops (Smyth el al., 2009) and the GHG savings meet the requirements of the EU Renewable Energy Directive (Korres et al., 2010). An indigenous grass biomethane industry could also provide employment and aid in developing the 'greentech' sector.

Biogas can be burned directly for heat or electricity generation or can be upgraded to natural gas standard, i.e. biomethane. Biomethane and natural gas are mixable and interchangeable; mixtures of biomethane and natural gas are termed bioNG and can be sold from the gas grid in a similar manner to renewable electricity. A 10:90 blend could be sold as a transport fuel to aid in meeting the target for 10% renewable energy in transport. While there is currently no market for gas as a transport fuel in Ireland, there are over 10 million compressed natural gas (CNG) vehicles worldwide (NGV, 2009) and the use of compressed biomethane, either on its own or mixed with natural gas (bioCNG), is growing.

5.2 Biomethane Potential in Ireland from Numerous Sources

If a biomethane industry develops in Ireland, grass will not be the only source. It is prudent to examine the potential of the industry and to assess the bioresource and the relative role of grass in this. Meaney et al. (2003) categorise agriculture as the single largest source of waste in Ireland. Organic agricultural wastes refer to all types of animal excreta (i.e. faeces and urine from cattle, sheep, pigs, and poultry) in the form of slurries and farmyard manures. Cattle slurry is generated for 20 weeks of the year (the period that the animals are housed in the winter). All slurries or litter from pigs and poultry are collected as the animals are housed throughout the year (Crowe et al., 2000). Total slurry production in Ireland is estimated as 34.89 Mt/year in 2020 (Singh et al., 2010b). Slurries are applied to land as organic fertiliser; however, the release of nutrients is not uniform and, as such, the fertiliser value is not definite, there is significant potential for run-off and eutrophication. Digested slurry is less offensive, has minimal odours and, more importantly, the nutrients are available in the year of application. Assuming 5% of collectable slurry from cattle, pigs and sheep and 75% of poultry slurry is available for digestion, the practical energy production will be 1.88 PJ in 2020 (Table 5.1). In Ireland approximately 8 million livestock (mainly cattle, pigs and sheep) and 12 million poultry are slaughtered annually for meat production. This is all collected at the abattoir and is a ready source of biomethane. The practical energy potential in 2020 from digestion of 50% of amenable slaughter waste (0.42 Mt) is estimated to be 0.68 PJ energy (Singh et al., 2010b). Abattoir waste varies in composition and in categorisation. The organic waste includes paunch content (belly grass), which is ideally suited for digestion. It is offensive and biodegradable and current practice is to plough it into arable land.

The OFMSW comprises food and garden waste only. The quantity of OFMSW is assumed to increase linearly with increasing population. Population estimates were taken from CSO data (CSO, 2009a) and used to calculate projected OFMSW in 2020, i.e. approximately 0.87 Mt for 2020. It is assumed that 25% of OFMSW will be digested in 2020 (in line with Brown (2004)); this has the potential to produce 0.57 PJ in 2020. Currently, OFMSW is landfilled and a relatively small proportion is composted. Compliance with the Landfill Directive will dictate that by 2016 practically all OFMSW will be either composted or digested.

The National Climate Change Strategy (DEHLG, 2000) proposed reducing methane from cattle by the equivalent of a 10% reduction in the projected herd size for 2010. As cattle are responsible for 86.6% of methane emissions from ruminant animals (1990) and 80% of the emissions from cattle come from non-dairy herds (DEHLG, 2000), the main target for herd reduction is likely to be in the beef sector. Currently, grass is grown on 3.94 Mha (more than 91% of agricultural land) (CSO, 2009b). If the size of the national herd is reduced as set out in the National Climate Change Strategy, 0.39 Mha of agricultural grassland may be surplus to animal feed requirements by 2020. Smyth et al. (2009) found that if grass is used for methane production it will provide 3,240 m_n^3 CH_4/ha; this is equivalent to 122 GJ/ha/year of gross energy. On this basis, 0.39 Mha of surplus grass has the potential to generate 47.58 PJ/year energy. If 25% of this area (0.1 Mha) were used in this industry in 2020, there is potential to generate 11.9 PJ energy (Table 5.1). For the practical scenario, there is potential to satisfy the Renewable Energy Supply in Transport (RES-T) target of 10% through biomethane alone; alternatively, there is potential to substitute 6.3% of natural gas demand in 2020 or 44% of residential gas demand.

Table 5.1. Biomethane potential in Ireland in 2020 (adapted from Singh et al., 2010b).

Feedstock	Total energy in 2020 (PJ)	Practical energy in 2020 (PJ)	Factor for RES-T	Contribution to RES-T target (PJ)	Percentage of transport energy in 2020 (240 PJ)	Percentage of gas demand in 2020 (240 PJ)	Percentage of residential gas consumption (34 PJ)
Slurry	15.53	1.88	×2	3.76	1.57%	0.78%	5.5%
OFMSW	2.26	0.57	×2	1.14	0.48%	0.24%	1.7%
Slaughter waste	1.37	0.68	×2	1.36	0.57%	0.28%	2.0%
Grass	47.58	11.90	×2	23.79	9.90%	4.95%	35.0%
Total	**66.74**	**15.03**		**30.05**	**12.52%**	**6.25%**	**44.2%**

RES-T, Renewable Energy Supply in Transport; OFMSW, organic fraction of municipal solid waste.

5.3 Economic Analysis of Grass Biomethane System

5.3.1 *Methodology*

A simple economic analysis is carried out on a grass biomethane system as outlined in Table 4.2 (137.5 ha of grass silage with an annual production of 7,500 t/year of pit silage, 820,000 m^3 biogas or 460,000 m^3 biomethane). 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. Annualised capital costs (*R*) (€/year) are calculated from Eqn 5.1:

$$R = [P(1 + r)^N r] / [(1+r)^N – 1] \qquad \text{(Eqn 5.1)}$$

where *P* is the principal (€), *r* is the rate of return (5%), and *N* is the lifetime of the project (15 years).

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. The calculated break-even tariffs are compared with existing tariffs where appropriate, and the effectiveness of the tariff system is assessed. The results also compare profitability under the current tariff structure with existing farm incomes. The use of biogas for energy can follow a number of different pathways. Two main scenarios are considered in this study:

- **Scenario 1:** biogas for on-site combined heat and power (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 of compressed biomethane 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.

5.3.2 *Capital costs of silage storage and AD plant*

Silage is to be stored in a horizontal silo or silage pit. In practice, the farms would already have pits; thus, the estimated construction cost of €456,250 for 21 pits (Table 5.2) must be viewed as conservative.

The cost of an AD plant depends on a number of factors, including the plant size and type, with larger plants generally having lower capital costs per cubic metre of biogas produced. The capital cost of a CSTR visited by the authors in Austria, of the same size, 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 feedstock). This is assumed to include the cost of in-situ hydrogen sulphide removal.

5.3.3 *Capital costs of a CHP and connection to the electricity grid*

From discussions with industry and values found in the literature (Murphy and McKeogh, 2004; Murphy and McCarthy, 2005), the cost of the CHP plant is conservatively taken as €1,500/kW_e, which is the fully installed cost, including civil works, 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

Table 5.2. Cost of a silage pit (Smyth et al., 2010b).

Component	Quantity[a]	Unit cost[b] (Teagasc, 2008)	Total cost
Silo wall	22 walls × 25 m long	€400/m	€220,000
Silage base	21 pits × 25 m long × 10 m wide	€42/m^2	€220,500
Effluent channel	Assume 250 m	€63/m	€15,750
Total			**€456,250**

[a]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 (ACA, 2008). Therefore 21 such pits would be required.
[b]Costs for silo wall and effluent channel are per linear metre.

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- to 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; 400-m lines costing €20,000 are assumed in this analysis, giving a total cost of €120,000.

5.3.4 Capital costs of upgrading plant and connection to the gas grid

The capital cost of an upgrading facility is highly dependent on plant size, with smaller plants having higher costs per cubic metre of upgraded gas. A membrane plant with a capital cost of €500,000 (€0.10/kWh/year) is assumed, which includes gas metering and quality monitoring (Murphy and Power, 2009a). 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 has been estimated to be between €150,000 and €400,000 in the literature (Biogasmax, 2008) and in discussions with Bord Gáis (the Irish Gas Board). Bearing in mind the variability associated with this, the total capital cost of connection to the gas grid is estimated as €200,000. Upgrading plants typically pressurise gas up to 7 bar, hence no additional compressor is required.

5.3.5 Operating costs of silage harvesting

Yield per hectare has the biggest influence on the silage cost, whereas the machinery and labour costs affect the cost of harvesting. Oil price fluctuations and their direct effects on fuel and fertiliser costs result in considerable fluctuations on the cost of silage production. The cost of getting grass into the pit is €950/ha (€17/t), which includes fertiliser, reseeding, lime, plastic and contractor charges (calculated from data in Teagasc, 2008). As the market price of silage is around 40% higher, it is important that grass silage is produced on-farm.

5.3.6 Operating costs of AD plant

The operational cost of an AD plant is made up of the cost of labour, electricity (for mixing and pumping), heating fuel, and maintenance. Previous work suggests annual operational costs of an AD plant (excluding feedstock) to be of the order of 10–12% of the unsubsidised capital costs (Murphy, 2004). Work in the UK (Holliday et al., 2005) and Sweden (Hagen et al., 2001) used values of 4% and 15%, respectively. A value of 10% is used in this analysis. An additional allowance of 6.67% of the unsubsidised 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.

5.3.7 Operating costs of CHP and upgrading plants

Typical running costs for a CHP plant are given as €0.01/kWh_e (Murphy and McKeogh, 2004; Murphy and McCarthy, 2005). The operating cost of the upgrading plant is taken as €0.02/kWh (€0.20/m^3) of upgraded gas, which equates to around €92,000/year, and gives a total (capital + operating) cost of €0.03/kWh (€0.30/m^3) for upgraded gas. This is at the lower end of the range quoted by the Swedish Gas Centre (Persson, 2003) for plants of this size. The plant in this analysis upgrades around 110 m^3/h of raw gas (85% operational efficiency) 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 (de Hullu et al., 2008). 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. 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.

5.3.8 Finance and subsidies

There is a national scheme in place offering capital grants for biogas CHP plants of up to 30% of the eligible capital costs (SEI, 2009b). 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 schemes that could potentially provide funding. Three sub-scenarios (30%, 50% and no grant towards capital costs) are investigated. The CAP is a system of subsidies and support programmes for agriculture in the EU. On top of standard farm payments, there are a number of schemes under the CAP that could provide additional support for a grass biogas/biomethane system, such as the Energy Crops Scheme and the REPS. The average direct payment received by cattle-rearing farms is €461/ha (from 2006, 2007 and 2008 farm survey data (Connolly et al., 2008, 2009)).

5.3.9 Income for biogas and digestate

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. Examples of average commercial fuel costs (SEI, 2010) are: oil at €0.058–0.069/kWh_{th} (depending on grade); wood pellets at €0.036/kWh_{th} (bulk) or €0.061/kWh_{th} (bagged); woodchips at €0.034/kWh_{th}; and natural gas at €0.04/kWh_{th} (based on a medium-sized business and including standing charges). It is assumed that €0.06/kWh_{th} is paid for heat in this analysis. Subtracting VAT of 13.5%, the income to the biogas plant is €0.053/kWh_{th}. The tariff for electricity from biogas CHP in Ireland is €0.12/kWh_e. Currently, there is 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 is assumed and this is considered the minimum tariff for biomethane injected into the grid and is used for comparison in the initial analysis. However, a biomethane tariff system should incentivise 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 sector, and the existing market conditions will influence the price paid. Potential markets and prices are discussed in Section 5.5.

For farm-based AD plants, it is common practice for the digestate to be returned to the land as replacement for chemical fertiliser, contributing to financial savings. The amount of fertiliser replaced depends on the nutrient content of the digestate which is highly dependent, amongst other factors, on the type of feedstock. Further difficulties arise as the price of chemical fertilisers, and hence the savings achieved through their replacement, varies considerably from year to year. Discussions with the AD industry in Ireland resulted in a conservative estimate for the net value of digestate of €4/t. The digestate quantity is assumed to be 90% of the silage input (Korres et al., 2010) and the value of digestate is therefore 4 x 0.9 x 7,500 = €27,000, or €196/ha.

5.4 Economic Analysis of Grass Biogas and Biomethane under Current Conditions

5.4.1 Scenario 1: Biogas to on-site CHP

The base-case analysis considers three different cases (Table 5.3):

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

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

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 to break-even, which is significantly higher than the current tariff of €0.12/kWh_e. Even when the average farming subsidy of €461/ha is included, the plant still operates at a loss (Table 5.4).

A relatively high value for operating costs is used in the base-case analysis (10% of unsubsidised capital costs) and an additional allowance is made for depreciation (6.67%) of the AD and CHP plants. Using a less onerous value of 10%, to cover both operating costs and depreciation, lowers the break-even prices (Table 5.4), but they are still higher than the current

Table 5.3. Scenario 1: Grass to biogas to combined heat and power base-case economic analysis (Smyth et al., 2010b).

System boundaries			Assumptions			Scenarios	
Biogas yield (m^3/year)	810,000					Grant included	G
Energy yield (GJ/year)	16,831					Electricity incl.	E
Electricity output (GJ/year)	5,891		35% electrical efficiency			Heat included	H
Electricity output (MWh_e)	1,636						
Electricity output (kW_e)	220		85% operational efficiency				
Heat output (GJ/year)	6,732		40% thermal efficiency				
Heat output (MWh_t)	1,870						
	(€)	**(€/year)**	**E+H (€/year)**	**G+E (€/year)**	**G+E+H (€/year)**	**Assumptions**	
Capital costs							
Silage pit	456,250	43,956					
AD plant	819,500	78,953					
Combined heat and power plant	330,000	31,793				CHP plant (€/kW_e)	1,500
Connection to electricity grid	120,000	11,561					
Total capital costs	**1,725,750**	**166,263**	**166,263**				
Capital finance	263,714					Max. grant (€/kW_e)	1,200
Total capital cost incl. grant	**1,462,036**	**140,856**		**140,856**	**140,856**		
Operating costs							
Depreciation		76,672				% capital costs	6.67
Silage production		130,625				€/ha	950
Anaerobic digestion plant		81,950				% capital costs	10
CHP plant		16,363				€/kWh_e	0.01
Total operating cost		**305,610**	**305,610**	**305,610**	**305,610**		
Capital + operating costs			**471,873**	**446,466**	**446,466**		
Income	**€/kWh**						
Heat	0.053	99,116					
Electricity	0.12	196,362		196,362			
Fertiliser savings		27,000		27,000		Estimate (€/t)	4
Total income		322,477	322,477	223,362	322,477		
Income – costs			–149,395	–223,104	–113,989		
Profit (€/ha)			–1,087	–1,623	–902		
Profit (€/m^3 biogas)			–0.184	–0.275	–0.153		
Profit (€/kWh_e)			–0.091	–0.136	–0.076		
Elec. price for break-even (€/kWh_e)			0.211	0.256	0.196		
Subsidy for break-even (€/ha)			1,087	1,623	902		

AD, anaerobic digestion; CHP, combined heat and power.
E+H, the sale of heat and electricity with no capital grant; G+E, the sale of electricity only with capital grant; G+E+H, the sale of electricity and heat with capital grant.

Table 5.4. Scenario 2: Biogas to biomethane to grid; tariff required for break-even (Smyth et al., 2010b).

	Scenario 1[a] (€/kWh$_e$)			Scenario 2[a] (€/kWh)		
	E+H	G+E	G+E+H	50%G	30%G	NG
Base case						
No subsidy	0.211	0.256	0.196	0.100	0.108	0.121
With subsidy (€461/ha)	0.173	0.218	0.157	0.086	0.095	0.107
Reduced operating costs and depreciation						
No subsidy	0.164	0.209	0.149	0.081	0.089	0.102
With subsidy (€461/ha)	0.126	0.171	**0.110**	0.067	0.075	0.088
Co-digestion[b]						
No subsidy	**0.100**	0.145	**0.084**	0.059	0.064	0.071
With subsidy (€461/ha)	**0.084**	0.129	**0.068**	0.053	0.058	0.066
Co-digestion (reduced operating costs and depreciation)						
No subsidy	**0.059**	**0.104**	**0.043**	0.045	0.050	0.058
With subsidy (€461/ha)	**0.043**	**0.088**	**0.027**	0.040	0.045	0.052

[a]Figures in bold indicate profitability under current conditions:
- €0.12/kWh$_e$ is paid for electricity from biogas combined heat and power; and
- €0.02–0.03/kWh is the wholesale price of natural gas.

[b]Co-digestion of 7,500 t/year grass and 7,500 t/year belly grass.

E+H, the sale of heat and electricity with no capital grant; G+E, the sale of electricity only with capital grant; G+E+H, the sale of electricity and heat with capital grant.

50%G, receipt of grant for 50% of capital cost; 30%G, receipt of grant for 30% of capital cost; and NG, no grant.

tariff of €0.12/kWh$_e$. Inclusion of the farming subsidy (€461/ha) brings the best-case scenario (G+E+H) into profit and results in an annual return of €117/ha. However, this is lower than the average FFI for cattle-rearing farms (€279/ha for 2006–2008, inclusive (Connolly et al., 2008; 2009)), and therefore uncompetitive with current farming practice.

As plant size increases, investment costs per kilowatt decrease (Murphy and McCarthy, 2005; Walla and Schneeberger, 2008); therefore, increasing the quantity of grass silage could increase profits. However, this would also result in increased transport distances for silage delivery and digestate disposal. Ideally, transport distances should be kept to a minimum because of associated costs, emissions and nuisance on rural roads. The average haul distance for 137.5 ha of silage is 1.25 km (Eqn 5.2; Walla and Schneeberger (2008)), which is within the range used in the literature (EPA, 2005; Murphy and McCarthy, 2005; Gerin et al., 2008). For a large plant of 1 MW$_e$ size, around 625 ha of grass silage are required, giving an average haul distance of 2.66 km.

$$\text{Average haul distance (km)} = \bar{x} = {}^{2}/_{3}x\tau \qquad \text{(Eqn 5.2)}$$

where x is the radius of area of supply (km) = $\sqrt{Q/(ya\pi)}$, τ is the tortuosity factor ($\sqrt{2}$ for rural roads), y is the silage yield (t/km), Q is the required amount of silage (t), a is the factor of silage availability[2].

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

- Keeping operational costs to a minimum;

2. On average in Ireland, silage, hay and pasture make up 50% of the total land area (CSO, 2009b; OSI, 2010). Assuming that half of the grass in a given area is used for AD, the factor of silage availability is 0.5 × 0.5 = 0.25.

- Finding a year-round market for heat, although this may prove challenging due to limited heat markets; and
- Maintaining current farming subsidies.

5.4.2 Scenario 2: Biogas to biomethane to grid

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

The break-even price of gas is found to be €0.100, €0.108 and €0.121/kWh, assuming 50%, 30% and 0% capital grant, respectively (Table 5.4). If the farming subsidy of €461/ha is included, the break-even price falls to between €0.086 and €0.107/kWh. 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 is assumed and this is considered the minimum tariff for biomethane injected into the grid and is used for comparison in the initial analysis. Reducing the operating costs and depreciation (as for the CHP plant) brings the break-even gas price down to €0.081–0.102/kWh, excluding the farming subsidy, and €0.067–0.088 if the subsidy is included (Table 5.4). Even in the best-case scenario, the break-even price is still more than double the wholesale price of natural gas.

5.4.3 Co-digestion

Co-digestion is a common practice, as this frequently improves the performance of the digester and increases the biogas production. Examples of co-substrates include manure, food remains, animal blood, rumen contents, fermentation slops and OFMSW. A gate fee can often be charged for the co-substrates, generating additional revenue for the plant, and larger plants can also take advantage of economies of scale, thus lowering the capital and operational costs per tonne of feedstock. Nevertheless, current legislation restricts the use of substrates from certain sources and may lead to higher AD processing and digestate disposal costs.

Animal by-products (ABP) may be a suitable feedstock for AD plant but they can pose a threat to animal and human health via the environment if not properly disposed of. The collection, transport, storage, handling, processing and use or disposal of all ABP are therefore tightly controlled by the Animal By-Products Regulations (ABPR). Compliance with the ABPR can add significant cost and must be weighed against the gate fees received. While the ABPR 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 recognised this and is currently in consultation with industry with the aim of facilitating the growth of AD (Farrar, 2009).

This study considers a co-operative AD plant among a group of livestock farmers; the co-substrate is therefore cattle slurry. From a microbiological perspective, cattle slurry is a recommended co-substrate for grass silage (Nizami et al., 2009). Previous studies (e.g. Yiridoe et al., 2009) 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/t VDS_{added} (Steffen et al., 1998)), meaning that larger digestion tanks and operational energy demands (heating and mixing) are required than for grass silage (22% DS, 300 m^3 CH_4/t VDS_{added}), but with much lower energy return. In the absence of financial incentives, co-digestion of cattle slurry with grass does not improve the economic viability of the plant. Grass biomethane is cheaper than slurry biomethane.

Greater economic benefit could be achieved by digesting co-substrates that attract a gate fee. For the CSTR, a low solids content substrate such as slaughter waste (belly grass) would be appropriate. Discussions with the slaughterhouse industry in Ireland suggest that gate fees of around €20/t could be attracted. Equal quantities (7,500 t/year of each) of grass silage and belly grass are used and it is conservatively assumed that there are no financial savings from the digestate. Substantial profits are achievable with the CHP plant (Table 5.4), showing that the current tariff system works well for feedstock that attracts a gate fee. However, for grid injection even the base-case scenario has a higher break-even price than the wholesale price of natural gas.

5.4.4 *Viability of grass biogas and biomethane under current conditions*

Under current 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 under way. This analysis shows that grass biomethane injected into the grid is not competitive with natural gas. Co-digestion can improve the economics, but the ABPR pose challenges for the industry.

5.5 Improving the Viability of Grass Biomethane for the Farmer and the Consumer

5.5.1 *Why should we subsidise grass biomethane?*

Grassland agriculture in Ireland is effectively subsidised for export (Howley et al., 2009a). It is suggested that diverting some grassland to biomethane production will allow the benefit of double credits (EC, 2009a) for meeting the 2020 targets for RES-T. Injecting biomethane into the gas grid is an effective means of distributing renewable energy to a large number of consumers without any requirement for new infrastructure beyond the existing modern, extensive natural gas grid. In addition, farm diversification is served well leading to a strong case for subsidising grass biomethane and AD plants in general. The use of biogas/biomethane reduces GHG emissions: 82% for cattle slurry biomethane compared with diesel have been reported (Singh and Murphy, 2009), while savings of 75–150% can be achieved for grass biomethane compared with diesel (Korres et al., 2010). Methane is a clean burning fuel in terms of local pollutants; it improves air quality and benefits health (Rabl, 2002; Goyal and Sidhartha, 2003). In addition, the digestion of wastes is a proven waste treatment option that reduces GHG emissions from uncontrolled fermentation and reduces pollution from poor waste management practices (Yiridoe et al., 2009).

A considerable uncertainty governs the non-market co-benefits of an AD plant and values are likely to change in the future as concerns over environmental issues heighten (Yiridoe et al., 2009). At the end of pipe, savings from methane through avoiding emissions, such as carbon dioxide, nitrogen oxides and particulate matter, have been estimated as €0.43/l of diesel replaced for a passenger car in an urban area (Biogasmax, 2008), which equates to €1,387/ha of grass digested. In city centres, this rises to €0.89/l diesel replaced (Biogasmax, 2008) or €2,870/ha of grass. If a waste feedstock is used, the benefit from avoided methane leakage is €0.26/l of diesel replaced and the total benefit including improved end-of-pipe emissions is €1.15/l of diesel replaced (Biogasmax, 2008). This equates to €13.8/t of cattle slurry digested (based on a biogas yield of 22 m^3/t of slurry at 55% methane).

5.5.2 *Competitive advantage of biomethane*

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 with other renewables. The existing natural gas network, which can serve as a vehicle for biomethane transport, yields the competitive advantage of biomethane.

The natural gas grid in Ireland is quite extensive and reaches all major cities and 23 out of the 32 counties. A programme has been completed replacing all of the old cast-iron pipes with polyethylene pipes, resulting in a more efficient network. There are currently about 619,100 domestic connections and 24,000 industrial and commercial connections to the gas grid in the Republic of Ireland and another 118,800 domestic customers and 8,400 industrial and commercial customers (NIAUR, 2009) in Northern Ireland.

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 woodchips (fuel storage areas) or horizontal geothermal installations; such space may be costly or unavailable in cities and towns (e.g. in apartment blocks).

There are clearly competitive advantages of grass biomethane; the issue is now to find the right market in order to exploit these advantages.

5.5.3 Grass biomethane in the renewable electricity market

Ireland's 40% renewable electricity target for 2020 (Howley et al., 2008) is expected to be provided largely by wind. There are also targets for electricity from ocean energy (500 MW_e of installed capacity by 2020) and for 30% biomass co-firing in existing peat-fired power plants (DCMNR, 2007). The presence of viable alternatives for renewable electricity means that there is not expected to be a large market for electricity from grass biomethane; 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 (SEI, 2009c).

There is a government target to achieve at least 800 MW_e from CHP by 2020, with emphasis on biomass-fuelled CHP (DCMNR, 2007). 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-fuelled 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 (O'Leary et al., 2007), there is significant market potential; however, the renewable bonus of €0.12/kWh_e for biomethane does not make financial sense as CHP plants typically displace electricity purchased from the grid and have returns of about €0.10–0.11/kWh_e.

It is suggested that a revised system of tariffs be introduced. Currently, a flat rate of €0.12/kWh_e 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 (BMELV, 2009) uses graded tariffs that depend on feedstock type, plant size and AD technology type, among other factors. The International Energy Agency (IEA) has stated (IEA, 2007) 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 a minimum of €0.1718/kWh for an on-site CHP plant and €0.1818/kWh for an off-site CHP plant using biomethane tapped from the grid (Table 5.5). Sale of heat off-site leads to an extra bonus of €0.03/kWh_e based on the proportion of heat sold. Thus there is potential for these rates to rise to €0.21/kWh_e.

Such a tariff structure would bring the on-site CHP plant into profit as long as there is a market for the heat (Table 5.6). The annual income for E+H and G+E+H is over twice the average FFI for cattle-rearing farms

Table 5.5. Potential revenues from combined heat and power (CHP) using the German tariff structure (simplified) (Smyth et al., 2010b).

Tariff	On-site CHP (€/kWh_e)	Off-site CHP (€/kWh_e)
Basic compensation	0.0918	0.0918
Emission minimisation bonus	0.01	–
Grass as a feedstock	0.07	0.07
Upgrading	–	0.02
Total	**0.1718**	**0.1818**

Table 5.6. Profitability of on-site combined heat and power (CHP) with German tariff structure and farming subsidies (Smyth et al., 2010b).

	Base case			Reduced operating costs and depreciation		
	E+H	G+E	G+E+H	E+H	G+E	G+E+H
Total income[a] (€/year)	407,240	308,124	407,240	407,240	308,124	407,240
Total costs (€/year)	471,873	446,466	446,466	395,201	369,794	369,794
Income – costs (€/year)	–64,633	–138,342	–39,266	12,039	–61,670	37,446
Income – costs (€/ha)	–470	–1,006	–285	88	–459	272
Average annual subsidy (€/ha)	461	461	461	461	461	461
Return including subsidy (€/ha)	–9	–545	176	549	12	733

[a]€0.1718/kWh$_e$ received for electricity, €0.053/kWh$_{th}$ received for heat.
E+H, the sale of heat and electricity with no capital grant; G+E, the sale of electricity only with capital grant; G+E+H, the sale of electricity and heat with capital grant.

(€279/ha) when reduced operating costs and depreciation are considered. In the case of the off-site CHP plant, a return of €0.085/kWh biomethane can be achieved, assuming 40% thermal and 35% electrical efficiency (€0.1818/kWh$_e$ + €0.053/kWh$_{th}$). This is over 25% higher (€0.085/kWh compared with €0.11/kWh) than the best-case break-even biomethane price (from Table 5.4). 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. There is potential for the use of biomethane in combined cycle gas turbine (CCGT) plants. The initial advantages of biomethane used in a CCGT facility include:

- An electrical efficiency of around 55% compared with 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.

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$_e$ (O'Leary et al., 2007). 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.

5.5.4 Grass biomethane in the renewable transport market

There is a target for 10% renewable energy in Transport 2020 (DCMNR, 2007). Unlike the electricity sector where significant progress is being made towards meeting the target, there are significant challenges in the transport sector. Penetration of renewables in transport currently stands at less than 1.2% (Howley et al., 2009a). 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. Smyth et al. (2010a) showed that the largest potential for the achievement of Irish 2020 targets in renewable energy in transport is grass biomethane.

The break-even price of compressed biomethane from grass varies between €0.078 and €0.132/kWh (Table 5.7). Excise duty is not charged on gas used as a propellant, but VAT at 21% has to be added (EC, 2010), giving a minimum selling price (i.e. break-even price) of between €0.096 and €0.163/kWh. The sale price of petrol and diesel lies within this range (Table 5.8). 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 (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), this is competitive.

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 (NGV, 2009). The development of biomethane for transport in other

Table 5.7. Break-even of compressed biomethane from grass silage as a vehicle fuel (Smyth et al., 2010b).

	Base case[a]			Reduced operating costs and depreciation[b]		
	50%G	**30%G**	**NG**	**50%G**	**30%G**	**NG**
Break-even price of biomethane injected to grid (€/kWh)	0.100	0.108	0.121	0.067	0.075	0.107
Cost of compression to 250 bar + filling station (€/kWh)[c]	0.011	0.011	0.011	0.011	0.011	0.011
Break-even price of compressed biomethane (€/kWh)	0.111	0.119	0.132	0.078	0.086	0.118
– including 21% VAT (€/kWh)	0.134	0.144	0.160	0.094	0.104	0.143
– including 21% VAT (€/m^3)	1.37	1.47	1.63	0.96	1.06	1.45

[a]Excludes farming subsidy.
[b]Includes farming subsidy (€461/ha).
[c]Estimated from values in the literature (Murphy and Power, 2009b) and discussions with industry.
50%G, receipt of grant for 50% of capital cost; 30%G, receipt of grant for 30% of capital cost; and NG, no grant.

Table 5.8. Comparison of vehicle fuel costs (Smyth et al., 2010b).

Fuel	Unit cost	Energy value	Cost per unit energy (€/MJ)
Petrol[a]	€1.224/l	30 MJ/l	0.0408
Diesel[a]	€1.150/l	37.4 MJ/l	0.0307
Compressed biomethane (high)[b]	€1.63/m^3	37 MJ/m^3	0.0441
Compressed biomethane (low)[b]	€0.96/m^3	37 MJ/m^3	0.0260
CNG – Austria[c]	€0.89/m^3	37 MJ/m^3	0.0241
CNG – UK[c]	€0.71/m^3	37 MJ/m^3	0.0192
CNG – Germany[c]	€0.70/m^3	37 MJ/m^3	0.0189
Bio-CNG (high)[d]	€0.80/m^3	37 MJ/m^3	0.0217
Bio-CNG (low)[d]	€0.74/m^3	37 MJ/m^3	0.0199

[a]Price of petrol and diesel is the price at the pumps (AA Ireland, 2010).
[b]Price of compressed biomethane is the minimum selling price of grass biomethane. The highest and lowest prices from Table 5.8 are used.
[c]In the absence of Irish compressed natural gas (CNG) prices, the prices in Austria, Germany and the UK (NGV, 2009) are shown for comparison.
[d]Bio-CNG price calculated using UK CNG prices and a blend of 10% biomethane/90% CNG.

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.

5.5.5 Grass biomethane in the renewable heat market

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 (DCMNR, 2007). The residential sector is responsible for the largest share of natural gas final energy consumption, at 40.7% (SEI, 2009c). Twenty-eight per cent of houses have gas central heating (O'Leary et al., 2008), with the highest proportion in Dublin, where there are almost 375,000 natural gas customers or about 60% of 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 houses solely on biomethane or 2,665 houses on bioNG containing 12% renewable gas. The potential for a large number of customers offers more flexibility than the electricity market.

Obviously, alternatives such as woodchips 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 5.1 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 woodchip and pellet heating systems (fuel, running and annualised capital costs). While grass biomethane is uncompetitive, a 12:88 (biomethane/CNG) bioNG fuel is competitive with the renewable energy alternatives. The analysis assumes that biomethane is produced from grass only; biomethane produced from feedstock with a gate fee, such as slaughter waste, would be considerably more competitive.

In Fig. 5.1, the cost of grass biomethane is the break-even price (highest and lowest values are taken from Table 5.4 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 woodchips and wood pellets includes capital and operational costs. Total woodchip, wood pellet and natural gas heating costs were calculated using a heat cost comparison spreadsheet

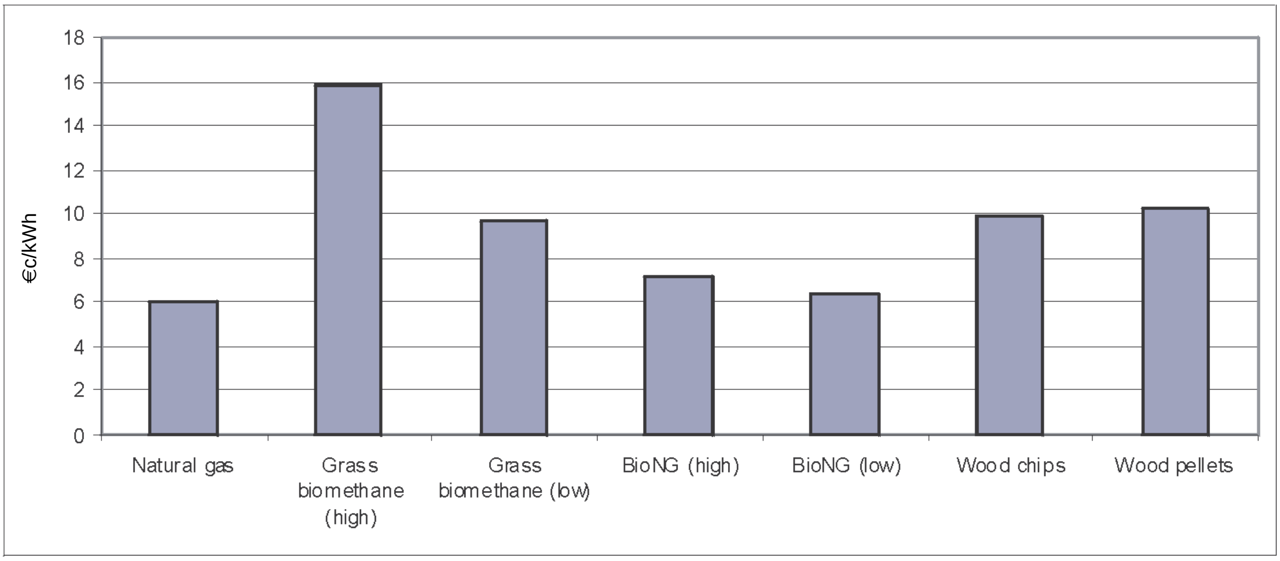

Figure 5.1. Comparison of heating costs for various systems (Smyth et al., 2010b).

(EVA, 2007), current commercial fuel costs (SEI, 2010) and work undertaken as part of a Master's thesis (Smyth, 2007). A 570-kW boiler with 900 h/year operation is assumed.

Although Directive 2009/73/EC on the natural gas market (EC, 2009c) 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.

5.6 Conclusions

The key to the competitiveness of biogas/biomethane is the renewable energy targets. 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 ABPR and uncertainty in the waste sector. The transport market offers the potential for profitability and provides a cheaper alternative to fossil fuels for the consumer. However, there is currently no market for CNG in Ireland and the transport market is therefore 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 new installation 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. However, a recurring theme is the lack of consistent legislation regarding AD 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.

6 Conclusions and Recommendations

6.1 Conclusions

- Grassland is the dominant agricultural landscape in Ireland, covering 91% of agricultural land. The size of the national herd has decreased and will continue to do so. Conversion of grassland to arable land is not encouraged due to cross compliance. Diversification of agricultural enterprise to grass biomethane production will assist rural development through sustainable employment, security of energy supply, and environmental benefits associated with reduced stocking rates.

- Perennial ryegrass is an excellent grass species for biogas production. Mixed pastures (ryegrass and clover) may result in higher biogas production and reduced fertilisation requirements. Excess fertilisation and late harvesting can negatively affect biogas production due to the increased structural carbohydrate content of grasses.

- The selection of the correct digester system for grass biomethane is an important decision. The wet continuous two-stage system offers readily available technology. However, grass has a tendency to float to the top of the liquid level in a wet system, which may inhibit the process; thus, great care must be taken in the choice of the mixing system. Dry-batch leach-bed systems coupled with a UASB have potential for increased biogas production in smaller chambers. These systems can be further optimised, particularly in leaching mode using pretreatment options. Membrane separation and HPWS are recommended for upgrading of biogas (typically at 55% CH_4) to biomethane (at 97%+ CH_4). In addition, HPWS also provides maximum purity (up to 98% CH_4) with minimal cost.

- An essential element of a grass biomethane facility is the reduction in emissions associated with parasitic energy demands. Thus, purchase of green electricity and minimisation of thermal energy input are essential. In use as a transport fuel the vehicle must be optimised for biomethane; bi-fuel vehicles may not meet this criterion. Through process optimisation, a GHG emission reduction of more than 60% as compared with diesel may be effected. Grassland sequesters carbon; a value of 0.6 t C/ha/year is deemed conservative. This would lead to a reduction in emissions of 89% which would suggest that grass biomethane is one of the most sustainable indigenous non-residue European transport biofuels.

- The key to the competitiveness of grass biomethane is the renewable energy targets. The principal advantage of biomethane over other renewables is that it can be distributed through the gas grid to a large existing customer base. It is suggested that biomethane has advantages in the transport and thermal sectors rather than the electricity sector. The transport market offers the best potential for profitability; however, there is currently no market for CNG in Ireland. Grass biomethane as a source of renewable thermal energy has a large, easily accessible customer base; existing natural gas customers would not require new installations. Cost competitiveness can be further improved by co-digestion with gate fee feedstock and by taking account of the associated non-monetary co-benefits. However, a recurring theme is the lack of consistent legislation regarding 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.

6.2 Recommendations

- **Employ a tariff scheme that differentiates the source of biomass:**
  Applying one tariff rate to biomass is a relatively

blunt instrument. The present tariff for AD CHP is €150/MW$_e$h for facilities smaller than 500 kW$_e$. This does not differentiate the source of biomass. Biogas may be made from OFMSW, which carries a gate fee, slurry, which typically has no gate fee, or silage, which must be purchased. Germany employs a tiered system for tariffs for biogas. There is a basic compensation for biogas with additional bonuses. One of these bonuses is priced to allow competitiveness for feedstocks, such as grass, which offer rural sustainable employment.

- **Employ a tariff scheme for biomethane:** At present, there is a tariff structure for electricity from biomass. It is suggested that the utilisation of biogas is better employed when upgraded to biomethane and used as either a source of heat (distributed through the natural gas grid to 620,000 houses) or as a transport fuel. There is no tariff scheme for these end uses. The German system allows a bonus for grid injection of biomethane and use at a different site. Support for transport fuel is of particular importance as biomethane is allowed a double credit for renewable energy in transport targets.

- **Develop, promote and regulate the CNG market:** The sale of biomethane for transport in other countries has been found to be profitable, offering higher returns than heat or electricity. 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 CNG market requires support through regulation and incentives from government. For example, a target of CNG vehicles could be introduced to mirror the target of 10% of all vehicles to be electric powered by 2020. Other examples include grant-aiding CNG service stations and mandating of public transport fleets to incorporate a certain percentage of CNG vehicles by specified dates.

- **Develop, promote and regulate biomethane as a source of thermal energy:** The sale of biomethane for renewable thermal energy has a significant advantage due to the existence of a modern, extensive natural gas grid. There are about 619,000 domestic connections to the gas grid, with an average demand of 51.9 GJ/house. This equates to 32 PJ of thermal energy. If we consider a 12% Renewable Energy Supply in Heat (RES-H) target, then 3.84 PJ/year can be met by 32,000 ha of grass or about 0.8% of existing grassland. Again, the renewable gas and heat market requires Government support. This may be done (similar to the biofuel obligation scheme) by mandating suppliers of gas to incorporate a specific percentage of renewable gas in their sales by specific dates.

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Acronyms and Annotations

a.i.	Active ingredient: chemical substance of a pesticide that kills the target pest
AAU	Agricultural area used
ABP	Animal by-products
ABPR	Animal By-Product Regulations
AD	Anaerobic digestion
ADF	Acid detergent fibre; an estimation of the cellulose and lignin content in a feed
ADL	Acid detergent lignin: estimates lignin content in feedstock
BioCNG	Compressed biomethane and natural gas
C-3 plant	First product of photosynthesis consists of three carbon atoms (cool or temperate grasses)
C-4 plant	First product of photosynthesis consists of four carbon atoms (warm or tropical grasses)
CAD	Centralised anaerobic digestion
CAN	Calcium ammonium nitrate
CAP	Common Agricultural Policy
CCGT	Combined cycle gas turbine
CF	Cocksfoot
CH_4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
CO_2e	Carbon dioxide equivalent
CP	Crude protein
CSO	Central Statistics Office
CSTR	Continuous stirred tank reactor
DAFF	Department of Agriculture, Fisheries and Food
DM	Dry matter
DMD	Dry matter digestible: percentage of the feed dry matter actually digested by animals
DMI	Dry matter indigestible: dietary fibre (roughage), the indigestible portion of plant food
DS	Dry solids
FE	Fuel efficiency
FFI	Farm family income
FM	Fresh matter
GDP	Gross Domestic Product
GHG	Greenhouse gas

GWP	Global warming potential
HPWS	High pressure water scrubbing
HRT	Hydraulic retention time
IEA	International Energy Agency
ktoe	Kilotonnes of oil equivalent
LCA	Life-cycle assessment
ME	Metabolisable energy: the feed energy actually used by the animal
MF	Meadow foxtail
N, P, K	Nitrogen, phosphorus, potassium
NDF	Neutral detergent fibre; estimation of hemicellulose and cellulose content, cell wall content
NDP	National Development Plan
ODM	Organic dry matter
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
PRG	Perennial ryegrass
PS	Photosynthetic
REPS	Rural Environment Protection Scheme
RES-H	Renewable Energy Supply in Heat
RES-T	Renewable Energy Supply in Transport
TS	Total solids
UASB	Upflow anaerobic sludge blanket
UCO	Used cooking oil
VDS	Volatile dry solids
VFA	Volatile fatty acids
WDGS	Wet distiller’s grains with solubles
WSC	Water-soluble carbohydrate