Biomethane and its potential from Biological, Thermal and Electrical Sources.

Professor Jerry D Murphy,
BioEnergy and Biofuels Research, Environmental Research Institute, University College Cork, Ireland
http://research.ucc.ie/profiles/D012/jerrymurphy/Home jerry.murphy@ucc.ie

National Bioenergy Conference, Louis Fitzgerald Hotel, Naas Road, Dublin Friday 8 November, 2013.

Bioenergy and Biofuels Research Group (B^2RG)

- Funding of €3 M since inception in 2007 from:
  - SFI, Ecoventii. EPA, DAFF, IRCSET, BGE, BGN, HEA PRTLI, Marie Curie ITN
- Funding for 10 PhD students and 2 post-doctorate students in place
- Published
  - 60 peer review journal papers
  - 30 peer review conference papers

Policy on Biofuels

Directive 2009/28/EC (Renewable Energy Directive)

- Share of renewable energy sources in transport by 2020 at least 10%
- Biofuels must achieve a 60% reduction in GHG as opposed to fossil fuel displaced.
- Biofuels from lignocellulosic material shall be considered at twice energy content.

EC, Proposal for a DIRECTIVE OF THE EUROPEAN PARLIMENT Brussels 2012.
In : http://ec.europa.eu/clima/policies/transport/fuel/docs/com_2012_595_en.pdf

- The share of biofuels from cereal and other starch rich crops, sugar and oil crops limited to consumption in 2011 (5%)
- Biofuels (from algae, municipal solid waste, manures and residues) and gaseous fuels from non biological origin shall be considered at 4 times energy content

- In September 2013 this limit on food biofuel was raised to 6% with a requirement that 2.5% energy in transport to come from advanced biofuels (such as those sourced from sea weeds) with no weightings applied. More arduous!!

Ireland

Agriculture

- 4.4 Mha agricultural (65%)
- 4 Mha grass land (91%)
- Export 85% of beef
- 400,000 ha arable (9%)
- Net importer of grain

Biofuel feed-stocks

Cross Compliance and EU Biofuels Directive do not encourage conversion of grass land to arable land for biofuels. Forestry less than 10%; Not a lot of straw.

Energy

Table 1 Forecasted final energy consumption in Ireland in 2020. Adapted from[11].

	PJ	% total
Electricity	124	21.5
Thermal	223	38.9
Transport (road and rail)	188	32.8
Other transport (not covered by RES-T)	39	6.8
Total	574	100

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

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

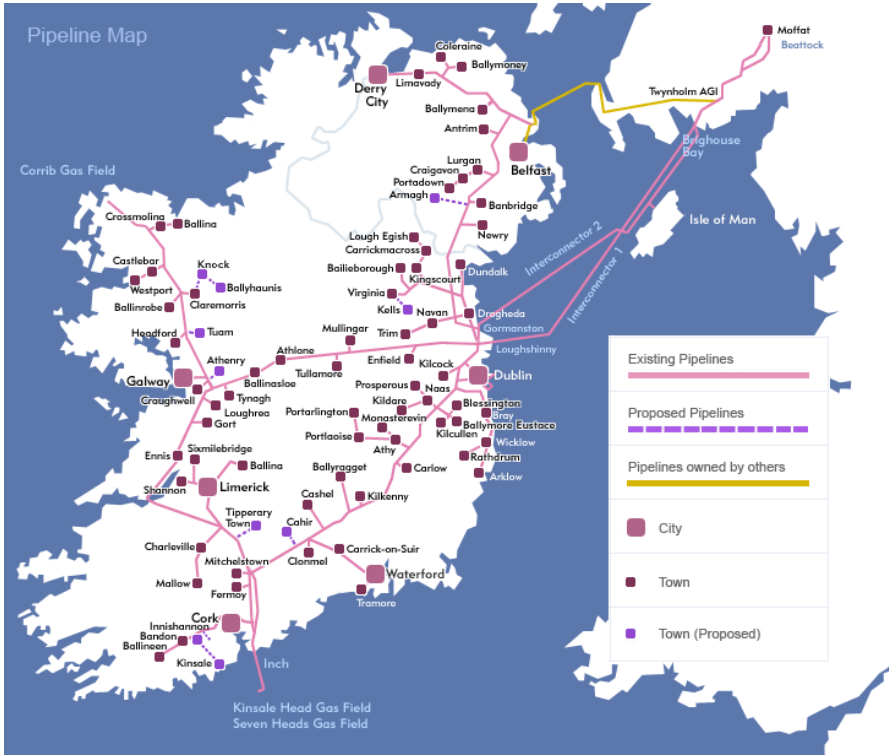
A roadmap for the introduction of gaseous transport fuel: A case study for renewable natural gas in Ireland

T. Thamsiriroj[a,b], H. Smyth[c], J.D. Murphy[a,b,*]

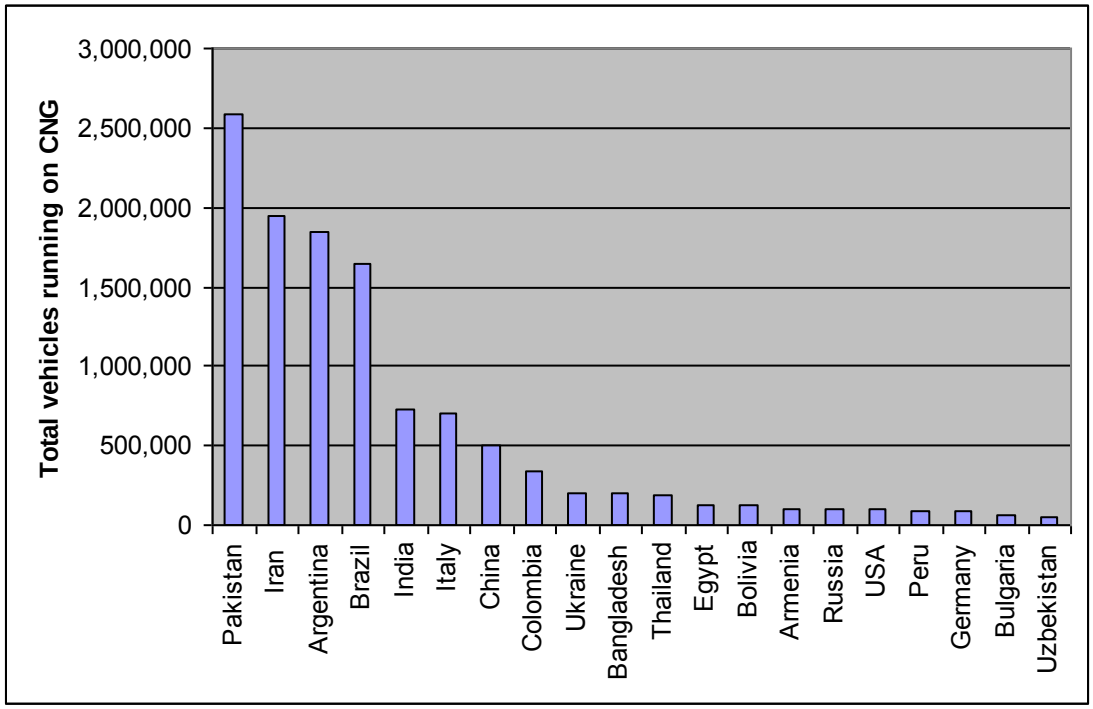
[a] Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland
[b] Environmental Research Institute, University College Cork, Cork, Ireland
[c] Bord Gáis Éireann, Cork, Ireland

Irish Gas Grid

Serves:
153 towns
19 counties (26 counties in Ireland)
619,000 houses (ca. 45% of houses)
24,000 industrial and commercial



Number of vehicles running on CNG worldwide



Grass to transport fuel in Austria

harvest →

weigh bridge →

silage storage ↓

macerator ←

anaerobic digester ←

Scrubbing & storage ←

Biogas service station

Source: energiewerkstatt, IEA and personal photos

Renewable and Sustainable Energy Reviews 13 (2009) 2349–2360

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

What is the energy balance of grass biomethane in Ireland and other temperate northern European climates?

Beatrice M. Smyth [a,b], Jerry D. Murphy [a,b,*], Catherine M. O'Brien [a,b]

[a] Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland
[b] Environmental Research Institute, University College Cork, Cork, Ireland

Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

Is grass biomethane a sustainable transport biofuel?

Nicholas E. Korres, Anoop Singh, Abdul-Sattar Nizami and Jerry D. Murphy,* Biofuels Research Group, Environment Research Institute, University College Cork, Ireland

Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

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

BIOMASS AND BIOENERGY 33 (2009) 504–512

Available at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

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BIOMASS & BIOENERGY

An argument for using biomethane generated from grass as a biofuel in Ireland

Jerry D. Murphy[a,b,*], Niamh M. Power[c]

Environ. Sci. Technol. 2009, 43, 8496–8508

Review of the Integrated Process for the Production of Grass Biomethane

ABDUL-SATTAR NIZAMI, NICHOLAS E. KORRES, AND JERRY D. MURPHY*

Department of Civil and Environmental Engineering, and Environmental Research Institute, University College Cork, Cork, Ireland

Received May 26, 2009. Revised manuscript received September 22, 2009. Accepted September 30, 2009.

ENVIRONMENTAL Science & Technology

Optimizing the Operation of a Two-Phase Anaerobic Digestion System Digesting Grass Silage

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ARTICLE

pubs.

Energy Fuels **XXXX**, *XXX*, 000–000 · DOI:10.1021/ef1003039

energy&fuels article

Difficulties Associated with Monodigestion of Grass as Exemplified by Commissioning a Pilot-Scale Digester

T. Thamsiriroj[†,‡] and J. D. Murphy*[,†,‡]

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Received March 15, 2010. Revised Manuscript Received July 13, 2010

Applied Energy xxx (2011) xxx–xxx

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Applied Energy

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

How much gas can we get from grass?

A.S. Nizami [a,b], A. Orozco [c], E. Groom [c], B. Dieterich [d], J.D. Murphy [a,b,*]

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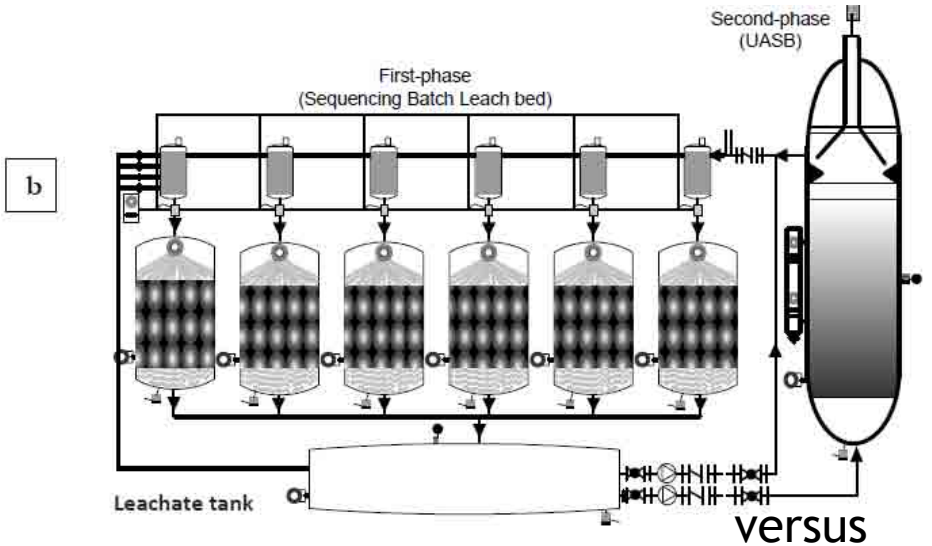
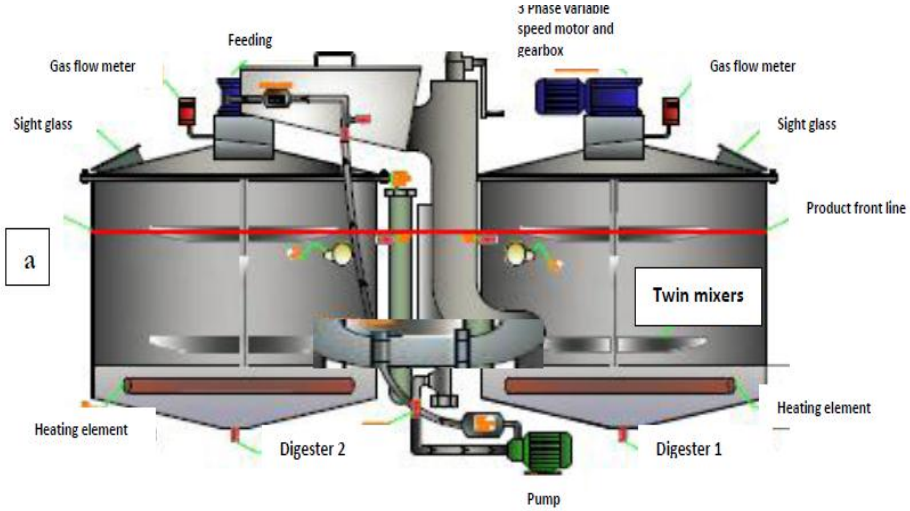
[c] School of Chemistry and Chemical Engineering, Queen's University Belfast, Ireland
[d] School of Biology & Environmental Sciences, University College Dublin, Ireland



versus



SLBR-UASB

CSTR

	SLBR–UASB	CSTR
HRT (Days)	30	50
CH_4 content (% CH_4 in Biogas)	71	52
CH_4 production (L CH_4 kg^{-1} VS added)	341	451

Bioresource Technology 149 (2013) 425–431

Contents lists available at ScienceDirect

Bioresource Technology

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

The potential for biomethane from grass and slurry to satisfy renewable energy targets

David M. Wall [a,b,c], Padraig O'Kiely [c], Jerry D. Murphy [a,b,*]

Table 1
Characteristics of substrates and inoculum.

Substrate/inoculum	DS (g/kg)	VS (g/kg)	VS/DS (%)	C:N
Grass silage	292.7 ± 3.4	268.4 ± 2.8	91.7	26:1
Slurry	87.5 ± 2.1	66.9 ± 1.8	76.5	19:1
Inoculum	30.0	18.9	63.3	–

Table 2
Assessment of biomethane potential of substrates in mono- and co-digestion.

Grass: Slurry VS basis g:g	BMP L CH_4 kg^{-1} VS	Buswell[a] L CH_4 kg^{-1} VS	Predicted yield[b] L CH_4 kg^{-1} VS	Difference[c] (%)	Biodegrad-ability Index[d]	Gas production m^3 CH_4 t^{-1} FW[e]
100:0	400 ± 4	443	–	–	0.90	107.4 ± 1.1
80:20	345 ± 6	–	368	−7	0.80	78.7 ± 0.6
60:40	321 ± 3	–	336	−5	0.76	60.3 ± 1.4
50:50	308 ± 5	–	320	−4	0.74	51.6 ± 0.6
40:60	273 ± 5	–	303	−11	0.66	40.3 ± 0.8
20:80	250 ± 8	–	271	−8	0.63	26.8 ± 0.7
0:100	239 ± 9	389	–	–	0.61	16.0 ± 0.9
Cellulose	348 ± 3	415	–	–	0.84	–

[a] Methane predicted from the stoichiometric formula of the substrate.
[b] Calculated in proportion to BMP values for Grass:Slurry 100:0 and 0:100.
[c] Difference between BMP results and predicted yield results.
[d] Biodegradability index = BMP/Buswell.
[e] FW – fresh weight; ±standard deviation.

Range of grassland available in excess of livestock requirements:

•Current production practices (excluding Food Harvest 2020): 1.7 million t DS of grass (equivalent to silage from 155,000 ha or 3.9% of grassland).

•If nitrogen applied to the limits permitted and if the grazed grass utilisation rate of cattle was increased from 0.60 to 0.80 kg DS ingested per kg DS grown: 12.2 million t DS (including Food Harvest 2020), equivalent to 1.1 million ha or 28% of Irish grassland

McEniry, J., Crosson, P., Finneran, E., McGee, M., Keady, T.W.J., O'Kiely, P., 2013. How much grassland biomass is available in Ireland in excess of livestock requirements? Irish Journal of Agriculture and Food Research (in press).

Table 5
Potential mixes of grass silage and slurry with associated renewable energy production.

Grass: Slurry VS basis	Energy in biomethane (PJ a^{-1})	% of expected energy in transport 2020 (%)	RES-T allowing for double credit (%)
Scenario 1 (equivalent to 0.4% of grass land)			
100:0	2.20	1.17	2.34
80:20	2.37	1.26	2.52
60:40	2.94	1.56	3.13
50:50	3.39	1.80	3.61
40:60	3.75	1.99	3.99
0:100	1.31	0.70	1.39
Scenario 2 (equivalent to 1.1% of grass land)			
100:0	6.60	3.51	7.02
80:20	7.11	3.78	7.56
60:40	8.82	4.69	9.38
50:50	10.16	5.40	10.81
0:100	3.94	2.10	4.19
Scenario 3 (equivalent to 2.8% of grass land)			
100:0	16.07	8.55	17.10
80:20	17.32	9.21	18.43
Scenario 4 (equivalent to 8.3% of grass land)			
100:0	48.21	25.64	51.29

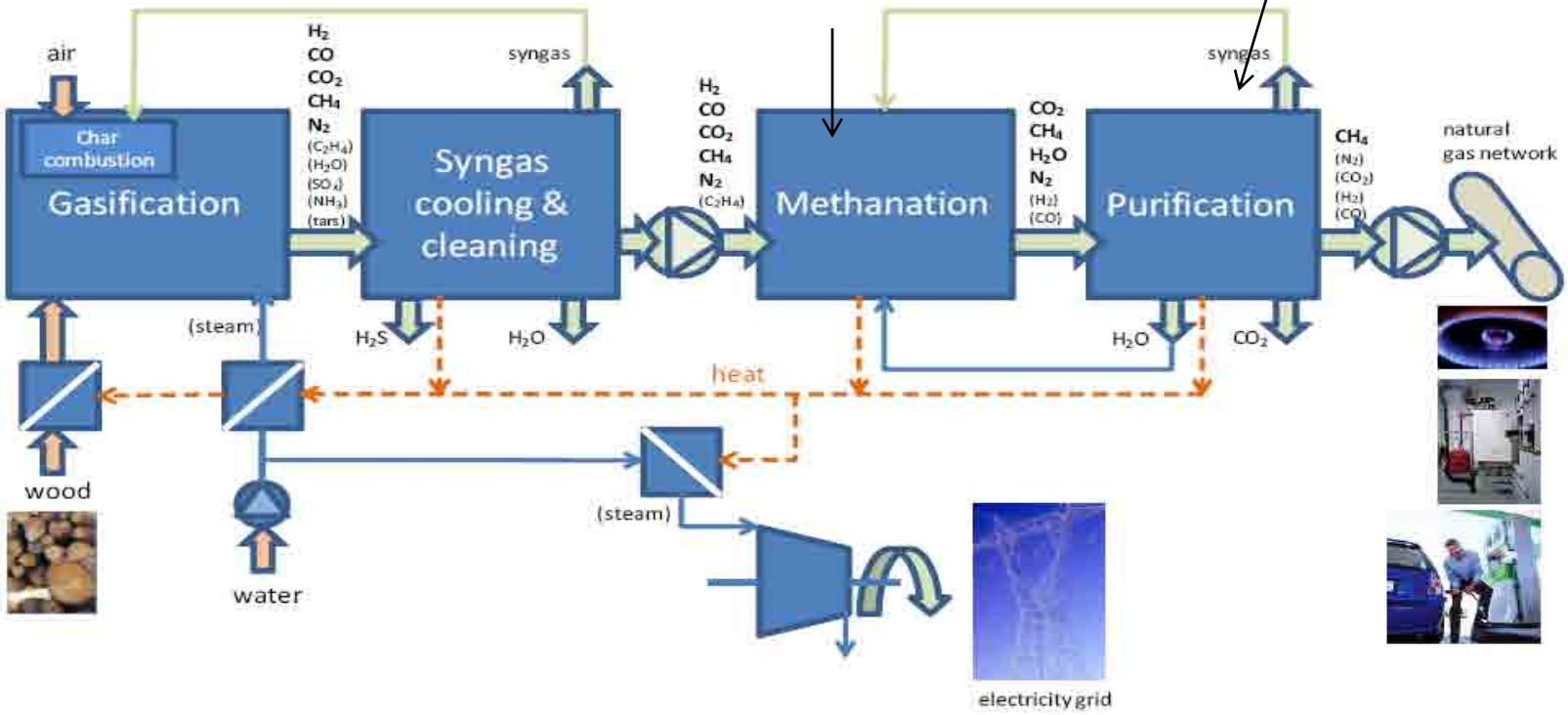
Thermal production of Biomethane

$CO + 3H_2 = CH_4 + H_2O$

$CO_2 + 4\,H_2 = CH_4 + 2H_2O$

$2CO + 2H_2 = CH_4 + CO_2$

Gas upgrading
Removal of CO2



Typically ca. 65% energy efficiency

Biofpr
Biofuels Bioproducts & Biorefining

Is it better to produce biomethane via thermochemical or biological routes? An energy balance perspective

Cathal Gallagher, Bord Gais Energy, Cork, Ireland
Jerry D Murphy, University College Cork, Cork, Ireland

Table 6. Best and worst case energy balances for grass and willow biomethane (values expressed in GJ/ha/a).

	Worst case		Best Case	
	Gross	Net	Gross	Net
Willow biomethane	95.3	82.7	130.6	116.7
Grass biomethane	122	77	163	122

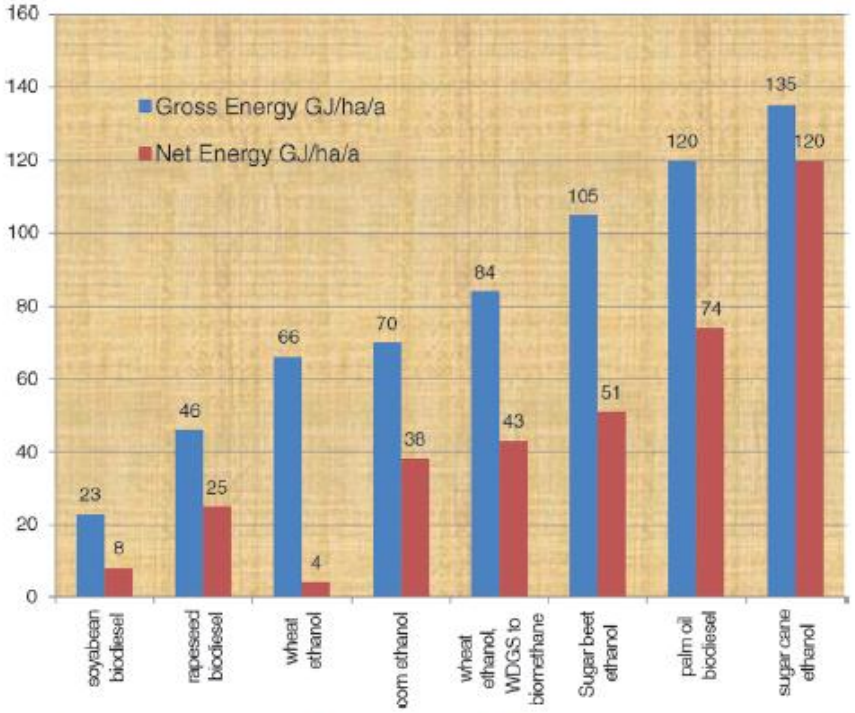


Fig. 2 Gross and net energy balance of selected biofuel systems. Adapted from[9].

Applied Energy 108 (2013) 158–167

Contents lists available at SciVerse ScienceDirect

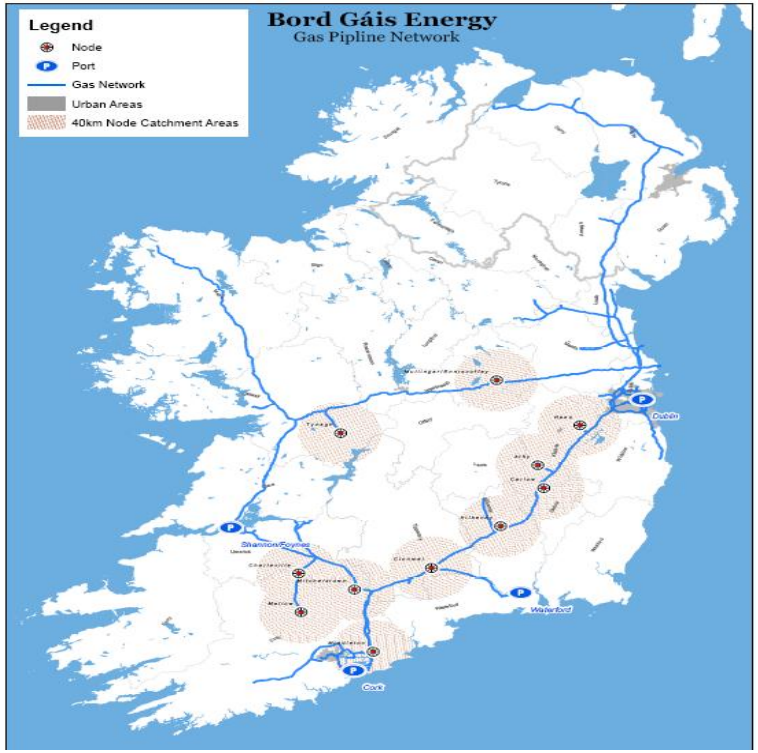
Applied Energy

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

What is the realistic potential for biomethane produced through gasification of indigenous Willow or imported wood chip to meet renewable energy heat targets?

Cathal Gallagher [a], Jerry D. Murphy [b,c,*]

Plant Size MWth	50
Land area (ha)	6800
Annual Energy Input (GJ)	1,440,000
Plant Efficiency	65%
Annual Energy Output (GJ)	936,000
Annual Energy Output (PJ)	0.94
Number of plants required	11
Energy Produced	10.34 PJ
As a % Energy in Transport	5.5%
As a % of agricultural land	1.7%



Contents lists available at SciVerse ScienceDirect

Applied Energy

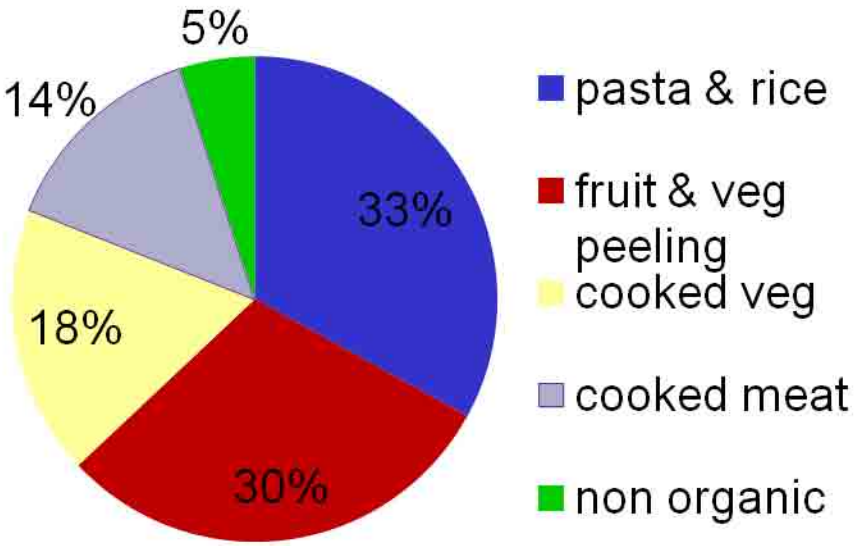
journal homepage: www.elsevier.com/locate/apenergy

Assessment of the resource associated with biomethane from food waste

James D. Browne, Jerry D. Murphy *

Department of Civil and Environmental Engineering, University College Cork, Ireland
Environmental Research Institute, University College Cork, Ireland

Food Waste from UCC canteen



Composition of UCC Food Waste (percentage mass)

$C_{16.5}\ H_{31.2}\ O_{9.5}\ N$

Table 1. Characteristics of Food Waste from UCC canteen

Parameters	Unit	Value
pH		4.05
Total Solids (dry solids)	% total mass	29.4 ± 1.1
Total Volatile Solids	% DS	95.3 ± 0.4
Proteins	% DS	18.1 ± 1.5
Carbohydrates	% DS	59.0 ± 3.0
Lipids (fats)	% DS	19.0 ± 0.8
% C	% DS	49.6 ± 1.2
% H	% DS	7.3 ± 0.2
% N	% DS	3.5 ± 0.4
% Ash	% DS	4.7 ± 0.4

Theoretical maximum methane production

(1) Energy Balance to estimate methane production

Energy content of food waste ~ 20.74 MJ/kg Volatile Solid (VS)

Energy content of CH_4 ~ 37.8 MJ/m^3

1 kg VS destroyed = 20.74MJ = 549 L CH_4 / kgVS

(2) Buswell Equation to estimate methane production

Stoichiometry description of food waste: $C_{16.5}\ H_{31.2}\ O_{9.5}\ N$

Buswell's Eqn.

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2$$

587 L CH_4 / kgVS

(3) Relationship between kg VS destroyed and COD produced

$$C_nH_aO_bN_c + \left(n + \frac{a}{4} - \frac{b}{2} - \frac{3c}{4}\right)O_2 \rightarrow nCO_2 + \left(\frac{a}{2} - \frac{3c}{2}\right)H_2O + cNH_3$$

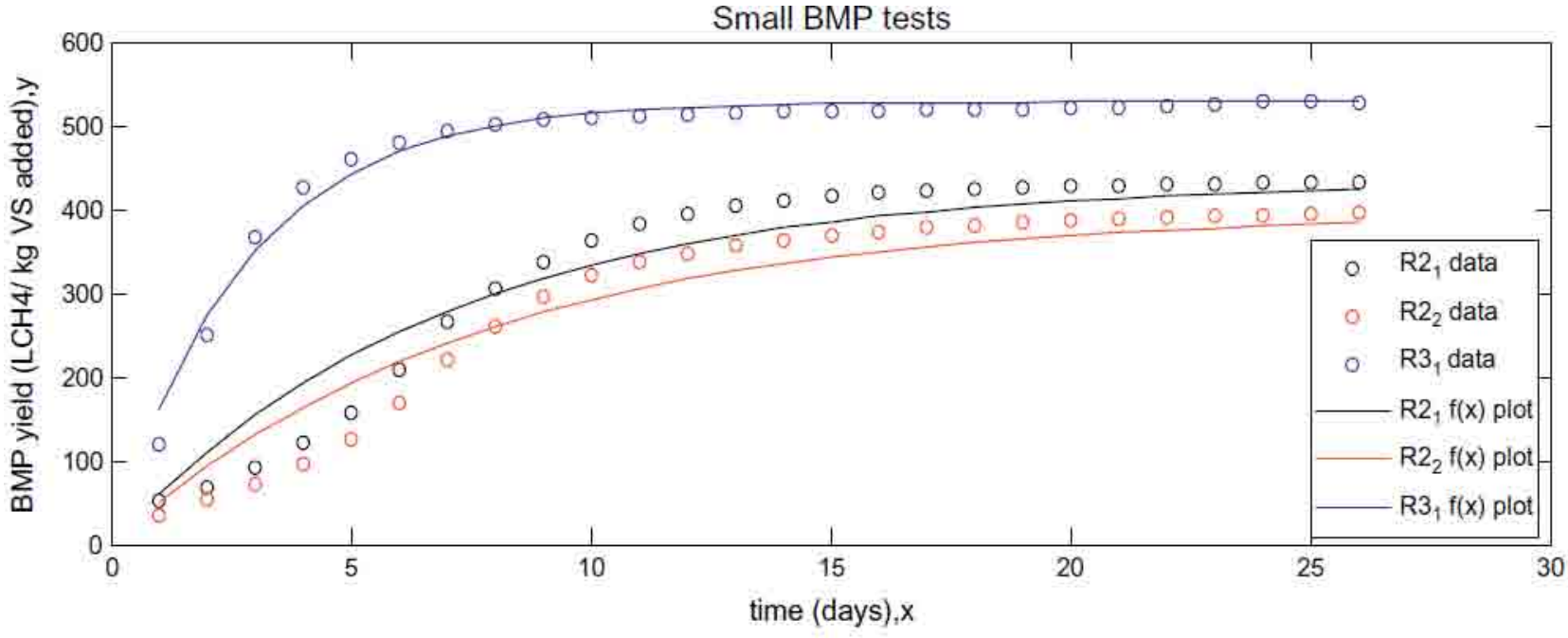
1.6 kg COD to oxidise 1 kg VS; 1 kg COD = 350 L CH_4;

560 L CH_4 / kgVS

Biomethane Potential Tests

Table 8
Biomethane yields from this study compared to the literature.

Author	Substrate	BMP yield ($m^3_N CH_4/tVS_{added}$)	Retention time (days)	Temp. range
This study	ssFW	467–529	30 days	37 ± 1 °C
Zhang et al. [12]	ssFW	455–456	30 days	36 ± 1 °C
Davidsson et al. [30]	ssOFMSW	300–400	15 days	55 °C
Cecchi et al. [29]	ssOFMSW	158–397	–	–
	ssFW	401–489		



Bioresource of Biomethane from OFMSW

Table 9
Bioresource of OFMSW beyond 2016.

Quantity of OFMSW	530,000 t/a
Quantity of VS (29.4% DS of which 95.3% VS)	148,500 t VS/a
BMP range 467–520 m^3_n CH_4/tVS	470 m^3_n CH_4/tVS
Biomethane production	70 million m^3_n/a
Energy value of methane (STP)	37.78 MJ/m^3_n
Biomethane production	2.65 PJ/a
Expected transport energy in Ireland 2020	188 PJ/a
Biomethane production (RES-T)	1.4%
Biomethane production (RES-T) including for credit	2.8%

Waste Management xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Waste Management

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

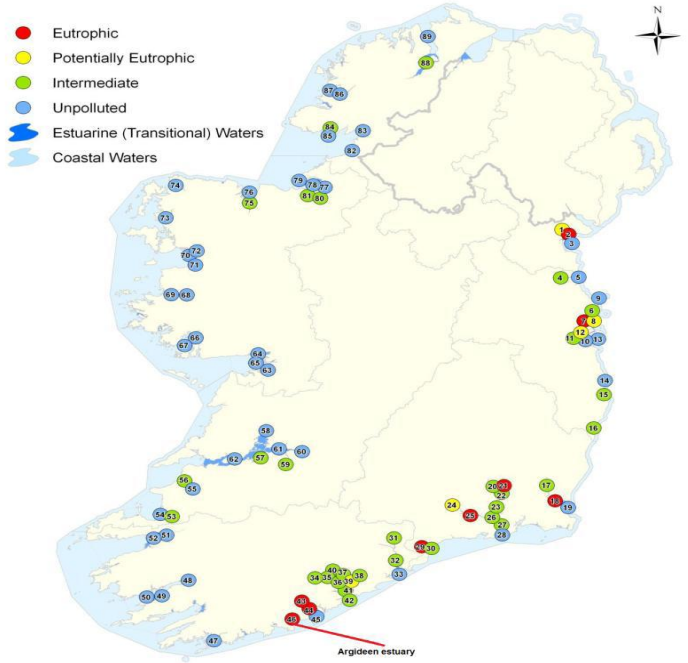
The potential of algae blooms to produce renewable gaseous fuel

E. Allen [a], J. Browne [a], S. Hynes [a], J.D. Murphy [a,b,*]

[a] Environmental Research Institute, University College Cork, Cork, Ireland
[b] Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland

Macro-algae: 3rd generation biofuel

- Green tides in eutrophic estuaries
- 10,000 tonnes of sea lettuce arise in West Cork annually
- Sufficient to power 264 cars per annum



20m3 CH4 /t wet vs 100 m3 CH4/t dry

Biogas from Ulva

Table 2
Ultimate analysis of *Ulva lactuca* samples.

Ulva lactuca	C	H	N	C:N ratio	DS (%)	VS (%)	pH	Protein (%)
1. Fresh	25.4	3.7	3.3	7.7	19	11	6.99	21.4
2. Wilted and unwashed	27.2	4.0	3.1	8.7	20	11	7.77	21.1
3. Washed and dried	22.3	3.3	2.3	9.6	72	40	7.35	23.7
4. Washed and wilted	23.3	3.2	2.6	8.8	32	16	7.60	20.8

Table 6
BMP results compared to theoretical yield.

Sample	BMP result L CH_4/ kg VS	Standard deviation	Max potential L CH_4/kg VS from Buswell, (Table 5)	Yield m^3 CH_4/t wet based on BMP	C:N ratio
Year 1					
1 Fresh	183.2	5.83	431	20.2	7.7
2 Wilted and unwashed	165.0	9.47	460	18.2	8.7
3 Washed and dried	250.2	13.32	394	100.1	9.6
4 Wilted and washed	221.1	22.74	402	35.4	8.8

Increased yields with co-digestion

Sample	BMP result L CH_4/ kg VS	Standard deviation	Max potential L CH_4/kg VS from Buswell, (Table 5)	Yield m^3 CH_4/t wet based on BMP	C:N ratio	Increased yield in co-digestion (%)
Slurry	136	2.99	382	7.00	19.8	
Dried Ulva	226	6.66	401	104.86	7.1	
Fresh Ulva	205	5.01	412	21.32	9.1	
Co-digestion						
Yield based on mono-digestion						
75% Fresh	220	4.91	188	20.11	11.77	+17.0
50% Fresh	200	11.2	171	15.88	14.45	+17.0
25% Fresh	183	7.85	153	12.30	17.12	+19.6
75% Dried	210	6.31	203	75.915	10.275	+3.4
50% Dried	193	5.42	181	50.064	13.45	+6.7
25% Dried	186	8.81	158	29.24	16.62	+17.7

Literature on Biogas from Ulva

Ulva Lactuca	Pre-treatment	SMY (L CH_4/kg VS)	Country	Reference
No pre-treatment				
Fresh		183	Ireland	Allen et al., 2013
Fresh		174	Denmark	Bruhn et al., 2011
Fresh		128	France	Peu et al., 2011
Unwashed				
Unwashed	Wilted	165	Ireland	Allen et al., 2013
Unwashed	Macerated	271	Denmark	Bruhn et al., 2011
Washed not dried				
Washed	Chopped	171	Denmark	Bruhn et al., 2011
Washed	Milled	191	Ireland	Vanegas and Bartlett 2013
Washed	Macerated	200	Denmark	Bruhn et al., 2011
Washed	Wilted	221	Ireland	Allen et al., 2013
Dried with size reduction				
Washed and dried	Chopped	241	France	Jard et al., 2013
Washed and dried	Macerated	250	Ireland	Allen et al., 2013

Himanthalia elongate

Laminaria Digitata

Fucus Serratus

Saccharina Latissima

Ascophylum Nodosum

Sea weed	BMP Yield	Country	Reference
Brown Seaweeds			
H. elongate	261	West Cork, Ireland	Allen et al. 2014
	202	Brittany, France	Gard et al., 2013
L. digitata	218	West Cork, Ireland	Allen et al. 2014
	246	Sligo, Ireland	Vanegas and Bartlett 2013
F. serratus	236	West Cork, Ireland	Allen et al. 2014
S. latissima	342	West Cork, Ireland	Allen et al. 2014
	335	Sligo, Ireland	Vanegas and Bartlett 2013
	223	Trondheim, Norway	Vivekanand et al, 2011
	220	Norway	Østgaard et al.
	209	Brittany, France	Gard et al., 2013
A. nodosum	166	West Cork, Ireland	Allen et al. 2014
U. pinnatifida	242	Brittany, France	Gard et al., 2013
S. polyschides	225	Sligo, Ireland	Vanegas and Bartlett 2013
	216	Brittany, France	Gard et al., 2013
S. muticum	130	Brittany, France	
Red Seaweeds			
P. palmata	279	Brittany, France	Gard et al., 2013
G. verrucosa	144	Brittany, France	Gard et al., 2013

Resource of Macro-algae

The island of Orkney has a kelp forest of 1 million tons covering 22,000 hectares along 800 km of coastline (Christiansen, 2008).

Assuming: 20% Dry Solids 250 L CH4/kg VS equivalent to 50,000,000 L diesel

A 1 ha farm could yield 130 wet tonnes of kelp per annum (Christiansen, 2008).

20% Dry Solids = 26 tDS/ha/a @ 250 L CH_4/kg VS

6,500 L diesel equivalent /ha/a or **234 GJ/ha/a**

(compare with rapeseed 1350 biodiesel L /ha/a or 44 GJ/ha/a)

Ryan C. Christiansen (2008) British report: Use kelp to produce energy Available In:http://www.biomassmagazine.com/articles/2166/british-report-use-kelp-to-produce-energy/

Table 6. Best and worst case energy balances for grass and willow biomethane (values expressed in GJ/ha/a).

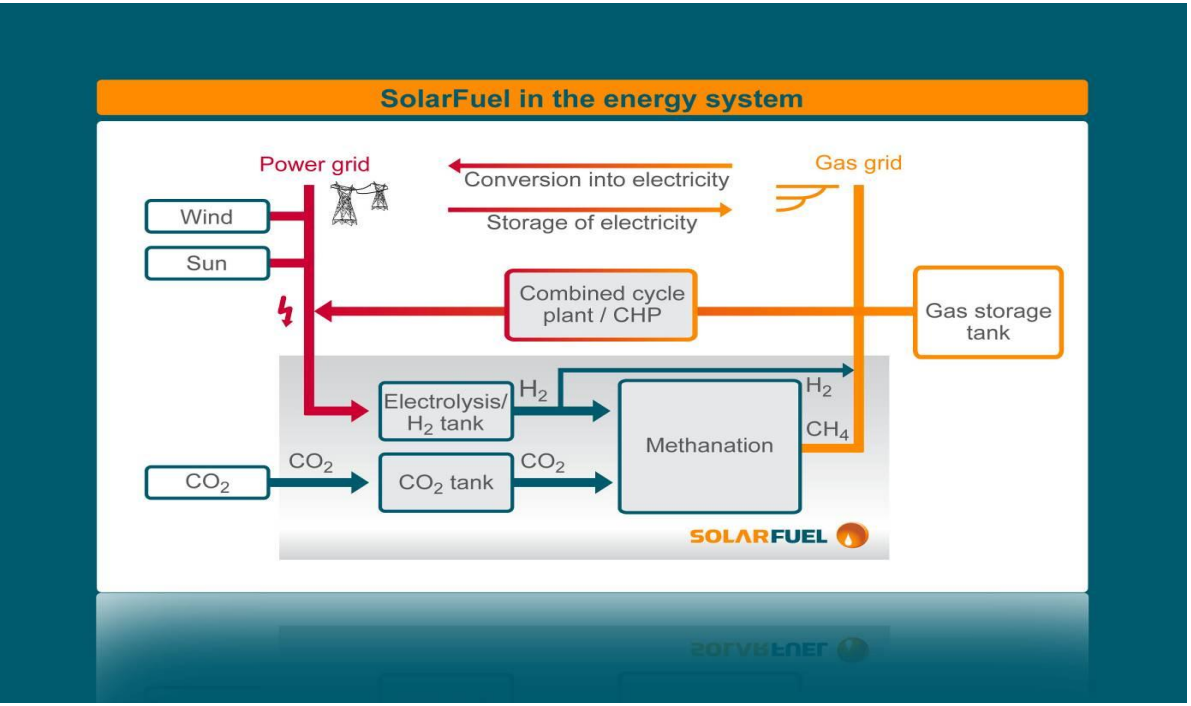
	Worst case		Best Case	
	Gross	Net	Gross	Net
Willow biomethane	95.3	82.7	130.6	116.7
Grass biomethane	122	77	163	122

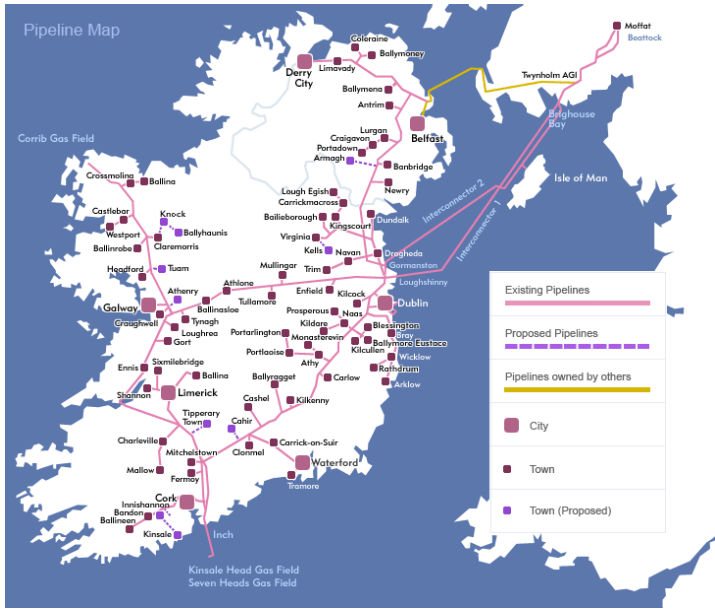
Electricity to Methane via Hydrogen coupled with Carbon Sequestration

H_2: energy Density 12.1 MJ/m_n^3 : CH_4: Energy density 37.6 MJ/m_n^3

Sabatier Equation: $4H_2 + CO_2 = CH_4 + 2H_2O$ ΔH_{298} =-165 kJ/mol

Typically ca. 60% energy efficiency
(75% conversion of electricity to H2; 80% conversion of H2 to CH4)





http://www.solar-fuel.net/en/the-challenge

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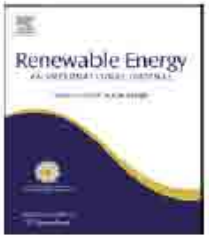

The resource of biomethane, produced via biological, thermal and electrical routes, as a transport biofuel

Jerry D. Murphy [a,b,*], James Browne [a,b], Eoin Allen [a,b], Cathal Gallagher [c]

Resource	Energy in transport	
Grass (100,000 ha)	15.8 PJ	8.4%
Food waste (530,000 t/a)	2.65 PJ	1.4%
Gasification 75,000 ha Willow	10.34 PJ	5.5%
Electricity	8 PJ	4.2 %
Total	36.8 PJ	19.5%

Resource equates to 1000 Mm^3/year biomethane, VW Passat consumes 4.5 kg / 100 km (6.3m^3/100km). Average car in Ireland travels 16,708 km/year

Resource equals 950,000 cars or 48% of private fleet

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SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

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With pressure increasing to utilise wastes and reduce effectively and sustainably, the production of biogas represents one of the most important routes towards reaching national and international renewable energy targets. *The biogas handbook: Science, production and applications* provides a comprehensive and systematic guide to the development and deployment of biogas supply chains and technology.

Following a concise overview of biogas as an energy option, Part I explores biomass resources and fundamental science and engineering of biogas production, including feedstock characterisation, storage and pre-treatment, and yield optimisation. Plant design, engineering, process optimisation and digestate utilisation are the focus of Part II. Topics considered include the engineering and process control of biogas plants, methane emissions in biogas production, and biogas digestate quality, utilisation and land application. Finally, Part III discusses international experience and best practice in biogas utilisation. Biogas cleaning and up-grading to biomethane, biomethane use as transport fuel and the generation of heat and power from biogas for stationary applications are all discussed. The book concludes with a review of market development and biomethane certification schemes.

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Arthur Wellinger is Managing Director of Triple E A.M, an internationally operating research and consulting company located in Switzerland, and President of the European Biogas Association. Jerry Murphy is the Lead Investigator in Bioenergy and Biofuels in the Environmental Research Institute at University College Cork, Ireland and represents Ireland at IEA Bioenergy. David Baxter is a Project Leader at the European Commission Joint Research Centre, The Netherlands and the leader of Task 37 of IEA Bioenergy.

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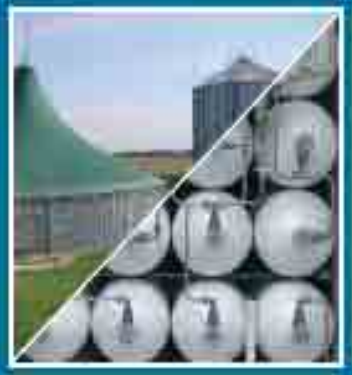

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