Optimisation of Grass Digestion

Dr Jerry Murphy, Dr Abdul Sattar Nizami, Dr Thanasit Thamsiriroj, Dr Beatrice Smyth, Dr Nicholas Korres, Dr Anoop Singh, James Browne, Eoin Allen, David Wall.

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Biogas Process Optimisation
18th April 2013,
International Energy Agency, Berne, Switzerland

ENVIRONMENTAL RESEARCH INSTITUTE
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Coláiste na hOllscoile Corcaigh, Éire
University College Cork, Ireland

Bioenergy and Biofuels Research Group (B^2RG)

- Funding of €3.5 M since inception in 2007 from:
  - EPA, SFI, DAFF, IRCSET, BGE, BGN, HEA PRTLI, Marie Curie ITN, Ecoventii
- Published
  - 58 peer review journal papers
  - 29 peer review conference papers
- Papers have received 1255 citations, H factor of 21
- Graduated 4 PhD students, 3 in place, funding for 6 more
- Supervised 4 post-doctorates, funding for 2 more.

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

Research in transport and thermal sector

Research Drivers

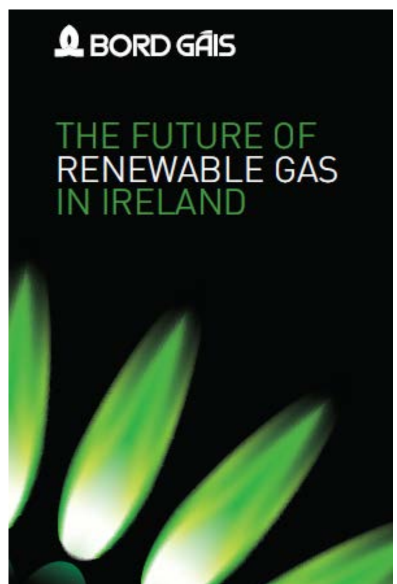
***EC, Proposal for a DIRECTIVE OF THE EUROPEAN PARLIMENT* Brussels 2012.**
In : http://ec.europa.eu/clima/policies/transport/fuel/docs/com_2012_595_en.pdf

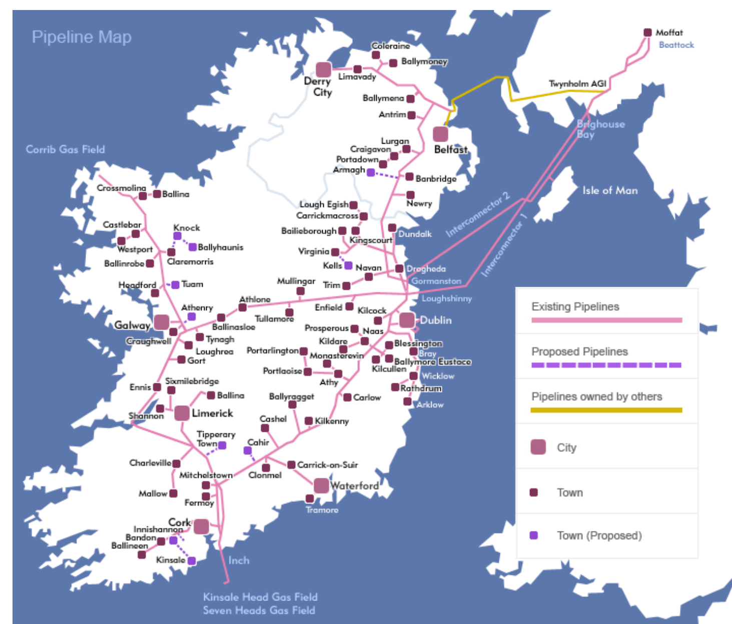
The share of biofuels from cereal and other starch rich crops, sugar and oil crops limited to consumption in 2011 (ca. 5%)

Biofuels (from algae, municipal solid waste, manures and residues) and gaseous fuels from non biological origin shall be considered at 4 times energy content

What will fuel transport systems of the future?

1.6% RES-T from 10% EVs





Laboratory

State of art measurement facilities

30 No.1.5 L reactors

16 No. 5 L reactors

2 step 60 L reactors

2 step 600 L reactors

2nd Gen bioreactor

High Solids Content Substrates

Compare Ultimate and Proximate Analysis of Food Waste and Grass Silage

Parameters	UCC Food waste	Grass Silage
pH	4.1	4.3
Dry Solids (%)	29.4	30.6
Total Volatile Solids (% DS)	95.3	92.5
% C (% DS)	49.6	43.0
% H (% DS)	7.3	5.8
% N (% DS)	3.5	1.6
% Ash (% DS)	4.7	7.5
C:N ratio	14.2	26.9

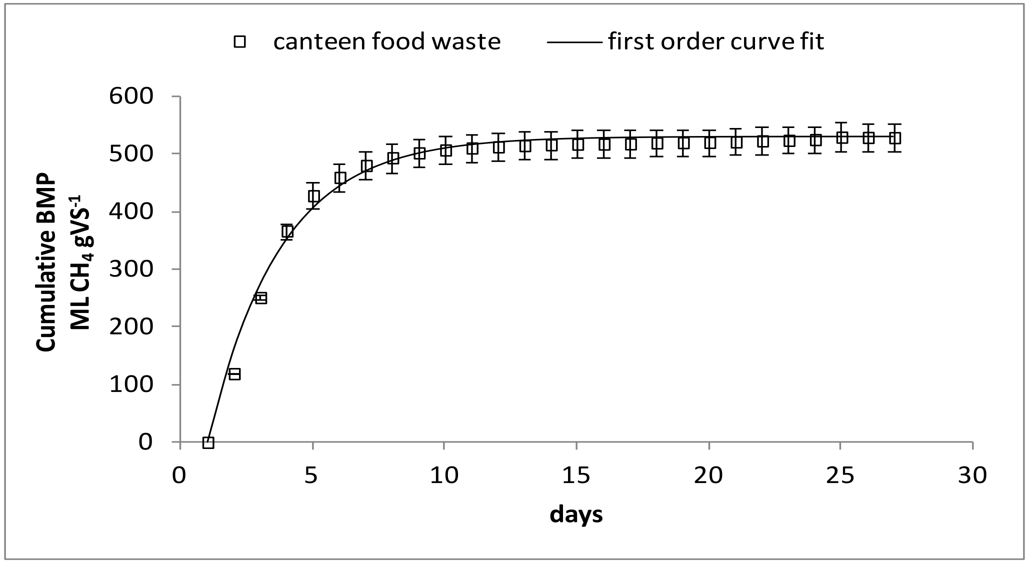
Theoretical maximum methane production from food waste

Buswell Equation

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

UCC Food waste (from ultimate analysis)	$C_{16.4}$ H_{29} $O_{9.8}$ N
Maximum Theoretical Production	550 L CH_4 / kgVS

Biomethane potential



AMPS system (from Lund University)

$Y = Y_m * (1 - \exp(^{-kt}))$ 1[st] order Equation, Y cumulative methane yield per day, Ym is ultimate methane yield and k is first order decay constant.

Substrate	BMP *L CH_4 kg^{-1} VS*	Buswell *L CH_4 kg^{-1} VS*	Biodegradability Index	k	Rsq
Food Waste	529	550	0.96	0.364	0.98
Grass	400	443	0.90	0.107	0.95
Fresh Ulva	183	431	0.42	0.110	0.98

Biogas from Crop Digestion

Jerry MURPHY
Rudolf BRAUN
Peter WEILAND
Arthur WELLINGER

Methane yields from digestion of crops

Tab. 1: Examples of methane yields from digestion of various plants and plant materials as reported in literature (Data compilation after Braun, 2007)

Methane yield (m^3 per tonne volatile solids added)

Maize (whole crop)	205-450	Barley	353-658
Wheat (grain)	384-426	Triticale	337-555
Oats (grain)	250-295	Sorghum	295-372
Rye (grain)	283-492	Peas	390
Grass	298-467	Alfalfa	340-500
Clover grass	290-390	Sudan grass	213-303
Red clover	300-350	Red Canary Grass	340-430
Clover	345-350	Ryegrass	390-410
Hemp	355-409	Nettle	120-420
Flax	212	Miscanthus	179-218
Sunflower	154-400	Rhubarb	320-490
Oilseed rape	240-340	Turnip	314
Jerusalem artichoke	300-370	Kale	240-334
Potatoes	276-400	Chaff	270-316
Sugar beet	236-381	Straw	242-324
Fodder beet	420-500	Leaves	417-453

BIOMASS AND BIOENERGY 33 (2009) 504–512

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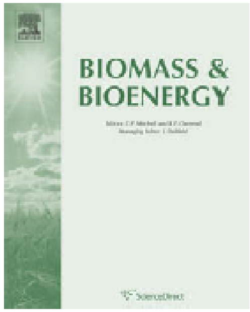

An argument for using biomethane generated from grass as a biofuel in Ireland

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

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[b]*Environmental Research Institute, University College Cork, Cork, Ireland*
[c]*Department of Civil, Structural and Environmental Engineering, Cork Institute of Technology, Cork, Ireland*

Grass is a perennial
Grass lands sequester carbon
Grass can be outside food fuel debate
Grass is ligno-cellulosic?
Grass is a second generation gaseous biofuel which can be used in NGV vehicles
Natural Gas Grid can be distribution system.

Grass to transport fuel

harvest →

weigh bridge →

silage storage ↓

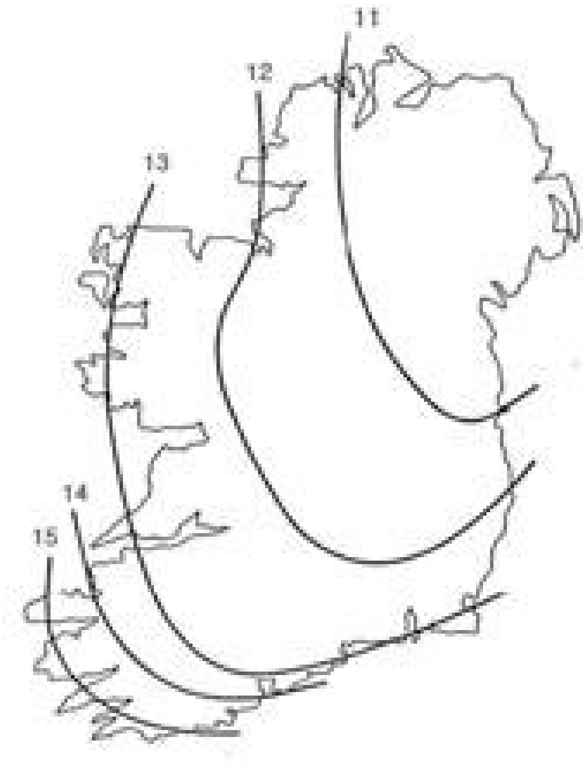
macerator

anaerobic digester → Scrubbing & storage

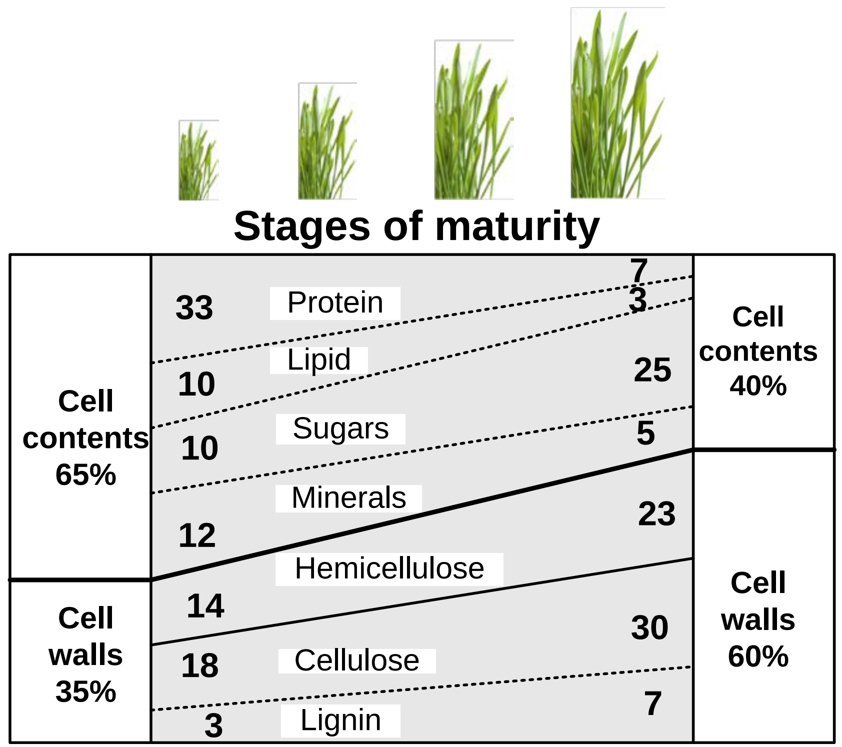
Biogas service station

Source: energiewerkstatt, IEA and personal photos

Variability of crop yields and digestibility



Grass yields t DS.ha^{-1}.a^{-1}



Reduced methane yield with age of grass

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*
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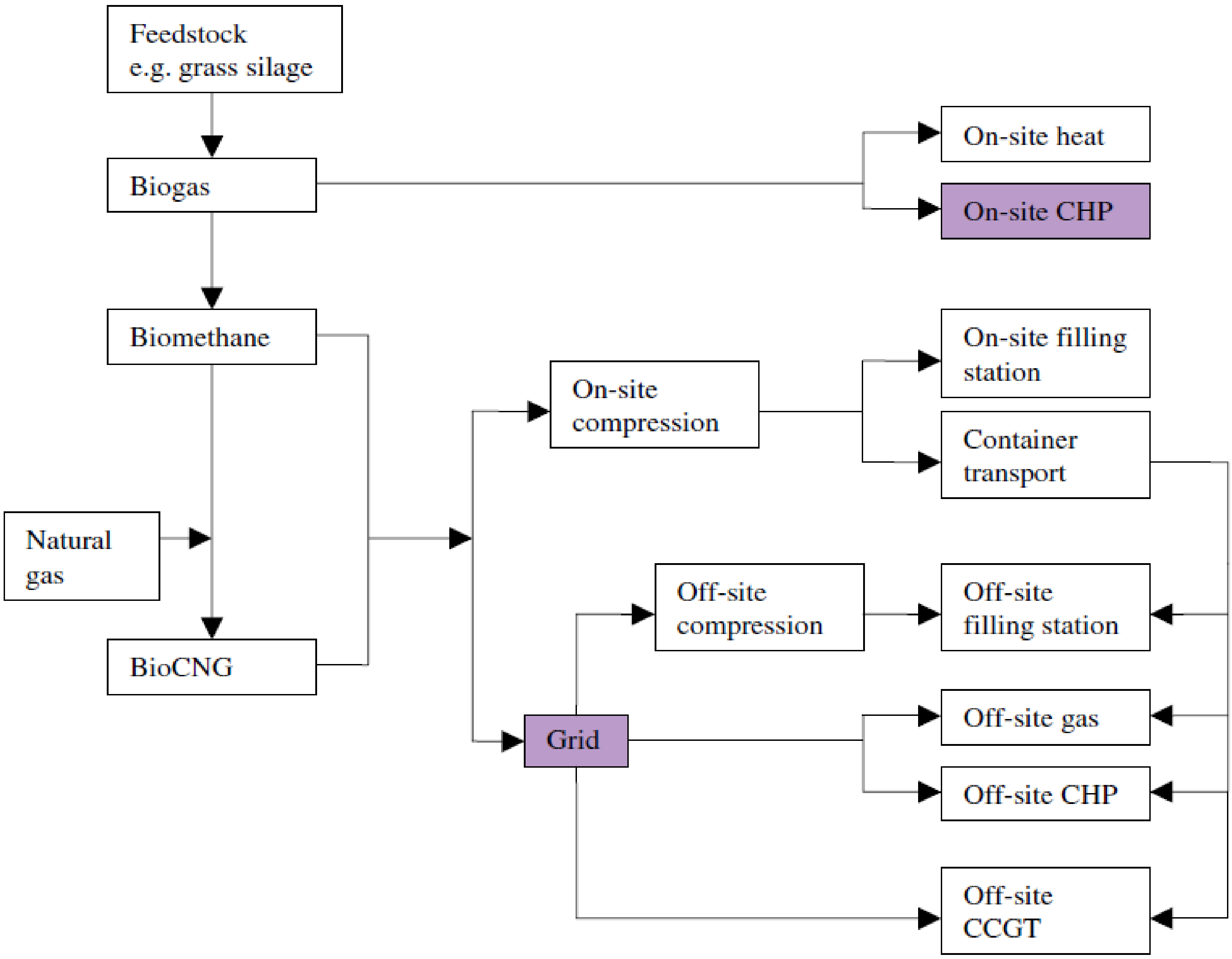
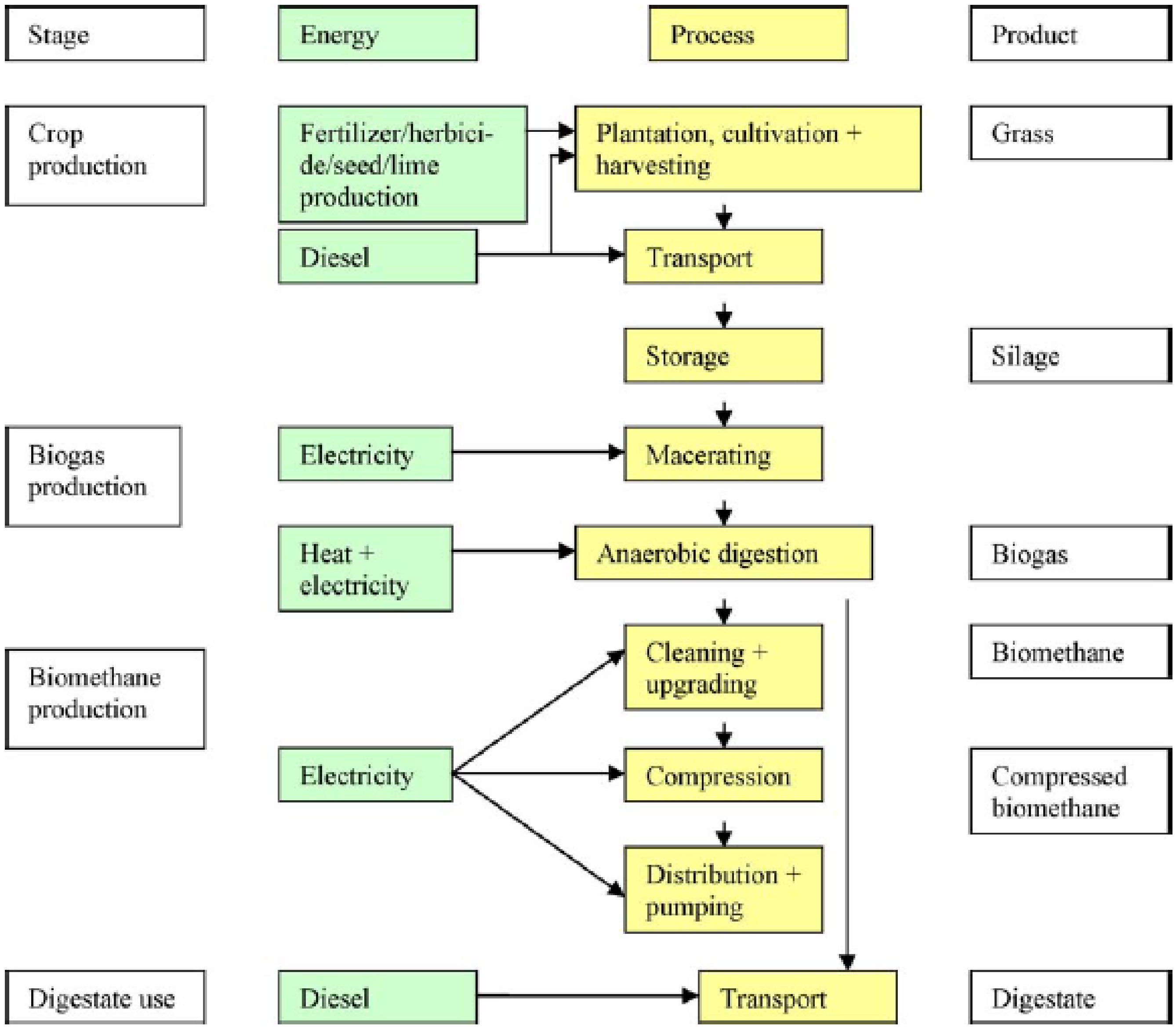
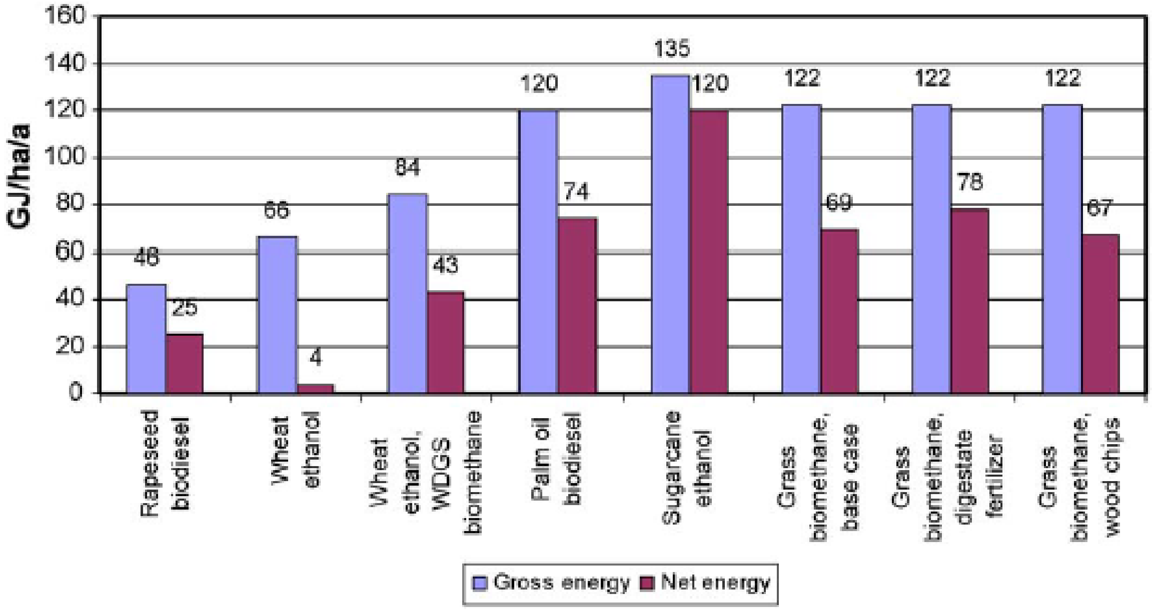
Pathways for use of biogas




Stage
Energy
Process
Product
Crop production
Fertilizer/herbicide/seed/lime production
Plantation, cultivation + harvesting
Grass
Diesel
Transport
Storage
Silage
Biogas production
Electricity
Macerating
Heat + electricity
Anaerobic digestion
Biogas
Biomethane production
Cleaning + upgrading
Biomethane
Electricity
Compression
Compressed biomethane
Distribution + pumping
Digestate use
Diesel
Transport
Digestate

Net energy yield per hectare of crops



Based on 300L CH4/kg VS and 12 t TS/ha/a

	Maize	Grass
Methane yield $m^3 . ha^{-1}$	5,748	4,303
$GJ . ha^{-1}$	217	163
Process energy demand for digestion $GJ. ha^{-1}$	33	24
Energy requirement in cropping $GJ. ha^{-1}$	17	17
Total energy requirement $GJ. ha^{-1}$	50	41
Net energy yield $GJ.ha^{-1}$	167	122
Output ($GJ.ha^{-1}$) / Input (tot. Energy)	4.3	4.0

Based on 380L CH4/kg VS and 12.5 t TS/ha/a

Modeling and Analysis

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

Received December 15, 2009; revised version received February 8, 2010; accepted February 11, 2010
Published online in Wiley InterScience (www.interscience.wiley.com); DOI: 10.1002/bbb.228;
***Biofuels, Bioprod, Bioref.* 4: 310–325 (2010)**

Table 3. Direct energy consumption and related CO_2 emissions during the eight year crop cycle (emissions from diesel production are included).

Operations	Energy Consumed (MJ ha^{-1} yr^{-1})		Average Energy consumed (MJ ha^{-1} yr^{-1})	CO_2 Emissions (kg CO_2 ha^{-1} yr^{-1})		Average Emissions (kg CO_2 ha^{-1} yr^{-1})	g CO_2 e MJ^{-1} Energy Replaced
	Year 1	Year 2-8		Year 1	Year 2-8		
Ploughing	1141.7	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
Fertilizer[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]	1309.0	1309.0	1309.0	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	**4210.5**	**2787.9 (2814.9, 2810.4)[h]**	**2975.3**	**375.5**	**247.7 (250.1, 249.7)[h]**	**264.5**	**2.67**

[a]Data of energy consumption for rolling and ensiling from Smyth *et al.*[3]
[b]Fertilizer is applied four times during the first year of the crop cycle and twice every other year after each harvesting .
[c]Lime is applied in two intervals during the crop cycle, the first and fifth year after establishment.
[d]Herbicides are applied before ploughing and after sowing to favor crop against weed competition at the first year and twice during the rest of crop cycle, the 3rd and 6th year (corresponding values for energy consumption and related emissions are shown in the 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 with excluding empty return. The energy consumption for transport is assumed as 1 and 1.6 MJ t^{-1} km^{-1} with excluding and including empty return, respectively.[9] Energy required for loading and spreading of digestate is assumed as 2.5 and 17 MJ t^{-1}, respectively.[21]
[f]Harvesting includes operations such as cutting, mowing and turning the grass.
[g]Ensiling is comprised of operations such as silage collection, unloading and inlaying.
[h]First number in the parentheses represent values for the 3rd and 6th year and second number for the 5th.

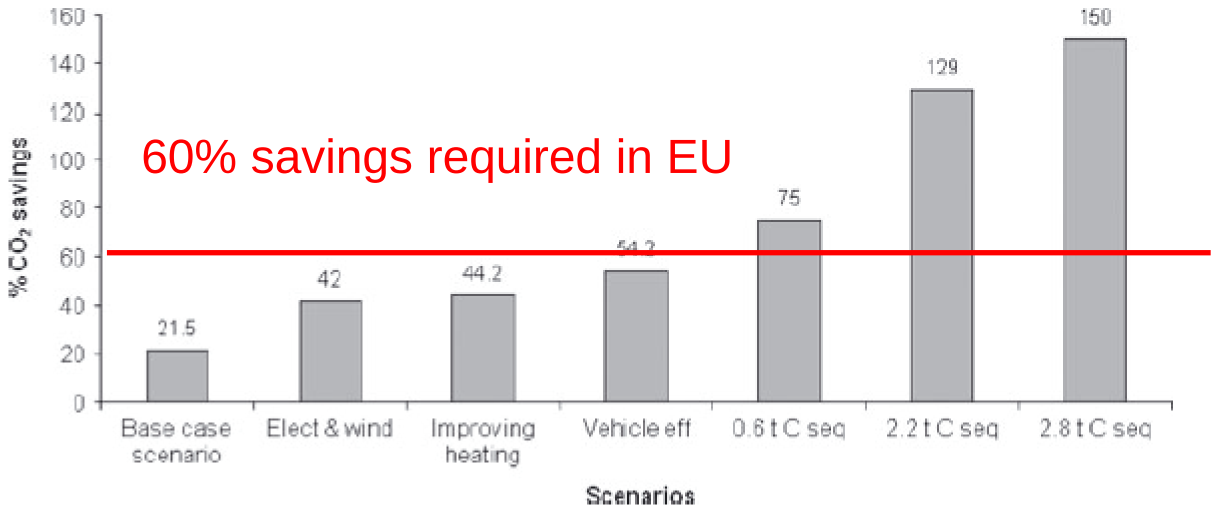


Figure 3. Percent CO_2 savings over fossil diesel under a range of C sequestration and various scenarios in biomethane production (The scenarios are cumulative left to right, for example improving heat includes for elect & wind and base case scenario).

Table 10. Typical values for greenhouse gas savings for biofuel systems from the renewable energy directive[4]

Biofuel system	% savings in greenhouse gas compared to fuel replaced
Wheat ethanol	32%
Rapeseed biodiesel	45%
Sunflower biodiesel	58%
Sugarbeet ethanol	61%
Palm oil biodiesel	62%
Biogas from MSW	80%

Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

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

Beatrice M. Smyth, Environmental Research Institute (ERI), University College Cork (UCC), Ireland
Henry Smyth, Bord Gáis Éireann, Cork, Ireland
Jerry D. Murphy, ERI, UCC, Ireland

Economic viability of biogas from energy crops

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

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

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

Grass silage:
Costs approximately €25 t^{-1} for pit silage (20% VS) = €125/ t VS
Produces about 400m_n^3 of CH4/ t VS
Feedstock cost is of the order of € c 31/ mn3 or € c 31/L diesel equiv

Economic viability of biogas as a transport fuel

Fuel	Unit cost	Energy value	Cost per unit energy ($€c\ MJ^{-1}$)
Petrol	€1.60 L^{-1}	30 MJ. L^{-1}	5.3
Diesel	€1.60 L^{-1}	37.4 MJ. L^{-1}	4.3
Biomethane from grass	€1.06 m_n^{-3}	37 MJ. m_n^{-3}	2.9
CNG – UK	€0.71 m_n^{-3}	37 MJ. m_n^{-3}	1.9
Bio-CNG [a]	€0.75 m^{-3}	37 MJ. m_n^{-3}	2.0

[a] Bio-CNG price calculated using UK CNG prices and a blend of 10% biomethane, 90% CNG. No excise on gas as a propellant; VAT charged at 21%

Renewable and Sustainable Energy Reviews xxx (2011) xxx–xxx

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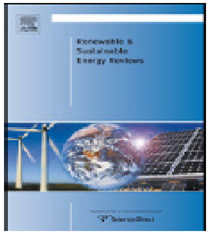

A roadmap for the introduction of gaseous transport fuel: A case study for renewable natural gas in Ireland

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

[a] *Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland*
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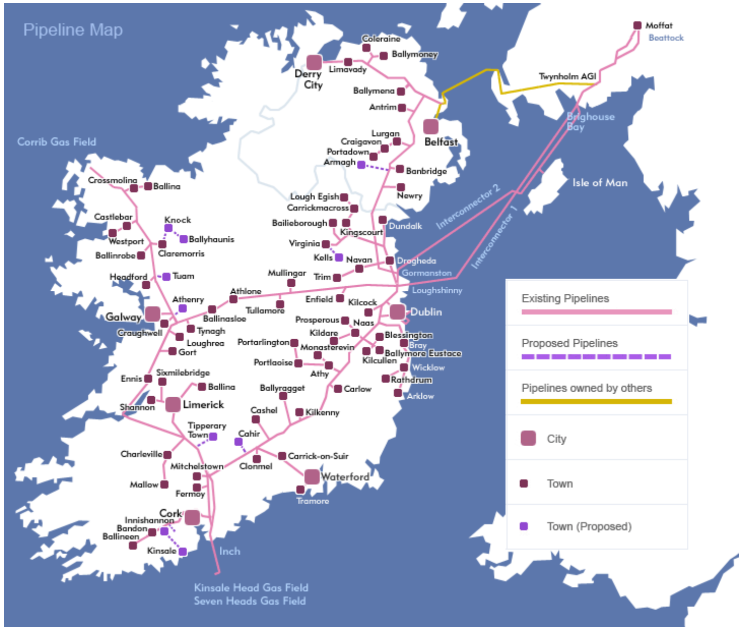
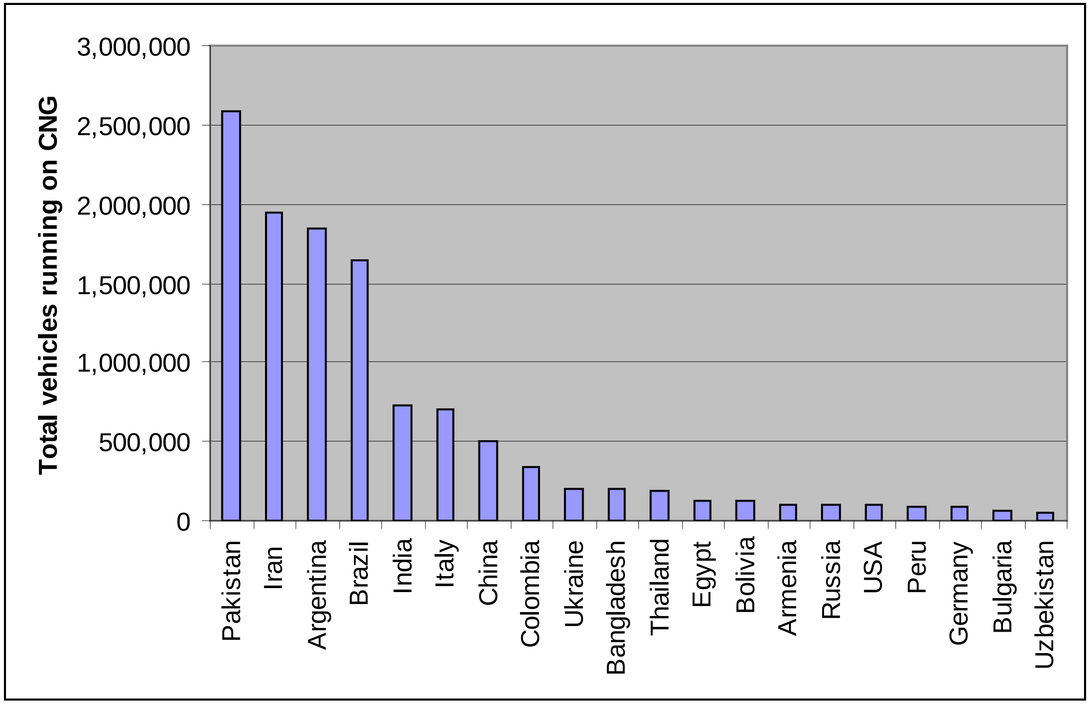
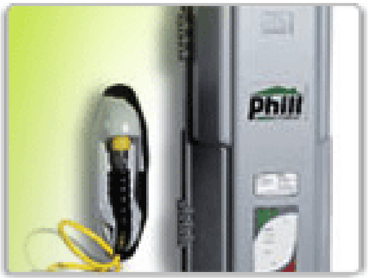


Number of vehicles running on GNG worldwide





Bioresource Technology xxx (2010) xxx–xxx

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Bioresource Technology

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

Modelling mono-digestion of grass silage in a 2-stage CSTR anaerobic digester using ADM1

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

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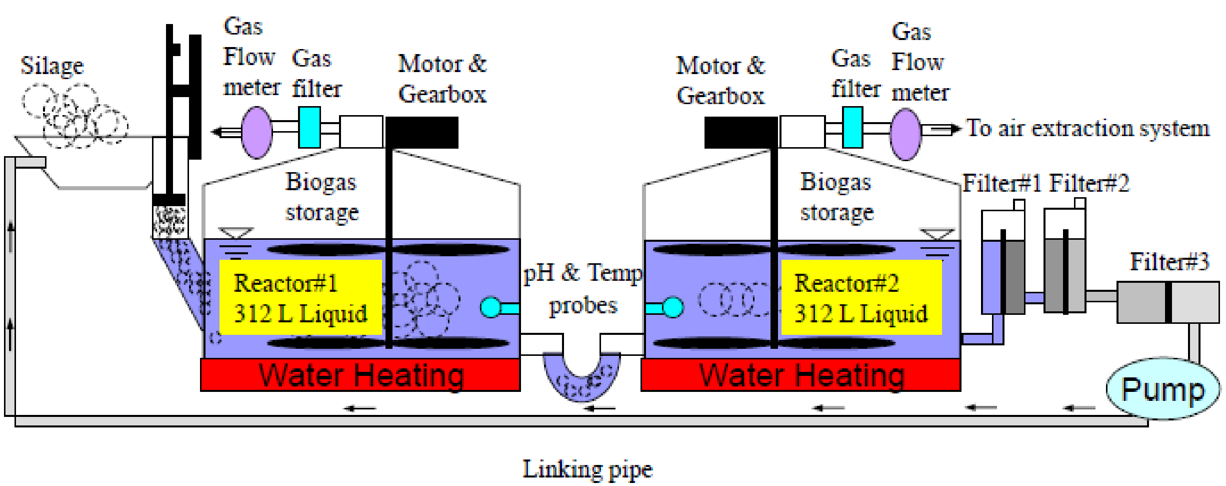
Continuously Stirred Tank Reactor



Continuously Stirred Tank Reactor

Achieved:

- 451 L CH_4 kg^{-1} VS
- 90% VS destruction
- 50 day retention time
- 2 kg VS m^{-3} d^{-1}

Energy Fuels XXXX, XXX, 000–000 · DOI:10.1021/ef100677s

energy&fuels article

Role of Leaching and Hydrolysis in a Two-Phase Grass Digestion System

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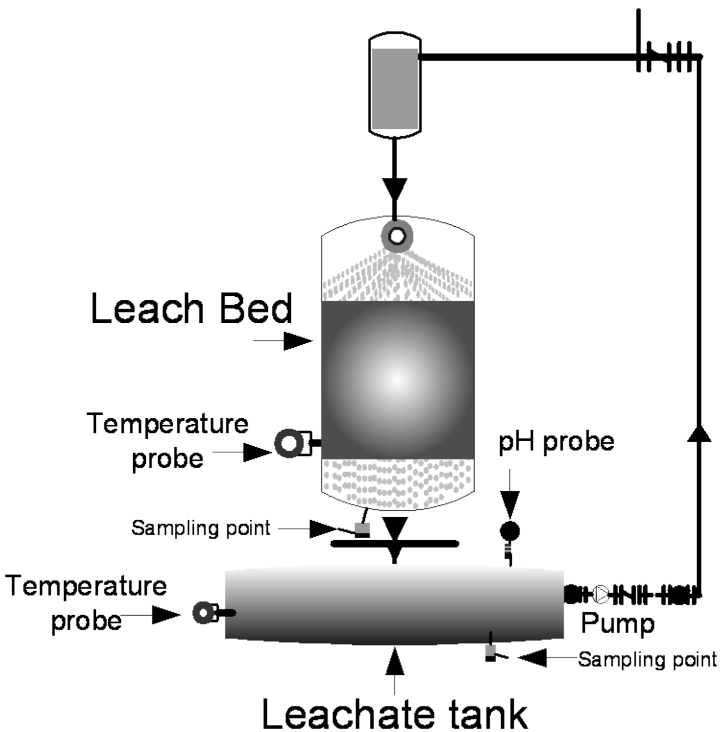


Four variables considered in analysis:
- Sprinkling v's flooding
- Pit (20% DS) v's Bale (30%DS)

Best result:
- Sprinkling of bale silage
- 70% destruction of volatiles in 30 days

Environmental Science & Technology

ARTICLE

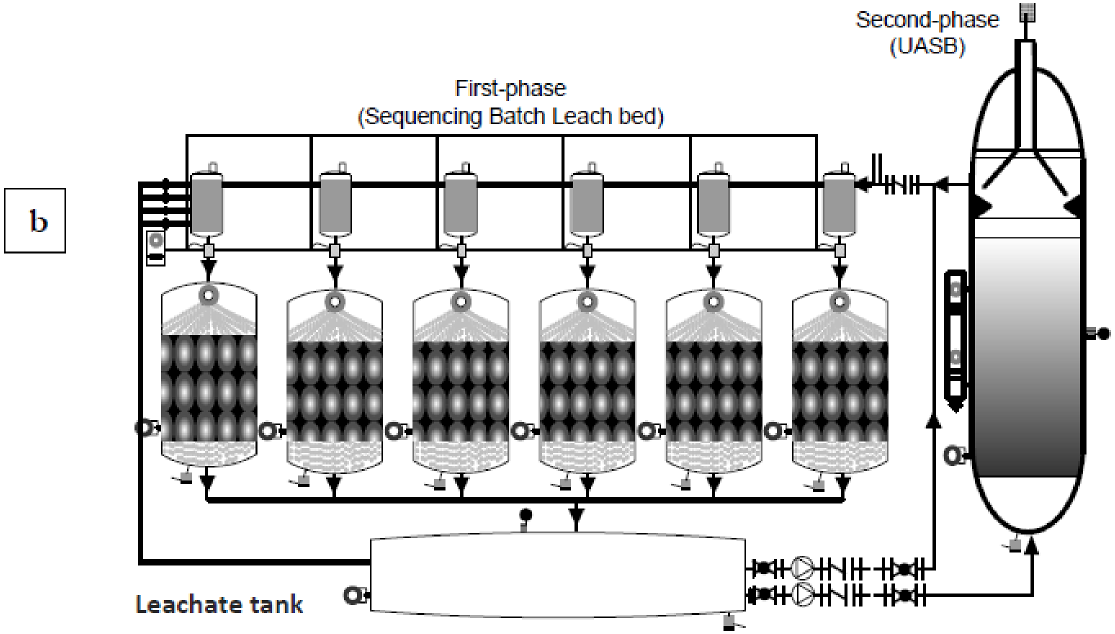
pubs.acs.org/est

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

Abdul-Sattar Nizami and Jerry D. Murphy*

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

Sequencing leach bed reactor complete with Upflow Anaerobic Sludge Blanket (SLBR-UASB)



Derived relationships

1 kg VS = 1.4 kg COD

1 kg COD = 350 L CH_4

One Pump: 70.5% destruction of volatiles * 1.4 kg COD / kg VS * 90% UASB efficiency * 350 L CH_4 / kg COD = 310 L CH_4 / kg VS added at 42 day HRT

Two Pumps: 75% destruction of volatiles * 1.4 kg COD / kg VS * 93% UASB efficiency * 350 L CH_4 / kg COD = 341 L CH_4 / kg VS added at 30 day HRT

Applied Energy xxx (2011) xxx–xxx

Contents lists available at SciVerse ScienceDirect

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

	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

Single phase versus two phase

Both ran for more than a year….inoculum acclimatized.

SLBR-UASB has a shorter retention time than CSTR;

- it should be a smaller (cheaper?) system

SLBR produces a biogas rich in methane (71% vs 52%)

- thus requiring less upgrading for use as a transport fuel or for grid injection.

SLBR produces a digestate with twice dry solids content of CSTR

- may have more potential for biorefinery concepts.

Ongoing Research

Food waste: 2nd generation biofuel

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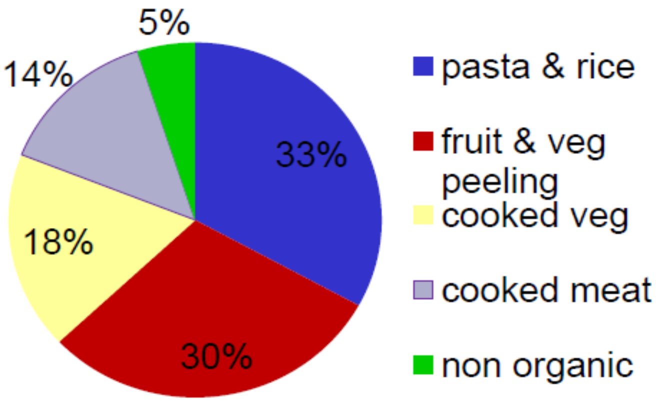
Applied Energy

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

Assessment of the resource associated with biomethane from food waste

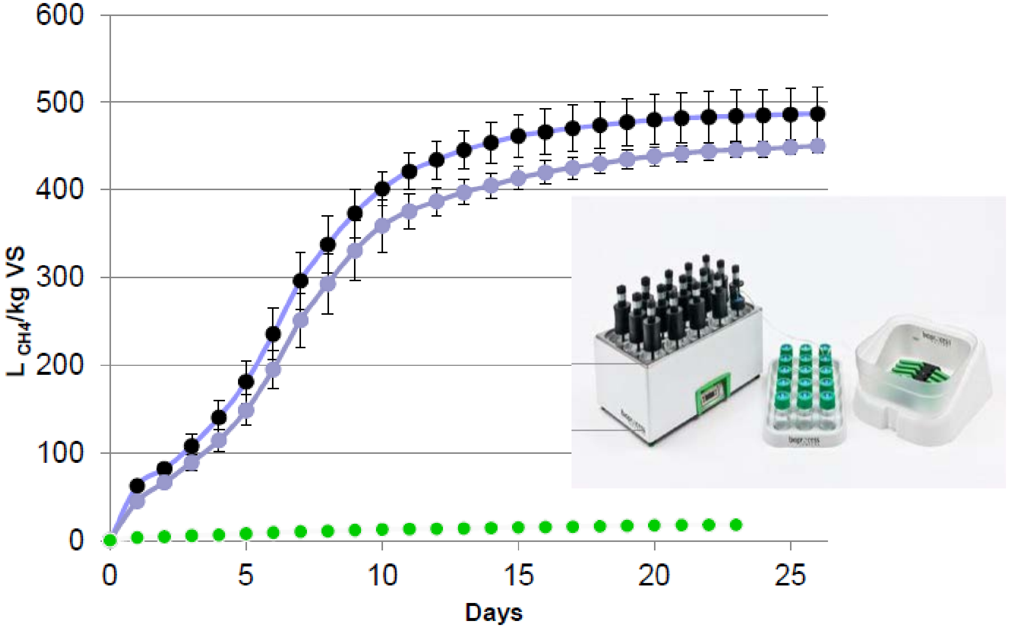
James D. Browne, Jerry D. Murphy *

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



Composition of UCC Food Waste (percentage mass)

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



530,000 t/a food waste can generate 2.8% RES-T

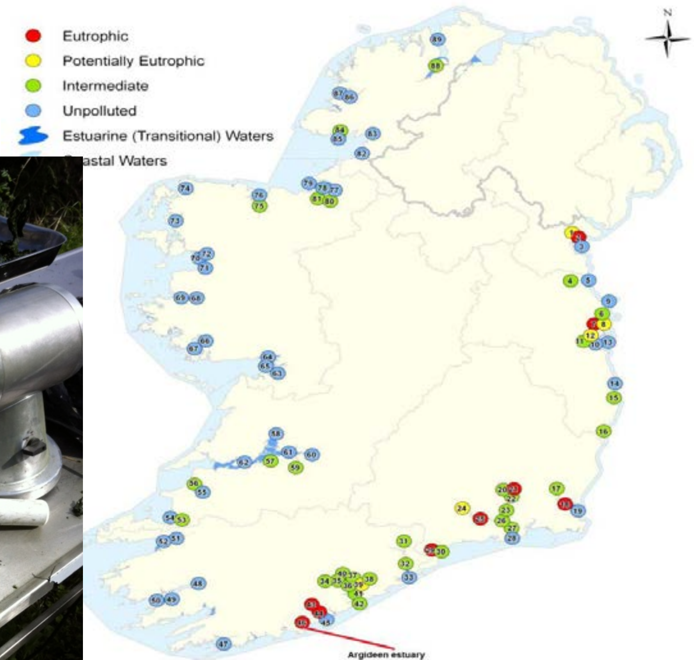
2nd generation biofuel: thermal biomethane

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%
RES-T	11%
As a % of agricultural land	1.7%

Gallagher, C., Murphy, J.D. (2013) What is the realistic potential for biomethane produced through gasification of indigenous Willow or imported wood chip to meet renewable energy heat targets? Applied Energy

Macro-algae: 3rd generation biofuel

- Green tides in eutrophic estuaries
- 10,000 tonnes of sea lettuce arise in Timoleauge annually.



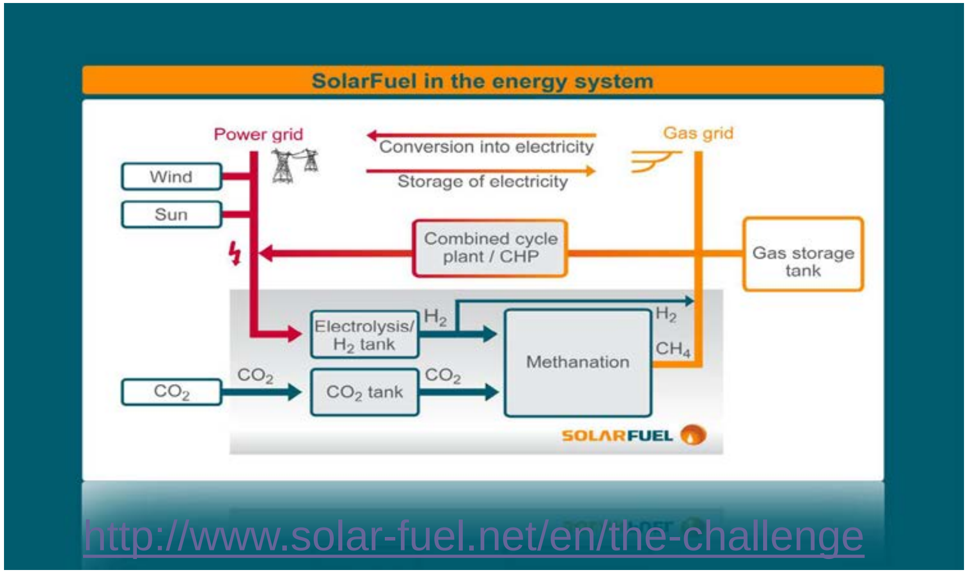
20m3 CH4 /t wet vs 100 m3 CH4/t dry

3^{rd} generation biofuel: gaseous biofuel from non-biological origin

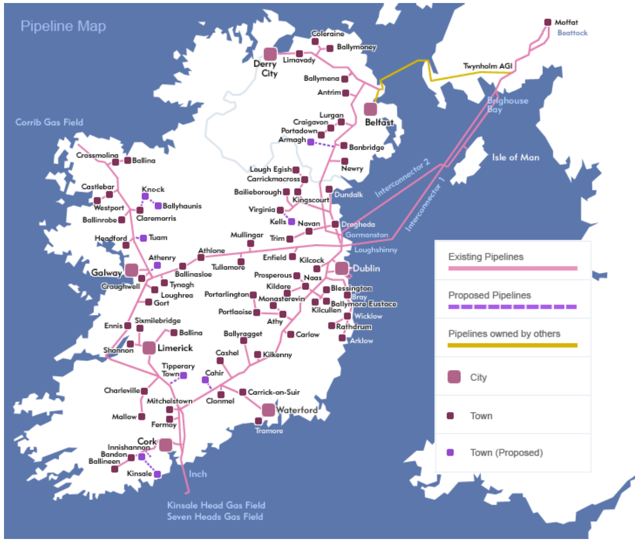
H_2: energy Density 12.1 MJ/m_n^3 : CH_4: Energy density 37.6 MJ/m_n^3

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

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



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



Source of CO2 from biogas:

Mix biogas (50% CH4 and 50% CO2) with H2; generate double the CH4 (1 mol CO2 generates 1 mol CH4).

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

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Resource	Energy in transport		Weighing	RES-T
Grass (100,000 ha)	15.8 PJ	8.4%	*2	16.8%
Food waste (530,000 t/a)	2.65 PJ	1.4%	*2	2.8%
Gasification 75,000 ha Willow	10.34 PJ	5.5%	*2	11%
Electricity	8 PJ	4.2 %	* 4	17%
Total	36.8 PJ	19.5%		47.6%

Resource equates to 1000 Mm^3/year biomethane,

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

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