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Ethanol production from energy crops and wastes for use as a transport fuel in Ireland

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Abstract

The Biofuels Directive places an onus on EU member states to ensure biofuels are available on their markets. This paper investigates the use of ethanol derived from biomass type 1 (residues and wastes) and biomass type 2 (energy crops). The technology involved in generating ethanol from energy crops is mature; the same cannot be said for generation of ethanol from residues; many proposals are mooted to generate ethanol from lignocellulosic biomass, but they are not at a commercial scale. Literature is available however on expected yields and economics of ethanol production from lignocellulosic biomass. This paper investigates three options which produce ethanol: 50 million Lpa of ethanol from sugar beet, 50 million Lpa of ethanol from waste paper and 200 million Lpa of ethanol from waste paper. The economics of ethanol production from sugar beet were the worst of the three due to the requirement to buy the sugar beet. Economies of scale are significant: larger plants produce cheaper ethanol. Indeed it was found that for the large plant, the production cost was zero if a gate fee of €100/t was charged for waste paper. The three options were applied to Ireland. It was found that an investment in an ethanol industry of €561 million would produce 5.7% of the energy value of petrol and diesel in Ireland; the reference value for the minimum portion of biofuels placed on the market in 2010 is 5.75%. The greenhouse-gas savings would equate to 18% of the 1990 transport emissions.

Keywords: Ethanol; Lignocellulosic biomass; Greenhouse-gas

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1. Introduction

The Biofuels Directive (2003/30/EEC) [1] stipulates that member states must ensure that a minimum proportion of biofuels and other renewable fuels is placed on their markets. It establishes reference values for the minimum proportion of 2% by 31 December 2005 and 5.75% by 31 December 2010. The aim of this paper is to examine the potential of ethanol to meeting these reference values. Of interest is the differential between ethanol from biomass type 1 (wastes and residues) and biomass type 2 (energy crops). Historically, production of ethanol was from biomass type 2; production of ethanol was limited to using sources of sugar that were available in soluble forms, such as molasses from sugar cane and sugar beet, or fructose from the corn plant.

However, technology now exists (though not yet at commercial scale) that allows for the production of ethanol from lignocellulosic biomass; this allows production of ethanol from biomass type 1 such as the paper fraction of MSW. The objectives of this paper are to compare and contrast the production of ethanol from biomass types 1 and 2 and to establish the quantity that could practically be produced in Ireland.

2. Lignocellulosic biomass

Lignocellulosic biomass is principally composed of the compounds cellulose, hemicellulose, and lignin. Cellulose, a primary component of most plant-cell walls, is made up of long chains of the 6-carbon sugar, glucose, arranged in bundles. In the plant-cell wall, the cellulose molecules are interlinked by another molecule, hemicellulose. The hemicellulose is primarily composed of the 5-carbon sugars and xylose [2]. Another compound called lignin is also present in significant amounts and

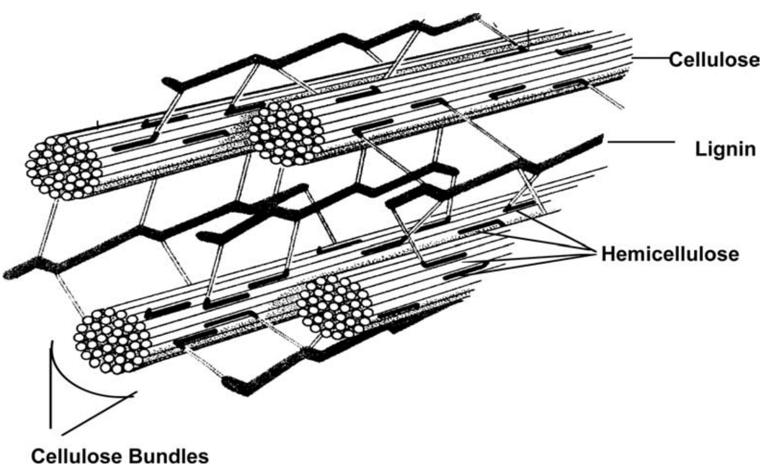

Fig. 1. Typical plant cell wall arrangement [3,4].

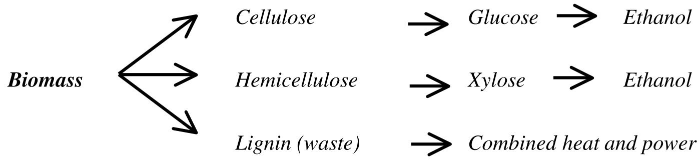

Fig. 2. Biomass to ethanol flowchart.

gives the plant its structural strength. A typical plant cell wall is illustrated in Fig. 1. Fig. 2 shows a biomass-to-ethanol flowchart.

3. Hydrolysis of lignocellulosic biomass

Since cellulose and hemicellulose are principally composed of tightly-bonded sugars, the bonds need to be broken before fermentation to ethanol can proceed. Cellulose and hemicellulose must be broken down into the simple sugars glucose and xylose respectively. This process, as illustrated in Fig. 3 for cellulose conversion, is known as hydrolysis.

There are various methods of completing the hydrolysis of the raw material into sugars. These methods include:

- Simultaneous saccharification and fermentation.
- Concentrated acid hydrolysis, neutralization and fermentation.

The above methods and others have been documented by various authors [3,4] and will not be covered in this paper.

4. Fermentation

Once the cellulose and hemicellulose have been broken down to simple sugars, fermentation can then take place as illustrated in Figs. 4 and 5. One molecule of glucose

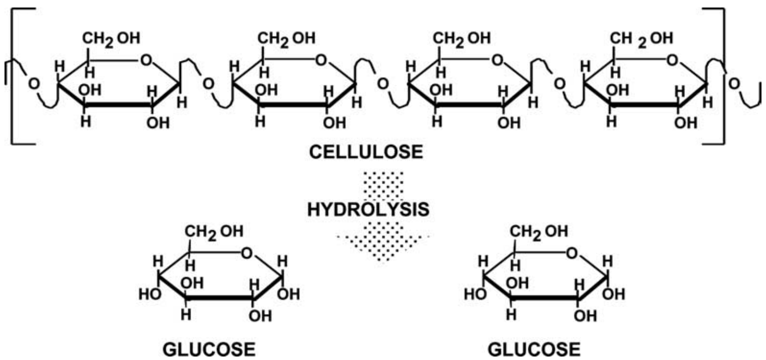

Fig. 3. Cellulose hydrolysis [3,4].

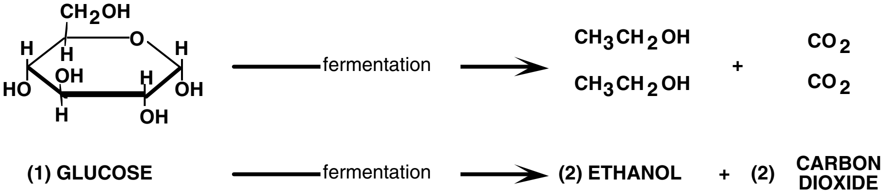

Fig. 4. Glucose fermentation [3,4].

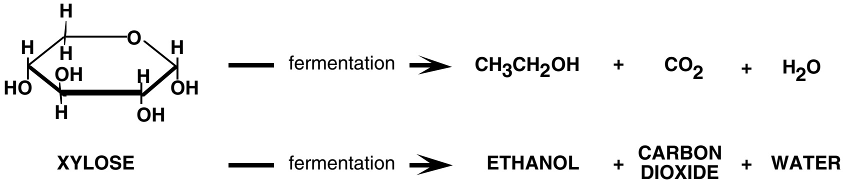

Fig. 5. Xylose fermentation [3,4].

produces 2 molecules of ethanol and 2 molecules of carbon dioxide. An examination of the molecular weights of the molecules (see Box 1) reveals that the weight of ethanol produced is equal to 51% of the weight of the starting material (glucose).

Box 1

Weight of ethanol produced from glucose

1 mol of glucose	$C_6H_{12}O_6$	molecular weight = 180
2 mol of ethanol	CH_3CH_2OH	molecular weight = 92
2 mol of carbon dioxide	CO_2	molecular weight = 88

Xylose fermentation is not as straight forward as glucose fermentation. Depending on the micro-organism and conditions, several fermentations are possible. The products can include ethanol, carbon dioxide, and water. Xylose ($C_5H_{10}O_5$) has a molecular weight of 150. Three conversions have been documented as outlined in Fig. 6 [3]. The yield of ethanol ranges from 20 to 51% of the weight of the starting material (weight ethanol/weight xylose) as outlined in Box 2. The literature states a range of 30 to 50% for xylose to ethanol conversions [3].

3 Xylose — fermentation → 5 Ethanol + 5 Carbon Dioxide

3 Xylose — fermentation → 4 Ethanol + 7 Carbon Dioxide

3 Xylose — fermentation → 2 Ethanol + 1 Carbon Dioxide + 1 Water

Fig. 6. Fermentation of xylose to ethanol.

Sucrose	+Water	→	Glucose	+	Fructose
$C_{12}H_{22}O_{11}$	$+H_2O$	→	$C_6H_{12}O_6$	+	$C_6H_{12}O_6$
Molecular weights: 342	+18	→	180	+	180

Fig. 7. Hydrolysis of sucrose.

Box 2
Weight of ethanol produced from xylose
Xylose ($C_5H_{10}O_5$) has a molecular weight of 150.
Ethanol (CH_3CH_2OH) has a molecular weight of 46.
Scenario 1:
3 mol of xylose to 5 mol of ethanol: weight of ethanol
(5 * 46/3 * 150) = 51% of weight of xylose.
Scenario 2:
3 mol of xylose to 4 mol of ethanol: weight of ethanol
(4 * 46/3 * 150) = 41% of weight of xylose.
Scenario 3:
3 mol of xylose to 2 mol of ethanol: weight of ethanol
(2 * 46/3 * 150) = 20% weight of xylose.

Yield of ethanol ranges from 20% to 51% of the weight of xylose

As well as glucose and xylose, there is another simple sugar called fructose that can be fermented into ethanol. Fructose is derived from the hydrolysis of common table sugar or sucrose (see Fig. 7). Hydrolysis of sucrose yields an equal amount of both glucose and fructose. In fact, fructose has the same formula as glucose ($C_6H_{12}O_6$) but differs from it in structure [5]. Once fructose had been formed, it can be readily fermented into ethanol with identical yields to that of glucose.

As well as the theoretical conversion rates of sugar to ethanol, different conversion efficiencies exist for the conversion processes. These depend on both the type

Table 1
Sugar-conversion process efficiencies [6]

Conversion	Low end of range	High end of range	Average
Sucrose to glucose and fructose	99	100	99.5
Cellulose to glucose	95	100	97.5
Hemicellulose to xylose	50	90	70
Glucose to ethanol	95	100	97.5
Fructose to ethanol	95	100	97.5
Xylose to ethanol	40	90	65
Sucrose to ethanol	94	100	97
Cellulose to ethanol	90	100	95
Hemicellulose to ethanol	20	81	50.5

and the efficiency of the production process being utilised. A range of conversion efficiencies is set out in Table 1.

5. Ethanol production rates

As shown previously, ethanol production rates are directly linked with the sucrose, cellulose and hemicellulose contents of the various feedstocks or wastes. These characteristics of the wastes being considered in this paper, along with average moisture contents are set out in Table 2. Utilising molecular weights and documented conversion efficiencies, as set out in Table 1, along with the values set out in Table 2, the theoretical ethanol production from newspaper is given in Box 3. The value used by Shleser [3] of 500 L of ethanol per tonne dry paper is slightly above the high range of values generated here (369–484 L/t dry paper). Based on the method of calculation outlined in Box 3, Table 3 outlines a range of theoretical ethanol production values from the feedstock under consideration.

Table 2
Feedstock composition data from [2,3,6,7]

Feedstock	Moisture %	Cellulose % (dry basis)	Hemicellulose % (dry basis)	Sucrose % (dry basis)
Newspaper	8.9 [6]	62 [3]	16 [3]	–
Paper	6.3 [6]	85–99 [7]	0 [7]	–
Sugar beet	76.5 [2]	5 [2]	5.5 [2]	70 [2]

Box 3
Ethanol production from Newspaper
Components of dry paper
1dry tonne of newspaper consists of approximately 620 kg cellulose and 160 kg hemicellulose
Theoretical ethanol production from cellulose:
Minimum: 620 kg/t * 0.51 kg ethanol/kg glucose * 90/100 (% eciency) = 285 kg ethanol
Maximum: 620 kg/t * 0.51 kg ethanol/kg glucose * 100/100 (% eciency) = 316 kg ethanol
Theoretical ethanol production from hemicellulose:
Minimum: 160 kg/t * 0.20 kg ethanol/kg xylose * 20/100 (% eciency) = 6 kg ethanol
Maximium: 160 kg/t * 0.51 kg ethanol/kg xylose * 81/100 (% eciency) = 66 kg ethanol
Theoretical ethanol production from dry paper:
Minimum: 291 kg ethanol/t dry paper
Maximum: 382 kg ethanol/t dry paper
Ethanol has a density of 0.789 kg/L
Therefore ethanol production equates to between 369 and 484 L/t dry paper.

Table 3
Ethanol production rates

Feedstock	Lower value (L/t dry)	Upper value (L/t dry)	Quoted value (L/t dry)
Newspaper	369	484	457 [6]
Paper	495	640	508 [6]
Sugar beet	346	405	430[a] [4]

[a] Quoted value is 101 L/t and is based on total weight. 101 L/t @76.5% moisture content is equal to 430 L/t dry.

6. Carbon balance of lignocellulosic ethanol plant

Generation of ethanol from lignocellulosic biomass is still at the research stage. Extensive modelling work has been carried out by NREL [8]. The model by Aden and co-workers [8] is based on 730,000 tpa of corn stover producing 262.3 million litres per annum of ethanol (360 L of ethanol/t corn stover). Corn stover contains about 45% carbon. The ethanol product contains about 34% of the carbon input. The plant is sustainable in that the carbon in the lignin is utilised in a combined heat-and-power (CHP) plant to provide for all energy requirements. Table 4 outlines the carbon balance of the plant.

Table 5 outlines the constituents of corn stover and Box 4 outlines the generation of ethanol from the feedstock. It may be noted that in Box 4, all the maximum values from the ranges suggested were used. The value generated (281 million Lpa) is slightly higher than the value given in the NREL report [8] of 262 million Lpa.

Table 4
Ethanol mass carbon balance for a 730 ktpa corn stover to ethanol plant, adapted from [8]

	Carbon flow (tpa)	Carbon flow (%)
Carbon inlets		
Feedstock	330,500	99.2
Enzymes	2628	0.8
Total	333,128	100
Carbon outlets		
Boiler exhaust	157,366	47.2
Ethanol product	112,059	33.6
Scrubber vent	56,240	19.9
Ash	1682	0.5
Gypsum	1051	0.3
Losses to atmosphere	420	0.1
Total[a]	328,818	98.3

[a] Discrepancy due to recycling of wastewater through plant.

Table 5
Corn stover constitution [8]

	%
Ethanol producing constituents	
Glucose	36.7
Xylose	21.1
Arabinose	2.9
Galactose	1.9
Mannose	1.5
Total	64.2
Non-ethanol producing constituents	
Lignin	30.8
Soluble solids	0.3
Acetate	2.6
Protein	0.8
Extractives	1.3
Total	35.8

Box 4
Production of ethanol from 730,000 tpa of corn-stover
Cellulose (6 carbon sugars):
Glucose + Galactose + Mannose = 40.1%
Maximum conversion eciency = 100% (Table 1)
Ethanol yield from cellulose = 51%
Ethanol production
$(730 \times 10^3)(0.401)(0.51)(1) = 149{,}292$ tpa

Hemicellulose (5 carbon sugars):
Xylose + Arabinose = 24%
Maximum conversion eciency = 81% (Table 1)
Ethanol yield from hemicellulose = 51% [maximum yield from Box 2]
Ethanol production
$(730 \times 10^3)(0.24)(0.81)(0.51) = 72{,}375$ tpa

Total ethanol production = 221,667 tpa
= 281 million Lpa (density 0.789 t/m^3)

7. Greenhouse-gas emissions in the utilisation of ethanol

The greenhouse-gas emissions produced from ethanol combustion (direct and indirect emissions) are outlined in Box 5. The direct combustion of ethanol generates 1.51 kg CO_2/L; however the emissions including the indirect plant-emissions are

4.8 kg CO_2/L. The cultivation, maintenance and harvesting of a crop generates about 490 kg CO_2/Ha [14,15] excluding fertiliser. A value of 660 kg CO_2/Ha is utilised in this report to allow for the indirect emissions for diesel utilised in cultivation through to harvesting. A value of 940 kg CO_2/Ha is used for fertiliser manufacture [16]. Thus the total greenhouse-gas production value for cultivation through to harvest including fertiliser use and indirect emissions for diesel combustion is taken as 1600 kg CO_2/Ha. Sugar beet in Ireland is typically generated at a rate of 55 t/Ha and 100 L of ethanol is generated per tonne of wet beet; in this case, the emission corresponds to 0.29 kg CO_2/L ethanol.

Box 5

Greenhouse-gas produced "Scheme in Place"

$CH_3CH_2OH + 3O_2 = 2CO_2 + 3H_2O$

1 mol of ethanol	2 mol of carbon dioxide	
molecular weight 46	molecular weight 88	
1 kg ethanol	1.913 kg CO_2	
1 L of ethanol	1.51 kg CO_2	(density of ethanol 0.789 kg/L)
Combustion of 1 L of ethanol generates	1.51 kg CO_2	
Indirect ethanol-plant emissions	2.9 kg CO_2/L	(Table 4 states ethanol responsible for 34% of emissions)
Cultivation/harvest emissions	0.29 kg CO_2/L	[14–16]
Transportation	0.1 kg CO_2/L	
Total ethanol emissions	4.8 kg CO_2/L	
Biomass regrowth	4.41 kg CO_2/L	(Table 4 states carbon in feedstock = 2.95 * carbon in ethanol)
Net Greenhouse-gas production	0.39 kg CO_2/L	
Greenhouse-gas savings		
Direct petrol emissions	2.13 kg CO_2/L	[11]
Indirect petrol emissions	0.75 kg CO_2/L	[12,13]
Total petrol emissions	2.88 kg CO_2/L	
Petrol displaced	0.87/L of ethanol	
Greenhouse-gas saved by displacing petrol	2.5 kg CO_2/L	
Net greenhouse-gas savings	2.11 kg CO_2/L	

An estimate for transport emissions of 0.1 kg CO_2/L is shown in Box 6. The calculated figure uses the average fuel-consumption on the assumption that a truck arriving at the ethanol plant with a full payload will have to return to its base empty. The NREL report [8] states that it is unlikely that biomass would be collected from outside an 80 km radius of the plant. Therefore, as a worse case, the greenhouse-gas emissions per truck per delivery would be 1617 g/km * 160 km. An average unloaded Volvo HGV weighs around 14 t. The maximum weight limit for a 5-axle articulated HGV in Ireland is 40 t [17]. Therefore, the payload of feedstock to the ethanol plant is approximately 26 t.

Box 6
Greenhouse-gas emissions in transporting sugar beet
Direct diesel-emissions = 2.69 kg CO_2/L [11]
Indirect diesel-emissions = 0.75 kg CO_2/L [13]
Total diesel-emissions = 3.44 kg CO_2/L
Truck fuel consumption ≈ 6 mpg = 2.11 km/L = 0.47 L/km
CO_2 emissions ($3.44 \times 10^3 \times 0.47$) = 1617 g CO_2/km
160 km round trip = 259 kg CO_2/trip
26 t sugarbeet/trip = 9.95 kg CO_2/t sugarbeet
100 L ethanol/t sugarbeet = 0.1 kg CO_2/L ethanol

Ethanol has a lower heating-value of 21.1 MJ/L [9], which is lower than that of petrol (32.2 MJ/L). However due to the higher octane value of ethanol and the higher efficiency of combustion, ethanol replaces 28 MJ/L of petrol [10]. Thus 1 L of ethanol displaces 0.87 L of petrol.

The net greenhouse-gas saving is calculated as 2.11 kg CO_2/L. Net greenhouse-production, as defined by Murphy and co-workers [11], may be defined as this figure less the savings from petrol displacement. Thus it may be said that ethanol produces 0.39 kg CO_2/L or 18% of the direct greenhouse-gas production of petrol when produced from an energy crop (sugar beet). The analysis will be different when examining biomass type 1 (waste/residue).

8. Production cost of ethanol from energy crops

In 1980, a 12 million Lpa ethanol plant was built in Cork for IR£5,000,000 (€6,330,000) [18]. Exponential cost estimating methodology is utilised in this paper to generate production costs specifically for Ireland (refer Eq. (1)). The power factor varies from industry to industry. For the ethanol industry, the power factor for capital costing is 0.7 [8].

$$X = Y(C2/C1)^{0.7} * \mathrm{CF}, \qquad (1)$$

where X is the cost of the new plant, Y is the cost of the existing plant, $C1$ is the capacity of the existing plant, $C2$ is the capacity of the new plant, and CF is the correction factor obtained from engineering indices.

The correction factor is based on inflation from the year the existing plant was built to the date of construction of the proposed new plant. The inflation index for Cork in 1980 was 150.3. The inflation index for Cork in 2002 was 395.6 [18]. Thus an ethanol plant producing 8 million Lpa of ethanol would have a capital cost as follows:

$$X = €6{,}330{,}000(8/12)^{0.7} * (395.6/150.3) = €12{,}540{,}000.$$

Using the above methodology, the capital cost for an ethanol plant from sugar sources is as outlined in Fig. 8. The costs are based on the year 2004. The graph is summarised in Eq. (2). The operating costs of a sugar-to-ethanol plant, excluding feedstock purchase, is typically 7% of the capital cost [19]. Thus the operating cost of a sugar-to-ethanol plant is given in Eq. (3).

$$C_s = -0.213\ln(x) + 1.754, \tag{2}$$

$$O_s = 0.07 * [-0.213\ln(x) + 1.754], \tag{3}$$

where, C_s is the capital cost of a sugar-to-ethanol plant, O_s is the operating cost of a sugar-to-ethanol plant, and x is the plant capacity in million Lpa.

Bazilian and co-workers [20] state that the capital cost of a 100,000 tpa ethanol plant producing 127,000,000 Lpa of ethanol from sugar beet is €95 million. Utilising Eq. (2), the capital cost is given as €0.72/Lpa or €91.7 million.

9. Production cost of lignocellulosic biomass to ethanol plant

NREL [8] and Washington State University (WSU) [21] have undertaken detailed studies on the equipment costs for a lignocellulosic biomass to ethanol plant. Dis-

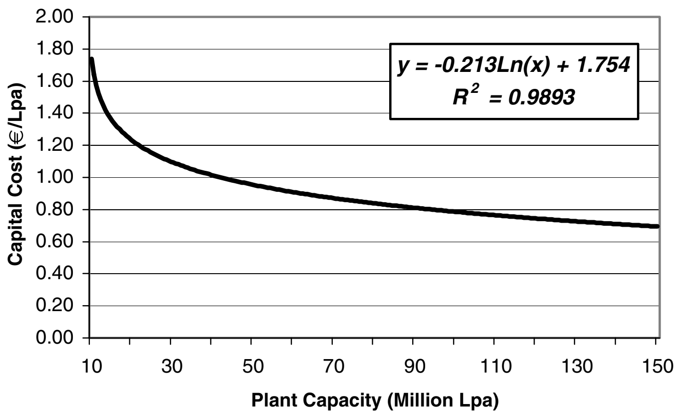

Fig. 8. Estimated capital cost of a sugar to ethanol plant.

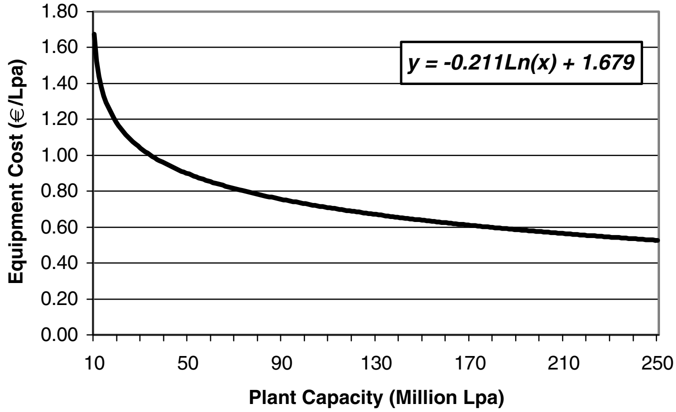

Fig. 9. Estimated equipment cost of a lignocellulose to ethanol plant.

crepancies exist in the data: Fig. 9 is constructed to best model the two sets of data. All data are converted to € in the year 2004. The NREL report [8] suggests that equipment costs equate to 42% of overall project costs; thus Eq. (4) may be produced. The expected operating costs are in the range of 6–8% of capital costs [8,21]. This paper uses 8%; thus Eq. (5) may be generated.

$$C_L = (-0.211\ln(x) + 1.679)/0.42 \quad (4)$$

$$O_L = 0.19^*[-0.211\ln(x) + 1.679], \quad (5)$$

where C_L is the capital cost of a lignocellulose to ethanol plant, O_L is the operating cost of a lignocellulose-to-ethanol plant, and x is the plant capacity in million Lpa.

10. Scenarios investigated

The scenarios are applicable to regions within a small country such as Ireland (population ~4 million). It is essential for the scenarios to be practical in so far as waste quantities cannot be excessive given the relatively small size of the country. Three different plants are considered. The first plant considered is a plant producing 50 million litres of ethanol per annum from sugar beet. This size plant was chosen because it requires a quantity of sugar beet less than that produced in County Cork and of an order similar to that processed in the sugar factory in County Cork, Ireland. The second is a plant producing 50 million Lpa from paper. This size plant was chosen in order to compare similar size plants using types 1 and 2 biomass; also the paper quantity corresponds to a typical Irish waste-strategy region (Cork Waste Strategy Region has a population of about 400,000) [22]. The third is a plant producing 200 million Lpa from paper (i.e. from approximately the quantity of waste paper produced in greater Dublin). The larger plant was chosen to investigate economies of scale. The scenarios are outlined in Table 6.

Table 6
Ethanol-plant scenarios

Option number	Quantity of ethanol	Feedstock	Land area or persons equivalent (PE)
1	50 million Lpa	526 ktpa sugar beet[a]	9750 Ha[b]
2	50 million Lpa	107 ktpa waste paper[c]	439,000 PE
3	200 million Lpa	428 ktpa waste paper[c]	1,770,000 PE

[a] 405 L/t dry sugarbeet equates to around 95 L/t at 76.5% moisture content.
[b] 55t sugarbeet/Ha.
[c] 468 L/t paper equates to 500 L/t dry paper at 6.4% moisture content.

11. Analysis option 1

County Cork produced 595 kt sugar beet in 2003 [23]. The 2004 sugar beet campaign will involve processing of 1.3 million tonnes of sugar-beet [25] in two sugar-production plants (Cork and Carlow). It is estimated that both these plants could have access to over 526 ktpa of sugar beet within an average collection distance of 45 km [23]. Box 7 outlines the minimum cost of ethanol from such a plant as €0.69/L. The average price paid to farmers for sugar beet in 2003 was €52.5/t [24]. However the reforms proposed by EU Agricultural Commissioner Franz Fischler call for sugar quota and price reductions of 16% and 33%, respectively [25]. This leads to the potential for an ethanol industry as an alternative to a sugar industry. A significant portion of the transport cost is borne by the farmer within the €52.5/t sugar beet price [23].

Box 7
Cost per litre of ethanol from a sugar beet plant producing 50 million Lpa of ethanol
Capital cost = $-0.213 \ln(50) + 1.754$ [Eq. (2)] = €0.92/L = €46,036,955
Production costs:
  Plant = $.07(-0.213 \ln(50) + 1.754)$[Eq. (3)] = €3,222,587 pa
  Beet cost @ €52.50/t = €7,631,590 pa
  Cost of capital = 4% over 20 years = €3,387,480 pa
Total production cost: = €0.685/L = €34,243,657 pa

Fig. 10 is generated using the same techniques outlined in Box 7. Fig. 10 highlights how the ethanol-production cost varies with plant size when using sugar beet as a feedstock. For a 127 million Lpa ethanol-plant, the production cost is €0.656/L. This is in close agreement with the estimate of Bazalian and co-workers [20] of €0.64/L. The production costs presented here do not include VAT or excise duty. Currently in Ireland, biofuels incur the same excise duty as low-sulphur diesel at €0.368/L [26] and the rate of VAT on fuels is set at 21%. A 50 million Lpa ethanol-plant would have to charge approximately €1.24/L of ethanol in order to break even. Fig. 11

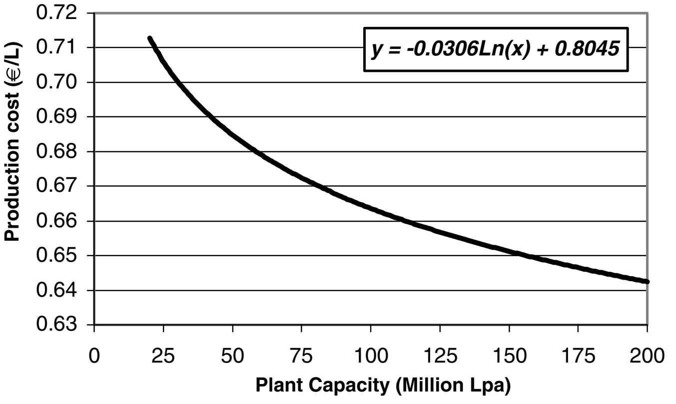

Fig. 10. Ethanol production cost from sugar beet for various plant sizes.

Fig. 11. Influence of beet cost on ethanol production cost from a 50 million Lpa plant.

highlights the sensitivity of production costs to the cost price of sugar beet for a 50 million Lpa ethanol plant (excise duty and VAT are not included). It can be seen that if the proposal to reduce sugar-beet prices by 33% (to €35.2/t) becomes a reality, then the production cost would fall to around €0.50/L.

The greenhouse-gas analysis is similar to that outlined in Box 5. A difference exists in the transport distance (i.e. 90 km round trip as opposed to 160 km). Thus the transport emissions reduce from 0.1 kg CO_2/L ethanol to 0.059 kg CO_2/L. The net greenhouse-gas production is 0.35 kg CO_2/L ethanol and the net greenhouse gas savings is 2.07 kg CO_2/L (refer to Table 11).

12. Analysis options 2 and 3

Option 2 uses 107 ktpa of waste paper: this equates to that quantity generated by 439,000 person-equivalents (PE) at 243 kg/PE/year. Only three waste-strategy regions in Ireland (Connaught, Cork and Dublin) landfilled this amount of paper waste in 2001 [23]. Dublin generates enough paper waste to supply two 50 million Lpa ethanol plants. Option 3 uses 428 ktpa waste paper (i.e. paper generated by 1.77 million PE). This amounts to 52% of waste paper produced in Ireland in 2001 [23]. Option 3 is only applicable to one site in Ireland (Dublin and its environs); thus only two applicable sites remain for option 2.

The minimum cost of ethanol from the 50 million Lpa ethanol plant is €0.312/L; this reduces to €0.205/L for the 200 million Lpa ethanol plant. Again allowing for excise duty and VAT, the respective costs are €0.82/L and €0.69/L. The advantage of using waste paper as a feedstock is that the biomass will not have to be purchased. Instead, it is a potential source of revenue considering that some local authorities charge up to €250 per tonne of waste received into a landfill [22]. Offering a gate fee lower than this rate could attract waste to an ethanol plant rather that to landfill. The analysis outlined in Box 8 assigns no gate fee to waste paper. Fig. 12 allows an investigation of the effect of gate fee on the cost of ethanol for the plant producing 200 million Lpa of ethanol. It may be noted that if a gate fee of €100/t is assigned, then the production costs are in effect zero.

Box 8

Cost per litre of ethanol from a waste paper plant producing 50 million Lpa of ethanol

Capital cost = (−0.211 ln(50) + 1.6679)/42 [Eq. (4)] = €2.03/L = €101,500,000

Production costs:

Plant = 0.19(−0.211 ln(50) + 1.679)[Eq. (5)] = €8,108,850 pa

Cost of capital = 4% over 20 years = €7,476,985 pa

Total production cost: = €0.312/L = €15,585,835 pa

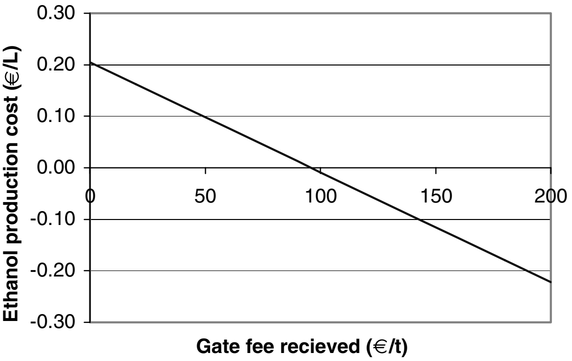

Fig. 12. Effect of gate fee for waste paper on ethanol production cost from a 200 million Lpa ethanol plant.

The net greenhouse-gas production is less than for sugar beet as there are no harvesting/cultivation emissions and transport distances are less than for sugar beet. Net greenhouse-gas production is in effect totally from transport; a value of 0.05 kg CO_2/L ethanol is evaluated. Net greenhouse-gas savings of 2.46 kg CO_2/L are evaluated (calculations as per Box 5).

13. Application of ethanol proposals to Ireland

Sites in Ireland where the three options could be situated were chosen. This allowed the practical maximum potential to be generated. Table 7 outlines the total ethanol potential from sugar beet and waste paper in Ireland. Table 8 estimates the maximum practical portion of transport fuel that ethanol could obtain in Ireland. Table 9 generates the investment cost required. Table 10 outlines the cost per litre of petrol and ethanol (complete with excise duty and VAT). Table 11 outlines the potential greenhouse-gas savings.

Table 7
Potential ethanol production in Ireland

Option	Ethanol production	Number of plants	Total ethanol production	Total energy[a]
	L/plant/year		Lpa	GJpa
1 (from sugar beet)	50,000,000	2	100,000,000	2,110,000
2 (from waste paper)	50,000,000	2	100,000,000	2,110,000
3 (from waste paper)	200,000,000	1	200,000,000	4,220,000
Total		5	400,000,000	8,440,000

[a] Ethanol at 21.1 MJ/L, not at its displacement value of 28 MJ/L petrol.

Table 8
Transport fuel consumption in Ireland, 2002 [20] and potential for market share for ethanol

Fuel type	ktpa	Lpa $*\ 10^6$	GJpa	%
Petrol	1514	2250	67,525,000	45
Diesel	1832	2155	80,600,000	55
Petrol and diesel	3346	4405	148,125,000	100
Ethanol		400	8,440,000	5.7

Table 9
Total capital cost for practical maximum ethanol production

Option	Number of plants	Plant capital cost	Total capital cost
1 (from sugar beet)	2	€46 million	€92 million
2 (from waste paper)	2	€101 million	€202 million
3 (from waste paper)	1	€267 million	€267 million
Total	5		€561 million

Table 10
Price per litre of petrol and ethanol

Fuel	Minimum production price	Sale price[a]
Unleaded petrol		€1/L
(Option 1) 50 million Lpa ethanol from sugar beet	€0.685/L	€1.24/L (€1.43/L petrol displaced)
(Option 2) 50 million Lpa ethanol from waste paper	€0.312/L	€0.82/L (€0.94/L petrol displaced)
(Option 3) 200 million Lpa ethanol from waste paper	€0.205/L	€0.69/L (€0.79/L petrol displaced)

[a] 1 L of ethanol displaces 0.87 L of petrol.

Table 11
Total greenhouse-gas savings commensurate with ethanol production

Option number	Ethanol production	Net greenhouse-gas savings	
		kg CO_2/L ethanol	kt CO_2 pa
Option 1	100	2.07	207
Option 2	100	2.46	246
Option 3	200	2.46	492
Total	400		945

Items of interest include:

- The practical maximum potential for ethanol is 5.7% of the total transport energy in 2002. This is very close to the 5.75% reference value for the minimum proportion as set in the Biofuels Directive [1].
- An investment cost of €561 million is required to complete the ethanol infrastructure.
- On comparing the price of ethanol in terms of petrol displaced with petrol, only options 2 and 3 are cheaper than petrol.
- The transport emissions in 1990 equated to 5083 ktCO_{2equiv} pa [27]. Thus the total greenhouse-gas saving equates to 18.5% of the transport emissions in 1990.

14. Conclusions

- Ethanol production from energy crops (biomass type 2) such as sugar beet and corn is a mature technology. However ethanol production from lignocellulosic biomass (typically wastes and residues, biomass type 1) is not yet at commercial scale, even though many technologies are mooted.

- The modelled capital costs and operating costs are significantly higher per unit of production for ethanol production from lignocellulosic material than from energy crops.
- When producing ethanol from energy crops, the crop must be purchased and greenhouse-gas production is associated with cultivation to harvest and transport of the crop.
- The economics of ethanol production from waste paper are significantly better than those from sugar beet. Indeed of the options investigated only those involving waste paper generated a cheaper fuel than petrol. If a gate fee of €100/t was obtained from waste paper, then the production cost could go to zero for a plant producing 200 million Lpa of ethanol.
- The reference value for the minimum portion of biofuels to be placed on the market in 2010 is 5.75% of the energy value of petrol and diesel. The ethanol scenarios as proposed here for Ireland would produce 5.7% of the energy value of petrol and diesel.
- An investment in an ethanol industry of €561 million would lead to a 16.6% substitution of petrol in Ireland. The greenhouse-gas savings equate to 18% of the 1990 transport emissions.
- Proposed ethanol production by volume would be 15% of combined petrol and ethanol volume. This proposal would involve all Irish cars, which operate on petrol converting to E15 (15% ethanol, 85% petrol).

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