Environmental RTDI Programme 2000–2006

Energy Crops in Ireland: An Assessment of their Potential Contribution to Sustainable Agriculture, Electricity and Heat Production

(2004-SD-DS-17-M2)

Final Report

Prepared for the Environmental Protection Agency

by

School of Natural Sciences, Trinity College Dublin

Authors:

David Styles and Michael B. Jones

ENVIRONMENTAL PROTECTION AGENCY

An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
E-mail: info@epa.ie Website: www.epa.ie

© Environmental Protection Agency 2007

ACKNOWLEDGEMENTS

This report has been prepared as part of the Environmental Research Technological Development and Innovation (ERTDI) Programme under the Productive Sector Operational Programme 2000–2006. The programme is financed by the Irish Government under the National Development Plan 2000–2006. It is administered on behalf of the Department of the Environment, Heritage and Local Government by the Environmental Protection Agency which has the statutory function of co-ordinating and promoting environmental research. The ERTDI programme 2000–2006 has been replaced by the Science, Technology, Research and Innovation for the Environment (STRIVE) programme 2007–2013. The STRIVE programme is funded by the Irish Government under the National Development Plan 2007–2013.

The authors are grateful to Dr Fiona Thorne, of Teagasc, for co-operation on farm economic calculations and access to FAPRI-Ireland economic data.

DISCLAIMER

Although every effort has been made to ensure the accuracy of the material contained in this publication, complete accuracy cannot be guaranteed. Neither the Environmental Protection Agency nor the author(s) accept any responsibility whatsoever for loss or damage occasioned or claimed to have been occasioned, in part or in full, as a consequence of any person acting, or refraining from acting, as a result of a matter contained in this publication. All or part of this publication may be reproduced without further permission, provided the source is acknowledged.

SOCIO-ECONOMICS

The Socio-Economics Section of the Environmental RTDI Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in this area. The reports in this series are intended as contributions to the necessary debate on socio-economics and the environment.

ENVIRONMENTAL RTDI PROGRAMME 2000–2006

Published by the Environmental Protection Agency, Ireland

PRINTED ON RECYCLED PAPER

ISBN: 1-84095-240-7

Price: €15

10/07/300

Details of Project Partners

David Styles*
School of Natural Sciences
Botany Building
Trinity College
University of Dublin
Dublin 2
Ireland

Tel.: +353 1 8963068
Fax: +353 1 6081147
E-mail: dstyles@tcd.ie

Michael B. Jones
School of Natural Sciences
Trinity College Dublin
Dublin 2
Ireland

Tel.: +353 1 608 72 74
Fax: +353 1 608 1147
E-mail: mike.jones@tcd.ie

***Current address:**
Environmental Protection Agency
McCumiskey House
Richview
Clonskeagh Road
Dublin 14
Ireland

Tel.: +353 1 2680100
Fax: +353 1 2680199
E-mail: d.styles@epa.ie

Table of Contents

Executive Summary

1 Background

This report assesses the potential contribution of energy crops to sustainable development in Ireland, quantifying their potential to reduce greenhouse gas (GHG) emissions through displaced agricultural land uses, and heat and electricity generation. An economic assessment of energy crops is also made from the perspective of farm producers, consumers, and a national cost–benefit analysis. Additional major environmental impacts are also considered. Energy crops were selected for study as a promising GHG-reduction strategy on the basis of increased conventional fuel prices, and decreased returns for conventional agricultural production since decoupling of subsidies from production in January 2005. Detailed evaluation was limited to the promising energy crops *Miscanthus* and short-rotation coppice willow (SRCW).

2 Greenhouse Gas Emissions

Life-cycle analysis (LCA) of energy-crop cultivation and conventional land uses (dairy, cattle and sheep rearing, and sugar beet) found that SRCW and *Miscanthus* cultivation emitted 1,346 and 1,938 kg CO_2 eq./ha/annum, respectively, and most of these emissions were associated with fertiliser manufacture and fertiliser-induced soil N_2O release. These emissions compared with 12,068, 5,237, 3,751 and 3,494 kg CO_2 eq./ha/annum for dairy, cattle, sheep and sugar beet, respectively, and with an assumed zero emission for grassland extensification (destocking) and set-aside. In addition, where SRCW and *Miscanthus* replaced sugar beet and set-aside, soil-carbon sequestration was equated to atmospheric CO_2 reductions of 1,881 and 4,265 kg/ha/annum, respectively. Cultivation emissions dominated the GHG budgets calculated for energy-crop fuel chains, assuming energy-crop biomass was co-fired with peat and coal to generate electricity, and combusted in dedicated boilers to generate heat. GHG emissions attributable to co-fired *Miscanthus* and SRCW electricity were 0.131 and 0.132 kg CO_2 eq./kWh_e, respectively, compared with emissions of 1.150 and 0.990 kg CO_2 eq./kWh_e for peat- and coal-generated electricity. Heat generated from *Miscanthus* pellets and SRCW woodchips was associated with emissions of 0.066 and 0.047 kg CO_2 eq./kWh_{th}, respectively, compared with emissions of 0.248, 0.331 and 0.624 kg CO_2 eq./kWh_{th} for heat produced from gas, oil and electricity, respectively. These data were extrapolated to an indicative national scenario involving 30% co-firing with *Miscanthus* at the peat power stations, 15% co-firing with gas produced from gasification of SRCW woodchips at the Moneypoint coal power station, and displacement of gas, oil and electric heat each in 2.5% of households (totalling 7.5% of households) with SRCW woodchip along with equivalent displacement in commercial/public premises. It was assumed that *Miscanthus* displaced sugar beet (33,784 ha), SRCW grown for electricity displaced dairy, cattle and sheep (19,789 ha each), and SRCW grown for heat displaced set-aside (36,645 ha) and destocked grassland (73,290 ha). The total GHG emission saving was calculated at 3.86 Mt CO_2 eq./annum (5.6% of 2006 emissions) yet required just 4.7% of agricultural land area. The agricultural portion of this emission saving is additional to forecast agricultural emission savings attributable to destocking in response to agricultural subsidy reform.

3 Economics

A net present value (NPV) approach was used to calculate the production costs of *Miscanthus* and SRCW biomass over their 16- and 23-year plantation lifetimes, applying a discount rate of 5% and annual inflation extrapolated from FAPRI-Ireland economic farm-modelling data. Discounted production costs of €46 and €48/t dry matter (DM) for SRCW and *Miscanthus* translated into discounted, annualised gross margins ranging from €211 to €383/ha, depending on the harvest and supply strategy employed, and based on a farm-gate biomass price of €100/t DM. These gross margins were competitive with FAPRI-Ireland projected gross margins for cattle rearing, sugar beet, winter wheat, spring barley and set-aside, but not with dairy. Gross margins calculated at a farm-gate price of €70/t DM ranged from €33 to €167/ha/annum, and were still competitive with gross margins from many of the conventional land uses. Including recently announced 50% establishment grants and €80/ha/annum top-up subsidies for *Miscanthus* and SRCW increased discounted gross margins to between

€327 and €527/ha/annum, at a farm-gate price of €100/t DM.

An NPV approach was also used to compare the cost difference for energy-crop-biomass electricity generation compared with dedicated peat and coal electricity generation, and for SRCW woodchip heat production compared with gas, oil and electric heat production at the household and small-commercial scale. Co-fired SRCW electricity cost €0.017/kWh_e more to produce than coal electricity (€0.0139/kWh_e more if direct co-firing at less than 5% is assumed), but co-fired *Miscanthus* electricity cost just €0.0021/kWh_e more to produce than peat electricity. These calculations assumed an EU Emission Trading Scheme (ETS) CO_2 allowance value of €14/t, and a farm-gate biomass price of €100/t DM. At a farm-gate biomass price of €70/t DM, *Miscanthus* co-fired with peat, and gasified SRCW co-fired with coal, produced electricity at €0.0095/kWh_e lower, and €0.0053/kWh_e higher, cost than peat and coal electricity, respectively. Without newly available subsidies, discounted annual SRCW household heating costs were €143, €277 and €722 lower than the equivalent gas, oil and electric heating costs, once woodchip boiler installation costs of €10,000 had been accounted for (5% discount rate, 20-year boiler lifetime). Including the available subsidy of €4,200 per household for wood-heat boilers, wood heat became €353–932/annum cheaper than conventional heat at the household scale. At the small-commercial scale (ten times average domestic heat load) wood heat was forecast to result in substantial savings compared with gas, oil and electric heat, even without subsidies (discounted, annualised bills €3,454, €5,757 and €11,222/annum less than gas, oil and electric heating, respectively). In fact, wood heat was less than half the price of oil heat.

4 National Potential

Applying the economic data to the non-optimised scenario used to indicate the scale of GHG emission reductions resulted in a (~20-year discounted) net national benefit (considering loss of any benefits associated with displaced activities) of €122 million/annum. Thus, energy crops have the potential to generate substantial GHG emission savings (3.86 Mt CO_2 eq./annum in the scenario presented here) and additional income. They offer further benefits in terms of national fuel security and rural income and employment, though these benefits have not been quantified in this report. Additional environmental benefits arising from the scenario presented in this report include reduced nitrogen and phosphorus loading to soils (by 4,709 and 492 t/annum) and, depending on the spatial distribution of energy crops, improved soil quality and biodiversity. These are set against increased potassium loading to soils (by 2,906 t/annum) and increased lorry traffic transporting the biomass (an additional 57,676 30-t lorry return journeys required in total) – the LCA only accounted for the GHG-emission impacts of these factors. In addition to relatively low nutrient application rates, the efficient nutrient cycling of *Miscanthus*, and the dense root mat and high transpiration rate of SRCW should minimise nutrient losses from soils to water.

The overall benefits of energy crops only become fully apparent when a broad (interdisciplinary, multi-sectoral), long-term view is taken. High up-front investment costs for producers and consumers, in conjunction with market uncertainty and negative perception of energy crops, are barriers to their utilisation. Co-firing electricity generation, and especially heat production, offer immediately viable opportunities for energy-crop utilisation. Longer-term options for SRCW and *Miscanthus*, with favourable energy and GHG budgets compared with traditional biofuel crops, include conversion to liquid and gaseous fuels, including hydrogen, through lignocellulosic digestion and gasification techniques. Such energy crops may ultimately be used as fuels for transport, and to generate electricity/heat efficiently in modern combined-cycle gas-turbine power stations and combined heat and power plants. By contributing to base-load energy demand, energy crops offer a high-value additional renewable resource that could complement promising but less constant renewable resources such as wind and tidal electricity generation. Similarly, although cheaper biomass sources may initially compete with energy-crop biomass, the large supply potential and greater spatial flexibility of energy crops should ensure a demand for them in a bio-energy market. Further, the additional benefits to the rural economy and environment (especially from an agricultural perspective) associated with energy crops, quantified in this report, justify some government financial support to cover the energy-crop biomass premium. Co-ordination among producers and consumers is also required – both sides are reluctant to make the necessary capital investments until they can be sure of long-term capacity commitments on the other side. The government could play a major role by hedging the risks for pioneers and setting mandatory targets.

1 Introduction

1.1 Energy Crops – A Sustainable Energy Source?

This report refers to information gleaned, and work carried out, during a 1-year desk study focused on identifying the potential for energy-crop utilisation to contribute to a sustainable future in Ireland. It aims to provide a broad overview of energy crops, in terms of their potential ecological and economic impacts, and in terms of their feasibility, development strategy, and compliance with legislation. The emphasis is on greenhouse gas (GHG) emissions, probably the most pressing threat to sustainability of which we are currently aware, and which may be reduced through the utilisation of energy crops. Energy crops were chosen for study due their relevance to a number of contemporary issues. In addition to potentially reducing GHG emissions, it was hypothesised that energy crops could:

- Contribute to long-term fuel price stability and security of supply in a time of volatile prices and supply, and higher costs associated with the introduction of carbon dioxide (CO_2)-emissions charging
- Help to secure the long-term financial viability of the agricultural sector and rural economy, after decoupling of subsidies from production in January 2005 and the likely future exposure of Irish farmers to a liberalised global market for agricultural produce
- Contribute to the 'greening' of agriculture, ensuring a sustainable future, through more efficient nutrient cycling and less intensive practices, and through a potentially beneficial impact on landscape biodiversity.

1.2 Definition of Energy Crops

Energy crops are crops specifically cultivated in order to utilise their biomass as fuel for energy production within a short time frame, and exclude biomass extracted from existing (long-rotation) forestry. In the UK, legislation defines energy crops as "*crops planted since 1989 and grown primarily for the purpose of being used as fuel*" (McKay, 2006). A wide range of crops may be used for energy purposes: some to produce liquid biofuels, others for use as solid fuels. Common liquid biofuel crops include oil-seed rape, sugar cane (in warmer climes) and sugar beet. Common solid-fuel energy crops include willow, poplar, *Miscanthus* grass (Photo 1.1), Switch grass, and hemp. For energy purposes, willow and poplar are grown in densely planted short-rotation coppice (SRC) systems, involving initial coppicing to stimulate multiple stem growth followed by frequent (usually 3–4 years)

Photo 1.1. A *Miscanthus* crop being harvested.
Source: The South West Renewable Energy Agency (www.regensw.co.uk/technology/biomass-faq.asp).

harvesting of the dense woody stems (see Photo 1.2 and Fig. 1.1). This study focuses on SRC willow (SRCW) and *Miscanthus*, specifically *Salix viminalis* L. and *Miscanthus* x *giganteus*. SRCW and *Miscanthus* are becoming established as favoured energy crops, and have been identified as the two most promising energy crops in the UK by the Department for Environment, Food and Rural Affairs (DEFRA). This reflects their efficient nutrient cycling, low chemical/energy input requirements, and relatively high biomass yield potential. *Miscanthus* utilises the efficient C4 photosynthetic pathway, which is more efficient at converting CO_2 into biomass C than the more common C3 photosynthetic pathway inherent in most agricultural crops, and plants generally, in temperate latitudes. Annually harvested liquid biofuel crops require substantial energy and chemical inputs, which can result in poor energy output/input ratios and low GHG emission savings (Hanegraaf *et al.*, 1998). Modern digestion and gasification techniques (Hamelinck and Faaij, 2002; Albertazzi *et al.*, 2006; Faaij, 2006) enable the tough, lignocellulosic material in SRCW and *Miscanthus* biomass to be converted into liquid fuels and hydrogen. Thus, although only heat and electricity generation are focused on in this study, the energy crops considered could ultimately offer an alternative, efficient source of transport fuels.

Photo 1.2. SRCW being harvested.

Source: Cranfield University Institute of Water and Environment (http://www.silsoe.cranfield.ac.uk/iwe/research/willow.htm)

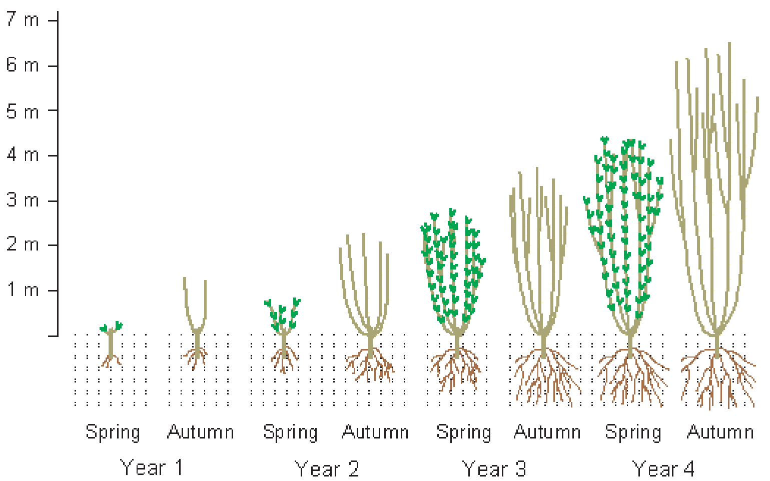

Figure 1.1. The establishment and growth cycle of SRCW up to the first harvest.

Source: Scottish Agricultural College (2006) www1.sac.ac.uk/.../WillowImages/W_growth.gif (accessed April 2006).

1.3 Energy Crops, the Carbon Cycle and Global Warming

As alluded to above, energy from energy crops (and other biomass) is not carbon (C) neutral, and does involve GHG emission. For energy crops, net GHG emissions principally arise during cultivation, from direct (e.g. tractor diesel consumption) and indirect (e.g. fertiliser manufacture) sources. However, the long cropping cycles of the perennial crops studied here (16[1] and 23 years for *Miscanthus* and SRCW, respectively) ensure that such emissions are low in comparison to other annual crops, including some energy crops. When combusted, biomass (from energy crops or otherwise) releases large quantities of CO_2, and small quantities of methane (CH_4) and nitrous oxide (N_2O) – similar to peat or coal combustion. However, because energy crops are produced from photosynthetic conversion of atmospheric CO_2 into solid biomass C, occurring shortly prior to combustion, the CO_2 released simply represents a cycling of 'current' atmospheric CO_2. This contrasts with fossil fuel combustion, which releases CO_2 from stored forms sequestered millions of years ago from a vastly different atmosphere and climate. Biomass combustion CO_2 release is thus regarded as C neutral from a global-warming perspective and according to GHG budgeting and accountability (IPCC, 2001). However, the release of small quantities of the potent GHGs, CH_4 and N_2O, with global-warming potentials (GWPs) 23 and 296 times greater than CO_2, respectively, means that non-abated biomass combustion emissions do contribute slightly to the net increase in the radiative forcing effect that constitutes the human contribution to global warming. In mitigation of this, energy crops may increase long-term C storage in above, but especially below, ground biomass and as soil C (Fig. 1.2), and the continuous removal of above-ground biomass for combustion may reduce CH_4 emissions associated with the decomposition process. The net GHG emission arising from energy-crop-to-energy-fuel chains depends on a multitude of factors, such as the methods of cultivation and energy conversion, transport distance of the fuel, etc. Total GHG emission savings from energy crops also depend on precisely what land uses and energy-conversion processes energy crops are substituting, and, ultimately, the impact of any consequent (knock-on) displacement effects (often difficult to identify and quantify).

1. A conservative estimate used in this study, based on DEFRA (2001) minimum production lifetime estimates. *Miscanthus* crops may maintain high yields for 20 years or more (Lewandowski and Heinz, 2003; Heaton *et al*., 2004) – longer cropping cycles would improve the life-cycle and cost–benefit analyses performance of *Miscanthus*.

1.4 Study Approach

Although the original aim of this study was to quantify all major environmental, social and economic implications of energy-crop utilisation in Ireland, time constraints meant that an emphasis was placed on detailed quantification of GHG emissions and economic impacts. Firstly, extensive life-cycle analysis (LCA), involving the quantification of environmental impacts arising over whole production and fuel chains, was applied to energy-crop fuel chains, from initial plant propagation and soil preparation through to combustion for electricity and heat generation. The focus in this study is on GHG emissions, but the LCA modelling process enabled other major environmental issues to be identified (fertiliser use, herbicide application, lorry traffic, etc.). Energy-crop cultivation was compared against the major agricultural systems it was assumed most likely to replace, and energy-crop heat and electricity production was compared against the conventional fuels it was assumed most likely to replace. Thus, it was necessary to construct comparative LCA models for conventional, displaced systems. Secondly, the financial attractiveness of energy-crop utilisation was considered from the perspectives of farmers and energy generators/

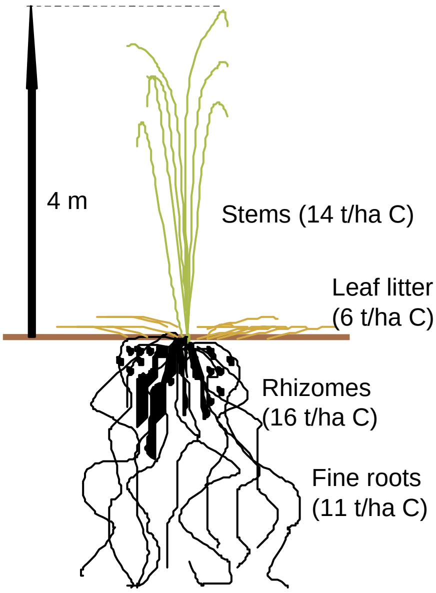

Figure 1.2. An illustration of the large quantities of carbon sequestered and stored in a typical *Miscanthus* stand.

consumers. This involved detailed costing of energy-crop cultivation, and, based on estimated farm-gate returns, calculation of both agricultural and energy-producer profitability (compared with conventional systems). Thirdly, combined GHG emission and economic impacts, and additional major impacts identifiable from life-cycle and economic analyses were considered in a national cost–benefit analysis for a scenario of energy-crop utilisation. From this, energy-crop utilisation was assessed for its potential as a cost-effective GHG abatement strategy, and to aid compliance with policy targets and general sustainability criteria. Finally, barriers and opportunities for energy-crop utilisation in Ireland are listed at the end of the report.

2 Background

2.1 Current Sectoral GHG Emissions and Sources

Rapid economic development in Ireland over the period 1990–2001 was a major driver of the 31% increase in national GHG emissions observed over that period, culminating in 2001 emissions of 70.5 Mt CO_2 eq. (McGettigan *et al*., 2005). Following subsequent emission reductions, emissions are again on the increase, and stood at 68.5 Mt CO_2 eq. in 2004, the latest date for which comprehensive data are available in the National Inventory Report (NIR) (McGettigan *et al*., 2006). This was 27% above 1990 levels, and faces Ireland with a considerable challenge to comply with its Kyoto commitment for GHG emissions not to exceed 13% above 1990 levels over the 2008–2012 commitment period. Unusually, the agricultural sector is the largest GHG-emitting sector in Ireland, accounting for 28% of 2004 emissions (McGettigan *et al*., 2006). This reflects the dominance of livestock rearing, with grassland accounting for 83% of agricultural land area (CSO, 2006: http://www.cso.ie/statistics/AgricultureandFishing.htm). Enteric fermentation, animal-waste management and grassland nitrous oxide (N_2O) emissions are the main agricultural GHG emission sources (detailed in Section 4.3). Casey and Holden (2004) conducted an LCA for a model farm representative of average Irish dairy farm characteristics. They attributed 49% of annual GHG emissions to enteric fermentation, 21% to fertiliser (production and post-application N_2O emissions), 13% to concentrate feed, 11% to dung management and 5% to electricity and diesel consumption.

Energy-related GHG emissions, which were estimated to total 65% of 2004 emissions, originated in approximately equal measure from heat production, electricity generation and transport (Howley *et al*., 2006). A C-intensive electricity sector, relying on coal and peat for 28% and 6%[2] of fuel-energy input, respectively (Fig. 2.1), emitted approximately 22% of 2004 GHG emissions. Heat production, among the domestic, commercial and public sectors, was responsible for another 22% of emissions (Howley *et al*., 2006). Figure 2.2 highlights the dominance of oil, electricity and gas as energy sources in these sectors, reflecting the low oil and gas costs of recent times. Transport accounted for just over 20% of 2004 emissions, but this is growing rapidly. Energy crops have the potential to reduce GHG emissions in all the aforementioned major GHG-emitting sectors.

2.2 Future Projections for Energy and Agricultural Sector GHG Emissions and Sources

The Howley *et al.* (2006) projections for the electricity-generation fuel mix in 2020 (Fig. 2.1) include a decrease in coal generation from a 28% to a 9% share of the total,

2. Peat electricity generation was down over 30% compared with 2003, as old peat stations were decommissioned prior to opening of new plants.

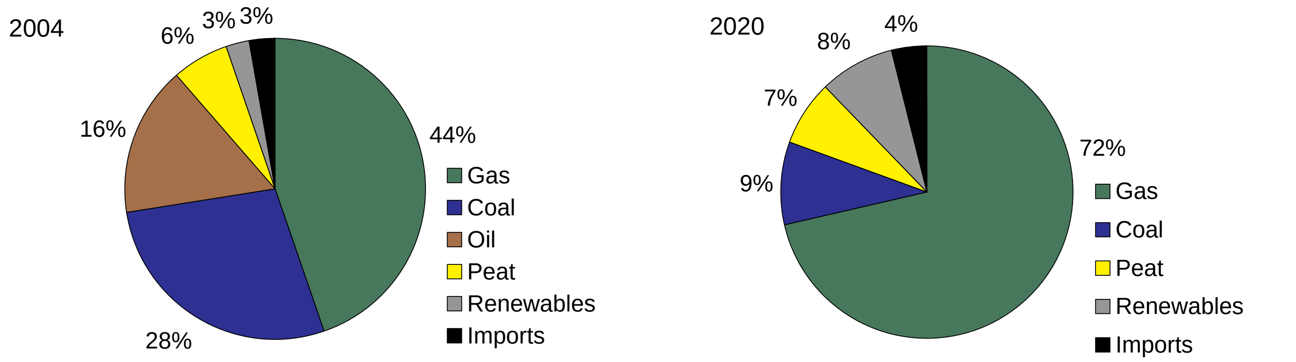

Figure 2.1. Electricity generation by fuel type, according to the Howley *et al.* (2006) statistics and projections. Total fuel energy requirements for electricity generation were assumed to increase from approximately 58 to 81 TWh/annum between 2004 and 2020.

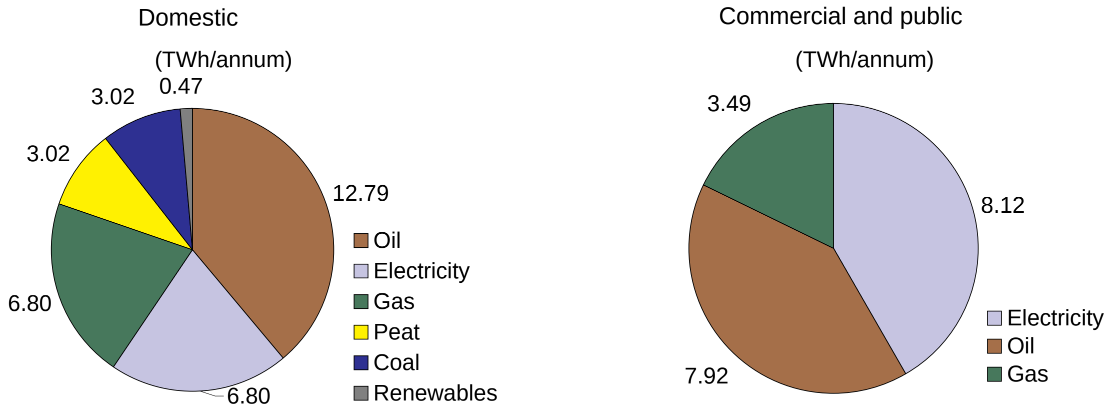

Figure 2.2. Total energy consumption by fuel source for the domestic (total 32.9 TWh/annum) and commercial and public (total 19.5 TWh/annum) sectors in 2004.

Source: Howley *et al.* (2006)

and an increase in gas generation from a 44% to a 72% share of the total. These were based on c. 2004 ESRI projections for fuel costs and European Union Emissions Trading Scheme (EU ETS) CO_2 allowance values. In contrast to oil prices forecast to rise from US $35.9 per barrel in 2004 to US $58.9 per barrel by 2010, current prices are sitting at over US $60 per barrel. Similarly, a rapid rise in ETS CO_2 allowance prices to around €30/t in early 2006 have been followed by a collapse, but are set to increase significantly under tighter allocations in the second phase (2008–2012) – in contrast to ESRI projections for a steady increase to €15/t CO_2 in 2010 and €30/t CO_2 in 2020. Additionally, there is increasing concern about over-dependence on a small number of gas suppliers and supply pipelines in politically unstable regions, and oil-production capacity is widely predicted to peak shortly. There are indications that high dependence on imported fossil fuels in economically developed nations (in Ireland, these supply >90% of our energy), in conjunction with a rapid increase in demand among some large economically developing nations (China and India in particular), will maintain high oil and gas prices, and result in market forces shifting towards renewables and coal. Thus, the Howley *et al.* (2006) projections may already be outdated.

The rapidly evolving fuel and CO_2 allowance markets, imposed on a recently liberalised electricity sector in Ireland, make accurate predictions of future fuel consumption elusive. In this report, a simple approach is taken to quantify emission reductions possible from energy crops, based on substitution of proportions of current fuels and land uses with energy crops. The Howley *et al.* (2006) projections for renewable electricity generation to increase from less than 3% in 2004 to over 8% in 2020 include the assumption of 30% biomass co-firing in the existing peat power stations[3] (also a major assumption in this report: Section 4.3.4), reflecting the findings of a detailed SEI survey into co-firing (SEI, 2004). This projection is short of the indicative renewable electricity target of 13.2% of gross electricity consumption by 2010, set out by the Renewable Energy Directive (2001/77/EC). However, in order to comply with this Directive, the Department of Communications, Marine and Natural Resources (DCMNR) has recently announced a target of 1,450 MW renewable electricity-generating capacity installation by 2010, to be achieved through new renewable energy feed-in tariff (RE-FIT). This will offer €0.072/kWh for biomass electricity, although it appears that co-firing will not be eligible. Latest estimates indicate that huge increases in installed wind-electricity capacity in 2004 and 2005 will continue and result in the 13.2% target being met by 2010 (Conlon *et al.*, 2006).

Economic modelling of farm-level responses to decoupled subsidy scenarios in Ireland (Binfield *et al.*, 2003) indicates that gross margins attributable to agricultural production will decrease substantially. Consequently, livestock numbers are forecast to decline significantly

3. Based on the SEI co-firing report (SEI, 2004), operation of the two new peat power stations (Lanesboro and Shannonbridge) will increase peat electricity-generation capacity to 344.5 MW_e (net), compared with a minimum capacity of 117.5 MW_e (net) from Edenderry in 2004 after closure of the old stations and prior to opening of the new ones.

over the period 2002–2012, by up to 12% for dairy cows, 19% for non-dairy cattle and 26% for sheep, resulting in large areas of destocked grassland available for either extensification of existing livestock rearing or alternative land uses. Based on destocking projections, Donnellan and Hanrahan (2003) forecast agricultural GHG emission reductions of 16% (2.8 Mt CO_2 eq./annum) from 1990 levels, by 2012. Energy crops may be planted on destocked land, or on uneconomic tillage land, but also may encourage further agricultural displacement through improved comparative economics under the decoupled subsidy system (explored in Section 5.3.4).

2.3 Current Energy-Crop Utilisation in Ireland

Although a few other countries have been pursuing energy-crop strategies for over a decade (with 15,000 ha of SRCW planted in Sweden in the early 1990s), current energy-crop utilisation in Ireland is virtually non-existent, with signs of commercial interest only beginning to emerge. The recent (3-year) availability of establishment grants in Northern Ireland from the Forestry Service, equal to half the establishment cost, has stimulated the establishment of approximately 800 ha so far (McCracken *et al*., 2006). A contractor and consultancy company, Rural Generation, has evolved from initial research and development work into willow cultivation and combined heat and power (CHP) generation through gasification, begun in 1996 at Brookhall Estate, Derry. It is currently promoting the use of SRCW for waste-water (WW) treatment to improve financial returns (see Chapter 5). In the Republic of Ireland, initial experimentation with SRCW cultivation on mined peat bogs in the 1970s was unsuccessful for a variety of reasons, and, despite an ideal wood-growing climate in Ireland, SRCW cultivation has yet to become established as a profitable land use (~100 ha planted). However, increased energy prices and agricultural subsidy decoupling have increased commercial interest in recent years, and the establishment of energy-crop consultancy and contracting companies such as Clearpower may signal the beginning of significant SRCW establishment. Examples of some recently established wood heat consumers in Ireland are listed in Appendix B.

Commercial interest in *Miscanthus* is less developed than for SRCW, although Ireland has hosted some long-running experiments with *Miscanthus* cultivation at Cashel (see Clifton-Brown *et al*., 2000) and Carlow (Teagasc). However, *Miscanthus* is estimated to have a high yield potential in Ireland, especially in the drier, warmer south-east (Clifton-Brown *et al*., 2000, 2004), and one company (Quinns of Baltinglass, personal telephone communication 30 January 2006) has recently begun offering contract planting and biomass-purchase agreements for *Miscanthus* (see Chapter 5). During final revision of this report (March 2007), the government had just announced establishment grants of up to €1,450/ha, and top-up subsidies of €80/ha/annum, for *Miscanthus* and willow cultivation (DAF, 2007: http://www.agriculture.gov.ie/index.jsp?file=pressrel/2007/18-2007.xml). Provision has been made for up to 1,400 ha to be planted in the first year of the scheme.

A number of previous studies looking at electricity production from biomass, including energy crops, in Ireland, have concluded that energy-crop biomass is an expensive source of electricity (van den Broek *et al*., 1997, 2001), and compares poorly (financially) with forestry residues and wastes. However, a combination of increased fuel prices and new CO_2 emission charges under the EU ETS, decreasing farm incomes, and increasing concern over both security of fuel supply and GHG emissions, have made energy crops a more attractive proposition. In Scotland, Andersen *et al*. (2005) have estimated that SRCW could displace 6 Mt C from fuel oil annually, reducing GHG emissions by 15% and supplying 31% of Scotland's electricity, and a significant portion of its heating, requirements. There is a need to explore the potential role of energy crops in Ireland within rapidly changing energy and agricultural sectors, from both environmental and economic perspectives.

3 Land-Use Change and GHG Emissions

3.1 Aims

This chapter quantifies the potential GHG emission reductions that could arise from land-use change where energy crops replace existing agricultural systems. LCA is applied to *Miscanthus* and SRCW cultivation, and also to the major conventional agricultural land uses initially considered most susceptible to displacement by energy crops (sugar beet, sheep rearing, cattle rearing, dairying). The differences in GHG emissions between energy-crop cultivation and conventional agricultural land uses are used to infer the likely land-use change GHG emission impacts of energy-crop cultivation. In Chapter 4, these data are combined with electricity- and heat-generating GHG emission data, in the context of an indicative national scenario, to estimate the magnitude of GHG emission changes possible from energy-crop utilisation in Ireland.

3.2 Methodology

3.2.1 Scope, aims and boundaries

In order to construct LCAs for different agricultural systems, it was first necessary to construct a model of an average farm representing each system, following the example of Casey and Holden (2004) for dairy systems. All relevant inputs to the system and induced processes (e.g. soil N_2O emissions) were then considered in a life-cycle inventory (LCI) up to the point of the farm gate, both for existing agricultural and energy cropping systems. All major inputs and sinks of the major GHGs (CO_2, CH_4 and N_2O) were considered. Published, nationally compiled statistical data were used to define existing agricultural systems, while a synthesis of international literature was used to define SRCW and *Miscanthus* cropping systems. Inventory mass balances were summed and converted into a final GWP, expressed as kg CO_2 eq. considered over a 100-year timescale, according to IPCC (2001) guidelines: i.e. CO_2 = 1, CH_4 = 23 and N_2O = 296. Land-use LCAs were calculated and expressed as kg CO_2 eq. per hectare of land area and per year, averaged over the lifetime of each crop. All indirect emissions associated with different land uses have been accounted for, in accordance with the aim of assessing the sustainability of energy cropping systems. However, this does mean that a small proportion of overall calculated emissions (and emission changes) occur outside Ireland. Similarly, the potential international land use and associated GHG emission impacts of land-use changes within Ireland (e.g. livestock production possibly displaced to other countries) are uncertain (discussed later in this chapter).

3.2.2 Emissions data

Energy use was divided into source categories of primarily diesel combustion or primarily electricity. For diesel, a lower heating value of 35.9 MJ/l was used (Dalgaard *et al.*, 2001), and emissions were calculated based on 1 kg (1.198 l) diesel combustion emitting 3.767 kg CO_2 eq., including indirect emissions of 0.544 kg CO_2 eq. (Flessa *et al.*, 2002). To this were added lubrication oil emissions, calculated at 5% of farm machinery diesel emissions based on Dalgaard *et al.* (2001), and assuming 50% oxidation (IPCC, 1996). For electricity consumption, the national average 2004 GHG intensity of delivered electricity (0.173 kg CO_2 eq./MJ_e) (Howley *et al.*, 2006) was applied to primary energy requirement values provided in the literature. These primary energy requirements were taken to represent the fuel-energy input to electricity generation, and thus were multiplied by the average electricity supply efficiency in Ireland of 0.406 (Howley *et al.*, 2006) prior to application of the emission-intensity factor. Electricity emissions are thus subject to error based on deviation in energy-conversion efficiencies between the country of data origin and Ireland, and these differences are likely to outweigh the minor (e.g. coal generation in Section 4.3.1) but unquantified national average indirect emissions from electricity generation. Indirect emissions associated with agricultural machinery production and maintenance were assumed to be proportionate to fuel consumption following the method of Dalgaard *et al.* (2001), i.e. 12 MJ primary energy requirement per litre fuel consumed, with emissions dependent on energy fuel source. Indirect emissions for fertiliser and lime manufacture were taken from representative sources in the literature, after comparison of multiple literature values. For fertiliser, all-inclusive manufacturing, packaging and transport energy intensities of 79.6, 34.5 and 10.5 MJ/kg for N, P and K, respectively (Elsayed *et al.*, 2003), were used, to which were added manufacturing N_2O emissions of 9.63 g/kg N.

For lime, combined manufacture and calcification emissions quoted by Elsayed *et al.* (2003) were divided into manufacturing and soil emissions based on the energy requirement (assumed to be supplied as electricity) of 6.43 MJ/kg. Soil emissions following fertiliser or manure application and grazing, and direct animal emissions, were based on values used in the NIR (McGettigan *et al*., 2005), i.e. 1.25% of applied N minus 4% NH_3-N volatilisation loss. Animal waste storage emissions were grouped with soil emissions for classification purposes. Table 3.1 lists the emission factors applied to the main activities and processes accounted for in the LCA. The multiplication factors displayed were used to arrive at average annual GHG emissions (kg CO_2 eq.) per hectare for each inventory item and for each land-use system, based on the proportional temporal and spatial occurrence of each activity over a whole rotation of each land-use system. In addition to these data, it was assumed that soil C remained constant after conversion of grassland to energy cropping (discussed later), but increased by 0.513 and 1.163 t/ha/annum after conversion of arable land to SRCW and *Miscanthus* cultivation, respectively (Matthews and Grogan, 2001).

3.2.3 Typical livestock land-use descriptions

Land management and animal numbers for the farming systems were obtained from the National Farm Survey (NFS) (Connolly *et al*., 2004). These data provide average values for all farms surveyed according to category (mainly dairy system, mainly cattle system, mainly sheep system). It was necessary to correct these data to ensure that only features integral to the named portion of each system were included in each model farm. Silage area was included for each livestock system (along with calculations for average feed, based on NFS data). Features not integral to each system were removed, and proportionate land areas recalculated (Table 3.2). Thus, the livestock systems were simplified to ‘dairy’, ‘cattle rearing’ and ‘sheep’. Land-use areas and corresponding average fertiliser application rates were taken from the Fertiliser Survey 2000 (Coulter *et al*., 2002) and are shown in Table 3.2. National average lime application rates (Culleton *et al*., 1999) were applied to dairy and cattle-rearing land at 5-year intervals (852 kg/ha every 5 years). Milking operations were included in the housing operations of Dalgaard *et al.* (2001), but no further processing or transport of any produce was considered in the land-use LCAs (these considered in combustion LCAs).

3.2.4 Typical sugar-beet land-use description

Fertiliser application rates for sugar beet were taken from the Fertiliser Survey 2000 (Coulter *et al*., 2002): 160, 46, 165 kg/ha/annum N, P and K, respectively (Table 3.2), and it was assumed that 1 t lime is incorporated every 3 years into sugar-beet soil. Emissions associated with sugar-beet seed production were taken from Kuesters and Lammel (1999). Diesel and lubricating oil consumption during soil preparation was taken from Dalgaard *et al.* (2001), assuming one pass each to plough, cultivate, sow and roll. Sugar-beet specific harvest fuel requirements were also taken from Dalgaard *et al.* (2001), assuming medium soil density. Harvested sugar beet was stored in barns, construction emissions for which were based on Elsayed and Mortimer (2001), and listed under ‘Housing’ in Table 3.1. For simplicity, it was assumed that sugar beet was the sole crop on land dedicated to its cultivation (i.e. no crop rotation or catch crops). The inventory cut-off point for the LCA of this system was defined as immediately after storage of harvested sugar beet. Therefore, no emissions related to transport and processing were considered.

3.2.5 Miscanthus cultivation description

The *Miscanthus* rotation used to define the LCA developed here is loosely based on the rotation described by Lewandowski *et al.* (1995), except that plants are propagated using the macro-propagation rhizome division technique recommended by DEFRA best-practice guidelines for energy crops (DEFRA, 2001). The life cycles for both *Miscanthus* and SRCW are outlined in Table 3.3. The first stage of ground preparation includes herbicide application, at a rate of 2.25 kg/ha of active ingredient (Elsayed *et al*., 2003), followed by subsoiling and ploughing in autumn of Year 0. Rhizomes are planted in spring of Year 1 using a potato planter, following lifting, rotovation and pick-up using a bulb harvester of 3-year-old *Miscanthus* rhizomes, where 1 ha supplies rhizomes to plant 10 ha at 20,000 rhizomes/ha, at a total energy intensity of 4,000 MJ/ha planted (Bullard and Metcalf, 2001). Herbicide application is considered necessary only in the establishment year, as leaf-litter ground cover and rapid canopy closure were assumed to suppress weed growth (DEFRA, 2001). Fertiliser application follows maximum recommendations of Heaton *et al.* (2004), at a rate of 100, 20 and 100 kg/ha/annum for N, P and K,

Table 3.1. GWP values, expressed as kg CO_2 eq./ha, applied to activities, processes and indirect emissions in LCA, and the relevant multiplication factors applied to generate GWP emissions on a per hectare, per annum basis.

Operation	Unit	GWP	Dairy	Cattle	Sheep	Sugar beet	Misc.	SRCW
Direct emissions								
Soil preparation								
Subsoiling	CO_2 eq./ha	83.38[a]	0	0	0	0	0.063	0.044
Ploughing[1]	CO_2 eq./ha	83.38[a]	0	0	0	1	0.125	0.087
Cultivating	CO_2 eq./ha	43.50[a]	0	0	0	1	0.063	0.044
Rolling	CO_2 eq./ha	6.59[a]	0	0	0	1	0.063	0.044
Planting	CO_2 eq. ha^{-2}	115.4[b]	0	0	0	0	0.063	0.044
Sowing	CO_2 eq. ha^{-3}	10.88[a]	0	0	0	1	0	0
Maintenance								
Fertiliser spreading	CO_2 eq./ha	6.59[a]	2	2	1.50	2	1.875	0.608
Lime application	CO_2 eq./ha	26.36[a]	0.20	0.20	0.20	0.53	0.063	0.043
Slurry spreading	CO_2 eq./ha	72.27[c]	1	1	0	0	0	0
Pesticide application	CO_2 eq./ha	4.94[a]	0	0	0	3.00	0.188	0.304
Housing operations (dairy)	CO_2 eq./ha	817.2[a]	1	0.14	0.04	0	0	0
Harvest								
Cutting + baling	CO_2 eq./ha	246.6[d,b]	0.18	0.12	0.06	0	0.537	0.304
Lifting	CO_2 eq./ha	61.63[a]	0	0	0	1	0	0
Indirect emissions								
Propagation (Misc.)	CO_2 eq./ha	288.74[e]	0	0	0	0	0.063	0.007
Seed	CO_2 eq./ha	11.81[f]	0	0	0	1	0	0
Machinery[2]	CO_2 eq./l	0.90[a]	–	–	–	–	–	–
Fencing – border	CO_2 eq./ha	776.48[d]	0.04	0.04	0.04	0.04	0.040	0.040
Fencing – internal	CO_2 eq./ha	869.69[d]	0.07	0.07	0.07	0.07	0.067	0.067
Fuel[2]	CO_2 eq./l	0.53[a]	–	–	–	–	–	–
Lubricating oil[2]	CO_2 eq./l	0.19[a]	–	–	–	–	–	–
Fertiliser N	CO_2 eq./kg	8.63[d]	160	52	36	160	94	58
Fertiliser P	CO_2 eq./kg	2.57[d]	13	8	5	46	19	13
Fertiliser K	CO_2 eq./kg	0.79[d]	35	20	11	165	94	81
Lime	CO_2 eq./kg	1.10[g]	170	170	170	333	188	130
Pesticide	CO_2 eq./kg	6.3[g]	0	0	0	6.75	0.422	0.685
Feed concentrate	CO_2 eq./kg	1.16[h]	1585	932	139	0	0	0
Housing (dairy)	CO_2 eq./ha	356.3[a,d]	1.000	0.424	0.120	0.172	0.172	0.172
Animal and soil emissions								
Fertiliser N_2O	CO_2 eq./kg N	5.58[i]	160	88	36	160	100	64
Slurry N_2O	CO_2 eq./kg N	4.83[i]	70	27	0	0	0	0
Grazing N_2O (dairy)	CO_2 eq./ha	1059[i]	1	0.37	0.63	0.00	0	0
Enteric fermentation	CO_2 eq./ha	4305[i]	1	0.41	0.46	0.00	0	0

[1]Ploughing used as part of root removal in final year of energy crops.
[2]Emission factors expressed per litre of fuel consumed.
[a]Dalgaard *et al.* (2001); [b]Lewandowski *et al.* (1995); [c]Rice and Quinlan (2003); [d]Elsayed and Mortimer (2001); [e]Bullard and Metcalf (2001); [f]Kuesters and Lammel (1999); [g]Wells (2001); [h]Casey and Holden (2004); [i]McGettigan *et al.* (2005).

Table 3.2. Land-use areas, fertiliser application rates, and livestock numbers for typical Irish farming system units (i.e. average dairy, cattle, sheep and sugar-beet farms), as derived from the National Farm Survey 2003 and Fertiliser Use Survey 2000.

Land use	Dairy		Cattle		Sheep		Sugar beet
	Area (ha)	N:P:K (kg/ha/annum)	Area (ha)	N:P:K (kg/ha/annum)	Area (ha)	N:P:K (kg/ha/annum)	N:P:K (kg/ha/annum)
Pasture	23.7	176:12:26	15.9	48:08:17	13.5	48:06:13	
Silage	13.8	151:16:53	6.3	95:14:41	3.1	94:13:39	
Rough grazing	1.5	0	4.1	0	7	0	
Total/average	**39.0**	**160:13:35**	**26.3**	**52:08:20**	**23.6**	**36:05:11**	**160:49:165**
Livestock	44 milking cows, 58 other cattle		41 cattle		254 sheep		0

Table 3.3. Life cycle of SRCW and *Miscanthus* crops, as used in life-cycle analyses.

Year	SRCW	Year	*Miscanthus*
0	Herbicide application Subsoiling and ploughing	**0**	Herbicide application Subsoiling and ploughing
1	Herbicide and insecticide (leather jacket control) application Lime application (3 t/ha) Soil rotovation Planting using a step or cabbage planter at density of 15,000 cuttings per ha Rolling Coppice	**1**	Fertiliser application (67, 13 and 67 kg/ha N, P and K) Lime application (3 t/ha) Soil rotovation Planting, potato planter at density of 20,000 rhizomes/ha Rolling Herbicide application
2	Fertiliser application (128, 28 and 178 kg/ha N, P and K) Herbicide application	**2**	Fertiliser application (67, 13 and 67 kg/ha N, P and K) Harvest late winter (i.e. winter Year 2/3) Cut and bale/chop harvest late winter Drying[a] Storage on farm[b]
5	Stick/chip harvest late winter (i.e. winter Year 4/5) Drying[a] Storage on farm[b] Fertiliser application (192, 42 and 267 kg/ha N, P and K)	**3–5**	Repeat Year 2, but apply fertiliser at 100:20:100 kg/ha N, P and K from Year 4 onwards Herbicide application if necessary[c]
8	Late winter harvest (i.e. winter Year 7/8) Drying[a] Storage on farm[b]	**16**	Apply herbicide to new growth and plough
8–22	Repeat Years 5–8 rotation five more times		
23	Remove stools		

[a]Drying depends on harvest method, storage and end use.
[b]Storage dependent on harvest method and end use.
[c]Assume every other rotation.

respectively, and it is assumed that 3 t of lime are incorporated prior to planting (Bullard and Metcalf, 2001). This covers the crop off-takes of 88, 11 and 95 kg/ha N, P and K , respectively, in 13.5 t of DM stems as calculated by DEFRA (2001). Herbicide is applied once prior to planting, once after establishment, and once in the final year to destroy the crop. Harvesting is assumed to occur in late winter[4] of each year (1 to 15), with winter leaf senescence and storage losses of 30% from annual peak

4. Or early spring. The ideal harvest time will depend on preceding meteorological conditions, and should occur late enough to allow for maximum leaf senescence (so as to minimise nutrient off-take) and drying, but before emerging shoots become susceptible to harvest damage.

Table 3.4. Annual biomass yields for SRCW and *Miscanthus*, during the first 3 years, during subsequent maximum-yielding years, and averaged over the plantation lifetimes. Results for low-, mid-, and high-yield estimates, as applied to economic analyses (mid-yield estimates used in LCA).

Yield level		SRCW		*Miscanthus*	
		Standing	Combustion	Standing	Combustion
		(t DM/ha/annum)			
Low	Average first cut(s)	4.0	3.4	9.3	6.5
	Subsequent	6.0	5.1	14.0	9.8
	Plantation average	5.2	4.4	11.7	8.2
Mid	Average first cut(s)	8.0	6.8	13.3	9.3
	Subsequent	12.0	10.2	20.0	14.0
	Plantation average	10.4	8.8	16.7	11.7
High	Average first cut(s)	9.3	7.9	17.3	12.1
	Subsequent	14.0	11.8	26.0	18.2
	Plantation average	12.2	10.3	21.7	15.2

productivity of 20 DM t/ha/annum achieved from the fourth year on (Clifton-Brown *et al.*, 2000). During Years 1–3, establishing plants were assumed to produce two-thirds of peak productivity, and were not harvested in the first year, resulting in an average annual DM yield of 11.6 t/ha delivered for combustion over the 16-year cycle. These values correspond with the 'mid-yield' data in Table 3.4 (low- and high-yield data applied in economic analyses). Harvesting was assumed to use 40.25 l diesel per hectare, based on Lewandowski *et al.* (1995). Annualised construction emissions for baled *Miscanthus* storage barns were taken to be the same as for sugar beet. It was assumed that stored *Miscanthus* bales will have a final moisture content of less than 20% (Lewandowski *et al.*, 2000). In the final, sixteenth, year, herbicide is applied to *Miscanthus* growth and the field ploughed. Stored, baled *Miscanthus* is the final product of the *Miscanthus* land-use LCA. Matthews and Grogan (2001) predict that *Miscanthus* cultivation on long-term tillage soils will result in net soil C sequestration of 1.16 t/ha/annum over a period of 100 years. This estimate of soil C sequestration is applied in land-use change calculations where *Miscanthus* displaces sugar beet and (rotated) set-aside.

3.2.6 *Willow cultivation description*

Soil preparation for SRCW was assumed to be identical to that for *Miscanthus* (including 3 t lime application), though emissions were divided by the longer rotation assumed for SRCW (seven cuts over 23 years) to calculate annualised emissions (based on Heller *et al.*, 2003). Fertiliser application rates were taken from DEFRA (2002) recommendations, and fertiliser was assumed to be applied in the first year of each 3-year rotation, in two passes. Harvesting was assumed to use 74.85 l diesel per hectare, based on Elsayed *et al.* (2003). Annualised combustible yields were estimated at 8.83 t/ha, accounting for two-thirds productivity in the first 3-year cycle, and 15%[5] harvest and storage losses (Gigler *et al.*, 1999) from the 12 t/ha/annum maximum yields ('mid-yield' data in Table 3.4). Storage-associated emissions are identical to those for sugar beet and *Miscanthus*, and it was assumed that stored willow bales will have a final moisture content of approximately 20% (Gigler *et al.*, 2004)[6]. Herbicide application on established SRCW plantations is highly dependent on local circumstances, and in many instances may not be necessary due to rapid canopy closure once the crop is established and the beneficial effect of some ground cover. Here, it was assumed that worst-case scenario herbicide applications are required every other harvest cycle (Rural Generation, 2004). In the year following the final harvest, willow regrowth is sprayed with herbicide and the field ploughed over. GHG emissions associated with fencing were based

5. Assume 90% harvest efficiency for above-ground biomass, then 1% per month (for average 6 months) stem dry-matter losses during storage (Gigler *et al.*, 1999).
6. Gigler *et al.* (2004) observed that outdoor storage of baled willow harvest enabled natural drying of the wood, from harvested moisture contents of around 50% down to below 15%. A 20% moisture content is used as a realistic condition for naturally dried willow bales in the LCA – alternative harvesting and drying strategies are discussed in Section 5.4.1.

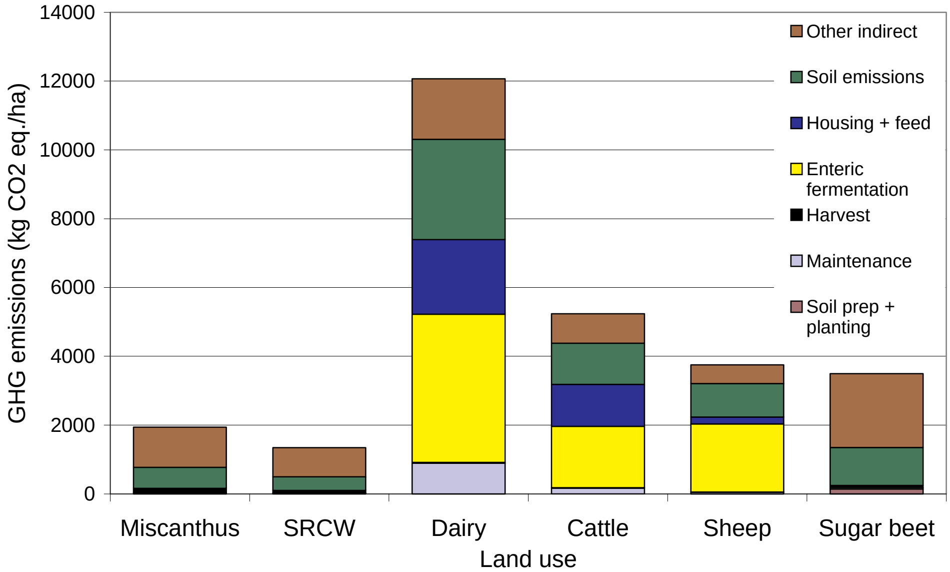

Figure 3.1. Annual GHG emissions per hectare associated with different land uses, divided into source categories, based on results of LCA.

on fence-construction energy requirements given in Elsayed and Mortimer (2001), and were assumed equal for all land uses. The tillage-soil SRCW C sequestration rate of 0.513 t/ha/annum predicted by Matthews and Grogan (2001) is applied to land-use change calculations where SRCW displaces sugar beet and (rotated) set-aside.

3.3 Results

3.3.1 Land-use GHG emissions

When annualised over the total rotation lifetimes of *Miscanthus* (16 years) and SRCW (23 years), GHG emissions arising from energy-crop cultivation are low compared with conventional agricultural land uses (Fig. 3.1). *Miscanthus* cultivation is responsible for an average annual emission of 1,938 kg CO_2 eq./ha, while SRCW cultivation is responsible for an average annual emission of 1,346 kg CO_2 eq./ha. This compares with annual GHG emissions of 12,068 kg CO_2 eq./ha calculated for dairy systems. Cattle, sheep and sugar-beet cultivation are associated with intermediate GHG emission intensities, though even the least GHG-intensive conventional productive land use considered here, sugar-beet cultivation, is associated with GHG emissions 50% higher than for *Miscanthus*. Figure 3.1 also shows a breakdown of GHG emissions into source categories. Enteric fermentation CH_4 contributes substantially to all the livestock system emissions (e.g. accounting for 36% of dairy emissions), while soil emissions are substantial across all land uses, dominated by fertiliser and animal waste application-induced N_2O emissions, and including lime calcification emissions. For the livestock systems, waste-storage emissions were classified under soil emissions, though they made relatively small contributions (e.g. 18% of soil emissions for dairy). Housing operations contribute to relatively high 'maintenance' emissions for dairy land use, while maintenance, soil preparation and planting emissions are low for the other land uses.

Indirect emissions were substantial for all land uses, and in all instances are dominated by N-fertiliser manufacture, which accounts for between 30% (cattle) and 65% (*Miscanthus*) of indirect emissions. When soil emissions stimulated by fertiliser-N application are also considered, fertiliser application contributes hugely to overall emissions, especially for non-livestock systems. For example, the manufacture, packaging and transport of the 87.5 kg of average[7] annual fertiliser-N required for 1 ha of *Miscanthus* cultivation requires 6,965 MJ of primary energy, associated with fossil-fuel emissions of 755 kg CO_2 eq.[8], while the application of this fertiliser results in soil emissions of 1.89 kg N_2O (558 kg CO_2 eq.) – thus contributing 1,313 kg/ha (68%) to the 1,938 kg/ha total annual CO_2 eq. emitted by *Miscanthus* cultivation. Indirect

7. Averaged over the plantation lifetime – less than the 100 kg/ha/annum applied during max yield years.
8. Energy supplied by combination of gas, electricity and oil-applied intermediate oil emission factors in this study.

emissions for livestock land uses were also divided into components attributable to housing and concentrate feed production in Fig. 3.1, and it is apparent that these activities account for a substantial proportion of overall dairy and cattle emissions.

3.3.2 Land-use change GHG emission effects

Whilst the above section quantified productive agricultural land-use emissions, non-productive agricultural land, such as set-aside and destocked grassland, may comprise some of the most suitable land for energy-crop cultivation (according to economic calculations in Section 5.3.4). For simplicity, it is assumed here that both set-aside and destocked grassland will be associated with zero net GHG emissions (in reality, some maintenance will result in small emissions, and if set-aside was left out of crop rotation significant soil C sequestration would occur). Net land-use change GHG emission reductions attributable to energy crops, including soil C sequestration effects where appropriate, are presented alongside total calculated GHG emission reductions in Tables 4.2 and 4.4. Table 4.2 indicates that displacement of agricultural production with *Miscanthus* cultivation may result in land-use GHG emission reductions of between 1,813 and 10,130 kg CO_2 eq./ha/annum, whilst displacement of agricultural production with SRCW cultivation may result in land-use GHG emission reductions of between 2,405 and 10,722 kg CO_2 eq./ha/annum. Data presented in Table 4.4 indicate that whilst displacement of set-aside with SRCW would result in a small net GHG emission reduction of 535 kg CO_2 eq./ha/annum (due to soil C sequestration), cultivation of SRCW on destocked grassland would result in net GHG emission increases of 1,346 kg CO_2 eq./ha/annum.

3.4 Discussion

3.4.1 Cultivation emissions

GHG emissions arising from field operations and machinery use are well summarised from the literature, modelled and validated in Dalgaard et al. (2001). These emissions were calculated to be minor in the context of the overall land-use LCAs studied here. A major source of emissions was fertiliser N, through both its manufacture and post-application soil N_2O emissions. A high degree of certainty may be attributed to fertiliser application rates for conventional agricultural systems, taken from the Fertiliser Survey 2000 (Coulter *et al*., 2002). The 100 kg/ha/annum fertiliser application rate for *Miscanthus* (Lewandowski *et al*., 1995) may err on the high side. Application of the 50 kg/ha/annum N-replenishment rates suggested by Lewandowski and Heinz (2003) and El Bassam (1998) to the *Miscanthus* LCA would have decreased cultivation emissions by 31% (though this is within the ±50% boundaries considered by the sensitivity analyses: Section 4.3.4). There is also scope for application of animal, human and industrial wastes, or combustion ash, to energy crops, which could substantially reduce the indirect emissions associated with fertiliser manufacture (and improve the economics: see Section 5.3.3). Similarly, there is scope for other management changes to minimise the environmental impact of energy-crop cultivation. For example, utilisation of mechanical weeding (e.g. Lewandowski *et al*., 1995; Perttu, 1998; Borjesson, 1999a), with an oil requirement of 2.2 l/ha (Dalgaard *et al*., 2001), could reduce both GHG emissions (6 l/ha oil required for herbicide manufacture and application: Dalgaard *et al*., 2001; Wells, 2001) and potential biodiversity and water quality impacts.

There have been considerable improvements in energy-cropping best practice over recent years, and cultivation techniques may continue to improve both the environmental and economic performance of energy crops. For example, rhizome propagation techniques are now recommended (DEFRA, 2001) due to superior establishment rate and substantially reduced costs compared with micro-propagation (Bayerische Landesanstalt für Landwirtschaft, 2000). The macro-propagation energy requirement of 4,000 MJ/ha in machinery diesel and energy for chilled storage of rhizomes (Bullard and Metcalf, 2001) is considerably lower than the 45,000 MJ/ha (Lewandowski *et al*., 1995) required for previously favoured and more expensive micro (*in vitro*) propagation techniques (involving greenhouse overwintering). However, when considered over plantation lifetimes, large one-off emission sources associated with crop establishment made relatively small contributions to the annualised LCA. For example, the 3,659 kg CO_2 eq./ha emissions attributable to one-off fence and storage-barn construction average out at a modest 146 kg CO_2 eq./ha on an annual[9] basis (7.6% of *Miscanthus* emissions).

9. 25-year fence and storage barn lifetimes (Elsayed and Mortimer, 2001).

3.4.2 Soil emissions

The most uncertain aspects of the LCA are those relating to soil processes and emissions. Here, simple fractions of applied N were assumed to be emitted directly from soils as N_2O, consistent with national GHG accounting procedures (McGettigan *et al*., 2006), and based on IPCC emission inventory guideline default values (IPCC, 2001). These emission factors account for N losses via ammonia volatilisation, and differentiate losses among chemical fertilisers, specific animal wastes, and different means of storage. Calculated N_2O emissions of 1.9 and 1.2 kg/ha/annum for *Miscanthus* and SRCW are within the range quoted by Heller *et al*. (2003), who attributed 1.7 kg N_2O/ha/annum to SRCW cultivation, and Hanegraaf *et al*. (1998), who suggest emission factors of 1.1 and 1.2 kg/ha/annum, respectively, for *Miscanthus* and SRCW (**including** subsequent combustion emissions). Although fertiliser application rate has been found to be a major driver of N_2O emissions (Harrison *et al*., 1995; Oenema *et al*., 1997; Flessa *et al*., 2002; Scanlon and Kiely, 2003), factors such as crop type (Dobbie *et al*., 1999; Flessa *et al*., 2002), the type of fertiliser applied (Harrison *et al*., 1995), soil type (Maag and Vinther, 1996; Flessa *et al*., 2002), and climate (Maag and Vinther, 1996; Dobbie *et al*., 1999) will also affect emissions. Changes in N_2O emissions arising from energy-crop cultivation could therefore be highly site-specific. For example, Leahy *et al*. (2004) calculated a fertiliser N_2O emission factor of 0.034 for intensively managed Irish grasslands, compared with the IPCC default fertiliser emission factor of 0.0125 applied here.

A number of studies have observed a rapid increase in organic matter mineralisation after grass or legume cover crops have been incorporated into the soil, increasing both CO_2 and N_2O emissions (Grigal and Berguson, 1998; Jug *et al*., 1999; Flessa *et al*., 2002). However, there is evidence that the long rotation and extensive fine-root system of SRCW, and the below-ground rhizome mass of *Miscanthus*, contribute to long-term below-ground C storage equal to or greater than under grassland systems (Grigal and Berguson, 1998; Zan *et al*., 2001; Hansson *et al*., 2003). Matthews and Grogan (2001) used long-term soil C data and C-cycle modelling to predict soil C accumulation rates of 0.513 and 1.16 t C/ha/annum over 100 years for SRCW and *Miscanthus,* respectively, planted on previously tilled soils. These values were used to account for soil C accumulation where energy crops replace sugar beet and set-aside in this study, but do not consider the shorter-term, one-off increases in *Miscanthus* rhizome C storage (estimated at 26.6 t C/ha; Matthews and Grogan, 2001), root C, or above-ground biomass C storage increases. Soil C accumulation rates will be dependent on existing soil C content, soil structure and conditions reflective of climate (e.g. moisture content, temperature). Therefore, as with N_2O emissions, there is likely to be considerable spatial variation in soil C accumulation rates attributable to energy-crop cultivation on tillage soils.

4 Fuel-Chain GHG Emissions and Total Possible Reductions

4.1 Aims

Work presented in this chapter aims to quantify GHG emission reductions possible from energy-crop electricity and heat generation, considering displacement of coal- and peat-generated electricity through biomass co-firing, and displacement of gas, oil and electric heat through the installation of biomass boilers in households and commercial/public buildings. Total fuel-chain emissions consider cultivation emissions for energy-crop electricity and heat, and total possible emission reductions also consider the displaced agricultural land uses. These data are then extrapolated up to a national scenario, and sensitivity analyses applied, in order to explore the magnitude of net GHG emission reductions possible, and the land areas required, for energy-crop utilisation in Ireland. Co-firing was considered as a technically mature and cost-effective initial energy-crop utilisation pathway for electricity generation (Tillman, 2000; Baxter, 2005). GHG emissions from alternative energy-conversion pathways will depend primarily on their overall efficiency, but should not differ hugely from conversion pathways considered here.

4.2 Methodology

4.2.1 Scope, aims and boundaries

The same process of LCA applied to land use was applied to *Miscanthus*, SRCW, peat and coal electricity-generating systems and *Miscanthus*, SRCW, gas, oil and electric heat production systems. For electricity generation, all emissions, from the mining of the peat and coal, to ash disposal, were considered, and energy-crop cultivation emissions fed into the energy-crop co-firing LCA. For heat-production emissions, all fuel-production and transport emissions were considered, but, due to insufficient available data, indirect emissions associated with boiler manufacture and installation and ash disposal were not considered (based on electricity emission data, these are likely to be minor, and should not differ significantly among the different fuels in any case). Fuel-chain LCA was based on the production of 1 GJ or 1 kWh of electricity/heat produced, averaged over the lifetime of the power stations and boilers. Calculated GHG emissions for energy-crop electricity and heat production included cultivation emissions, which were related according to energy-crop net combustible-yield estimates.

4.2.2 Electricity-generation emissions

Direct CO_2 emissions from peat and coal combustion in power stations for the reference scenarios were based on the SEI co-firing report (SEI, 2004). From this report, coal and peat annual generating capacities were calculated at 23.7 and 9.18 PJ/annum exportable electricity, based on annual loads of 7,700 and 7,400 h for the coal and peat power stations, respectively. Indirect extraction, mining and transport emissions associated with peat and coal electricity chains were taken from Connolly and Rooney (1997), and the contributions of CH_4 and N_2O to combustion emissions were taken from McGettigan *et al.* (2005) for peat and coal electricity generation. Connolly and Rooney (1997) produced a detailed LCA for the environmental impact of peat and coal electricity generation based on the planned Edenderry and Moneypoint power stations, from mining and peat extraction to final ash disposal, but did not include construction-related GHG emissions. Coal is sourced from the USA and Colombia, and transported via train and ship to Moneypoint. The greatest uncertainty in the peat combustion LCA is associated with the impact of peat extraction on peat bog emissions, estimated to be a net increase in peat bog emissions of 2,908 kg CO_2 eq./ha/annum after drainage (the balance of increased C oxidation set against reduced CH_4 and N_2O emissions, based on data presented by Connolly and Rooney, 1997). For all fuel combustion, indirect construction and decommissioning, GHG emissions were calculated per GJ electricity produced, based on Hartmann and Kaltschmitt (1999). They assumed emissions of approximately 1.6 kg CO_2 eq./GJ electricity produced from both coal, and co-fired straw and wood, in a 509 MW_e pulverised coal power plant in Germany. Table 4.1 summarises the major inputs to the combustion LCAs.

It is assumed that late harvesting and natural air-drying during covered storage result in maximum final SRCW and *Miscanthus* moisture contents of 20% wet weight (Lewandowski *et al.*, 2000; Gigler *et al.*, 2004). Although this report does not examine spatial distribution of energy cropping potential in detail, it is assumed that SRCW will

Table 4.1. Typical fuel characteristics per 'wet' tonne of each fuel, as applied in LCA.

	Peat	Coal	*Miscanthus*	SRCW
Moisture content (% weight)	55[a]	10[a]	20[b]	20[c]
Energy content (GJ/t)	7.7[a]	28.04[a]	14.56[d]	14.46[e]
Prep./extraction (kg CO_2 eq./t)	3.28[a]	26.52[a]	3.32[f]	12.16[f]
Combustion (kg CO_2 eq./t)	900[g]	2680[g]	203	193
Transport (kg CO_2 eq./t)	0.48[a]	47.86[a]	4.24[h]	4.24[h]

[a]Connolly and Rooney, 1997; [b]Lewnadowski *et al*., 2000; [c]Gigler *et al*., 2004; [d]El Bassam, 1998; [e]Matthews, 2001; [f]van Loo and Koppejan, 2003; [g]McGettigan *et al*., 2005; [h]Elsayed *et al*., 2003.

be more competitive in cooler and wetter parts of the country (e.g. north and west), where most grassland agriculture occurs, whilst *Miscanthus* cultivation will require the well-drained soils and warmer, drier climate found in the south-east and Midlands, where most tillage agriculture occurs. Thus it is assumed that both SRCW and *Miscanthus* are transported an average distance of 50 km for co-firing with coal at the Moneypoint power station on the west coast, and for co-firing with peat at the three peat power stations in the Midlands.

Prior to combustion with peat, *Miscanthus* must be chopped, whilst willow wood must be chipped and pulverised for injection into the pulverised coal boilers at Moneypoint. van Loo and Koppejan (2003) attribute an energy consumption of 0.054 GJ/t DM for woodchipping. It is assumed here that the same quantity of energy is required for *Miscanthus* chopping (a probable overestimate), and a further 0.144 GJ/t DM is required for chipped willow wood pulverisation (van Loo and Koppejan, 2003). Chipping and chopping are assumed to be diesel powered, whilst pulverisation at Moneypoint power station is electrically powered. *Miscanthus* and willow wood contain a lower proportion of N than coal or peat, and have been found to reduce NO_x (including N_2O) emissions from co-fired coal combustion (van Loo and Koppejan, 2003). However, NO_x emissions vary widely according to factors including operating conditions and abatement technology, and it was conservatively assumed that combustion N_2O (and minor CH_4) emissions from *Miscanthus* and willow combustion were the same as for peat. Net conversion efficiencies for the new-generation peat and Moneypoint coal power stations were taken from SEI (2004): 38.4% and 37.5%, respectively. Biomass co-firing has no effect on net electrical-conversion efficiency in the peat power stations, and results in a negligible reduction in the net efficiency of the Moneypoint power station (boiler efficiency decreases from 93.4% to 93.3% due to higher moisture content in biomass compared with coal: SEI, 2004). SEI (2004) considers that gasification is necessary when co-fired biomass constitutes more than 10% of total energy input to the Moneypoint power station. However, it is indicated in the report that this has minimum impact on the overall efficiency of the energy-conversion process (assume 98% gasification efficiency), so the existing LCA data are applied[10].

4.2.3 Heat-production emissions

Total emissions from heat-production chains were calculated more simply than electricity emissions, and, due to difficulty of obtaining relevant data, indirect emissions from boiler manufacture and installation were not considered. These should be similar between wood and conventional biomass boilers, and minor in total (though proportionately higher than the negligible contribution of power station construction to electricity-generating emissions). To ensure inter-fuel comparability, indirect emissions associated with fuel transport were based on values calculated by Gustavsson and Karlsson (2002), based on Swedish circumstances. They assume an oil and natural gas supply from Norwegian off-shore rigs, and account for GHG emissions arising from leakage and energy consumption during extraction, treatment and transmission/transport. It was assumed that the 21 kJ energy required to pelletise[11] each MJ (energy content) of wood (Gustavsson and Karlsson, 2002) was also applicable to *Miscanthus* pelleting, and supplied by electricity from the national grid. Direct combustion emissions for biomass, gas and oil were based on NIR (ultimately, IPCC) data (McGettigan *et al*., 2005). As with

10. There will be minor additional indirect emissions associated with gasification and gasifier construction, though milling emissions will be avoided (all negligible according to Fig. 4.1).
11. Pelleting biomass involves initial comminution, followed by shaping and compaction (sometimes with added binding agent) into pellets – it thus requires considerably more energy than chipping.

electricity-generation emissions, only CH_4 and N_2O direct-combustion emissions were considered for biomass.

4.2.4 Sensitivity analyses

Sensitivity analyses were performed for indicative purposes on the electricity-generating scenario only, by varying those parameters associated with the greatest uncertainty. The average distance over which energy-crop biomass was transported for electricity generation was varied between 30 and 100 km. Both cultivation emissions per hectare and yield were altered by ±50%. In the case of yield, cultivation emissions per hectare were corrected to account for harvest fuel consumption and fertiliser application rates changed in direct proportion to yield changes. Yield changes were also translated into changed land area requirements for each GJ electricity produced from energy crops. Where net per hectare, per GJ, and national GHG emission changes attributable to energy-crop utilisation were calculated, the cultivation emissions associated with energy-crop fuel chains were attributed to land-use change. Thus, net energy-crop electricity and heat emissions used to calculate emission reductions from these sectors were based on LCA emissions minus the cultivation contribution.

4.3 Results

4.3.1 Electricity fuel chain emissions

Over the entire fuel chain, co-fired *Miscanthus* and SRCW emit almost identical quantities of CO_2 eq. per kWh net electricity generated (0.132 and 0.130 kg, respectively). This compares with 1.150 and 0.990 kg CO_2 eq./kWh net electricity for milled peat and pulverised coal combustion, respectively. Figure 4.1 shows a breakdown of these emissions, and highlights that energy-crop emissions are primarily attributable to cultivation (accounting for 67% and 62% of emissions from *Miscanthus* and SRCW electricity production, respectively). Transport of the fuel to the power station is responsible for only a very small proportion of total GHG emissions, even in the case of long-distance coal transport. Milling (chopping *Miscanthus* and chipping followed by pulverisation for SRCW) emissions are also minor, with most of the remaining energy-crop electricity emissions (~25% of total) attributable to combustion release of N_2O and CH_4. Combustion emissions, primarily CO_2, dominate peat and coal electricity GHG burdens (contributing approximately 95% and 97%, respectively). Indirect emissions, mainly arising from construction and decommissioning, were relatively minor when considered over the remaining plant lifetimes. Higher indirect emissions for peat combustion reflect the inclusion of emissions arising from peatland drainage for harvesting (calculated at approximately 0.044 kg CO_2 eq./kWh electricity).

Table 4.2 displays net GHG emission reductions arising when both land use and electricity substitution are considered. To do this, emission savings from displaced peat and coal are based on net energy-crop electricity emissions, minus cultivation, as cultivation emissions are

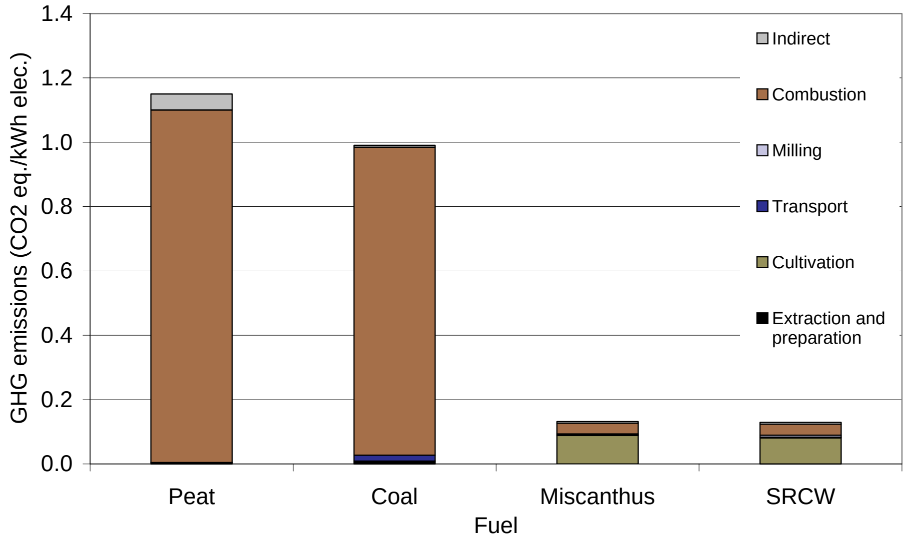

Figure 4.1. GHG emissions per kWh electricity generated from coal, peat, *Miscanthus* co-fired with peat and pulverised SRCW woodchip co-fired with coal, based on results of LCA.

Table 4.2. GHG emission reductions attributable to land-use and fuel substitution in electricity generation, amalgamated to produce net savings per hectare of land converted and per GJ electricity produced.

Energy crop	Fuel replaced	Agriculture replaced	Electricity produced	Soil CO_2 sequestered	Electricity GHG reduction[a]	Agriculture GHG reduction	Total CO_2 eq. reduction	
			(GJ_e/ha/annum)	(kg CO_2 eq./ha/annum)			(per ha/annum)	(per GJ_e)
Miscanthus								
	Peat	Dairy	**81.5**	0.00	25,080	10,130	**35,209**	**432**
		Cattle	**81.5**	0.00	25,080	3,299	**28,378**	**348**
		Sheep	**81.5**	0.00	25,080	1,813	**26,893**	**330**
		Sugar beet	**81.5**	4265	25,080	5,821	**30,901**	**379**
	Coal	Dairy	**81.5**	0.00	21,438	10,130	**31,568**	**387**
		Cattle	**81.5**	0.00	21,438	3,299	**24,737**	**303**
		Sheep	**81.5**	0.00	21,438	1,813	**23,251**	**285**
		Sugar beet	**81.5**	4265	21,438	5,821	**27,259**	**334**
SRCW								
	Peat	Dairy	**59.9**	0.00	18,297	10,722	**29,019**	**485**
		Cattle	**59.9**	0.00	18,297	3,891	**22,188**	**371**
		Sheep	**59.9**	0.00	18,297	2,405	**20,702**	**346**
		Sugar beet	**59.9**	1881	18,297	4,030	**22,327**	**373**
	Coal	Dairy	**59.9**	0.00	15,623	10,722	**26,345**	**440**
		Cattle	**59.9**	0.00	15,623	3,891	**19,514**	**326**
		Sheep	**59.9**	0.00	15,623	2,405	**18,028**	**301**
		Sugar beet	**59.9**	1881	15,623	4,030	**19,653**	**328**

Cells with darker shading represent components of indicative scenario.
[a]Based on net electric emissions (LCA emissions minus the cultivation emissions accounted for under agricultural land-use emissions).

considered at the land-use stage of the fuel chain. When displaced agricultural emissions are considered as part of the fuel chain, reductions in GHG emissions per hectare of land utilised, or per GJ electricity produced, are large. On an area basis, total annual GHG emission reductions range from 18,028 kg CO_2 eq./ha/annum for SRCW co-fired with coal and replacing sheep farming to 35,209 kg CO_2 eq. for *Miscanthus* co-fired with peat and replacing dairy agriculture (Table 4.2). Higher yields for *Miscanthus* result in greater total GHG emission reductions per hectare compared with SRCW, whilst a higher emission factor for electricity generated using peat, compared with coal, results in greater overall GHG emission reductions for peat substitution. Although sugar-beet cultivation was calculated to be less GHG intensive than livestock systems (Fig. 3.1), this did not account for reduced soil C storage through organic matter oxidation after conversion to this system from pre-existing native woodland or grassland. When long-term (100-year) soil C accumulation rates under *Miscanthus* and SRCW planted on tillage land are taken into consideration (Matthews and Grogan, 2001), net GHG emission reductions arising from the displacement of sugar beet with *Miscanthus* and SRCW were greater than reductions resulting from the displacement of grassland cattle or sheep systems (Table 4.2). Although smaller than emission reductions arising from the displacement of peat and coal electricity production, emission reductions arising from the displacement of conventional agricultural systems were substantial. In the instance of SRCW co-fired with coal and displacing dairy agriculture, displaced diary emissions of 10,722 kg CO_2 eq./ha/annum equated to 70% of the emission reduction arising from coal electricity displacement (15,623 kg CO_2 eq./ha/annum), and 40% of the combined land-use/electricity-generation emission reduction (Table 4.2).

4.3.2 Heat fuel chain emissions

Figure 4.2 displays a breakdown of total GHG emissions arising from the cultivation and combustion of SRCW woodchips and *Miscanthus* pellets, compared with emissions arising over the entire fuel chains of oil, gas and electricity. These equated to 0.045 and 0.066 kg/kWh heat for woodchips and *Miscanthus* pellets, respectively, reflecting energy-conversion efficiencies much greater

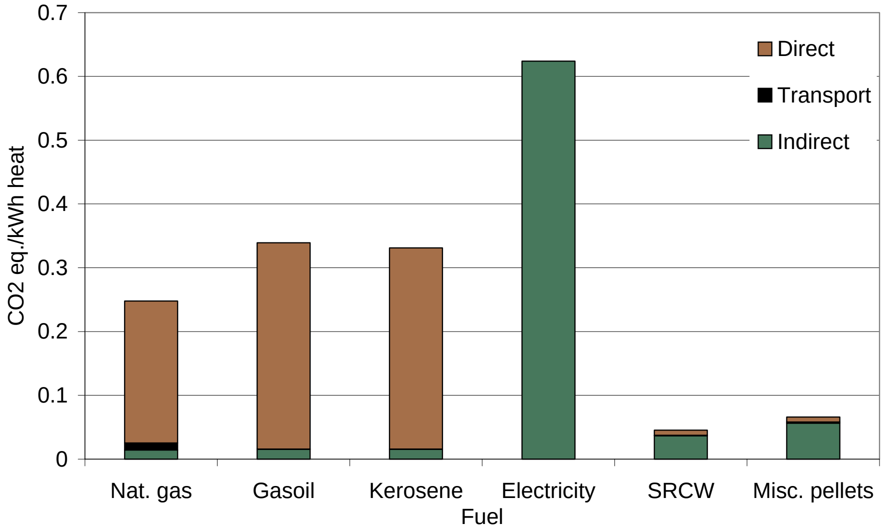

Figure 4.2. GHG emissions per kWh useful heat produced from natural gas, gasoil, kerosene, electricity, SRCW woodchip and *Miscanthus* pellets.

than for electricity production (85% and 90%, respectively). Oil and gas boilers were calculated to emit 0.331 and 0.248 kg CO_2 eq./kWh heat, whilst electric heating emissions were based on final electricity consumption emissions of 0.624 kg CO_2 eq./kWh electricity, including generation and transmission losses (Howley *et al.*, 2006). Consequently, SRCW and *Miscanthus* heat emissions were 86% and 80% lower than for oil heating, 81% and 73% lower than for gas heating, and 93% and 90% lower than for electric heating, respectively. As with electricity production, energy-crop emissions were dominated by cultivation, which (including chipping) accounted for 81% and 62% of total woodchip and *Miscanthus* pellet heat emissions. *Miscanthus* pellet emissions included a 23% contribution from pelleting, accounting for most of the difference with SRCW heat emissions. Indirect emissions were relatively small for oil and natural gas heat production, accounting for 4.7% and 5.8%, respectively. Natural gas transport contributed 4.4% towards total gas heating emissions.

Table 4.3 displays whole fuel-chain GHG emissions and emission reductions arising from use of energy-crop biomass in heat production. For heat production, no additional livestock displacement was considered. Instead, it was considered that energy crops were grown either on grassland made available from forecast destocking, or on set-aside land. Area-based GHG reductions range from 7,671 kg CO_2 eq./ha/annum for SRCW replacing gas and grassland to 34,187 kg CO_2 eq./ha/annum for *Miscanthus* pellets replacing electricity and set-aside. As with electricity generation, the higher *Miscanthus* yields, and a larger soil-C sequestration effect on set-aside land, resulted in greater area-based GHG emission reductions compared with SRCW.

4.3.3 Total GHG emission reductions

To explore potential impacts of these GHG emission reductions on a national basis, a simple scenario was developed, based on individual scenarios for electricity and heat production from energy crops. In the electricity-generation scenario, 30% of national peat electricity and 15% of national coal electricity were substituted with co-fired *Miscanthus* and SRCW, respectively (based on SEI, 2004). It was assumed that the required *Miscanthus* cultivation displaced sugar beet, whilst the required SRCW cultivation displaced equal areas of dairy, beef and sheep agriculture. The key fuel chains for this scenario are shaded in Table 4.2, and key assumptions and results are displayed in Box 4.1. In total, this scenario amounts to an annual national GHG emission reduction of 2.31 Mt CO_2 eq. (3.4% of national emissions in 2004). The total land area required amounts to 93,165 ha, including 33,784 ha of displaced sugar-beet cultivation (approximately equal to total sugar-beet land area). Overall, this represents just 2.16% of the 4.31 Mha land area appropriated for agricultural use in Ireland in 2004 (CSO, 2006: http://www.cso.ie/statistics/AgricultureandFishing.htm).

The heat-production scenario is outlined in Box 4.2. SRCW woodchip boilers were assumed to displace

Table 4.3. GHG emission reductions attributable to land-use and fuel substitution in heat production, amalgamated to produce net savings per hectare of land converted and per GJ heat produced.

Energy crop	Fuel replaced	Agriculture replaced	Heat produced	Soil CO_2 sequestered	Heat GHG reduction[a]	Agriculture GHG reduction	Total CO_2 eq. reduction	
			(GJ_{th}/ha/annum)	(kg CO_2 eq./ha/annum)			(per ha/annum)	(per GJ_{th})
Miscanthus								
	Electricity	Set-aside	**191**	4265	31,860	2,326	**34,187**	**179**
		Grass	**191**	0	31,860	–1,938	**29,922**	**157**
	Oil	Set-aside	**191**	4265	15,343	2,326	**17,669**	**92**
		Grass	**191**	0	15,343	–1,938	**13,404**	**70**
	Gas	Set-aside	**191**	4265	11,171	2,326	**13,497**	**71**
		Grass	**191**	0	11,171	–1,938	**9,232**	**48**
SRCW								
	Electricity	Set-aside	**136**	1881	23,194	535	**23,729**	**175**
		Grass	**136**	0	23,194	–1,346	**21,848**	**161**
	Oil	Set-aside	**136**	1881	12,155	535	**12,690**	**94**
		Grass	**136**	0	12,155	–1,346	**10,809**	**80**
	Gas	Set-aside	**136**	1881	9,017	535	**9,552**	**70**
		Grass	**136**	0	9,017	–1,346	**7,671**	**57**

Cells with darker shading represent components of indicative scenario.
[a]Based on net heat emissions (LCA emissions minus the cultivation emissions accounted for under agricultural land-use emissions).

electric, oil and gas heating, each in 2.5% of the number of households recorded in the last census (2002: CSO, 2006: http://www.cso.ie/census/default.htm), equating to 7.5% of all households. Average household heat consumption was taken from Howley *et al.* (2006), at 21,249 kWh/annum (76.50 GJ/annum). Given the absence of any large-scale *Miscanthus* pelleting facilities, and the logistical and cost uncertainties regarding pelleting, *Miscanthus* pellet heat was not included in the national scenario (see Section 6.2.2). An equal commercial fuel displacement was assumed, on the basis of lower overall heating demand from the commercial sector, but greater convenience and cost savings (Section 6.3.2) compared with the domestic sector. In this scenario, SRCW cultivation was assumed to displace set-aside land and grassland in the ratio of 1:2 (with grassland-grown SRCW displacing electric heating), utilising most of the available set-aside area. The total annual GHG emission saving attributable to this scenario was 1.55 Mt CO_2 eq. This was made up of a net 1.63 Mt CO_2 eq./annum saving from displaced electricity, oil and gas heat, and a net land-use change emission increase of 0.084 Mt CO_2 eq./annum from the 36,645 ha set-aside conversion and 73,290 ha grassland conversion to SRCW cultivation. Amalgamating the electricity- and heat-generation scenarios results in a total potential annual GHG emission reduction of 3.86 Mt CO_2 eq. (5.6% of 2004 emissions). The total land area required in this scenario would be 203,100 ha (4.7% of Ireland's agricultural land area).

4.3.4 *Sensitivity analyses*

Sensitivity analyses presented in Table 4.4 explore the impacts of changes in yields, cultivation emissions and transport, in the context of the electricity-generation scenario. Results indicate that GHG emission reductions per hectare are heavily dependent on yield, with a 50% yield increase resulting in an annual GHG emission reduction of 44,814 kg CO_2 eq./ha/annum for *Miscanthus* (compared with 30,901 kg CO_2 eq./ha/annum for sugar-beet displacement in the standard scenario) (Table 4.2). However, changes in GHG emission savings are proportionately lower than yield changes as a result of the assumption that certain cultivation emissions (i.e. those attributable to fertiliser application, harvest and storage) will vary in accordance with yields. For example, under the 50% yield reduction scenario, annual cultivation emissions are reduced from 1,938 and 1,346 to 1,169 and 839 kg CO_2 eq./ha for *Miscanthus* and SRCW, respectively (Table 4.4). Net GHG emission savings per hectare were relatively insensitive to changed cultivation emissions. A 50% increase in cultivation emissions

Box 4.1. Co-fired energy-crop electricity-generating scenario

Miscanthus

Land area:	**33,784 ha**, displacing[1] sugar beet
Gross biomass production:	515,042 t DM (16.7 t DM/ha/annum)
Cultivation emissions:	1,938 kg CO_2 eq./ha/annum compared with 3,494 kg CO_2 eq./ha/annum for sugar beet, and soil C sequestration equivalent to 4,265 kg CO_2/ha/annum
Agricultural emission change:	**–196,655 t/annum CO_2 eq.**
Net combustible yield:	360,530 t DM (11.7 t DM/ha/annum)
Displaced fuel:	852,000 t peat (55% moisture content) Edenderry, Lough Rea and West Offaly
Electricity production:	**850 GWh_e/annum** (30% of peat electricity)
Electricity GHG emissions:	Gross and net[2] life-cycle emissions of 0.131 and 0.044 kg CO_2 eq./kWh electricity produced (compared with 1.150 kg CO_2 eq./kWh for peat)
Electricity emission change:	**–847,294 t/annum CO_2 eq.**
Total emission change:	**–1,043,950 t CO_2 eq./annum**

SRCW

Land area:	**59,381 ha**, displacing dairy, cattle and sheep
Gross biomass production:	619,628 t DM (10.4 t DM/ha/annum)
Cultivation emissions:	1,346 kg CO_2 eq./ha/annum compared with 12,068, 5,237 and 3,751 kg CO_2 eq./ha/annum for dairy, cattle and sheep
Agricultural emission change:	**–336,859 t/annum CO_2 eq.**
Net combustible yield:	524,205 t DM (8.8 t DM/ha/annum)
Displaced fuel:	240,358 t coal (10% moisture content) at Moneypoint
Electricity produced:	**987.5 GWh_e/annum** (15% of Moneypoint output)
Electricity GHG emissions:	Gross and net[2] life-cycle emissions of 0.132 and 0.051 kg CO_2 eq./kWh electricity produced (compared with 0.99 kg CO_2 eq./kWh for coal)
Electricity emission change:	**–927,698 t/annum CO_2 eq.**
Total emission change:	**–1,264,557 t CO_2 eq./annum**

Total co-firing scenario GHG emission reduction of 2.31 Mt/annum CO_2 eq.

[1]NB: Does not necessarily require *Miscanthus* to be grown in same field as displaced crop.
[2]Excludes cultivation emissions accounted for under agricultural emission.

resulted in 6% and 7% lower area-based GHG emission reduction for *Miscanthus* and SRCW, respectively.

Emissions per GJ electricity produced were most sensitive to cultivation emissions, more than doubling in response to a change in cultivation emissions from 50% below to 50% above the standard value (i.e. a tripling in cultivation emissions) calculated in the LCA (Table 4.4). Although lower yields resulted in significantly lower area-based GHG emission reductions, greater total emission reductions for the lower yield estimates reflect the greater area of displaced agricultural land use and the lower emissions per hectare in the low-yield scenarios. The land area required for a 50% yield reduction is, proportionately, three times that required for a 50% yield increase, and the displaced agricultural emissions more than compensate for the modest increases in electricity-production emissions (by 6.64 and 7.40 kg CO_2 eq./GJ electricity for *Miscanthus* and SRCW, respectively) under the lower compared with the higher yielding scenarios. Varying transport distances had a minor effect on area-based and overall GHG emission reductions from energy crops.

4.4 Discussion

4.4.1 Electricity-generation GHG emissions

Data presented here indicate the possibility to displace large quantities of GHG emissions from peat and coal electricity generation through simple, low-tech substitution of these fuels with energy crops in Ireland. In

Box 4.2. Energy-crop heat-production scenario

SRCW

Land area:	**109,034 ha**, displacing 73,290 ha extensified grassland and 36,645 ha set-aside
Gross biomass production:	1,143,316 t DM (10.4 t DM/ha/annum)
Cultivation emissions:	1,346 kg CO_2 eq./ha/annum compared with zero emissions for extensified grassland, but soil C sequestration of 1,881 kg CO_2 eq./ha/annum where set-aside displaced
Agricultural emission change:	**+79,000 t/annum CO_2 eq.**
Net combustible yield:	970,720 t DM (8.8 t DM/ha/annum)
Displaced fuel:	~1.63 Ml heating oil, ~1.42 Mm^3 natural gas, 1,381 GWh electricity (equates to 7.5% domestic heating energy, plus an identical displacement of public/commercial heating energy)
Heat produced:	**4,144 GWh_{th}/annum**
Heat GHG emissions:	Gross and net[1] life-cycle emissions of 0.045 and 0.010 kg CO_2 eq./kWh heat produced (compared with 0.248, 0.339 and 0.624 kg CO_2 eq./kWh for gas, oil and electric heat)
Heat emission change:	**–1,626,000 t/annum CO_2 eq.**
Total emission change:	**–1,547,000 t/annum CO_2 eq.**

Total heat-production scenario GHG reduction of 1.55 Mt/annum CO_2 eq.

[1]**Excludes cultivation emissions accounted for under agricultural emission changes.**

this study, peat and coal electricity production were calculated to emit, respectively, 1.150 and 0.990 kg CO_2 eq./kWh net electricity generated. When all cultivation emissions were accounted for, co-firing substitution of peat with chopped *Miscanthus* and coal with milled or gasified willow woodchip was found to reduce these GHG emissions by approximately 89% and 87%, respectively. It was conservatively assumed that direct combustion emissions of CH_4 and N_2O were similar for energy crops as for peat and coal. In practice, these emissions should be lower due to lower N contents in *Miscanthus* and SRCW – supported by observations of reduced N_2O emissions after co-firing coal boilers with biomass (van Loo and Koppejan, 2003). Removing energy-crop biomass from fields for combustion will also reduce the quantity of methane release arising from decomposition, although quantification of the net effect would depend on the change in decomposition relative to displaced land uses, and management practices such as harvest timing, etc. Combustion control and emission abatement technologies will also affect final non-CO_2 emissions. Fuel preparation made a minor contribution to emissions, based on a chipping energy requirement of 0.054 GJ/t DM.

It is notable that indirect emissions are minor in the electricity LCAs. Following Hartmann and Kaltschmitt (1999), construction and decommissioning GHG emissions were considered identical for electricity produced from co-fired biomass and from coal. Any additional emissions associated with retro-fit modifications for energy-crop handling and co-firing at the plants should have a negligible impact on the overall GHG balance of energy crops. Similarly, transport, irrespective of distance variation, had a minor impact on the final electricity LCA (although it is an important economic consideration for energy crops – Section 6.2 – and has traffic implications). In the case of peat electricity production, indirect emissions were dominated by peatland drainage emissions. This value is poorly quantified, and could vary significantly according to local conditions, but is unlikely to have a large impact on the overall emission balance as it contributes less than 4% to overall peat electricity emissions. It is recommended by SEI (2004) that biomass co-firing above 10% of total fuel energy in the Moneypoint power station should be based on prior biomass gasification. However, the overall impacts on biomass energy-conversion efficiencies were deemed to be negligible (SEI, 2004). Therefore, considering the minor contribution of indirect emissions, and the negated milling requirement, total GHG emissions for SRCW co-firing at 15% were assumed to be the same as those at 5% (the significant additional cost of gasification equipment is included in economic analyses, Section 6.2.1).

Table 4.4. The effect of varying yield, cultivation emissions and transport distance on GHG emissions/emission reductions in the national co-firing scenario outlined in Section 4.2.2, expressed on an area and national basis, and per GJ electricity produced.

Yield (DM t/ha/annum)	Cultivation emisssions (kg CO_2 eq./ha/annum)	Transport distance (km)	Gross electricity emissions[a] (kg CO_2 eq./GJ)	Net electricity emissions[b] (kg CO_2 eq./GJ)	Area (ha)	Elecricity GHG reduction[c] (t CO_2 eq./annum)	Total GHG reduction (t CO_2 eq./annum)	Area GHG reduction (kg CO_2 eq./ha/annum)
Miscanthus								
–50%	1169	50	**40.82**	**12.12**	67,568	847,294	**1,148,472**	**16,997**
+50%	2697	50	**34.18**	**12.12**	22,523	847,294	**1,009,344**	**44,814**
11.7	**–50%**	50	**24.44**	**12.12**	33,784	847,294	**1,076,691**	**31,870**
11.7	**+50%**	50	**49.07**	**12.12**	33,784	847,294	**1,011,209**	**29,931**
11.7	1938	**30**	**36.51**	**11.82**	33,784	848,130	**1,044,785**	**30,925**
11.7	1938	**100**	**37.52**	**12.88**	33,784	845,206	**1,041,861**	**30,839**
SRCW								
–50%	839	50	**42.19**	**14.16**	118,762	927,698	**1,661,584**	**13,991**
+50%	1852	50	**34.79**	**14.16**	39,587	927,698	**1,132,214**	**28,600**
8.8	**–50%**	50	**25.40**	**14.16**	59,381	927,698	**1,344,475**	**22,641**
8.8	**+50%**	50	**47.88**	**14.16**	59,381	927,698	**1,224,597**	**20,623**
8.8	1346	**30**	**36.33**	**13.85**	59,381	928,809	**1,265,668**	**21,314**
8.8	1346	**100**	**37.42**	**14.94**	59,381	924,919	**1,261,778**	**21,249**

[a]Gross emissions are total LCA emissions, including cultivation emissions also accounted for under agricultural land-use change.
[b]Net emissions are total LCA emissions minus cultivation emissions accounted for under agricultural land-use change.
[c]Based on net electricity emissions.

4.4.2 Heat-production GHG emissions

Energy conversion is highly efficient for heat production compared with electricity generation. In the LCA considered here, typical energy conversion efficiencies of 85% for oil and woodchip boilers, 90% for gas and *Miscanthus* pellet boilers, and 100% for electricity conversion were used. Combined with lower C densities for oil and gas compared with peat and coal, this resulted in lower GHG emissions and emission savings for heat production compared with electricity generation. Nonetheless, SRCW woodchip and *Miscanthus* pellets offer substantial GHG reductions compared with the conventional heating systems considered here. Compared with oil, gas and electric heating, GHG emissions from SRCW heating were 86%, 83% and 93% lower, respectively, and GHG emissions from *Miscanthus* heating were 80%, 75% and 89% lower, respectively. Energy-crop cultivation was responsible for most of the SRCW and *Miscanthus* emissions, though pelleting also contributed significantly to *Miscanthus* pellet emissions. As with electricity generation, GHG emissions arising from biomass transport were relatively minor, and indirect emissions for fossil-fuel heat were also low. It was not possible to find reliable estimates for boiler construction emissions, but based on the electricity LCA, and given the probable similarity in emissions associated with biomass and fossil-fuel boiler construction, this should not have a major impact on the results. GHG emissions over the whole fuel chains for SRCW and *Miscanthus*, respectively, were substantially lower when they were used to produce heat (0.045 and 0.066 kg CO_2 eq./kWh_{th}) than when they were used to produce electricity (0.132 and 0.130 kg CO_2/kWh_e), before electricity transmission losses are considered. Heat production is thus a more efficient way to utilise energy-crop biomass, but ultimately results in lower emission savings compared with substitution of C-intensive peat and coal electricity generation (except where C-intensive electric heating is displaced). The newly built peat power stations present a good opportunity to easily achieve substantial emission reductions with energy-crop biomass utilisation.

4.4.3 Total potential GHG emission savings

Cultivation accounted for most of the comparatively low GHG emissions arising from energy-crop electricity and heat production, but also resulted in the displacement of GHG-intensive conventional agriculture. Consequently, producing electricity and heat from energy crops could reduce national GHG emissions even before the displacement of fossil fuels is considered, depending on the comparative economics of energy crops with conventional agricultural systems (Chapter 5) – assumptions and knock-on effects discussed below. In the electricity-generating scenario, energy-crop land-use displacement contributed between 13% (SRCW displacing sheep and coal) and 41% (SRCW displacing dairy and coal) of total emission reductions. In the case of *Miscanthus* planted on tillage land, the (~100-year duration) annual soil C sequestration effect is greater than CO_2 eq. emissions arising over the entire *Miscanthus* electricity fuel chain. Thus, this scenario of *Miscanthus* electricity generation is actually better than C neutral. *Miscanthus* substitution of peat electricity and dairy agriculture results in the greatest GHG emission reduction – over four times greater per hectare of land used than the reduction for SRCW substitution of gas heat and destocked grassland. The combination of land use and energy displaced by energy crops, and the choice of energy crop, will have a significant impact on overall emission reductions. Overall, the large GHG emission displacements possible through fossil-fuel substitution, alongside the considerable possible land-use emission reductions, combine to make energy-crop utilisation a highly efficient GHG abatement strategy for Ireland.

The indicative scenario developed here (30% peat electricity and 15% coal electricity substitution with co-fired *Miscanthus* and SRCW, 7.5% of houses using SRCW woodchips for heat and an equal commercial sector uptake) results in annual GHG emissions savings of 3.86 Mt CO_2 eq. (5.6% of 2004 emissions), yet requires just 4.7% of agricultural land. It would result in the displacement of only relatively small numbers of livestock (e.g. 3.5% of the national dairy herd). This reflects the large agricultural land area and low population density in Ireland, and highlights the great potential for energy crops to contribute to Ireland's energy requirements (in contrast to more densely populated countries). The extent of this potential is almost unique within the EU. Almost all set-aside and sugar beet land would be utilised for SRCW and *Miscanthus*, respectively, under this scenario. This, and the displacement of non-dairy livestock agriculture, is supported by the comparative economics presented in Section 5.3.4. However, dairying remains a high earner for farmers, and energy-crop cultivation may only prove competitive with dairying in specific circumstances, such as where SRCW is considered for wet, less productive grazing land. Initial energy-crop cultivation may be most likely to occur on set-aside land, or destocked grassland, which generate no (pre-subsidy) economic returns. Cultivating energy crops on destocked grassland would result in the lowest ecological benefit of energy crops (compared with other land-use displacement options), as they will be essentially substituting grassland extensification. However, there is evidence that the extensification of livestock systems, whilst decreasing GHG emissions per hectare, may increase GHG emissions per unit product output (Oenema *et al*., 1997; Martin and Seeland, 1999; Flessa *et al*., 2002) – work is needed to identify optimal spatial patterns of extensification and land-use changes in response to recent subsidy decoupling from production.

Data presented in this report indicate that energy-crop cultivation on destocked land could result in GHG emission reductions substantially greater, on a per hectare basis, compared with extensification alone. For example, SRCW planted on destocked sheep-grazing land and replacing coal electricity would displace 18,028 kg CO_2 eq./ha/annum (Table 4.2) compared with a 3,751 kg CO_2/ha/annum (sheep grazing LCA: Fig. 3.1) reduction for destocking alone (a fivefold increase in GHG emission reduction). For *Miscanthus* displacing sugar beet and peat, compared with extensification of sugar-beet area to set-aside, the GHG emission saving is nine times greater. Smith *et al*. (2000) found that, in terms of C mitigation, energy-crop cultivation on the 10% surplus EU arable land was three times more effective than agricultural extensification. Thus, whilst the mixture of land uses converted to energy cropping will depend on a multitude of factors, especially perceived economic benefit for individual farmers, and result in differing levels of overall GHG emission abatement, all scenarios of land-use substitution offer substantial GHG benefits.

Sensitivity analyses indicate that the GHG emission savings presented in the scenario are robust, and, when land use and electricity production are considered together, net emission savings are not particularly sensitive to either cultivation emissions or yields. The yield assumptions are probably the most uncertain variable, and will be dependent on such factors as the variety of SRCW planted, site-specific conditions, inter-annual climatic variations, and management. Surprisingly, lower yields could actually be considered to increase net GHG emission reductions when displaced land uses are considered as part of the fuel chain, though this assumes larger areas of various land uses suitable for substitution with energy crops, and would not apply where energy crops are grown on destocked land. Higher yields result in greater GHG emission reductions per hectare of land, and, by generating higher financial returns, would act to increase the area farmers dedicate to energy cropping and improve the prospects of actual GHG reduction through energy-crop utilisation.

Ultimately, GHG emissions and sustainable development are global issues, and the LCAs developed here account for all emissions, regardless of national borders. Some of the emissions, and the emission savings, attributed to energy-crop utilisation will occur outside Ireland's borders. The most significant manifestation of this relates to the substantial GHG emissions attributable to fertiliser manufacture. Fertiliser is no longer manufactured in Ireland, so any GHG emission reductions attributable to reduced fertiliser use under the energy-crop scenarios would be accounted for in other countries' GHG emission inventories, and would not translate to a reduction in Irish GHG emissions according to official national inventory reporting. Conversely, the contribution of fertiliser manufacture emissions to final energy-crop electricity and heat production could be discounted as national emissions, thus increasing the GHG emission savings from energy-crop heat and electricity generation compared with conventional sources. From a global perspective, the impact of 'displaced' land use depends on whether this land use is merely displaced to another country, and the associated emissions implications in that country, or is simply removed from production. Here, the latter is assumed for livestock and sugar-beet production, on the basis that Common Agricultural Policy (CAP) subsidies stimulated overproduction in these areas. The final balance of national, inventory-accountable GHG emission reductions may differ slightly as a result of these issues, but should not deviate greatly from the calculations applied here. The GHG emission reductions calculated here should reflect the global impact of Irish energy-crop utilisation, assuming only agricultural overproduction is replaced. Most of the emission reductions calculated in the national scenario will be in addition to GHG emission reductions already forecast to occur through destocking. The global context of energy crops, including international land-use implications, is discussed in Section 7.2.3.

5 Economic Competitiveness of Energy-Crop Cultivation

5.1 Aims

This section aims to explore the financial competitiveness of energy crops from the perspective of producers (i.e. farmers) as an alternative to existing conventional agricultural land uses. The costs of cultivating and processing energy crops to the farm-gate stage are compared for different supply strategies using a life-cycle cost analysis (LCCA) approach. The magnitude and timing of all costs are then fed into a net present value (NPV) model, along with the magnitude and timing of revenue from harvested biomass, to determine discounted average gross margins for different SRCW and *Miscanthus* energy-crop supply strategies. These gross margins are then compared with discounted gross margins for conventional crops to determine the economic competitiveness of energy crops. The economic benefits of utilising SRCW to treat WW are considered, and sensitivity analyses are used to determine the impact of different activity cost estimates, biomass prices, yields, and discount rates.

5.2 Methodology

5.2.1 Production life-cycle cost analysis

Life-cycle cost analyses for 23-year, 7-cut SRCW, and 16-year, 14-cut *Miscanthus* plantations were conducted, based on the farm operation sequences displayed in Table 3.3 (as used for the LCA), and for each of the supply strategies listed in Table 5.1. Costs for each activity were taken from the literature, and converted to 2006 prices (Table 5.2) using inflation rates for agricultural inputs up until 2004 (see CSO, 2006: http://www.cso.ie/statistics/AgricultureandFishing.htm) and FAPRI-Ireland projections for variable cost inflation thereafter (Fig. 5.1). This ensured accurate comparison with FAPRI-Ireland projections for conventional agricultural system gross margins after 2004. The same inflation rate was applied to farm-gate biomass prices.

Also shown in Table 5.2, based on *Miscanthus* strategy 'A' (see Table 5.1), is an estimate of cultivation costs based on new contracts provided by one agricultural contractor (Quinns of Baltinglass). This contractor provides an assurance of successful establishment for a cost of €2,470/ha to the farmer, and is currently guaranteeing to buy the harvested *Miscanthus* for a price of approximately €50/t at up to 20% moisture content (€63/t DM). *Miscanthus* plantations may maintain high productivity for up to 20 years after planting (Lewandowski and Heinz, 2003; Heaton *et al.*, 2004), but the conservative assumption of a 15-year productive lifetime was applied here. Herbicide application is not necessary for established *Miscanthus* plantations, and is highly dependent on local circumstances for established SRCW plantations – in many instances, it should not be necessary due to rapid canopy closure once the crop is established and the beneficial effect of some initial weed-induced ground cover. Here, it was assumed that worst-case scenario herbicide costs of €84/ha are incurred every other harvest cycle for SRCW (Rural Generation, 2004).

Table 5.1. Harvest and supply strategy abbreviations and descriptions for SRCW and *Miscanthus.*

	SRCW				*Miscanthus*		
	S1	**S2**	**C1**	**C2**	**C**	**B**	**A**
Harvest	Stick	Stick	Chip	Chip	Chopped	Baled	Chopped, delayed
Storage	Outdoors, covered	Outdoors, covered	Shed	None	Outdoor, covered	Outdoor, covered	None
Drying	Natural	Natural	Forced, heating	None	Natural	Natural	Delayed harvest
Process	Chip on farm	Bundle	None	None	None	None	None
Supply	Dried chips	Dried sticks	Dried chips	Wet chips	Dried, chopped	Dried bales	Semi-dry, chopped

Table 5.2. Costs (adjusted to 2006 prices) associated with each of the activities outlined in Table 5.1 (establishment costs grouped together), based on mid-cost estimates from the literature and total yields of 12 and 20 t/ha/annum (combustible yields of 10 and 14 t/ha/annum) for SRCW and *Miscanthus*, respectively. Low- and high-cost estimates from the literature are also displayed beneath. *Miscanthus* costs based on Quinns contract are displayed on the right.

Activity	SRCW (€/ha)				*Miscanthus* (€/ha)		
	Stick, store, chip	Stick, store	Chip, dry, store	Chip	Chop	Cut and bale	Contractor
Establishment	**2,736[a]**				**2,470[b]**		**2,470**
	1,500–3,215				1,060–2,555		
Fertiliser applied	**336[b]**				**161[b]**		**161**
	274–494				80–241		
Herbicide applied	**84[a]**				**31[a]**		**31**
	31–84				31–84		
Harvest	**682[d]**	**682[d]**	**417[e]**	**417[e]**	**237[f]**	**389[f]**	**237**
	514–1,056	514–1,056	140–541	140–541	233–237	315–389	
Dry + store	**24[g]**	**24[g]**	**701[g]**	**n/a**	**110[f]**	**48[f]**	**0**
	0–948	0–948	455–948		28–261	48–141	
Chipping	**243[h]**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**0**
	112–524						
Removal	**517**				**207**		**207**
	174–1,864				154–259		

[a]Rural Generation, 2004; [b]DEFRA, 2006, [c]CSO, 2006 (http://www.cso.ie/statistics/AgricultureandFishing.htm); [d]van den Broek *et al.*, 2001; [e]Rosenqvist and Dawson, 2005a; [f]Venturi *et al.*, 1999; [g]Gigler *et al.*, 1999; [h]van Loo and Koppejan, 2003.

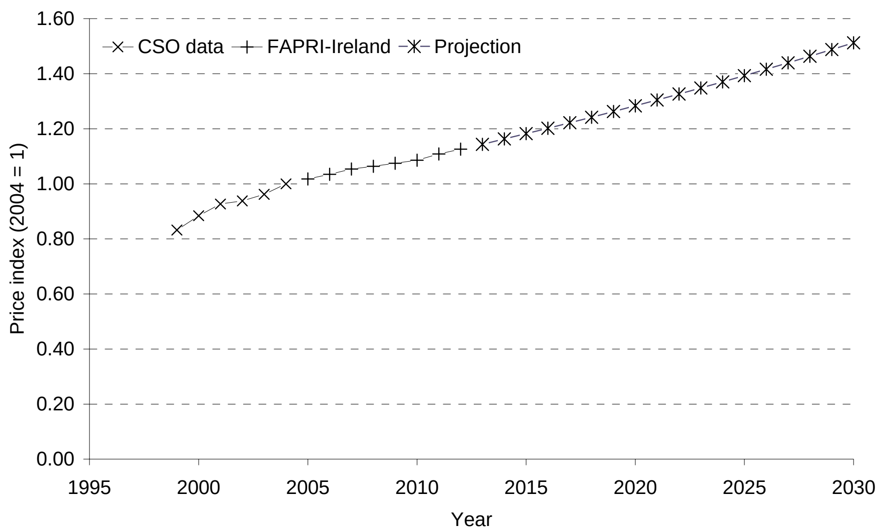

Figure 5.1. CSO, FAPRI-Ireland, and projected price inflation applied to model (Source: Binfield *et al.*, 2003; CSO, 2006: http://www.cso.ie/statistics/AgricultureandFishing.htm). Projections based on 3-year rolling average extrapolated from FAPRI-Ireland data.

The 2006 cost estimates displayed in Table 5.2 include low-, mid- and high-cost estimates for each activity, representing the range of values found in the literature. These were used to generate low, mid and high production cost estimates, denoted by the suffices ‘a’, ‘b’ and ‘c’, respectively, applied to supply strategy labels (e.g. S1b refers to mid-cost stick harvest and supply). The most appropriate values were chosen for the mid-cost estimates, based on similarity to Irish circumstances and contemporaneousness. In some instances, it was possible to find only one or two values for specific activities in the literature, or values that included certain fixed costs, such as shed construction and rent, not considered here (see Section 5.4.1). Mid-cost estimates were thus sometimes at the lower or upper extreme of the quoted literature range, but were considered by these authors to be the most realistic costs. It is clear that there is a wide variation in cost estimates for some activities. Rabbit fencing may be required for SRCW if there are large rabbit populations in the area, and this is considered in the high establishment cost estimate (Table 5.2). A high degree of certainty may be associated with establishment costs based on data from Rural Generation and Quinns of Baltinglass, who base their business practice on these costs. In fact, the *Miscanthus* establishment cost quoted by Quinns is identical to (and perhaps based upon) the 2006-inflated DEFRA cost estimate. Fertiliser costs, based on average fertiliser prices quoted by CSO (2006: http://www.cso.ie/statistics/AgricultureandFishing.htm), are also reliable. In contrast, drying and storage costs varied widely in the literature, depending on the techniques/equipment used and assumptions made in the cost calculations (discussed later), and these were associated with the greatest uncertainty. Fixed shed costs were not included in woodchip storage costs here, and outdoor storage of stick-harvested SRCW and *Miscanthus* under plastic sheeting was assumed (Gigler *et al*., 1999). *Miscanthus* storage costs of €48 and €110/ha/annum for baled and chopped material (Venturi *et al*., 1999) were high compared with SRCW storage costs of €24/ha/annum (Gigler *et al*., 1999), but this may be representative of higher yields and less favourable handling/storage properties of *Miscanthus,* so they were applied.

5.2.2 *Ex ante methods for comparing gross margins of different land uses*

From the costs listed in Table 5.2, an economic spreadsheet model was generated to evaluate the life-cycle economics of SRCW and *Miscanthus*. An NPV approach was adopted, similar to that presented by Rosenqvist *et al.* (1997), in which the two perennial energy crops considered were converted to an annual income stream, enabling a comparative economic analysis with competing conventional farming systems. Total costs and returns for the two energy crops over their 16- and 23-year lifetimes were calculated as NPV for the year of plantation using a 5% discount rate, annualised, and expressed per hectare. Where literature values were expressed per tonne DM they were converted to per hectare costs based on DM yield scenarios set out in Table 3.4. For *Miscanthus*, leaf senescence, harvest and storage losses were estimated at 30% of DM (e.g. Clifton-Brown *et al*., 2000; Lewandowski *et al*., 2000), whilst for SRCW, harvest and storage losses were estimated at 15% (though this will vary according to harvest, drying and storage methods: Gigler *et al*., 1999). Within each cost level, the model varied fertiliser input, harvest, drying and storage costs in proportion to yield. A number of harvest and supply routes were considered – if energy crops are to continuously supply heat and power generation throughout the year, a range of harvest strategies may be required depending on the time period between harvest and combustion, and the method of combustion (e.g. Gigler *et al*., 1999). Unless otherwise stated, the main results presented are based on the mid-cost estimates.

In the absence of well-defined markets for energy biomass, with only a pioneer market for wood fuels in Ireland, the price farmers could expect to receive for energy-crop biomass is uncertain, though likely to benefit from recent increases in energy costs. Quinns is offering a guaranteed price of approximately €50/t of *Miscanthus* at up to 20% moisture content (€63/t DM), and this value is applied to the *Miscanthus* A scenario. Once a demand is established for biomass (discussed later), or if farmers sell directly to consumers, higher prices should be expected. Here, we have assumed identical prices for *Miscanthus* and woodchips, at €70, €100 and €130/t DM for low, mid and high estimates. These prices are in line with the delivered price of moist woodchips quoted by Rural Generation in Northern Ireland (~€100/t DM: Rural Generation, personal telephone communication, February 2006) and the current wood pellet price of approximately €168/t DM in the Republic of Ireland (Kerry Biofuels, 2006: http://www.kbf.ie/fuel/plts_lse_brites.htm), considering pellets contain 20 GJ/t DM energy compared with 18 GJ/t DM for woodchips at 20% moisture content, and have superior handling and combustion properties. In the S2 supply strategy, where the farm-gate product is bundled sticks rather than chips, the price of the wood is reduced by €5/t DM over the price range considered (i.e. farm-gate prices of €65, €95 and €125/t DM). This accounts for the additional cost of (more efficient) centralised chipping incurred by the consumer (based on the 2006-adjusted prices of €3.52/t DM quoted by Gigler *et al.*, 1999, and €7.68/t DM quoted by van Loo and Koppejan, 2003). Some form of size reduction is necessary prior to wood energy conversion, and SRCW sticks may be more cheaply converted into chunks (€2.81/t DM: Gigler *et al.*, 1999) for use as combustion fuel in some power stations (e.g. the peat power stations). Similarly, in the C2 supply strategy, where wet chips are sold immediately after harvest, the price received for them is reduced by the additional transport cost (~€3.24/t DM, over 50 km) and the according lower net heat of combustion[12]. Thus, farm-gate prices of 60, 87 and 115 €/t DM are applied to C2 supply strategy gross margin calculations.

Energy-crop NPVs were compared with gross margin NPVs calculated for traditional farming systems in the Republic of Ireland, namely specialist dairy farms, specialist beef-rearing farms, specialist other beef farms, and sugar beet, spring barley, winter wheat and set-aside, as defined by the Teagasc NFS. The most up-to-date version of this survey (Connolly *et al.*, 2005) presents 2004 values, but gross margins have been extrapolated up to 2012 in the FAPRI-Ireland model (Breen and Hennessy, 2003; Thorne, 2004) based on predictions of the response to the new, decoupled subsidy scheme (Fig. 5.2). Unfortunately, farm-level FAPRI projections for sheep farming could not be obtained, and this land use is therefore omitted from the comparison despite its probable high potential for substitution in Ireland. In 2005, there was a large decrease in gross margins associated with each agricultural system, reflecting the decoupling of subsidy payments from production (Fig. 5.2). The area-based single farm payment (SFP) is activated simply by farming the 2000–2002 reference land area in accordance with good environmental practices, and so would also be received by farmers growing energy crops. Therefore, this subsidy is not considered in the calculations here. However, the energy-crop-specific EU subsidy of €45/ha/annum is considered in the energy-crop NPV, as it is activated only by growing energy crops. The CAP also enables farmers to sustain set-aside payments (though not the €45/ha/annum subsidy) on set-aside land used for energy crops, so financial comparison of energy cropping with this land use excludes the energy-crop subsidy and is based on the maintenance costs for set-aside land (Thorne, 2004). Gross margins in the NFS include labour costs, but not land rental or fixed farm costs. These costs are therefore not considered in the economic analyses of energy crops applied here, following the example of Heaton *et al.* (1999), Rosenqvist and Dawson (2005a) and Ericsson *et al.* (2006). The use of contractor prices for specialised operations such as planting and harvesting ensures that specialised machinery costs are indirectly accounted for.

At the time of report revision (March 2007) the Department of Agriculture and Food (DAF) has just

12. Lower heating value (LHV) of 16.4 GJ/t DM at 50% MC compared with 18.1 GJ/t DM at 20% MC (Matthews, 2001).

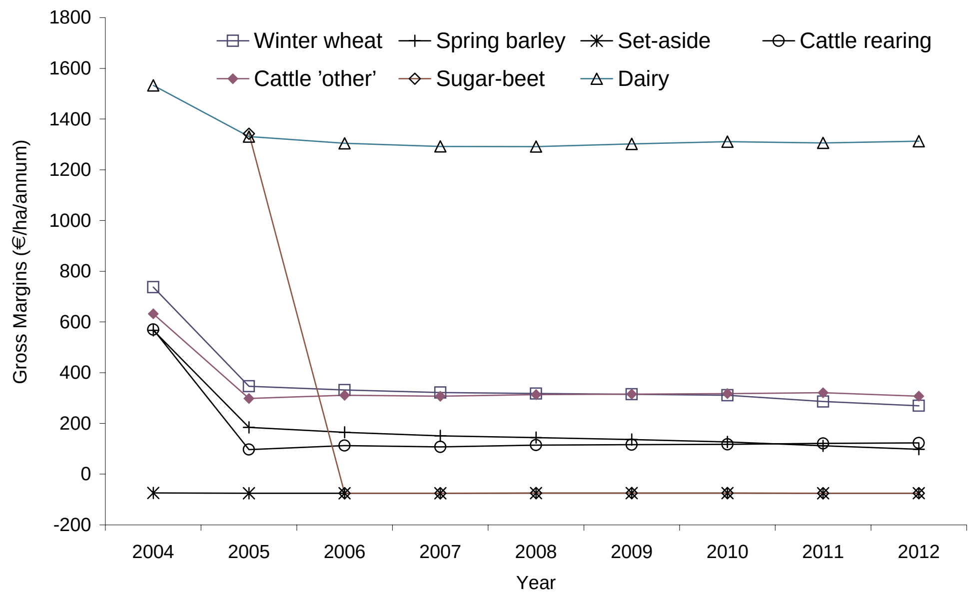

Figure 5.2. FAPRI-Ireland farm-level forecast gross margins for conventional systems.

introduced a 50% establishment grant for *Miscanthus* and SRCW, and an €80/ha/annum energy-crop premium top-up (bringing the total energy-crop premium to €125/ha /annum, except on set-aside). This establishment grant and additional subsidy will be limited to 1,400 ha in the first year. The combined impact of these supports on discounted annual gross margins is included in NPV model runs for *Miscanthus* and SRCW, and the results presented alongside biomass-price sensitivity.

5.3 Results

5.3.1 *Production costs for different supply routes*

Figure 5.3a displays the total, discounted annual production costs for each hectare of SRCW and *Miscanthus*, up to the farm gate, over plantation lifetimes of 23 and 16 years, respectively. Figure 5.3b displays the same costs expressed per tonne DM product. In both instances, total production costs for each supply route are broken down into major source categories. Discounted, annualised production costs for *Miscanthus* range from €430 to €559/ha, or, expressed per unit product, from €37 to €48/t DM. These compare with annualised SRCW-production costs ranging from €275 to €407/ha, or €31 to €46/t DM. For *Miscanthus*, the B (baled) harvest strategy was slightly more expensive than the C (chopped) harvest strategy (discounted costs of €48 compared with €43/t DM), whilst the A (Quinns) supply strategy (delayed, chopped harvest and immediate

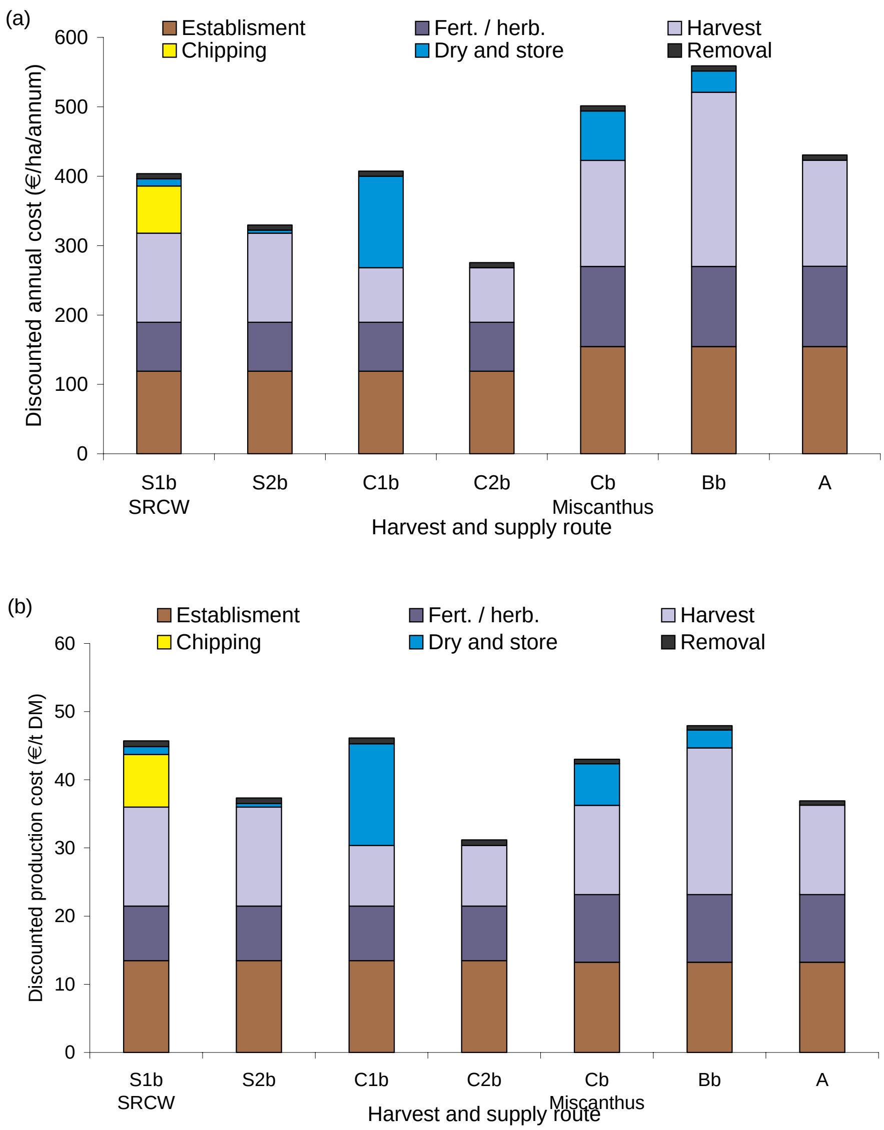

Figure 5.3. 2006 production costs, expressed per hectare (a) and per tonne of combustible dry matter (b) for SRCW and *Miscanthus* broken down into main source categories.

supply) was the least expensive at €37/t DM. For SRCW production, the C1 (chip and dry) supply strategy was the most expensive, though only slightly more costly than the S1 (stick harvest and chip) supply strategy (discounted cost of €46/t DM), and the C2 (wet chip supply) strategy was the least expensive (discounted cost of €32/t DM).

For SRCW supply strategies, establishment accounted for the largest portion of production costs (€13/t DM), whilst annual harvesting accounted for the largest portion of *Miscanthus*-production costs. Drying and storage incurred the largest cost in the case of the SRCW C1 supply strategy (€15/t DM), though incurred low costs for the other supply strategies. Fertiliser and herbicide application costs were significant, accounting for approximately one-fifth of SRCW-production costs (€8/t DM) and approximately one-quarter of *Miscanthus*-production costs (€10/t DM). After discounting and division over the crop lifetime, the cost of crop removal made a small contribution to overall costs.

5.3.2 *Energy-crop gross margins and sensitivity analyses*

Table 5.3 displays annualised discounted gross margins for SRCW and *Miscanthus*, and variation of these margins in response to changed costs, yields and discount rates. Values are centred around mid-costs (Table 5.2), mid-yields (Table 3.4), a 5% discount rate, and a biomass price of €100/t DM (NB: corrected to €95 and €87/t DM for SRCW S2 and C2 strategies), and vary according to low and high estimates for costs presented in Table 5.2, yields presented in Table 3.4, and alternative discount rates of 3% and 8%. Based on the mid-cost and mid-price estimates for energy-crop production and sale, discounted, annualised gross margins from SRCW range from €211/ha/annum for the C1 supply strategy to €270/ha/annum for the C2 supply strategy (Table 5.3). For *Miscanthus*, gross margins are €383 and €326/ha/annum for chopped and baled supply strategies, respectively (Table 5.3), and €172/ha/annum in the instance of €63/t DM Quinns' price.

Applying the low cost estimates results in substantially higher discounted annual gross margins, of up to €397 and €586/ha/annum for SRCW (C2a) and *Miscanthus* (Ca), respectively. Conversely, applying the high cost estimates diminishes discounted annual gross margins down to –€139 and –€13/ha/annum for SRCW (S1c) and *Miscanthus* (Bc), respectively. Positive gross margins were maintained assuming combustible yield reductions of 50% and 30% for SRCW and *Miscanthus*, but were reduced by up to 91% (SRCW C1) and 30% (*Miscanthus* C), respectively (Table 5.3). The assumption of yield increases of 17% and 30% for SRCW and *Miscanthus* resulted in gross margin increases of up to 62% (SRCW C1) and 64% (*Miscanthus* B), respectively (Table 5.3). Discounted *Miscanthus* gross margins exceeded €600/ha/annum under the high-yield scenario. Gross margins proved less sensitive to variation in discount rates than to variation in costs and yields. Reducing the

Table 5.3. Results of sensitivity analyses, comparing discounted, annualised profit margins (2006 prices) at different cost levels, yields, and discount rates. Mid-yield and cost estimates, 5% discount rate, and €100/t DM price are applied unless otherwise stated

		SRCW (€/ha/annum)				*Miscanthus* (€/ha/annum)	
		S1	**S2**	**C1**	**C2**	**C**	**B**
Cost							
	Low	526	364	385	397	586	519
	Mid	245	261	211	270	383	326
	High	–139	–71	59	166	103	–13
Yield							
	Low	32	44	19	49	270	230
	Mid	245	261	211	270	383	326
	High	334	354	291	365	609	535
Discount rate							
	3%	294	314	251	325	472	405
	5%	245	261	211	270	383	326
	8%	128	139	102	146	279	232

discount rate from 5% to 3% increased discounted annual per hectare gross margins to between €251 (39% increase) and €325 (20% increase) for SRCW, and to €405 (24% increase) and €472 (18% increase) for *Miscanthus*. Increasing the discount rate applied from 5% to 8% reduced discounted annual per hectare gross margins to between €102 (43% decrease) and €146 (46% decrease) for SRCW, and to €232 (29% decrease) and €279 (27% decrease) for *Miscanthus* (Table 5.3).

Discounted annual gross margins were highly sensitive to variation in the energy-crop biomass price from €70 to €130/t DM (Table 5.4). At a €70/t DM price, SRCW gross margins were reduced to between €33 and €110/ha /annum, and *Miscanthus* gross margins to €109 and €167/ha/annum. At a €130/t DM price, SRCW gross margins were increased to between €388 and €436/ha/annum, and *Miscanthus* gross margins to €651 and €708/ha/annum. Incorporating the new 50% establishment grant (up to €1,450/ha) and €80/ha/annum energy-crop premium top-up would result in substantial increases for energy-crop gross margins. The impact is especially great for low farm-gate biomass prices, where gross margins are increased by between 105% and 352% for SRCW, and by between 87% and 132% for *Miscanthus*. At mid and high biomass prices, these subsidies would have a proportionately smaller, but significant, overall effect on discounted annual gross margins. For example, they would increase mid-price gross margins for SRCW by between 43% and 55%, and for *Miscanthus* by 38% and 44%, enabling healthy mid-price discounted gross margins of up to €386 and €527/ha/annum for SRCW and *Miscanthus*, respectively (Table 5.4).

The gross margins referred to throughout this results section are based on discounted and price-inflated future costs and returns – over 16 years for *Miscanthus* and 23 years for SRCW. Therefore, they are not directly comparable with current gross margins with which some readers may be more familiar. Table 5.5 provides an indication of mid-cost, mid-price and mid-yield discounting- and inflation-corrected[13] gross margins for

13. Discounted total plantation gross margins were divided by the discounted number of years, after each year had been adjusted for inflation.

Table 5.4. The impact of varying farm-gate energy crop biomass prices (€70, €100 and €130/t DM), use of SRCW for waste-water treatment, and the 50% establishment subsidy with €80/ha/annum top-up payment, on discounted, annualised gross margins for different energy crop strategies.

Price (€/t DM)	SRCW (€/ha/annum)				*Miscanthus* (€/ha/annum)	
	S1	S2	C1	C2	C	B
Biomass						
70	68	84	33	110	167	109
100	**245**	**261**	**211**	**270**	**383**	**326**
130	423	439	388	436	708	651
Biomass + waste-water treatment						
70	631	647	596	673		
100	**808**	**824**	**774**	**833**		
130	986	1002	951	999		
Subsidy (50% est. + €80/annum)						
70	184	200	149	226	311	254
100	**362**	**377**	**327**	**386**	**527**	**470**
130	539	555	504	552	853	795

Table 5.5. Mid-cost, mid-price, discounting- and inflation-corrected annualised profits (for indicative purposes).

	SRCW (€/ha/annum)				*Miscanthus* (€/ha/annum)	
	S1	S2	C1	C2	C	B
Standard	347	369	297	381	513	436
Subsidy	510	533	461	545	707	629

the different energy-crop production strategies – these values are more directly comparable with current agricultural gross margins, and are included for indicative purposes.

5.3.3 Waste-water treatment

There is an increasing realisation of the potential to utilise SRCW for bio-filtration treatment of wastes and contaminated land, owing to the dense root network and high transpiration rate of willow. Borjesson (1999b) and Rosenqvist and Dawson (2005b) estimated the WW treatment capacity of SRCW and attributed values to this, in the contexts of Sweden and Northern Ireland respectively. Figures from Rosenqvist and Dawson (2005b) were applied here, with the assumption that circumstances should be similar between the North and Republic of Ireland. Their figures comprised an estimated annual cost of €1,306/ha for capital investment in irrigation ponds, pumps and pipes, ongoing pumping costs, labour, etc., and a 100% reduction in fertiliser costs. The potential net annual income from WW treatment, assuming full payment of the conventional treatment cost, was estimated at between €1,159 and €2,947/ha depending on conventional treatment method. Here, the mid-point value of €2,053/ha/annum was used as an estimate of farm revenue from WW treatment, resulting in a net income of €747/ha/annum, before discounting. Table 5.4 displays discounted, annualised gross margins for the range of energy-crop biomass price scenarios, for mid-yield estimates, when WW treatment returns are applied. Assuming a biomass price of €100/t DM, WW treatment could increase discounted gross margins substantially to between €774 and €833/ha/annum for SRCW.

5.3.4 Comparison with conventional agricultural crops

Figure 5.2 displays the data from the farm-level FAPRI projections for selected conventional agricultural systems, extrapolated from 2004 data, and running until 2012. Most of the conventional agricultural systems exhibit a sharp decline in gross margins between 2004 and 2005, after which they remain relatively stable through to 2012, reflecting the decoupling of subsidy payments from production (and thus exclusion from gross margin calculations) in 2005. Sugar-beet gross margins decline steeply from a high 2005 value of €1,342/ha/annum to the equivalent of set-side payments in 2006, reflecting the recent announcement that the only sugar processing factory in Ireland is to close. On the other hand, high initial dairy gross margins remain fairly steady at over €1,300/ha/annum through to 2012.

Figure 5.4 displays results of an economic comparison of annualised, discounted gross margins for the different conventional agricultural land uses and energy cropping strategies, calculated over the 16- and 23-year timescales of *Miscanthus* and SRCW cultivation, respectively. Both the *Miscanthus* C and B supply strategies prove highly competitive with all but the dairy (€965/ha/annum) land uses, whilst the *Miscanthus* A strategy fails to match the gross margins for ‘cattle and other’ (€229/ha/annum) or winter wheat (€214/ha/annum) land-use classifications, but is competitive with spring barley (€87/ha/annum), sugar beet (–€56/ha/annum), set-aside (–€56/ha /annum) and cattle rearing (€88/ha/annum). All but the C1 SRCW strategies proved competitive with all the land-use classifications except dairy (€867/ha/annum). Removing the €45/ha/annum subsidy has little impact on energy-crop returns, reducing discounted gross margins for *Miscanthus* by approximately €35/ha/annum, and for SRCW by approximately €31/ha/annum. Therefore, all energy-crop production and supply strategies return gross margins considerably higher than set-aside (Fig. 5.4). The annualised, discounted gross margin resulting from including WW treatment in combination with the mid-range SRCW S1 strategy (€808/ha/annum) proved highly competitive with all land uses, and was only 10% below the average dairy gross margin. Similarly, including the recently announced energy-crop establishment grant and subsidies significantly elevated energy-crop gross margins compared with most conventional land uses (Fig. 5.4). This was especially true for the SRCW C2, wet-chip supply strategy, reflecting the lower overheads for this strategy (Fig. 5.3). Considering the higher gross margins associated with high yields, high biomass prices and low costs (Tables 5.3 and 5.4) would also substantially increase the financial attractiveness of energy crops compared with conventional agricultural systems.

5.4 Discussion

5.4.1 Energy-crop production costs

The least certain cost estimates are those for storage and drying. These largely depend on the techniques used, but the range of values in the literature also reflects different methods of calculation. If the shed storage cost of €2.77/t DM/month calculated by Gigler *et al.* (1999) was applied in this study, woodchip production would increase in cost

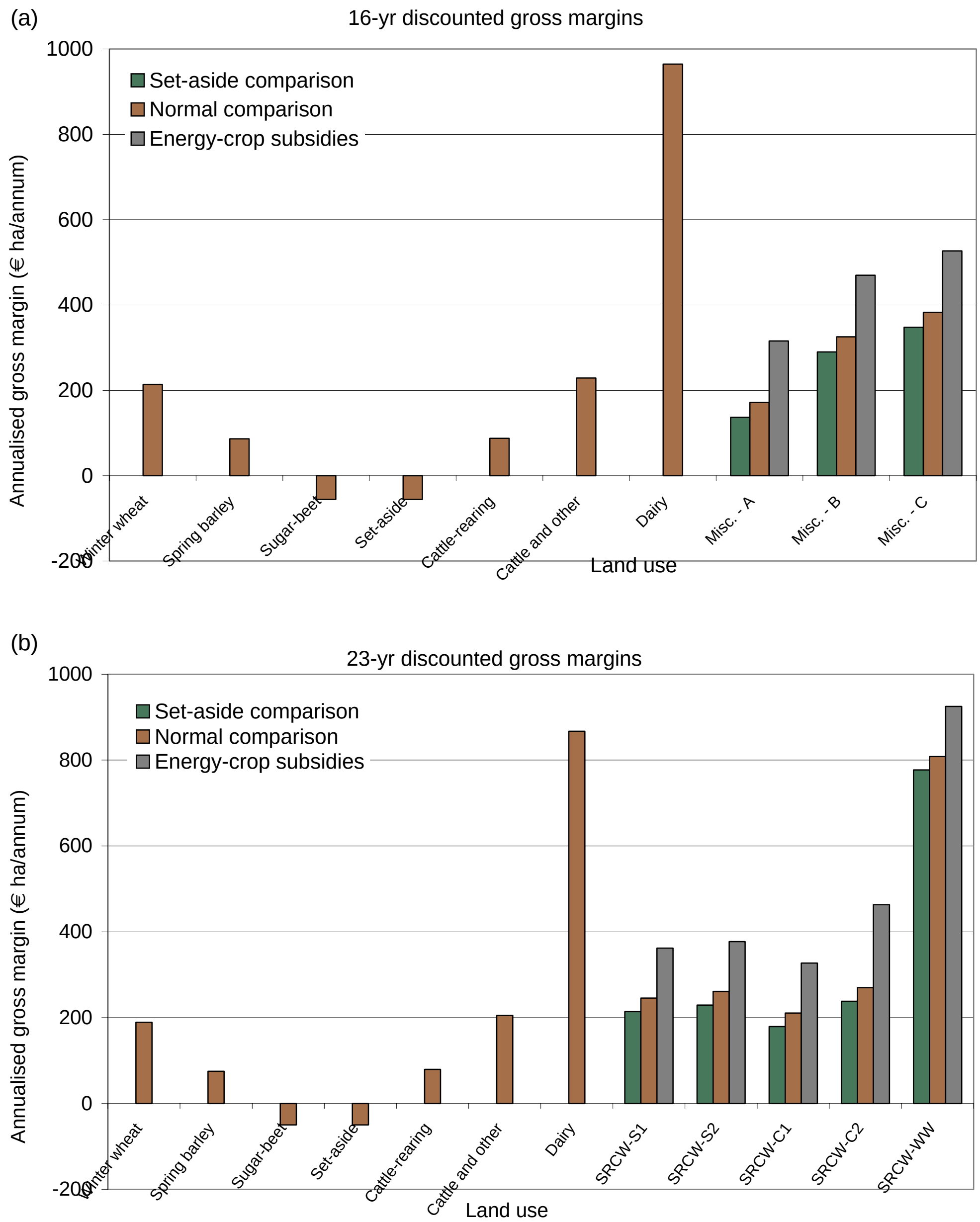

Figure 5.4. Discounted, annualised gross margins for future income from conventional agriculture and energy crops over the 16- (a) and 23- (b) year plantation lifetimes of *Miscanthus* and SRCW. Included are set-aside comparisons (–€45/ha/annum energy-crop subsidy), and energy-crop subsidy (50% establishment grant plus additional €80/ha/annum top-up) comparisons.

by approximately €284/ha/annum. Such fixed costs are not directly considered in the FAPRI-Ireland model projections, or energy-crop cost calculations in this study, although machinery costs are indirectly accounted for through contractor costs for planting, maintenance and harvest operations. Flexible harvest timing for SRCW offers the possibility to plan harvesting around storage availability, and Heaton *et al.* (1999) ignored fixed costs associated with SRCW production on the assumption that only 10–15% of any farm's land would be converted to SRCW cropping, ensuring that existing facilities would be adequate. For stick-harvested SRCW and *Miscanthus*, 6 months of outside storage may reduce moisture content to less than 15% (Lewandowski *et al.*, 2000; Gigler *et al.*, 2004). In this study, a final moisture content of 20% was assumed after outdoor storage under plastic sheeting, at relatively low costs (Table 5.2). Harvesting SRCW as chips requires the forced drying of woodchips prior to storage, unless moist chips are to be used immediately (e.g. in gasification boilers or large combustion plants) or cheaply dried by the consumer (e.g. using waste heat from power station). Forced ventilation drying of woodchips with heated air is expensive, and was calculated to cost between €14 and €29/t DM by Gigler *et al*. (2000). Another cost not considered in the mid-cost estimate for SRCW is rabbit fencing, which may be necessary in some areas with large rabbit populations. Within a total establishment cost estimate of €2,860/ha (similar to that applied here), Gilliland (2005) includes fencing costs of €430/ha, which, if added to establishment costs applied here, would decrease discounted annualised gross margins by 5–9%.

Higher costs of production per hectare for *Miscanthus* compared with SRCW reflect the higher fertiliser requirements, annual (compared with 3-yearly) harvesting requirement, and shorter plantation time over which establishment costs are divided for *Miscanthus*. However, these higher costs are compensated for by higher yields, and discounted production costs per tonne of DM (Fig. 5.3) are similar for SRCW (€32–47) and *Miscanthus* (€36–47). The longer discounting period considered for SRCW (23 compared with 16 years) will have lowered the numeric value of discounted production costs for SRCW compared with *Miscanthus.* Sensitivity analyses indicated that the cost of production was more susceptible to variation in yield and discount rate for SRCW than for *Miscanthus*, reflecting the higher portion of costs (fertiliser application, annual harvest and storage) linked directly with yield, and the shorter crop lifetime in the case of *Miscanthus.* The (non-discounted) cost of dried woodchip production quoted by Rural Generation (€50/t DM), based on forced drying, is similar to the discounted cost of dried woodchip production calculated here.

5.4.2 Supply strategies

It is apparent that the harvest and supply strategy has a critical impact on production costs, and on additional transport, handling and preparation costs that may be borne by either the producer or consumer. Combined harvest and chipping is cheaper than stick harvest (€417 compared with €682/ha), and saves substantial post-harvest chipping costs of €226/ha (decentralised) or €106/ha (centralised). However, unless chips are immediately used, they incur substantial drying costs of €701/ha (Gigler *et al*., 1999) and will require shed storage space, compared with cheap outdoor stick storage. The lower density of *Miscanthus* enables natural drying of both baled[14] and chopped material (Lewandowski *et al*., 2000). Higher costs for baled harvest compared with chopped harvest (€389 *vs* €287/ha) are partially offset by lower storage costs for baled material (€48 *vs* €110/ha), and may also result in higher combustible yields through collection of senesced leaf material (though this would also increase nutrient removal and deteriorate combustion properties). Transport of the baled material may also be cheaper, though this should be considered against any necessary disaggregation and chopping costs incurred prior to combustion. Non-adjusted transport costs calculated by Venturi *et al.* (1999) of €6.8 and €8.9/t over 20 km for baled and chopped *Miscanthus*, respectively, are considerably higher than biomass transport costs of €4.1/t for 50 km calculated for Ireland by SEI (2004).

Here, variable costs incurred by the consumer according to the supply strategy are reflected in variable biomass prices: i.e. the chipping costs for supply of stick bundles, and the additional transport costs and reduced LHV of wet woodchips, are translated into reduced biomass prices received for these products. This standardises the product output to an equivalent of chipped, dried (20% MC) woodchips for SRCW, but may underestimate the impact of supply strategy on gross margins. Ultimately, there will be a need for co-ordination along the supply chain, and this may optimise cost sharing between producers and consumers. For example, some large consumers may be able to cost-effectively dry woodchip utilising waste heat (with associated energy-balance benefits compared with forced drying). The lowest-cost supply strategy depends on a number of factors, including moisture content at harvest, the time between harvest and combustion, the method of energy conversion, and the possibility to utilise waste heat in drying (Gigler *et al*., 1999). Further work is needed to explore the logistics and feasibility of possible energy-crop supply to consumer chains within Ireland, with the aim of optimising the energy balance and economics.

5.4.3 Prices and market establishment

The farm-gate price range of €70, €100 and €130/t DM applied here for indicative purposes is based around current actual prices in Ireland's fledgling wood-fuel market. In Northern Ireland, Rural Generation is delivering woodchips for around €100/t DM (Rural Generation, 2006), and wood pellets are sold for prices of €168/t DM in bulk, and up to €303/t DM by the bag (Kerry Biofuels,

14. Assuming moisture reduction prior to late winter harvest.

2006: http://www.kbf.ie/fuel/plts_lse_brites.htm). Pellets will command significantly higher prices than woodchips due to their higher energy content (20.0 GJ/t DM compared with 18.1 GJ/t DM) and superior handling and combustion properties. Irish woodchip prices are high compared with some woodchip price estimates used elsewhere, such as the €40 and €59/t DM used by Ericsson *et al*. (2006)[15] to calculate the economics of willow production in Poland. However, those same authors refer to a wide range of woodchip prices in Europe, citing examples ranging from €47/t DM in Germany to €94/t DM in Denmark. In fact, biomass prices are likely to have somewhat shadowed large energy-price increases over recent years, subsequent to values quoted in much of the peer-reviewed literature. *Miscanthus* prices are more speculative, as no market exists for *Miscanthus* yet in Ireland. Here, it is assumed that ultimately energy producers may be willing to pay the same price for *Miscanthus* as for woodchip once a market is established, but initially farmers can only expect the farm-gate price of €63/t DM offered by Quinns (although presumably this is less than the end consumer is willing to pay). Whilst farmers could maximise farm-gate prices through direct supply to final consumers, intermediaries may prove necessary to hedge some of the risk involved and guarantee contracts for both farmers and consumers. Additionally, as indicated by Rosenqvist and Dawson (2005a), initial small-scale pioneer grower costs could prove to be higher than cost estimates used here as techniques are adapted to, though this effect could be reduced if contractors are used. It is therefore possible that initial returns for pioneer farmers may be closer to those based on the lower price estimate of €70/t DM – this emphasises the importance of government financial support for pioneer growers.

There are signs that momentum is building in the Irish biomass fuel market, with positive implications for future energy-crop biomass prices. In recent years, a small number of woodchip suppliers have begun operating in Ireland, and Edenderry Power is keen to begin co-firing with alternative biomass fuels in its versatile fluidised combustion boiler. After adding transport costs to the farm-gate prices used in this study, *Miscanthus* and SRCW are borderline competitive as a fuel for electricity generation compared with peat through co-firing (when reduced CO_2 allowance liabilities are considered – Section 6.3.1), and SRCW woodchip is highly competitive as a source of domestic and commercial heat generation (Section 6.3.2). Upward pressure on energy prices through fossil fuel and CO_2 emission costs may increase the value of C neutral (under the EU ETS) biomass fuels in the future, towards the speculative upper price level of €130/t DM used here. The agricultural price inflator (Fig. 5.1) applied to future costs and revenues in the NPV model may well underestimate future energy-price increases, and thus gross margins attainable from energy-crop cultivation. Rosenqvist and Dawson (2005a) report that market development in Sweden resulted in a decline in woodchip prices to around €57/t DM (~2003) as a consequence of abundant supply from vast forests and large areas of efficient SRCW cultivation. The availability of competing wood sources in Ireland is far lower than in Sweden (discussed in Section 8.2.1), but it is possible that increasing forestry and realisation of alternative biomass supply potential (e.g. meat and bonemeal (MBM)) could act to dampen future energy-crop prices here.

The recently announced establishment and annual subsidy top-up payments for *Miscanthus* and SRCW cultivation in Ireland (DAF, 2007: http://www.agriculture.gov.ie/index.jsp?file=pressrel/2007/18-2007.xml) significantly improve NPV calculations for energy-crop plantations, and extend the benefit of energy crops compared with most of the conventional agricultural systems referred to in this study. These payments offer good insurance against potential losses associated with high costs and low yields, and generate a high probability that energy-crop gross margins will be favourable compared with alternative land uses. However, the greatest impact is likely to be the reduced risk and shorter payback period associated with the 50% establishment grant (two-thirds paid in the establishment year, one-third in the subsequent year). Worth up to €1,450/ha, this grant substantially reduces the high initial outlay (€2,736 and €2,470/ha for SRCW and *Miscanthus*, respectively) required by farmers to cultivate these energy crops, and thus reduces the risk-based inertia and payback commitment period.

5.4.4 Competitiveness with conventional crops

The decoupling of subsidy payments from production after January 2005 resulted in large reductions in calculated gross margins for all agricultural systems between 2004 and 2005, though dairy gross margins

15. Converted from 2003 prices expressed per MWh fuel to 2006 price expressed per t DM, based on 5 MWh (18 GJ)/t DM lower heating value and inflation values in Fig. 5.1.

remain relatively high compared with competing farming systems. The proposed reform of the EU sugar Common Market Organisation (CMO) and the decision by Irish Sugar to cease processing sugar in 2006 reduces the market-based gross margin for sugar beet to levels equivalent to that of set-side land. In combination with the modest EU biofuel subsidy of €45/ha/annum, these factors present a strong opportunity for energy crops, such as *Miscanthus* and SRCW, to compete financially with existing agricultural land uses. When all possible land uses are compared as a stream of future net revenue over the plantation lifetimes of *Miscanthus* and SRCW using the NPV method, annualised returns for these crops prove to be highly competitive with a number of the major current agricultural land uses compared here. In particular, future gross margins predicted for sugar beet, spring barley and cattle rearing are low, and uncompetitive with any of the energy-cropping strategies considered here. The most profitable energy-cropping strategies (i.e. SRCW C2 and *Miscanthus* C) are competitive with all the other land uses considered, except dairy. Well managed, and planted on appropriate[16] soils, these crops thus have a relatively high earning potential for farmers compared with current options. Planting on set-aside land is financially an attractive option, but would disrupt current crop-rotation systems and may cause some logistical difficulties. Opportunities for multiple uses, such as WW and sewage sludge treatment, further enhance the financial attractiveness of SRCW, and could substantially increase farm revenues.

16. *Miscanthus* requires good-quality (e.g. current tillage) soils, whilst SRCW may grow well on wetter soils that support more marginal conventional agricultural production.

The main barriers to realising these profits are market uncertainty combined with the risk of large upfront establishment costs, and lack of strategic government policy that co-ordinates support for long-term investment among both consumers and farmers. Most farmers are not willing to invest in such long-term commitments as SRCW and *Miscanthus* plantations until there is a developed market for their biomass. Conversely, potential consumers (domestic homes and electricity generators) are not willing to invest in the infrastructure necessary for biomass utilisation until a guaranteed biomass supply is established, including, but not confined to, energy crops. There are positive signs of change, in the form of government subsidies for household renewable energy sources (up to €4,200 available for wood-boiler installation) and energy-crop establishment grants.

Overall, higher yields, a shorter period to first harvest, a greater similarity with existing cropping practices, and the potential to apply existing farm machinery and techniques, may favour *Miscanthus* over SRCW from a farmer perspective. However, SRCW may be grown on wetter, less agriculturally productive (less profitable) soils, and offers the opportunity to generate extra revenue through WW treatment. Ultimately, the comparisons here were based on numerous stated assumptions, and used average values. Gross margins within Ireland vary widely according to variations in climate and soil type, and management practices on individual farms. Thus, the decision as to whether energy crops are an attractive alternative will vary among farms, and according to the views of individual farmers. However, data presented here indicate that energy crops have good potential to generate extra revenue, both as alternatives to conventional agricultural systems, and compared with extensification.

6 Economic Competitiveness of Biomass Electricity and Heat Production

6.1 Aims

This chapter aims to assess the economic competitiveness of *Miscanthus* and SRCW woodchip as fuels for electricity generation (compared with peat and coal, respectively) and SRCW woodchip as a fuel for domestic- and commercial-scale heat production (compared with gas, oil and electricity). An NPV approach is used to determine the discounted, annualised cost differential between heat supplied by woodchip boilers, and gas, oil and electric heating systems, for typical household heat loads, and commercial premises with heat loads ten times higher. Electricity-production costs based on co-fired *Miscanthus* and SRCW are compared with electricity-production costs from dedicated peat and coal firing, respectively, through quantification of additional capital investment and fuel costs, and reduced CO_2 allowance costs.

6.2 Methodology

6.2.1 *Ex ante methods for comparing electricity-generating costs*

In this report, only relative electricity-production costs were assessed. This was done by first accounting for biomass co-firing investment costs in Moneypoint (negligible for 5% direct co-firing, €60 million for 15% gasified co-firing in all three boilers) and the peat power stations (€200,000 for each station, assuming 30% co-firing) according to SEI (2004). To these costs were added additional biomass fuel costs compared with coal and peat, based on the three farm-gate biomass prices used in the previous section, and a transport cost of approximately €5.1/t DM[17] – assuming 50 km transport distance and 20% moisture content. Peat costs were based on SEI (2004) data for 2003, and inflated to 2006 prices using CSO and FAPRI-Ireland data (Fig. 5.1). Coal costs have varied widely over the past few years, and an estimate of current delivered coal prices of €60/t was used[18]. Reduced CO_2 allowance costs were also considered based on biomass burning being regarded as C neutral. Spot prices for EU ETS CO_2 allowances have fluctuated wildly since their introduction, peaking at almost €30/t in early 2006, before declining to a current level of around €1/t (Point Carbon, 2007: http://www.pointcarbon.com, accessed March 2007) following initial over-allocation. Futures prices for the second round have remained more stable, and are currently (March 2007) trading at approximately €14/t for 2008/2009 (Point Carbon, 2007) – this value is applied as a mid-estimate in electricity-generating calculations. Additional fuel costs and reduced CO_2 allowance costs for energy-crop biomass were calculated over 20 years, and assuming 5% or 15% co-firing with coal and 30% co-firing with peat (see Table 6.1). This represents the remaining lifetime of Moneypoint, but is 15 years short of the remaining peat power station lifetimes (SEI, 2004). These costs were converted to a NPV based on a discount rate of 5%, and divided by the quantity of biomass electricity produced to generate the cost difference of production for 1 kWh electricity, compared with coal and peat. A price-inflation correction of 3% per annum was applied to coal, peat and CO_2 allowance costs, whilst biomass prices increased as described in Section 4.2.1. High uncertainty regarding future coal and CO_2 allowance prices is considered through sensitivity analyses, though this was considered unnecessary for more stable costs associated with indigenous peat supply. Low and high cost estimates were €30 and €90/t for coal, and €5 and €40/t for CO_2 allowances, respectively.

6.2.2 *Ex ante methods for comparing heat-production costs*

Domestic and commercial heating costs comprised initial boiler system investment, and fuel costs over the following 20 years of estimated boiler lifetimes. Boiler prices were estimated for capacities of 15 and 95 kW, identified as appropriate for the average household and commercial premises requiring ten times as much heat, and based on advertised boiler prices in Ireland. Prices included

17. Based on SEI (2004) estimated biomass transport cost in Ireland of €0.081 t.km (tonnes multiplied by kilometres transported).

18. Based on data for late 2005 from SEI (2006, personal communication), and forecasts from Lane (2004).

Table 6.1. Key parameters fed into the NPV model for 5% and 15% SRCW co-firing with coal at the 915 MW_e Moneypoint power station, and 30% *Miscanthus* co-firing with peat in the 117 MW_e Edenderry power station.

	Coal – 5%	Coal – 15% (Gas)	Peat – 30%
Plant efficency (%)	37.46	37.38	38.4
Biomass input (green t/annum)	213,750	641,250	168,750
Biomass input (GJ/annum)	3,078,000	9,234,000	2,430,000
Total electricity (kWh/annum)	6,416,903,134	6,420,020,136	864,000,000
Biomass electricity (kWh/annum)	320,845,157	963,003,020	259,200,000
Discounted bio-electricity (kWh/annum)	209,918,091	630,060,176	169,585,758
CO_2 reductions (t/annum)	277,500	832,500	264,000
Additional capital cost (€)	0	60,000,000	200,000
Additional fuel cost (€/annum)	11,360,816	34,082,449	6,022,890
Reduced ETS CO_2 cost (€/annum)	3,885,001	11,655,000	3,696,000
Discounted additional cost (€/annum)	4,472,555	16,417,667	534,874
Discounted CO_2 abatement cost (€/t)	16	20	2

installation of fuel storage facilities for oil and woodchip boilers. The boiler prices subsequently applied were (for 15 and 95 kW, respectively) €10,000 and €30,000 for biomass boilers, €1,500 and €8,000 for gas boilers, and €2,000 and €10,000 for oil boilers. Oil and woodchip boilers were considered to be 85% efficient, gas boilers 90% efficient. For simplicity, the costs of the heat delivery systems (plumbing and radiators, etc.) were not included, although these costs will affect comparison with electric heating systems (see Section 6.4.2).

Average annual household heat loads of 21,249 kWh_{th} were taken from Howley *et al.* (2006), and typical commercial/public premises were considered to have heat loads ten times higher than this (detailed in Section 4.3.4). To avoid the complexities and uncertainties involved in calculating pelleting (and consequent increased transport) costs for *Miscanthus*, only SRCW woodchip heat was considered here. Future fuel costs over the 20-year boiler lifetimes were discounted at 5%, added to the initial investment cost, and divided by the boiler lifetime to produce a comparable annualised NPV for each option. For biomass heating, the impacts of recently announced subsidies (up to €4,200 per household) for biomass boiler installation were assessed, as were subsidies of up to 25% for commercial-scale biomass boiler installation (SEI, 2006: http://www.sei.ie). Gas and electricity prices were based on the most appropriate contracts from An Bord Gáis and the ESB (Appendix A). Standing charges were not included for electricity as it was assumed that all premises would be connected to the grid in any case. Oil costs were based on advertised, delivered prices in November 2006 (€0.55/l kerosene delivered; international oil prices trading at ~US$58 per barrel). These prices were considered to increase by 3% per annum. For household and commercial woodchip deliveries, high transport and handling costs of €16.83/t DM were applied, along with 13.5% VAT costs.

6.3 Results

6.3.1 Electricity-generating costs

Table 6.2 displays typical delivered fuel prices per GJ energy content, for electricity and heat production. Compared with peat and coal, energy-crop biomass is expensive as a fuel, being over 2.5 times more expensive

Table 6.2. Fuel costs for houses and commercial premises.

	Electricity	Heat	
		Domestic	Commercial
	(€/GJ fuel)	(€/GJ fuel)	
SRCW-70	4.17	5.58	
SRCW-100	5.83	7.48	
SRCW-130	7.49	9.38	
Coal	2.14		
Peat	3.38		
Gas		14.96	13.38
Oil		15.57	15.57
Electricity		27.61	26.83

than coal, and 72% more expensive than peat, at a farm-gate price of €100/t DM (€5.83 *vs* €2.14 and €3.38/GJ energy content, respectively). Based on current futures prices, reduced CO_2 allowance liabilities associated with biomass co-firing equate to between 42% (SRCW gasification co-firing with coal) and 86% (*Miscanthus* co-firing with peat) of additional fuel costs (Fig. 6.1). Applying these costs to a model calculating the cost difference for electricity generation (Table 6.3) resulted in marginally more expensive electricity generation compared with peat (by €0.0021/kWh$_e$, discounted) and significantly more expensive electricity generation compared with coal (by €0.0139 and €0.017/kWh$_e$ compared with direct and gasification co-firing, respectively). If energy-crop biomass left the farm-gate at €70/t DM, co-fired *Miscanthus* and SRCW could produce electricity at lower cost than peat (by €0.0095/kWh$_e$) and at a slightly higher cost than coal (by €0.0022 and €0.0053/kWh$_e$ for direct and gasification co-firing, respectively). Conversely, at a farm-gate price of €130/t DM, *Miscanthus* and SRCW would produce electricity at substantially higher costs than either peat or coal (€0.0136 and €0.0288/kWh$_e$ higher than peat and coal, respectively: Table 6.3). For reference, CER (2006a) forecast best new entrant gas and average ESB electricity-generating prices of €0.0864 and €0.1064/kWh$_e$, respectively, whilst coal-fired electricity generation at Moneypoint probably costs in the region of €0.06/kWh$_e$ (restricted access to this information)[19]. These cost differences are not particularly sensitive to the discount rate applied, with opposing effects attributable to each direction of rate changes. For example, the cost differential for gasification co-firing of

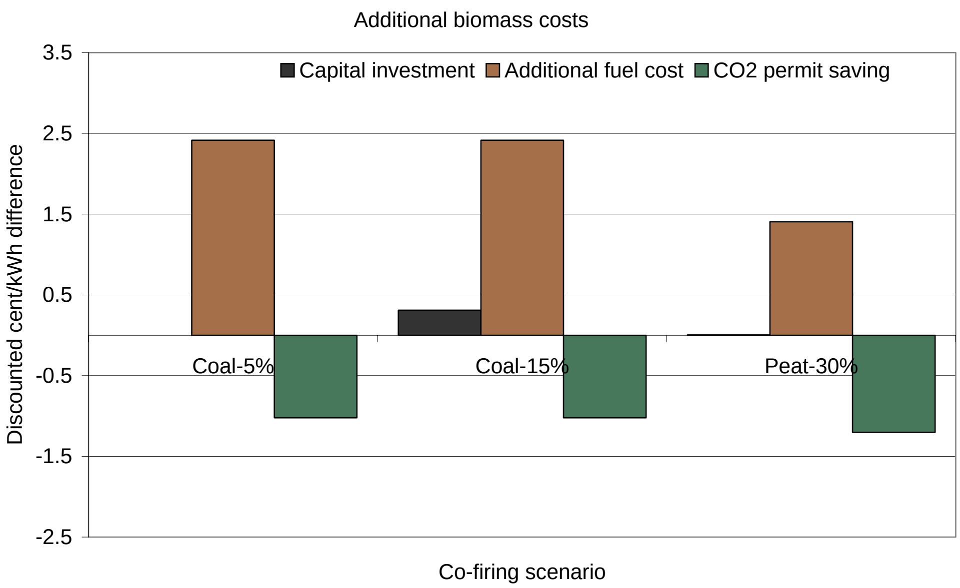

Figure 6.1. Electricity-production cost difference (discounted over 20 years) per kWh, broken down into sources, for co-fired SRCW compared with coal and co-fired *Miscanthus* compared with peat.

Table 6.3. Discounted production cost difference for co-fired energy crop biomass electricity compared with coal (for 5% and 15% co-firing options) and peat (for 30% co-firing option) electricity.

	(€/t)	Coal – 5%		Coal – 15%		Peat – 30%	
		(k€/annum)	(€/kWh)	(k€/annum)	(€/kWh)	(k€/annum)	(€/kWh)
Farm-gate biomass price	70	696	0.22	5,088	0.53	–2,460	–0.95
	100	**4,473**	**1.39**	**16,418**	**1.70**	**535**	**0.21**
	130	8,249	2.57	27,748	2.88	3,530	1.36
Discount rate	3%	5,201	1.62	18,603	1.93	530	0.20
	5%	**4,473**	**1.39**	**16,418**	**1.70**	**535**	**0.21**
	8%	3,659	1.14	13,978	1.45	527	0.20

SRCW compared with coal to generate electricity increases to €0.0193/kWh_e at a 3% discount rate (Table 6.3), indicating the dominance of the reduced devaluation effect over the reduced importance of upfront capital investment relative to future money flows within the NPV analyses.

19. Note that the electricity-generating cost differences expressed in this section are based on NPV differences, involving discounting over a 20-year time period (standard rate of 5% applied), but also 3% annual inflation. Thus, these cost differences will be slightly lower than actual cost differences relevant for direct comparison with current electricity-generating costs.

The electricity-generating cost differences between conventional fuels and energy-crop biomass are highly sensitive to the conventional fuel prices and ETS CO_2 allowance prices applied. Figure 6.2 indicates that if coal prices increased to €100/t, direct and gasification co-firing of mid-cost SRCW woodchip could generate electricity at a similar price to coal if ETS allowance prices increased to €17 and €22/t CO_2, respectively. Conversely, if coal prices dropped to €30/t delivered, then direct and gasification co-firing of mid-cost SRCW woodchips would require ETS allowance prices of €45 and €49/t CO_2 to become competitive with coal. If coal prices remained at

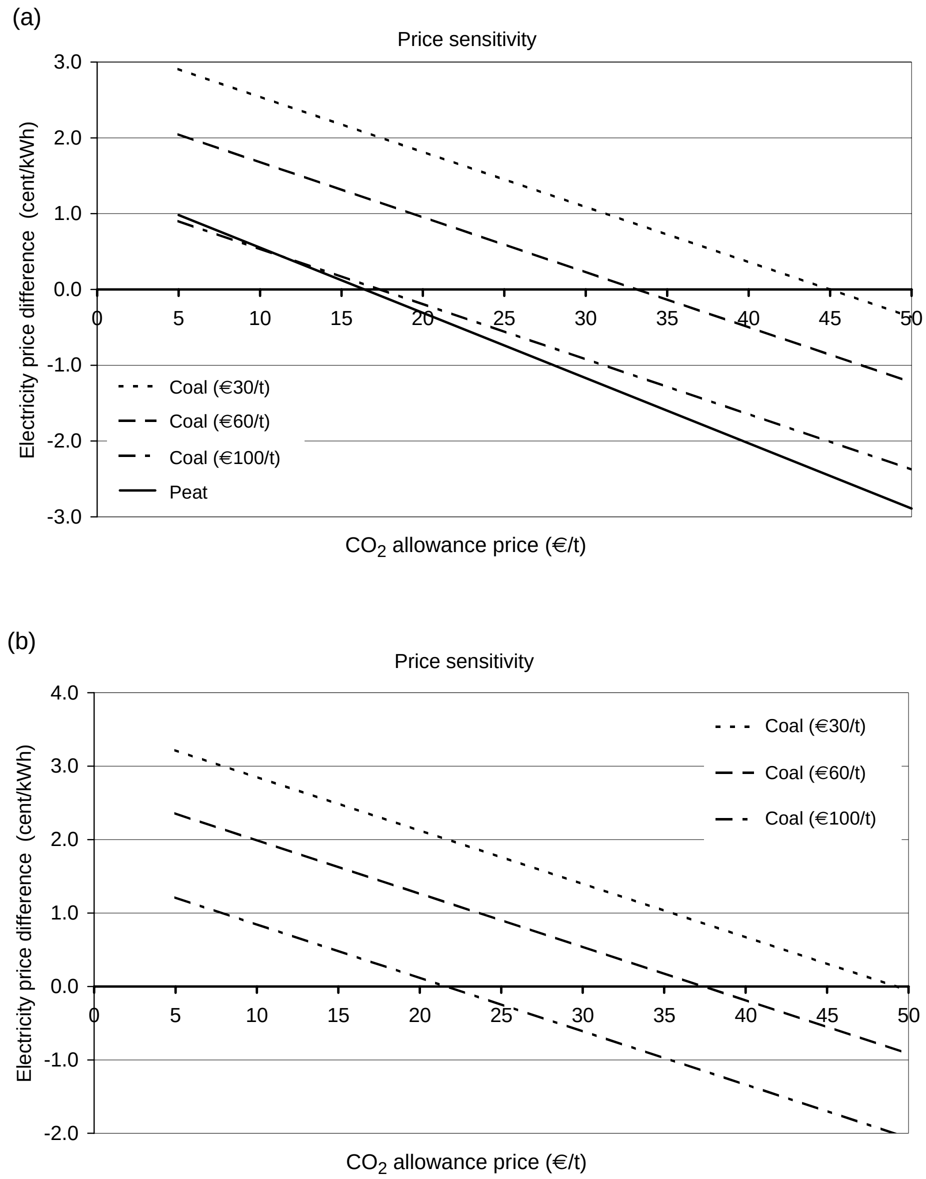

Figure 6.2. Variation in discounted electricity-generating cost differences for directly co-fired SRCW and *Miscanthus* compared with coal and peat electricity (a), and for gasified SRCW woodchip compared with coal electricity (b), according to variation in the price of coal and CO_2 allowances.

€60/t, and ETS allowance prices decreased to €5/t CO_2, direct and gasification co-firing of SRCW woodchip would generate electricity at respective discounted costs of €0.0205 and €0.0236/kWh_e higher than coal, whilst co-fired *Miscanthus* would generate electricity at a discounted cost of €0.0098/kWh_e higher than peat. If ETS allowance prices reach €40/t CO_2, then these respective cost differences are transformed into cost advantages of €0.005, €0.0019 and €0.0203/kWh_e generated by direct and gasified SRCW, and *Miscanthus*, respectively.

6.3.2 Heat-production costs

Table 6.4 and Fig. 6.3 display the NPV cost differences, annualised and expressed per kWh useful heat produced

Table 6.4. Discounted annual heating cost differences between SRCW woodchip heating and oil, gas and electric heating on an average household and small commercial (e.g. hotel) scale, over a 20-year time period.

€/annum cost difference		Household			Commercial		
		Oil	Gas	Electricity	Oil	Gas	Electricity
	€/GJ:	15.57	14.96	26.83	15.57	13.38	27.61
Biomass cost (€/t DM)							
€70	(5.58)	–403	–270	–849	–7,034	–4,721	–12,489
€100	(7.48)	**–277**	**–143**	**–722**	**–5,767**	**–3,454**	**–11,222**
€130	(9.38)	–150	–16	–596	–4,500	–2,188	–9,956
Biomass cost (subsidy) (€/t DM)							
€70	(5.58)	–613	–480	–1059	–7,409	–5,096	–12,864
€100	(7.48)	**–487**	**–353**	**–932**	**–6,142**	**–3,829**	**–11,597**
€130	(9.38)	–360	–226	–806	–4,875	–2,563	–10,331
Discount rate (subsidy)							
3%	(5.58)	–623	–468	–1,206	–7,500	–4,760	–14,106
5%	(7.48)	**–487**	**–353**	**–932**	**–6,142**	**–3,829**	**–11,597**
8%	(9.38)	–334	–223	–664	–4,611	–2,765	–8,811

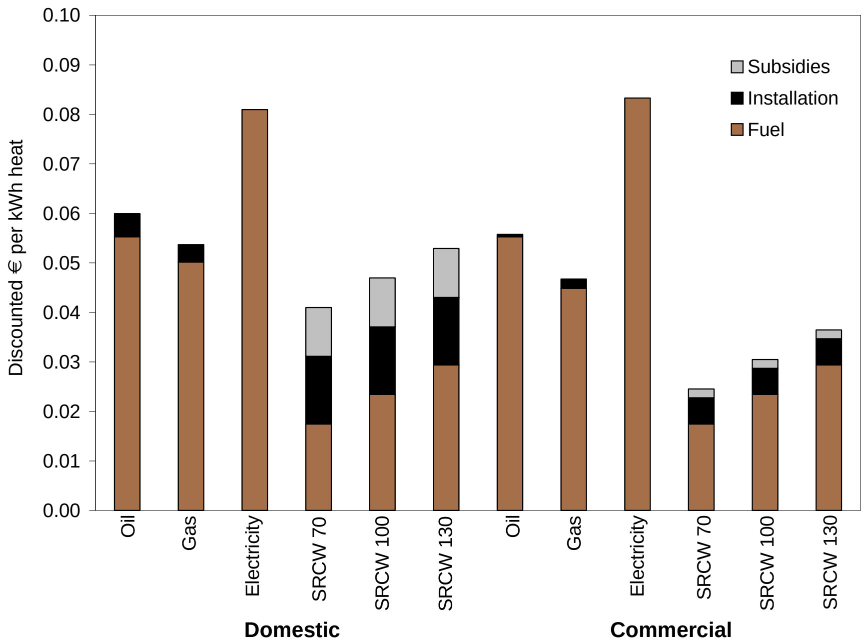

Figure 6.3. Heating costs for SRCW wood chips, at farm-gate prices of €70, €100 and €130/t DM, compared with oil, gas and electric heating, at the household and commercial scales, broken down into contributing elements (including subsidy cost reductions).

respectively, for wood heat compared with oil, gas and electricity. At a farm-gate price of €100/t DM, delivered woodchip energy is approximately half the price of oil and gas, and considerably less than one-third of the price of electricity, per unit energy content. After accounting for high woodchip boiler installation costs of €10,000, and without subsidies, wood heat remains considerably cheaper than the alternatives. Considered over a 20-year period (and with a 5% discount rate), the discounted annualised savings of wood heating compared with oil, gas, and electric heating are substantial, at €277, €143 and €722/annum, respectively. Including the available wood-boiler subsidy of €4,200 in the calculations increases discounted annual savings to €487, €353 and €932/annum, respectively. For the gas comparison, this represents a 147% increase in annualised wood heat cost reduction. These cost savings are moderately sensitive to the farm-gate woodchip price and the discount rate applied – reflecting the high capital investment costs – but wood heat remains competitive at a high farm-gate biomass price and high discount rate (Table 6.4). Figure 6.3 illustrates the small contribution of installation costs to overall fossil heating costs (4% and 7% for oil and gas, respectively), compared with the large contribution of installation to overall wood heating costs (44–57% depending on woodchip price), excluding subsidies and applying a 5% discount rate over 20 years.

In a domestic context, the competitiveness of wood heat is sensitive to oil and gas prices, and a fall in kerosene prices to €0.41/l delivered would result in wood heat losing its competitive advantage over oil heating, excluding subsidies (Fig. 6.4). Including installation subsidies reduces the kerosene break-even price to €0.31/l. Wood heat competitiveness is even more sensitive to gas prices, with break-even gas prices of €12.95 and €10.00/GJ energy content without and with wood heat subsidies, respectively (data not shown). The economic competitiveness of wood heat is also dependent on the annual heat demands required. Figure 6.5a displays the results of sensitivity analyses exploring the effects of varying annual heat demand on NPV savings for wood heat compared with oil, gas and electric heat at the domestic scale. Lower heat loads favour conventional heating systems with lower installation costs. In the absence of wood-boiler installation subsidies, NPVs for oil and gas heating break even with wood heating at heat loads of approximately 13,000 and 16,000 kWh_{th}/annum, respectively (approximately 60% and 75% of the 21,249 kWh_{th}/annum used in the standard calculations). Inclusion of the subsidies reduced these break-even heat loads to approximately 6,000 and 8,000 kWh_{th}/annum, respectively.

The discounted annualised reductions in heating costs possible from wood heat utilisation in commercial buildings are substantial, ranging from €3,454/annum compared with gas to €11,222/annum compared with electric heating, without installation subsidies (Table 6.4). When available installation subsidies are included in the

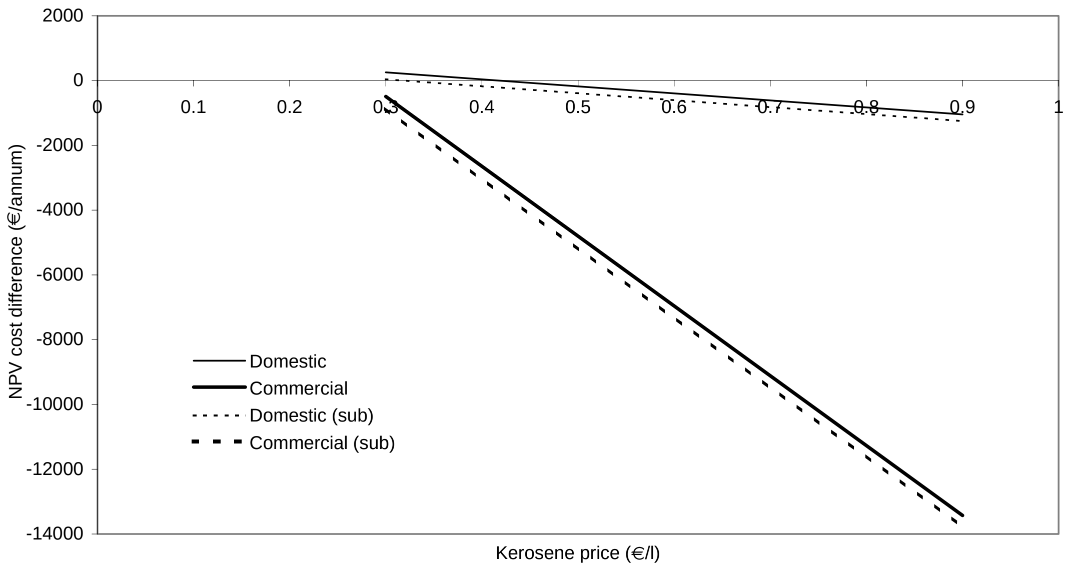

Figure 6.4. Sensitivity of NPV cost difference between wood heat and oil heat to oil price, at the domestic and commercial scales, with and without subsidies.

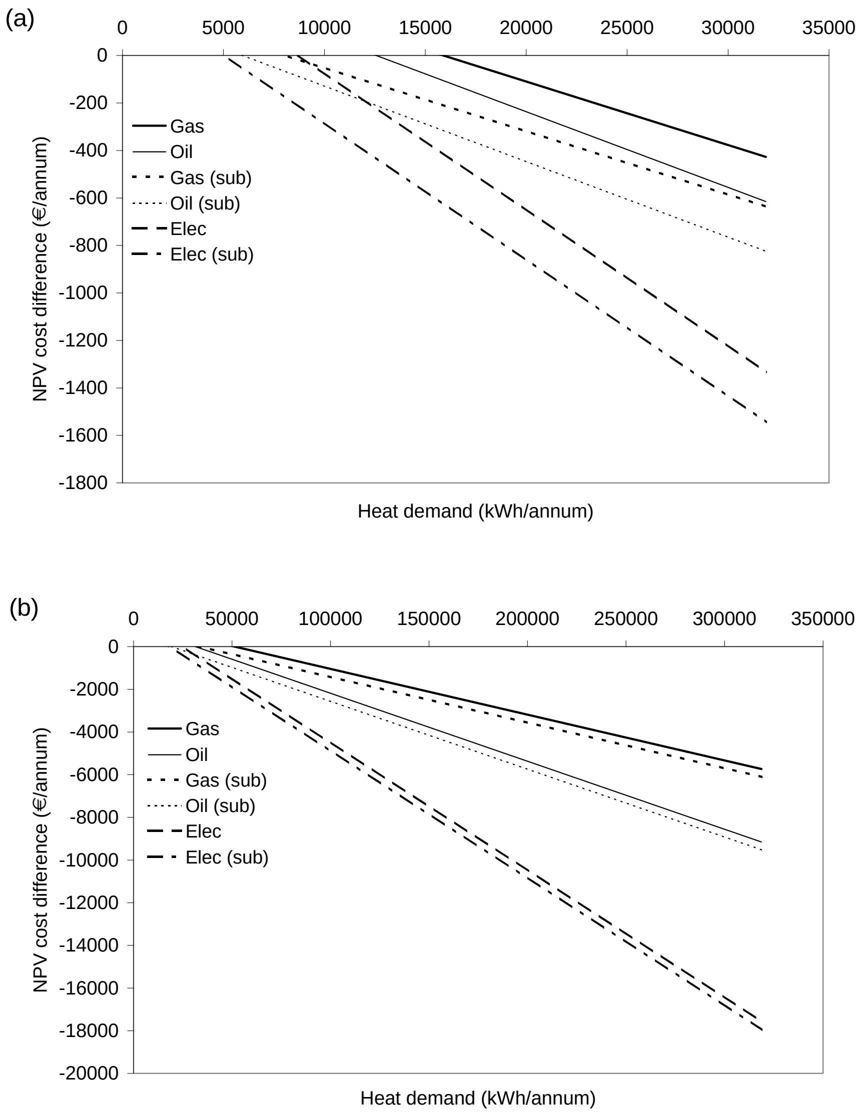

Figure 6.5. Sensitivity of NPV cost differences between wood heat and oil, gas and electric heat, with and without wood heat subsidies, on domestic (a) and commercial (b) scales.

calculations, savings increase to €3,829 and €11,597/annum, respectively. The relative importance of installation costs declines on a commercial scale, where they contribute between 19% and 29% of overall wood heat costs (Fig. 6.3), excluding subsidies and applying a 5% discount rate over 20 years. The economic competitiveness of wood heat is more robust at this scale, where heat from mid-cost energy-crop woodchip can be produced at half the cost compared with oil heat (Fig. 6.3). It remains competitive at a kerosene price of €0.30/l (Fig. 6.4) and a gas price of €8.6/GJ energy content, without subsidies. Figure 6.4 also indicates that the **magnitude** of savings is more sensitive to variation in oil and gas prices at the commercial scale, compared with the domestic scale, reflecting the lesser importance of installation costs at this scale. The results of sensitivity analyses exploring the effects of varying annual heat demand on NPV savings for wood heat compared with oil, gas and electric heat are displayed in Fig. 6.5b. On a commercial scale, wood heat remains cost competitive with oil, gas and electric heat down to heat loads in the region of 20,000–50,000 kWh_{th}/annum (9–24% of the 212,490 kWh/annum used in the standard NPV calculations).

6.4 Discussion

6.4.1 Electricity-generating costs

The model applied here to determine additional electricity-generating costs arising from energy-crop biomass is based on fuel costs, capital investment, and EU ETS CO_2

allowance costs. These should account for the major cost differences arising from the relatively straightforward process of biomass co-firing, which is a well-understood process ready for commercial exploitation and applied in numerous other countries (Tillman, 2000; Raskin *et al*., 2001; SEI, 2004; Baxter, 2005). However, there may be additional costs associated with operation and maintenance, particularly in the early stages of co-firing when combustion control may need to be adjusted and boilers are being carefully monitored. It is assumed here that any such costs are relatively minor compared with the major costs considered, and the model provides an indication of how fuel and CO_2 allowance prices will affect electricity-generating costs, and affect the comparative economics of biomass combustion. Following the decline in EU ETS CO_2 allowance prices, from a high of over €30/t in early 2006 to around €1/t now, and with futures prices at around €14/t, energy-crop biomass is not competitive with coal electricity, but is borderline competitive with subsidised peat electricity in Ireland. If coal prices remain stable, large and sustained increases in CO_2 allowance prices (to around €40/t) and/or high availability of low-cost biomass would be needed to make biomass co-firing in Moneypoint financially attractive to the ESB. A cheaper source of biomass, to prime demand for and complement energy-crop biomass supply, may be required in the first instance.

In contrast, there is a strong case for energy-crop biomass co-firing in the three new peat power stations. Even before considering GHG emissions and economic aspects, there is a need to find a substitute fuel to power the new generation of peat power stations for their remaining lifetimes whilst reducing the ecologically damaging extraction of finite and sensitive peat bogs. The first of the new peat power stations, Edenderry, has recently been purchased by the peat-supply company (Bord na Móna) which has obtained permission for the combustion of MBM, a free agricultural waste product, and woodchip. The real challenge for energy-crop biomass will be to find a niche among cheaper, but more quantitatively or geographically limited, sources of biomass such as MBM and forestry thinnings (see Section 8.2.1). At current EU ETS allowance prices, *Miscanthus* would only be cost competitive with peat if it were sold at a low farm-gate price of €70/t DM. At a mid-estimate farm-gate price of €100/t DM, ETS allowance prices would need to increase slightly to €16/t CO_2 for *Miscanthus* to become a competitive fuel. The price of extracted peat is unlikely to change dramatically into the near future, unless new legislation is introduced that disincentivises its extraction.

Ultimately, mid- to long-term ETS allowance prices will be highly dependent on EU GHG emission targets and legislation. With climate change moving up the European public and political agenda, and the prospect of a 20% GHG emission reduction by 2020 (relative to 1990) being written into EU legislation, it is likely that future ETS allowance prices will be buoyant, and at least exceed the value necessary to make energy-crop biomass a financially attractive fuel for peat power station operators. The financial case for co-firing energy-crop biomass in Moneypoint is best summarised as uncertain, with significant but not large additional electricity-generating costs likely in the short term. From a national perspective, subsidisation of the large upfront investment costs necessary for any significant degree of coal co-firing could easily be justified from the added benefits of energy-crop utilisation apparent on a national level (see Chapter 7).

6.4.2 Heat-production costs

Comparing the costs of heat production among different conventional sources and SRCW woodchip was more straightforward than electricity-generating comparisons, and associated with greater certainty. Irrespective of variation in farm-gate biomass prices applied here, and despite high transport costs applied, delivered energy-crop woodchip energy is significantly less expensive than oil, gas and electricity. Excluding subsidies, these lower fuel costs translated into substantially lower discounted annual heating costs for wood heat at the household scale. At the commercial scale, annual heat cost savings associated with wood heat are large, and wood heat is half the price of oil heat. When new subsidies are considered in the NPV calculations, the financial benefit of wood heat is increased significantly at the domestic scale, especially for oil and gas comparisons, where high wood-boiler installation costs contribute substantially to overall wood heat costs. At the commercial scale, available subsidies have a smaller effect, reflecting the lesser importance of installation costs at this scale. This scale effect highlights the huge potential for wood heat to realise large reductions in heating costs for large buildings, and through district heating schemes for new developments (perhaps also producing electricity in CHP plants).

The magnitude of the wood heat financial advantage is sensitive to oil and gas prices at the domestic, and especially the commercial, scale. However, there is considerable scope for oil and gas prices to fall before wood heat becomes more expensive than oil and gas heating, again especially at the commercial scale. Similarly, wood heat remains competitive with oil and gas heat at heat loads significantly lower than average household heat loads applied to calculations here, though the lower the heat load the smaller the saving. At the commercial scale, heat loads would need to be very low (approaching average household levels) before oil and gas heating become competitive. Thus, it can be concluded with a high degree of certainty that the economics of SRCW as a heating fuel are favourable compared with oil, gas and electricity at both the domestic, and especially the commercial, scale. Costed over the 20-year lifetime of boilers, and set against expectations of continuing high oil and gas prices, wood energy makes financial sense. However, the high boiler installation costs may still deter people (particularly at the household scale) from taking the longer view. The major effect of the available subsidies should be to increase uptake through reducing the initial outlay and thus reducing the payback period, in addition to the modest improvements in 20-year NPV calculations.

For completeness, the cost of electric heating was considered in this study, although it is expensive compared with the alternatives, especially wood heat. An 80:20 split between low-rate night-time and full-rate daytime consumption was assumed. In some commercial premises it may not be possible to exploit cheaper night-time heating, in which case electric heating will be more expensive than presented here (€38.99/GJ, assuming a typical 40:60 night/day split in electricity demand, compared with the €27.61/GJ applied in calculations here). However, premises currently utilising electric heating may require additional conversion costs, or new premises additional installation costs, for air or water heat distribution systems capable of utilising wood heat. Furthermore, the convenience and space-efficient nature of electric heating may command a price premium over alternative fuels. Nonetheless, the potential cost savings of wood heat compared with electric heat include scope for considerable additional wood heat expenses before the financial benefits are outweighed. An additional €14,500 and €224,000 could be spent on capital investment, for domestic and commercial premises, respectively, before the NPV of electric heating is exceeded by wood heat (under mid-cost estimates for woodchip, without installation subsidies, and applying a 5% discount rate). Electric heating systems are common in new apartment developments, where whole-building wood boilers could realise massive reductions in heating costs (these should be more than sufficient to overcome the additional administrative burden, and perhaps suspicion, of communal schemes to management and residents).

7 Putting it Together – A Cost–Benefit Overview of Energy Crops

7.1 Aims

The original aim of this project was to amalgamate data on the environmental, social and economic impacts of energy crops, and to apply environmental economic analyses in order to generate a full cost–benefit analysis for scenarios of energy-crop utilisation in Ireland. Ultimately, this ambitious task was not completed in the 1-year time frame of the project, but the most important aspects of it were. This chapter aims to consider the overall GHG emission savings alongside the estimated financial costs and benefits realised throughout the energy-crop fuel chains relative to conventional land uses and fuels. The indicative (non-optimised) scenario generated in Chapter 4 for national GHG emission savings is used for this. In addition to the economics of land use, electricity generation and heat production, the additional environmental effects are considered, in a quantitative manner where possible (from the LCA model). Thus, it is intended to calculate the cost-effectiveness of energy-crop utilisation as a GHG abatement strategy, and the contribution that energy-crop utilisation could make towards sustainable development.

7.2 Major Environmental and Economic Effects

7.2.1 A national indicative scenario

Life-cycle analysis data from Chapters 3 and 4, and financial data from Chapters 5 and 6 were amalgamated, to present national GHG emission savings and net financial cost/benefit arising from the component elements of the indicative national energy-crop utilisation scenario developed in Chapter 4 (Fig. 7.1). GHG and financial changes are presented on three levels: per hectare of changed land use, per total area of each specific land use displaced, and as a combined national total (Table 7.1). Financial returns are based on calculations for SRCW S1 (stick harvest) and *Miscanthus* B (baled harvest) gross margins relative to conventional land uses (the mid or less profitable supply strategies detailed in Chapter 5), and the net difference in electricity and heat-generation costs, excluding all subsidies, at a farm-gate biomass price of €100/t DM. Also included are data on total land applications of N, P and K (from fertiliser and livestock waste), and herbicide, and the additional transport t.km necessary for energy-crop utilisation (based on conservative assumptions of reduced sugar-beet and heating-oil transport associated with the indicative scenario).

For simplicity and clarity, the same scenario as developed in Chapter 4 is applied. This scenario was shaped by initial consideration of likely energy-crop deployment, but was not informed by later financial modelling results, which are likely to have a large bearing on farmer decisions. Therefore, it is not an optimised scenario for energy cropping. In particular, based on economic modelling presented in Chapter 5, SRCW is unlikely to displace dairy agriculture on a large scale. However, all models were based on data for average farm circumstances, and the economics for individual farms will vary according to their specific circumstances. Additionally, subsidies have not been considered in any of the calculations (with the exception of the EU-level, energy-crop-specific agricultural subsidy of €45/ha /annum), and neither have GHG and financial benefits associated with possible utilisation of wastes as fertilisers (e.g. SRCW WW treatment). The purpose of this scenario is to demonstrate the positive/negative balance and scale of overall impacts likely to accrue from energy-crop utilisation.

7.2.2 Cost-effective GHG emission abatement

Data presented in Table 7.1 indicate that the discounted financial benefits of cultivating *Miscanthus* in place of sugar beet (or set-aside) are significant, at €381/ha/annum, and outweigh the small additional cost of substituting peat with co-fired, mid-cost *Miscanthus* to generate electricity – equivalent to €47/ha/annum (based on a €0.0021/kWh cost difference). The discounted financial benefits of substituting cattle and sheep rearing with SRCW cultivation are modest, at €166/ha/annum, and if the woodchip produced is used to generate electricity through gasification co-firing at Moneypoint, the additional electricity-generating costs equivalent to €284/ha/annum would result in a net loss of €2.33

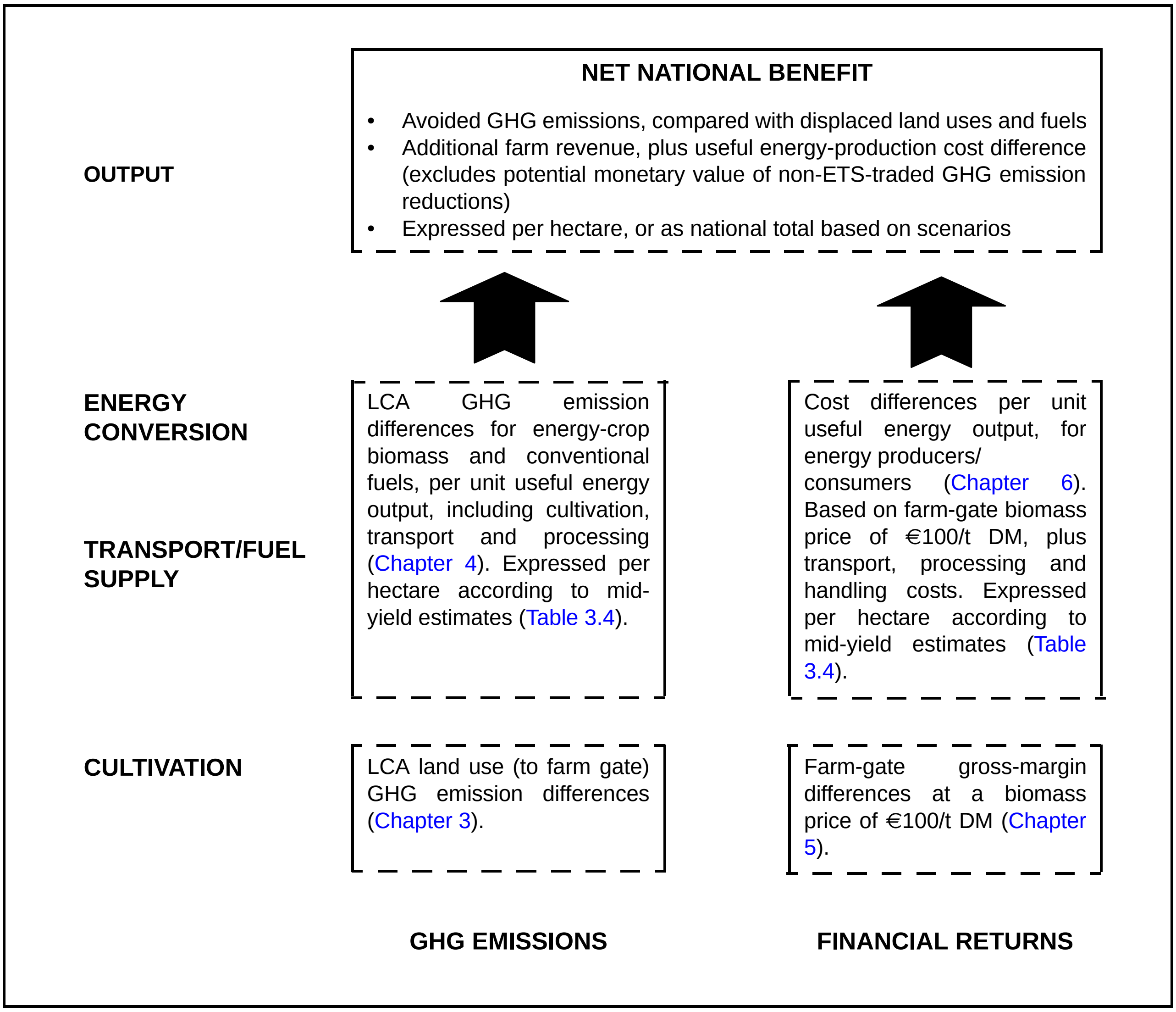

Figure 7.1. An overview of how energy-crop fuel chains were compared with displaced activities to quantify net national GHG and economic benefits.

million/annum for both the 19,794 ha areas of cattle and sheep rearing substitution. However, considering the large associated GHG emission reductions of 386 and 357 kt CO_2 eq./annum, these costs equate to CO_2 abatement costs of just €6 and €7/t, respectively. Replacing dairy with SRCW is not likely to be financially attractive for many farmers, and, combined with the additional electricity-generating costs associated with woodchip combustion in Moneypoint, would result in a total cost of €17.92 million attributable to the 19,794 ha dedicated to this purpose in the indicative national scenario. This would equate to a discounted CO_2 abatement cost of €34/t.

In contrast, utilising SRCW woodchip for heat production results in large financial benefits associated with heat production per hectare converted, equivalent to €574 and €1,107/ha/annum, based on scenario-specific set-aside and grassland woodchip end-use assumptions[20]. Combined with land-use conversion benefits of €264 and €295/ha/annum where SRCW is cultivated on set-aside and destocked grassland, respectively, these translate into substantial financial benefits of €30.71 and €102.75 million/annum for the 36,645 and 73,290 ha converted, respectively, in the indicative national scenario. The cumulative value of all land-use and energy-conversion assumptions is a net national discounted benefit of €122 million/annum, and a net GHG emission saving of 3.86 Mt CO_2 eq./annum (in addition to agricultural emissions savings attributable to subsidy reform). Thus, energy-crop cultivation and utilisation has the potential to generate

Table 7.1. The major environmental and economic consequences of conventional land-use and fuel substitution with energy crops (*Miscanthus* and SRCW), expressed on an area and national basis, according to the indicative national scenario described in Section 7.2.1, and based on a CO_2 allowance price of €14/t.

	Miscanthus	SRCW					Total
Displaced land use:	**Sugar beet**	**Dairy**	**Cattle**	**Sheep**	**Set-aside**	**Extensification**	
				(per ha per annum)			
Land use							
GHG emissions (kg)	–5,821	–10,722	–3,891	–2,405	–535	1,346	
Financial returns (€)	381	–622	166	166	264	295	
Energy conversion							
Additional elecricity cost (€)	47	284	284	284			
GHG emissions (kg)	–25,080	–15,623	–15,623	–15,623			
Additional heat cost (€)					–574	–1,107	
GHG emissions (kg)					–10,586	–16,890	
				Nationally per annum			
Area	33,784	19,794	19,794	19,794	36,645	73,290	**203,101**
Net GHG emissions	–1,044	–521	–386	–357	–408	–1,139	**–3,855**
Net financial difference (M€)	11.29	–17.92	–2.33	–2.33	30.71	102.75	**122**
CO_2 abatement cost (€/t)	–11	34	6	7	–75	–90	**–32**
Additional impacts[1]							
Additional lorry k t.km	0	10,924	10,924	10,924	16,760	36,983	**86,514**
Additional lorry return journeys	0	7,283	7,283	7,283	11,173	24,655	**57,676**
Additional total N applied (t)	–2,449	–5,606	–1,470	–1,305	2,040	4,081	**–4,709**
Additional total P applied (t)	–1,064	–510	–138	–119	446	893	**–492**
Additional total K applied (t)	–2,618	–2,685	–410	107	2,837	5,675	**2,906**
Additional pesticide applied (t)	–214	14	13	13	25	50	**–99**

[1]NB: The GHG emissions associated with 'Additional impacts' have been included in the above LCA data.

additional revenue, in addition to considerably reducing national GHG emissions. Further, the reduced reliance on imported fossil fuels (and possibly fertiliser) both improves security of fuel supply and the national balance of payments. Energy-crop utilisation also has the potential to help Ireland avoid future financial liabilities (carbon credit purchase), potentially totalling billions of euro, for failing to comply with legally binding Kyoto, and post-Kyoto, EU GHG emission targets. At €10/t, the 3.86 Mt CO_2 eq. saving would reduce Ireland's Kyoto exceedance liability by €39 million/annum (this could be added to the net benefit of the indicative national scenario).

Optimisation of energy-crop utilisation (including application of the more profitable supply strategies in Chapter 5) could substantially increase the net benefit of energy-crop utilisation, counteracting any negative impacts from additional costs not considered here (such as increased operation and maintenance at the power stations). For example, the application of WW treatment could increase SRCW returns by €563/ha/annum over those considered in the scenario, and this could translate into millions of euro of additional benefit if extrapolated to just a few thousand hectares. It is clear that focusing on heat production, especially at the larger scale (with the potential to utilise CHP for district heating schemes), would maximise the economic benefits of energy-crop utilisation. If the total area dedicated to energy-crop cultivation in the indicative national scenario was used only to grow SRCW for heat production, then the net discounted national benefit would be €227 million/annum (with an associated net GHG emission reduction of 3.46 Mt CO_2 eq./annum). Wood heat can easily be pursued at the household and commercial scales, but may require a degree of coercion or assistance for potentially cost-effective but logistically more complicated district and apartment block schemes.

It is important to note that the figures quoted are discounted, annualised financial returns over a period of approximately 20 years (discount periods range from 16 years for *Miscanthus* cultivation, through 20 years for heat and electricity generation, to 23 years for SRCW cultivation) based on a 5% discount rate. The critical assumptions on which this scenario is based are:

1. Average annual combustible yields of 8.8 and 11.7 t DM for SRCW and *Miscanthus*, maximum biomass productivity of 12 and 20 t DM/ha/annum, respectively
2. Discounted biomass-production costs of €46 and €48/t DM for SRCW and *Miscanthus*
3. Delivered fuel prices of €60/t for coal, €0.55/l for heating oil, and €0.0966/€0.0994 and €0.0539/€0.0482/kWh energy-content for domestic/commercial electricity and natural gas, respectively
4. An EU ETS CO_2 allowance value of €14/t
5. A farm-gate biomass price of €100/t DM; this determines the distribution of costs and benefits between producers (farmers) and consumers (energy producers), but is not critical for the overall net benefits.

Long-term ETS allowance prices are likely to be buoyant in response to increasingly rigorous EU GHG emission targets. Table 7.2 expresses the financial implications of a €40/t ETS CO_2 allowance price applied to the indicative national scenario. Whilst the heat-production scenarios are unaffected, the electricity-generating scenarios become positive, with energy-crop biomass co-fired with peat and coal generating net financial benefits of €374 and €32/ha/annum, respectively, in additional to the land-use substitution benefits (except where dairying is replaced). The net discounted national benefit increases to €155 million/annum. Applying a €5/t ETS allowance price decreases the discounted net national benefit to €110 million/annum.

7.2.3 Additional environmental effects

Large-scale energy-crop utilisation would have a multitude of additional impacts, and quantification of all of these is beyond the scope of this report. However, some of the major, more readily quantifiable, impacts are included in Table 7.1. These include reduced soil-nutrient application, reflecting efficient energy-crop nutrient cycling, and the displacement of livestock-waste emissions[21]. Slurry storage, and the quantities and timings of application, are issues of particular concern in Ireland in relation to water quality. Energy crops could both displace some of the livestock responsible for slurry production (e.g. 381 million l/annum slurry reduction from

20. Assume that woodchip grown on displaced set-aside land is used to displace equal quantities of oil and gas heating at the domestic and commercial scales, whilst woodchip grown on displaced grassland is used to displace equal quantities of oil, gas and electric heating at the domestic and commercial scales (Box 4.2).

Table 7.2. The major environmental and economic consequences of conventional land-use and fuel substitution with energy crops (*Miscanthus* and SRCW), expressed on an area and national basis, according to the indicative national scenario described in Section 7.2.1, and based on a CO_2 allowance price of €40/t.

	Miscanthus	**SRCW**					**Total**
Displaced land use:	**Sugar beet**	**Dairy**	**Cattle**	**Sheep**	**Set-aside**	**Extensification**	
				per ha per annum			
Land use							
GHG emissions (kg)	–5,821	–10,722	–3,891	–2,405	–535	1,346	
Financial returns (€)	381	–622	166	166	264	295	
Energy conversion							
Additional electricity cost (€)	–374	–32	–32	–32			
GHG emissions (kg)	–25,080	–15,623	–15,623	–15,623			
Additional heat cost (€)					–574	–1,107	
GHG emissions (kg)					–10,586	–16,890	
				Nationally per annum			
Area (ha)	33,784	19,794	19,794	19,794	36,645	73,290	**203,101**
Net GHG emissions (kt)	–1,044	–521	–386	–357	–408	–1,139	**–3,855**
Net financial difference (M€)	25.49	–11.68	3.91	3.91	31	103	**155**
CO_2 abatement cost (€/t)	–24	22	–10	–11	–75	–90	**–40**
Additional impacts[1]							
Additional lorry k t.km	24,629	6,591	6,591	6,591	12,203	24,406	**118,599**
Additional lorry return journeys	16,419	7,324	7,324	7,324	13,559	27,117	**79,066**
Additional total N applied (t)	–2,449	–5,606	–1,470	–1,305	2,040	4,081	**–4,709**
Additional total P applied (t)	–1,064	–510	–138	–119	446	893	**–492**
Additional total K applied (t)	–2,618	–2,685	–410	107	2,837	5,675	**2,906**
Additional pesticide applied (t)	–214	14	13	13	25	50	**–99**

[1]NB: The GHG emissions associated with 'Additional impacts' have been included in the above LCA data.

the dairy substitution scenario), and offer an environmentally sound disposal option for remaining slurry production (high transpiration rates and efficient nutrient uptake of SRCW). In total, national application/deposition of N and P would be decreased by 4,709 and 492 t/annum, respectively, and K application increased by 2,906 t/annum. Thus, the national nutrient balance of N and P (the two nutrients of greatest concern for freshwater quality) would be improved by energy-crop cultivation. Further benefits could arise from the use of WW, sewage sludge, and other wastes to fertilise energy crops (as they are non-food crops), simultaneously reducing emissions from fertiliser production and solving issues of waste disposal, nutrient requirements, and water requirements on drier soils (Perttu and Kowalick, 1997; Perttu, 1998). Alternatively, energy crops could be planted on buffer strips adjacent to vulnerable waterbodies, where compliance with the EU Water Framework Directive (2000/60/EC) may restrict conventional agricultural land uses. It may also be possible to reapply ash from biomass combustion, reducing the mining and international transport of fertiliser P and K.

Infrequent herbicide application for energy-crop establishment and severe cases of weed infestation, and occasional application of fungicide to SRCW, could result in increased pesticide use compared with grassland, although the assumption here of zero application on grassland is an underestimate. Much of the low herbicide application considered in LCA and production-cost calculations for *Miscanthus* and SRCW (averaging 0.42 and 0.63 kg/ha/annum active ingredient, respectively) could be substituted with environmentally superior harrowing (see Section 3.4.1). Compared with tillage crops such as sugar beet, pesticide use would be reduced substantially, and the net impact in the indicative national scenario is of a net decrease in pesticide application (Table 7.1). The major detrimental impact of large-scale energy-crop utilisation is likely to be increased lorry traffic, especially on supply routes to the central electricity-generating stations. Assuming a 30-t lorry carrying capacity (SEI, 2004) and an average transport distance of 50 km, the net increase in lorry traffic attributable to energy-crop utilisation would equate to a maximum of 86.51 million t.km/annum (57,676 return journeys annually). This assumes that *Miscanthus* transport equals displaced sugar-beet transport, that there was no transport associated with dairy-, cattle- and sheep-rearing systems, and that displaced oil use equates to a reduction in oil transport equivalent to 50 km/t delivered. For electricity generation, there may be potential to mitigate energy-crop transport impacts through utilisation of existing rail infrastructure (including the Bord na Móna light-rail peat-delivery system), or the canal and river network which passes all the power stations concerned.

Biodiversity has not been considered in detail in this report, but it is considered that the impact of the energy-crop scenario presented here would be neutral to positive. Negative biodiversity impacts could accrue from a reduction in grassland extensification, and possibly from low levels of pesticide application. Positive impacts could accrue from the introduction of different habitats, reduced nutrient applications, and overall reductions in grazing and tillage. Much will depend on the management and integration of energy cropping, but, given that up to 90% of current agricultural land (excluding forestry) is grassland, planting 5% with tall grasses and coppiced trees has the potential to improve overall biodiversity. Borjesson (1999b) and DEFRA (2001) attribute biodiversity improvements to SRCW and *Miscanthus* displacing tillage agriculture in Sweden and the UK, respectively, and in the UK *Miscanthus* is planted as a habitat for game birds. Borjesson (1999b) also attributed improved soil quality and reduced erosion to SRCW cultivation.

The overall impact of energy crops on emissions of acidifying gases and other pollutants to the atmosphere may be neutral to beneficial. Likely reductions in SO_x and NO_x from co-firing biomass in peat and coal power stations may be offset by potential increases in SO_x and hydrocarbon emissions where wood boilers displace gas boilers, and additional lorry-transport emissions. The final impact will depend on where these emissions occur (i.e. in densely populated, already polluted urban areas, or in sparsely populated rural areas where they will rapidly disperse). Advances in commercial biomass combustion technology will have an important bearing on these emissions in the future, with good prospects for large- and small-scale gasification to reduce emissions.

21. Total livestock-waste nutrient emissions are considered because although some of these will represent cycling from soil through grass, and subsequent animal, uptake, they nonetheless represent the surface deposition of readily available nutrients (often on wet soils) and thus increase nutrient run-off risk.

7.2.4 The global context

In Ireland, large areas of agricultural land are forecast to undergo destocking in response to the new decoupled EU CAP subsidies. Set-aside, destocked grassland, and also land that was used for sugar-beet cultivation (and may now be set-aside or used to grow other tillage crops), will be available for energy-crop utilisation, enabling farmers to generate additional income. According to the economic comparisons of land use presented in Chapter 5, energy-crop cultivation could offer farmers new, marketable products and further accelerate the move away from traditional livestock-rearing systems. Thus, the land-use substitution patterns outlined in the indicative national scenario, and associated GHG emission reductions, are plausible. Given historical overproduction stimulated by the EU CAP system, and the proportionately small displacement effects considered in the indicative national scenario (e.g. 3.5% of national dairy herd), little if any production (and GHG emission) displacement to other countries may be anticipated. However, Ireland exports livestock-derived products, and if larger livestock displacement were to occur, displacement effects to other countries would be likely, and the implications should be considered. In the context of a global market, it may make environmental sense to concentrate production in areas where LCA indicates that the environmental impacts per unit of product (inclusive of transport requirements and indigenous land-use displacement) are minimised. Whether Ireland is such an area for livestock production that could justify livestock export from an international GHG emission perspective is uncertain. A high proportion of peaty and gleyed soils, with elevated emissions to air and water, indicate that possibly it is not. This would support a shift towards more suitable crops such as SRCW and *Miscanthus*.

The potential for energy crops in Ireland may be almost uniquely good, owing to an ideal climate for wood growth, a large agricultural land area relative to the population size, and a small proportion of forested land. Internationally, the prospects for energy crops may be more restricted by pressure on productive land to feed a growing global population. Currently, there is concern over global demand for high-input crops such as corn for ethanol production, and rapeseed and oil palm for biodiesel production (the latter crop typically displaces ancient forest in Malaysia). Globally, it is important that any pressure on land resources arising from energy-crop utilisation is not translated into increased deforestation or food shortages for impoverished populations (both serious threats to sustainable development). In an ideal world, a sophisticated global market, reflecting social and environmental values, could be relied upon to efficiently allocate land use between energy- and food-production requirements. In reality, global utilisation of energy crops to reduce dependence on GHG-emitting fossil fuels will need to be carefully considered and managed. Developing countries may benefit from further reform of hitherto highly protected EU and US agricultural-product markets, although the contribution towards **sustainable** development will be highly dependent on institutional structures and governance in the producing countries – to ensure indigenous food requirements are met and environmentally damaging effects minimised. There are worrying indications that political expediency is encouraging inefficient biofuel utilisation strategies, with dubious environmental credentials (e.g. imported biodiesel produced from Malaysian palm oil in the EU; ethanol inefficiently produced from corn in the US). Conversion of wood and grass from well-managed, high-yielding, yet relatively low-impact, SRCW and *Miscanthus* into liquid biofuels and hydrogen, could solve many of the aforementioned issues. Commercialisation of the necessary conversion processes (e.g. enzymatic lignocellulosic digestion) should be prioritised over dependence on more energy-intensive and environmentally dubious liquid biofuel crops, within energy-crop utilisation and agricultural development strategies.

7.3 Policy Compliance

Within Ireland, energy crops could contribute substantially towards achieving legally binding Kyoto and post-Kyoto EU GHG emission targets. Rapid energy-crop establishment would be necessary if they are to contribute significantly towards compliance within the 2008–2012 Kyoto commitment period, and help to avoid hefty expenditure on national ETS allowances at the end of that period (when prices could be significantly inflated depending on the EU-wide demand/shortfall). In addition, energy-crop utilisation could help Ireland to comply with the following legislation and targets.

7.3.1 EU RES-E Directive (2001/77/EC)

Under this Directive, Ireland agreed a national indicative target of 13.2% final electricity consumption from renewables by 2010 (this target has since been increased to 15%, and 20% in 2020). These targets may be largely met by huge increases in wind generation in Ireland (Conlon *et al.*, 2006), but additional renewable electricity generation may require the baseload-production capability of biomass. Meanwhile, the 2010 EU target of 12% total energy consumption originating from renewables by 2010 will require biomass heat production. The EU White Paper (COM(95)682) and Green Paper (COM(2000)769) targeted biomass as the major renewable source for increase, contributing up to 74% of EU renewable energy.

7.3.2 EU Biofuels Directive (2003/30/EC)

The EU has biofuel market penetration reference targets of 2% for 2005 and 5.75% for 2010. These fuels are primarily derived from purpose-grown bioenergy crops such as oilseed rape. In the near future, new techniques to extract alcohols from woody material may be applied to the herbaceous energy crops studied in this report, to derive transport biofuels more efficiently, with lower life-cycle impacts, than at present.

7.3.3 EU Water Framework Directive (2000/60/EC) and EU Nitrates Directive (91/676/EEC)

The EU requirement for all waterbodies to be of good ecological status by 2015 under the Water Framework Directive, and the need to reduce maximum N-application rates in order to comply with the Nitrates Directive, will encourage less nutrient-demanding crops such as *Miscanthus* and SRCW. Furthermore, the tolerance of wet soils, high transpiration rates and nutrient-uptake efficiency exhibited by willow could actively reduce soil nutrient losses to water in vulnerable areas (i.e. SRCW could provide effective and profitable buffer zones) where conventional agricultural production should be avoided.

8 Barriers, Opportunities and Recommendations

8.1 Main Barriers to Energy-Crop Utilisation

- **The economics of energy-crop co-firing at Moneypoint:** Energy-crop co-firing is heavily dependent on EU ETS allowance prices to ensure profitability, and high initial capital investment costs for biomass gasification at Moneypoint require a long-term market certainty which currently doesn't exist, in addition to external financial assistance (e.g. government subsidy). Additionally, although GHG-intensive, coal is once again a favoured fuel for reasons of supply security and cost, and there may be a perception that co-firing could jeopardise the reliable supply of low-cost baseload electricity supplied by Moneypoint. The economics of peat co-firing are more promising due to high peat electricity-generating costs.

- **Existing peat-supply and electricity contracts:** Current 15-year guaranteed peat-supply contracts between the ESB and Bord na Móna, and the current Public Service Obligations (PSO) Levy structure, do not encourage co-firing. Current electricity-supply contracts ensure that high peat-generating costs are passed directly on to the electricity consumer through the PSO Levy, so there is consequently no incentive for peat electricity generators to limit their CO_2 liability.

- **RE-FIT:** Recently announced price support for renewable electricity generation (the RE-FIT scheme) provides inadequate financial incentive for biomass, and does not include co-firing uses.

- **High initial investment costs and uncertainty:** Both energy-crop cultivation and their use in energy generation require large upfront capital investment, and relatively long return periods to ensure profitability. Given current uncertainty about future agricultural revenue and fuel costs, investors may be cautious and unwilling to commit to energy crops. Recently announced energy-crop subsidies will reduce this risk (see Chapter 5), but only for a small number of farmers (1,400 ha in first year), inadequate to stimulate a new market.

- **Negative perception and reluctance to change:** Beyond the caution outlined above, there is often an inherent scepticism to alternative processes and products. Previous false dawns for renewable energy and recent acclimatisation to cheap, deregulated energy sources make this particularly true for energy supplies.

- **The requirement for co-ordination:** Market establishment of energy-crop cultivation as a large-scale profitable land use, and energy-crop biomass as a large-scale fuel source, both await one another's development into reliable consumers and producers in a classic 'chicken and egg' situation. SRCW cultivation may require co-operatives or contractors to purchase specialised harvest machinery[22]. The returns to private investors, although likely positive, are modest: appreciation of the full benefits of energy-crop fuel chains requires an interdisciplinary, societal perspective. Full appreciation of, and efficient stimulatory policy for, energy-crop utilisation will require close co-operation between the DCMNR and DAF. Co-ordination will also be required to optimise the logistics and economics of supply and utilisation chains for energy-crop biomass.

- **Lack of information:** Much work has been conducted in other countries, and some in Ireland, regarding energy-crop agronomics and economics. However, these data are currently not compiled in a readily accessible format, yet alone disseminated to farmers. Farmers firstly need to be made aware of the potential of energy crops, then advised on optimum management practices (e.g. adequate clone diversity in appropriate planting patterns) in order to avoid problems such as foliar rust in willow and to ensure maximum yields and profitability.

- **Availability of cheaper biomass supplies:** Whilst this report has indicated that energy-crop co-firing and heat production may be cost-competitive with conventional fuels, there are alternative, less-

22. Currently, the small areas of SRCW in the Republic of Ireland are chip-harvested, but the potential storage advantages of stick harvest may justify investment in new stick harvesters.

expensive sources of biomass that are likely to be preferentially used where available and feasible. These include forestry residue, pulpwood and sawdust, and a range of dry agricultural residues. For example, SEI (2004) indicates that, by 2010, approximately 82,000 t DM forestry residue could be supplied at a cost of approximately €55/t DM to power plants in Ireland. In addition, permission is being sought to co-fire MBM – an agricultural waste product supplied at no cost to the electricity generator – at the Edenderry power plant (Edenderry Power, 2006: http://www.edenderrypower.ie/). Nevertheless, these cheaper sources could just as easily prime a biomass market for exploitation by energy-crop biomass, which has greater spatial flexibility and ultimate supply potential (Section 8.2). Compared with more expensive oil and gas heating fuel, for example, there is potentially a huge market for biomass heating that would exhaust cheaper biomass supplies.

8.2 Opportunities for Energy Crops

8.2.1 Role alongside cheaper biomass sources

As outlined in this report, the decoupling of agricultural subsidies, high fuel prices, and CO_2 emission pricing, coupled with increasing pressure to reduce GHG emissions, present new opportunities for energy crops to be profitable for both producers and consumers. SEI (2006: http://www.sei.ie) has compiled information on a number of wood heat projects projected to save the commercial premises involved substantial sums of money. A few of these projects are summarised in Appendix B. Additionally, biomass co-firing at the Edenderry peat power station is being actively pursued. The forthcoming RE-FIT scheme, offering generators €0.072/kWh for biomass electricity, may provide some additional financial incentive for biomass (including energy-crop biomass), although co-firing is not eligible. The following points support the case for promotion of energy crops alongside cheaper biomass sources:

- Some of the wood-industry waste is currently used in other processes, such as panel-board manufacture, and competition for this waste could ultimately increase the price of this biomass for current users.

- Energy crops have the potential to supply substantially greater quantities of biomass on a planned, regular timescale and may be cultivated in locations to suit final consumption. For example, the quantity of forestry residues SEI (2004) forecast to be available by 2010 for energy purposes is equal to just 9,000 ha of SRCW (0.2% of agricultural land area).

- Energy crops offer additional and substantial benefits to farmers (Chapter 5), and when these are considered, energy crops offer greater total economic advantages compared with forestry biomass. This emphasises the need for multi-sectoral assessment. Ultimately, cheaper forestry and agricultural-waste biomass could be used to stimulate a wood heat or co-firing market, paving the way for more abundant energy-crop biomass as the market expands. These biomass sources must be regarded as complementary if substantial biomass energy is to be realised in Ireland. A good example is the current demand for imported wood pellets in Ireland, following strong uptake of wood-boiler installation grants leading to the supply capacity of indigenous pellets (supplied by Belcas in Northern Ireland) being exceeded.

8.2.2 Additional future utilisation pathways

The co-firing and heat-production scenarios listed here are based on utilisation of existing infrastructure and technology, and may be implemented relatively rapidly. However, there are a number of additional routes for more efficient and extensive future energy-crop utilisation, some of which are outlined below.

- ***Miscanthus* heat production:** Small-scale utilisation of *Miscanthus* will require pelleting, the economics of which will be dependent on future market development. In the shorter term, the higher yield and profitability potential of *Miscanthus* compared with SRCW could be maximised through utilisation in large-scale boilers to supply heat, perhaps via gasification (pilot trials would be needed to establish this).

- **Advanced, dedicated biomass electricity plants:** New power stations using biomass as their main fuel source could be built in suitable locations, close to energy-crop production. Emerging commercial technologies could be applied to build biomass integrated gasification/combined cycle (BIG/CC) power stations for example. These have the potential to utilise energy crops more efficiently, with net electrical-conversion efficiencies of over 50%, compared with 38% for co-firing, and cost-competitive electricity generation at the larger scale (>100 MW_e) (Faaij, 2006). Alternatively, gas produced from biomass gasification could be co-fired with natural gas in existing, efficient CC gas-turbine stations (e.g. Marbe *et al.*, 2006). Atmospheric emissions may be minimised through biomass conversion to gas prior to combustion. However, further development is required to address remaining problems such as efficient gas cleaning and turbine corrosion.

- **Combined heat and power (CHP):** New CHP plants could be built, ranging in scale from small plants in individual buildings (e.g. schools, hospitals, apartment blocks, office blocks) to centralised plants serving towns. Overall efficiencies of CHP plants can reach 90%[23], but they ideally require integration at the planning stage of development and may be costly to install retrospectively. Issues relating to the potential and feasibility of CHP are explored in a report written by the Irish Energy Centre (2001). Both advanced electricity-generating plants and CHP plants would minimise the net emissions arising from the production of useful energy from energy-crop biomass, though CHP could exploit the favourable economics of energy-crop heating. Also, by potentially supplying additional baseload electricity, they could complement wind power (and other non-constant renewable supplies) to maximise the proportion of renewable-electricity generation.

- **Lignocellulosic digestion and biofuel production:** With the trend towards higher liquid fuel prices, there is considerable scope for competitive production using lignocellulosic digestion techniques. Further development of new methods utilising enzymes to digest the lignocellulosic material prior to fermentation will enable sustainably produced solid energy crops (such as *Miscanthus* and SRCW) to be converted into liquid fuels at costs competitive with petrol and diesel, displacing transport-related GHG emissions. Faaij (2006) estimates that, if by-products are used for electricity generation, production of ethanol from wood could be achieved with an overall conversion efficiency of 60% and fuel costs of €4–7/GJ in the longer term (2020), and €12–17/GJ in the shorter term (compared with current, taxed petrol prices equivalent to approximately €28/GJ).

- **Gasification and hydrogen production:** Methane (~natural gas), methanol and hydrogen can be produced from gasification of biomass. Hamelinck and Faaij (2002) estimate that large-scale production of methanol and hydrogen may be achieved at efficiencies of 55% and 60%, respectively, and costs of €6.7–10/GJ now, and €4–6/GJ in the longer term. This fuel could be used for a multitude of purposes, from electricity generation to transport. It may also be possible to produce liquid biofuels sustainably and cost-competitively in Europe through gasification and pyrolysis techniques (Brammer *et al.*, 2006). Gasification of biomass may be conducted prior to direct (co-)firing in energy plants, or the syngas produced may be pumped directly into the gas supply network to reduce the overall CO_2 burden of natural gas consumers (up to specified mixing limits, this could avoid issues of syngas purity and avoid syngas cleaning problems).

- **Co-firing in modern 'clean-coal' power stations:** The projected economic competitiveness of coal compared with more limited oil and gas reserves has resulted in a focus on developing CO_2 sequestration techniques for application to coal combustion. Co-firing energy-crop biomass in such 'clean-coal' power stations could result in a net CO_2 sequestration effect (i.e. atmospheric CO_2 removal), offsetting other GHG emissions. To be economically viable, this CO_2 sequestration would need to be compensated for under future CO_2 allowance trading.

8.2.3 *Improved, low-cost cultivation*

There is currently a wide range of ongoing research aimed at improving energy-crop yields and decreasing production costs. For example, the Department of Agriculture and Rural Development (DARD) in Northern Ireland is successfully working to optimise genotype planting mixtures in SRCW plantations, in order to minimise the spread of foliar rust disease and maximise yields (McCracken *et al.*, 2006). Research is also being conducted to determine the potential of lay-flat planting techniques, where long willow rods are laid flat in soil grooves, saving time and money compared with conventional planting techniques where small billets are inserted individually and vertically into the soil. Similarly, the potential for whole-stem SRCW harvest and supply to

23. Maximum efficiency, but problems matching heat and electrical outputs with one another and with demand.

power stations is being assessed. This could reduce harvest costs, storage costs, and handling costs. Ongoing plant-breeding work will identify and amplify favourable characteristics, or engineer such characteristics through genetic manipulation. Dedicated energy cropping is relatively undeveloped, and future developments in breeding and management have the potential to significantly improve efficiency, environmental performance and profitability.

8.3 Feasibility

There are no technical limitations to the production and initial use of energy-crop biomass through either co-firing or heat production in woodchip boilers, as described in the indicative scenario. Specialised harvest machinery is necessary for SRCW, and the chip harvester currently used for the small areas of SRCW currently planted in Ireland will need to be supplemented with additional machinery, including stick harvester(s). The cost of this machinery (in the region of €250,000 for a harvester) will necessitate purchase by either contractors or farmer co-operatives. Co-firing is becoming well recognised as a feasible initial option for biomass utilisation in electricity generation (Tillman, 2000; Savolainen, 2003; Baxter, 2005). With co-ordinated effort and incentives, a scenario of 30% energy-crop biomass co-firing with peat could easily be implemented within 10 years. The main time restraint would be associated with energy-crop establishment, especially for SRCW where it takes 4 years after initial planting to obtain the first harvest, and 7 years to obtain the first maximum-yield harvest. In Sweden, 15,000 ha of land were planted with SRCW over a period of 6 years during the early 1990s in response to generous planting subsidies and an optimistic outlook for energy crops. However, this initial expansion was not continued for a number of reasons, including the absence of long-term incentives, inappropriate planting locations, and insufficient guidance/adherence to optimum agronomic practices, as revealed in an extensive survey of Swedish farmers (Helby *et al.*, 2006). The same survey indicated that although farmers are generally content with the economics of willow production, willow market potential is restricted by competition with the dominant wood-fuel supplies from vast forests covering 66% of Sweden's land area. This latter point would be less of an issue in Ireland, where less than 9% of land area is covered by forest.

Modifications required for co-firing at the peat power stations would be minor, relating to fuel handling, and Edenderry Power is actively pursuing a strategy to co-fire up to 50% of energy input with biomass from agricultural wastes and wood. Energy crops could provide a reliable, proximate source of biomass within this strategy. Significant (>10%) co-firing at Moneypoint coal station is likely to require substantial investment in gasification facilities (SEI, 2004), and will therefore require greater incentives.

The geographic potential for energy-crop production in Ireland has not been assessed in this report, though van den Broek *et al.* (2001) refer to a map of willow yield potential in Ireland, and Clifton-Brown *et al.* (2000) model theoretical *Miscanthus* yields across Ireland. However, given that the scenario presented in this report requires just 4.7% of Ireland's agricultural land, and that Ireland has an ideal climate for wood growth, it seems reasonable to assume that geographical potential should not be a limiting factor, although there is a need for work to identify the optimum planting locations for energy crops with respect to both yield potential, proximity to end-users in relation to transport logistics, and, ultimately, economics. In the instance of SRCW co-firing at Moneypoint, the 59,381 ha of SRCW cultivation required would amount to approximately 25% of the land within a 50 km (inland) radius of the plant, though this could be reduced to less than 15% if transport across the Shannon estuary was economically viable (and 11% if, alternatively, the gasification feedstock was supplied by 44,968 ha of *Miscanthus*). Water-based transport of energy-crop biomass has not been considered in this study. Given that the major power stations are adjacent to coastal or inland waterbodies, and the potential for SRCW (and perhaps *Miscanthus*) to provide nutrient buffer zones close to watercourses, there may be potential for utilising Ireland's extensive river and canal network for cost-effective transport over distances greater than 50 km. This may merit further investigation.

8.4 Recommendations

- **Set up an energy-crop advisory service for farmers:** This could be incorporated into the existing Teagasc agricultural advisory network. Detailed, Ireland-specific guidelines should be devised, based on the results of energy-crop trials aimed at identifying the influence of factors such as soil characteristics, fertiliser application, planting density and variety on yield and profitability. Fresh attempts at cultivating SRCW and *Miscanthus* on cutaway peatland would be of interest if energy crops are to be co-fired in peat power stations. It is important that accurate advice is given from the outset, with due consideration of logistics and market demand, to minimise negative experiences.

- **Establish a nationally recognised biomass fuel certification scheme, to ensure consumer confidence and boiler reliability:** For example, only high-quality woodchip (i.e. less than 30% moisture content and nominal particle size of 8–15 mm; Kofman, 2006b) can be used in small-scale domestic boilers. Farmers or intermediate suppliers would need to ensure adequate fuel preparation. A range of fuel quality standards could be sold at different prices (as implied in Chapter 5 supply strategy revenues).

- **Extend recently announced planting subsidies:** Notwithstanding enhanced long-term revenues, the high up-front investment costs associated with energy-crop cultivation are a deterrent to farmers. The recently announced scheme, applicable to 1,400 ha in the first year, needs to be extended if a reliable supply of biomass is to stimulate a significant end-user market.

- **Long-term regulatory and financial stimulus of biomass electricity:** Energy-crop co-firing to generate electricity is close to financial competitiveness in the new peat power stations and, in the longer term, commercialisation of current technology (e.g. BIG/CC) and high costs associated with CO_2 emissions may make energy crops a competitive electricity source. However, to ensure timely incentivisation of the required capital investment for biomass utilisation (and associated cost-effective GHG emission abatement), financial support should be offered within a transparent, long-term framework. This support should be specifically targeted at (energy-crop) biomass (in the UK Renewable Obligation Certificates (ROCs) scheme, a minimum energy-crop component to biomass is stipulated – see Drax example, Appendix B). This could involve an extension of the RE-FIT scheme to specify an energy-crop component of biomass, and higher guaranteed prices (the €0.072/kWh currently offered is low compared with best-new-entrant estimates of €0.0864/kWh for natural gas power stations). In the absence of such targeted support, there is a danger that competition from the most commercially developed renewable sources (i.e. wind generation in Ireland) will delay the development and market penetration of complementary renewable sources with good near-term potential.

- **Devise a long-term, government strategy for biomass energy:** The multi-sectoral opportunities presented by biomass energy and energy crops, and the need for both inter-sectoral and inter-departmental (especially DCMNR and DAF) co-ordination, requires an integrated approach to development and stimulation. A government-commissioned working group, including members from all the government departments and sectors involved, should be set up to look at optimum development routes, including logistical considerations regarding integrated supply strategies.

9 Conclusions

Energy-crop utilisation could contribute substantially to GHG emission reductions in Ireland, through displacement of less profitable conventional agriculture and associated emissions, through displacement of conventional peat and fossil-fuel energy sources, and through soil C sequestration. In the indicative scenario developed here, utilisation of SRCW and *Miscanthus* grown on just 4.7% of agricultural land was estimated to reduce national GHG emissions by 3.86 Mt CO_2 (5.6% of Ireland's 2004 emissions).

Discounted production costs for SRCW and *Miscanthus* biomass to the farm gate were calculated at €46 and €48/t DM (over the 23- and 16-year plantation lifetimes). At farm-gate biomass prices of €100/t DM, farmers could realise discounted annual gross margins of €211 to €383/ha, competitive with most current agricultural land uses under the single farm payment scheme. Use of SRCW to treat WW could return discounted gross margins of up to €833/ha/annum. The harvest and supply strategy (e.g. chipped or stick SRCW harvest, chopped or baled *Miscanthus* harvest) has a significant impact on production costs, and should be optimised according to end-user requirements. This becomes more critical at low farm-gate biomass prices of €70/t DM, when energy crops return low (yet still competitive) discounted gross margins of €33–167/ha/annum. Recently announced establishment and maintenance subsidies could increase mid-estimates of discounted gross margins to between €327 and €527/ha/annum.

At a farm-gate biomass price of €100/t DM, energy-crop biomass could be used to generate electricity at a discounted cost just €0.0021/kWh_e higher than peat if co-fired in peat power stations, and with minimal capital investment requirements. If co-fired with coal at Moneypoint, SRCW woodchip could generate electricity at a discounted cost €0.0139/kWh_e higher than coal at 5% co-firing, and at a cost €0.017/kWh_e higher than coal if the wood is gasified prior to combustion. The latter option would be necessary for co-firing above 10%, and would require €60 million of capital investment. These values depend on EU ETS permit prices of €14/t. If biomass was supplied at a farm-gate price of €70/t DM (realising respectable farmer returns under the new energy-crop subsidy system) direct and gasified co-fired biomass could produce electricity at discounted costs just €0.0022 and €0.0053/kWh_e higher than coal. The use of SRCW woodchips in domestic boilers for heat production could result in significant heating-bill reductions, ranging from €143/annum compared with gas, to €277/annum compared with oil, and to €722/annum compared with electricity (discounted). At the small commercial scale, these reductions become substantial, at €3,454, €5,767 and €11,222/annum compared with gas, oil and electric heating, respectively. At this scale, wood heat is less than half the cost of oil heat after additional capital investment costs are considered. The new wood-boiler subsidies of up to €4,200 per household further improve the financial advantage of wood heat compared with oil, gas and electric heating at the domestic scale.

All the aforementioned additional costs and benefits of energy-crop utilisation (relative to displaced activities) were extrapolated to a national scale in a non-optimised, indicative scenario. Stick-harvest SRCW and baled *Miscanthus* production were considered, and consequent gross margins at €100/t DM price compared against those for dairy, cattle rearing, sheep rearing, sugar-beet production, set-aside and grassland extensification, to calculate land-use change profitability. The net financial consequences of 30% *Miscanthus* co-firing with peat, 15% SRCW co-firing with coal, and displacement of oil, gas and electric heating with SRCW woodchip in 7.5% of households, and an equal displacement in commercial premises, were also calculated. In total, alongside the 3.86 Mt CO_2 eq. GHG emission reduction, and despite significant financial losses from SRCW co-firing with coal and displacement of dairy agriculture, the net ~20-year-discounted financial benefit was calculated at €122 million/annum. This value excluded both subsidies available for energy-crop utilisation and potential additional incomes from WW treatment, and could be increased substantially if more profitable cultivation to consumer chains were pursued. Thus, in current market circumstances, energy crops offer a modestly profitable route to GHG emission reductions, and those pathways involving additional cost (SRCW co-firing with coal) offer cost-effective GHG abatement options.

Additional environmental impacts predicted for the indicative scenario include reduced soil nutrient loading, improved soil quality, and possibly enhanced biodiversity, set against an increase in lorry traffic. National fuel security would be improved, whilst rural areas would receive an income boost and some job creation.

If current market circumstances prevail, energy crops could prove highly beneficial to Ireland, but full appreciation of these benefits requires a long-term, broad view that considers the multiple sectors involved. The future potential for energy crops extends beyond the initial co-firing and heat-production options detailed here, and involves higher efficiency gasification and CHP applications, in addition to liquid fuel production. By potentially contributing to baseload energy supply, energy crops offer additional benefits, and a complementary resource, to less constant renewable electricity sources such as wind. Some government financial assistance, and perhaps coercion, is necessary to encourage investment in, and commitment to, energy-crop infrastructure and utilisation. This is justified on the basis that:

- Modest net financial returns for growers (and potentially peat electricity generators) may not be sufficient to overcome the perceived risk of relatively high establishment costs
- Whilst the overall net financial returns of energy-crop cultivation to electricity fuel chains could be positive (e.g. *Miscanthus* grown on set-aside and co-fired with coal), the electricity-generation part of the chains may incur a net cost
- Where net financial costs are incurred over the entire fuel chain, GHG abatement costs are predicted to be low.

The economics of energy-crop cultivation to heat-production chains are positive and robust throughout. These benefits could be maximised through economies of scale if district heating schemes were encouraged in new developments, perhaps utilising CHP generators to increase biomass-electricity penetration. Simple information dissemination may also help to overcome negative perceptions of energy-crop utilisation. An integrated government strategy, co-ordinating the multiple sectors involved, would greatly assist the efficient implementation of energy-crop utilisation in Ireland. The good energy balances and environmental performance of *Miscanthus* and willow suggest that these energy crops should be prioritised over more energy-intensive and environmentally damaging liquid biofuel crops.

References

Albertazzi, S., Basile, F., Brandin, J., Einvall, J., Hulteberg, C., Fornasari, G., Rosetti, V., Sanati, M., Trifiro, F. and Vaccari, A., 2006. The technical feasibility of biomass gasification for hydrogen production. *Catalysis Today* **106:** 297–300.

Andersen, R.S., Towers, W. and Smith, P., 2005. Assessing the potential for biomass energy to contribute to Scotland's renewable energy needs. *Biomass and Bioenergy* **29:** 73–82.

Baxter, L., 2005. Biomass-coal co-combustion: opportunity for affordable renewable energy. *FUEL* **84:** 1295–1302.

Bayerische Landesanstalt für Landwirtschaft, 2000. *Examination of Various Cultivation Techniques for* Miscanthus giganteus *for Improving Young Plants' Ability to Survive the Winter as well as for Reducing the Costs of Setting Up Crop Stands*. Institut für Pflanzenbau und Pflanzenzuchtung, Giessen, Germany.

Behan, J. and McQuinn, K., 2002. Projecting net greenhouse gas emissions from Irish agriculture and forestry. *In: The Sky's the Limit: Efficient and Fair Policies on Global Warming.* pp. 18. Teagasc Agriculture and Food Development Authority, Dublin, Ireland.

Binfield, J., Donnellan, T., Hanrahan, K., Westhoff, P., 2003. *The Luxembourg CAP Reform Agreement: Implications for EU and Irish Agriculture*. Teagasc, Dublin, Ireland. pp. 1–79.

Borjesson, P., 1999a. Environmental effects of energy crop cultivation in Sweden – I: Identification and quantification. *Biomass and Bioenergy* **16:** 137–154.

Borjesson, P., 1999b. Environmental effects of energy crop cultivation in Sweden – II: Economic valuation. *Biomass and Bioenergy* **16:** 155–170.

Boyd, J., Christersson, L. and Dinkelbach, L., 2000. *Energy from Willow.* Scottish Agricultural College, Edinburgh, UK.

Brammer, J.G., Lauer, M. and Bridgewater, A.V., 2006. Opportunities for biomass-derived "bio-oil" in European heat and power markets. *Energy Policy* **34:** 2871–2880.

Breen, J. and Hennessy, T., 2003. The impact of the MTR and the WTO reform on Irish farms. *In:* O*utlook 2003, Medium Term Analysis for the Agri-Food Sector*. (conference proceedings). Teagasc, Dublin, Ireland. pp. 78–92.

Bullard, M. and Metcalf, P., 2001. *Estimating the Energy Requirements and* CO_2 *Emissions of the Perennial Grasses Miscanthus, Switchgrass and Reed Canary Grass*. Energy Technology Support Unit, Harwell, UK.

Casey, J.W. and Holden, N.M., 2004. Analysis of greenhouse gas emissions from the average Irish milk production system. *Agricultural Systems* **86:** 97–114.

CER, 2006a. *Direction to ESB Power Generation on Allowable Costs for 2007*. CER/06/203, Dublin.

CER, 2006b. *Direction to ESB PES on Tariffs to apply from 1st January 2007*. CER/06/252, Dublin.

Clifton-Brown, J.C., Neilson, B., Lewandowski, I. and Jones, M.B., 2000. The modelled productivity of *Miscanthus* x *giganteus* (GREEF et DEU) in Ireland. *Industrial Crops and Products* **12:** 97–109.

Clifton-Brown, J.C., Stampfl, P.F. and Jones, M.B., 2004. Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Global Change Biology* **10:** 509–518.

Conlon, M.F., Basu, M., Jayanti, N.G. and Gaughan, K., 2006. A survey of the installed wind generation capacity in Ireland. p. 55 in: *Conference Proceedings for Renewable Energy in Maritime Climates*. DIT Bolton Street, Dublin, Ireland. 26–28 April 2006.

Connolly, D. and Rooney, S., 1997. *A Study of the Environmental Impacts of the Generation of Electricity at the Europeat 1 and Moneypoint Powerstations.* Environmental Institute, University College Dublin, Dublin, Ireland.

Connolly, L., Kinsella, A. and Quinlan, G., 2004. *National Farm Survey 2003*. Report No. ISBN 1-84170-365–6. Teagasc, Dublin, Ireland.

Connolly, L., Kinsella, A. and Quinlan, G., 2005. *National Farm Survey 2004*. Report No. ISBN 1-84170-405-9. Teagasc, Dublin, Ireland. Available online at http://www.teagasc.ie/publications/2004/20060119.htm#_INTRODUCTION.

Coulter, B.S., Murphy, W.E., Culleton, N., Finnerty, E. and Connolly, L., 2002. *A Survey of Fertiliser Use in 2000 for Grassland and Arable Crops*. Report No. RMIS 4729. Teagasc, Dublin, Ireland.

Culleton N., Murphy, W.E. and Coulter, B., 1999. *Lime in Irish Agriculture*. The Fertilizer Association of Ireland, Dublin, Ireland.

Dalgaard, T., Halberg, N. and Porter, J.R., 2001. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture, Ecosystems and Environment* **87:** 51–65.

DEFRA, 2001. *Planting and Growing Miscanthus.* Report No. 5424. DEFRA, London, UK.

DEFRA, 2002. *Growing Short Rotation Coppice*. Report No. 7135. DEFRA, London, UK.

DEFRA, 2006. *Establishment Costs for Energy Crops in England*. http://www.defra.gov.uk/farm/acu/pdf/cambridge-estabcosts.pdf (accessed April 2006).

Dobbie, K.E., McTaggart, I.P. and Smith, K.A., 1999. Nitrous oxide emissions from intensive agricultural systems: variations between crops and seasons, key driving variables, and mean emission factors. *Journal of Geophysical Research* **104:** 26891–26899.

Donnellan, T. and Hanrahan, K., 2003. *Greenhouse Gas Emissions from Irish Agriculture*. Teagasc, Dublin, Ireland.

Dornburg, V., Termeer, G. and Faaij, A.P.C., 2005. Economic and greenhouse gas emission analysis of bioenergy production using multi-product crops – case studies for the Netherlands and Poland. *Biomass and Bioenergy* **28:** 454–474.

El Bassam, N., 1998. *Energy Plant Species: their Use and Impact on Environment and Development.* James and James, London, UK.

Elsayed, M.A. and Mortimer, N.D., 2001. *Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates*. Report No. ETSU B/U1/00644/REP. Sheffield Hallam University, Sheffield, UK.

Elsayed, M.A., Matthews, R. and Mortimer, N.D., 2003. *Carbon and Energy Balances for a Range of Biofuels Options*, Report No. B/B6/00784/REP. Sheffield Hallam University, Sheffield, UK.

Ericsson, K., Huttunen, S., Nilsson, L.J. and Svenningsson, P., 2004. Bioenergy Policy and market development in Finland and Sweden. *Energy Policy* **32:** 1707–1721.

Ericsson, K., Rosenqvist, H., Ganko, E., Pisarek, M. and Nilsson, L., 2006. An agro-economic analysis of willow cultivation in Poland. *Biomass and Bioenergy* **30:** 16–21.

Faaij, A., 2006. Bio-energy in Europe: changing technology choices. *Energy Policy* **34:** 322–342.

Flessa, H., Ruser, R., Dorsch, P., Kamp, T., Jimenez, M.A., Munch, J.C. and Beese, F., 2002. Integrated evaluation of greenhouse gas emissions (CO_2, CH_4, N_2O) from two farming systems in southern Germany. *Agriculture, Ecosystems and Environment* **91:** 175–189.

Gigler, J.K., Meerdink, G. and Hendrix, E.M.T., 1999. Willow supply strategies to energy plants. *Biomass and Bioenergy* **17:** 185–198.

Gigler, J., van Loon, W.K.P., Vissers, M.M. and Bot, G.P.A., 2000. Forced convective drying of willow chips. *Biomass and Bioenergy* **19:** 259–270.

Gigler, J.K., van Loon, W.K.P. and Sonneveld, C., 2004. Experiment and modelling of parameters influencing natural wind drying of willow chunks. *Biomass and Bioenergy* **26:** 507–514.

Gilliland, J., 2005. Willow woodchip production potential in Ireland. Presentation in the *Renewable Energy Opportunities for Biofuel Crops* conference. July 11th 2005. Kildare, Ireland.

Goor, F., Jossart, J.M. and Ledent, J.F., 2000. ECOP: an economic model to assess willow short rotation coppice global profitability in a case of small scale gasification pathway in Belgium. *Environmental Modelling & Software* **15:** 279–292.

Grigal, D.F. and Berguson, W.E., 1998. Soil carbon changes associated with short rotation systems. *Biomass and Bioenergy* **14:** 371–777.

Gustavsson, L. and Karlsson, A., 2002. A system perspective on the heating of detached houses. *Energy Policy* **30:** 553–574.

Hamelinck, C.N. and Faaij, A.C.P., 2002. Future prospects for production of methanol and hydrogen from biomass. *Journal of Power Sources* **111:** 1–22.

Hanegraaf, M., Biewinga, E.E. and van der Bijl, G., 1998. Assessing the ecological and economic sustainability of energy crops. *Biomass and Bioenergy* **14:** 345–355.

Hansson, P.-A., Dahlin, B. and Blinge, M., 2003. Air emissions from the fuel supply system of a Swedish CHP plant and the effects of stricter emissions regulations. *Biomass and Bioenergy* **24:** 59–68.

Harrison, R.M., Yamulki, S., Goulding, K.W.T. and Webster, C.P., 1995. Effect of fertiliser application on NO and N_2O fluxes from agricultural fields. *Journal of Geophysical Research* **100:** 25923–25931.

Hartmann, D. and Kaltschmitt, M., 1999. Electricity generation from solid biomass via co-combustion with coal: Energy and emission balances from a German case study. *Biomass and Bioenergy* **16:** 397–406.

Heaton, R.J., Randerson, P.F. and Slater, F.M., 1999. The economics of growing short rotation coppice in the upland area of mid-Wales and an economic comparison with sheep production. *Biomass and Bioenergy* **17:** 59–71.

Heaton, E.A., Clifton-Brown, J., Voigt, T.B., Jones, M.B. and Long, S.P., 2004. Miscanthus for renewable energy generation: European Union experience and projections for Illinois. *Mitigation and Adaptation Strategies for Global Change* **9:** 433–451.

Helby, P., Rosenqvist, H. and Roos, A., 2006. Retreat from Salix – Swedish experience with energy crops in the 1990s. *Biomass and Bioenergy* **30:** 422–427.

Heller, M.C., Keoleian, G.A. and Volk, T.A., 2003. Life cycle assessment of a willow bioenergy cropping system. *Biomass and Bioenergy* **25:** 147–165.

Howley M., O'Leary F. and Ó Gallachóir B.P., 2006 *Energy in Ireland 1990–2004: Trends, issues, forecasts and indicators.* Report published by Sustainable Energy Ireland 06-EPSSU-001-R/01 (http://www.sei.ie/getFile.asp?FC_ID=1067&docID=68).

IPCC, 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* UK Meteorological Office, Bracknell, UK.

IPCC, 2001. Chapter 6: Radiative Forcing of Climate Change. *In:* IPCC. *Climate Change 2001: The Scientific Basis.* http://www.grida.no/climate/ipcc_tar/wg1/248.htm (Accessed September 2007). IPCC, Geneva, Switzerland.

Irish Energy Centre, 2001. *An Examination of the Future Potential of CHP in Ireland.* A report prepared for public consultation. Irish Energy Centre, Dublin, Ireland.

Jones, M.B. and Walsh, M., 2001. *Miscanthus: for Energy and Fibre* James and James, Ltd., London, UK.

Jug, A., Makeschin, F., Rehfuess, K.E. and Hofmann-Schielle, C., 1999. Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. III. Soil ecological effects. *Forest Ecology and Management* **121:** 85–99.

Kofman, P.D., 2006a. *Harvesting Wood for Energy from Early First Thinnings.* Harvesting/Transportation No. 3. COFORD, Dublin, Ireland.

Kofman, P.D., 2006b. *Quality Wood Chip Fuel.* Harvesting/Transportation No. 6. COFORD, Dublin, Ireland.

Kuesters, J. and Lammel, J., 1999. Investigations of the energy efficiency of the production of winter wheat and sugar beet in Europe. *European Journal of Agronomy* **11:** 35–43.

Lane, M., 2004. *Quarterly Review of the Irish Electricity Market.* Eirgrid, Dublin, Ireland.

Leahy, P., Kiely, G. and Scanlon, T., 2004. Managed grasslands: A greenhouse gas source or sink? *Geophysical Research Letters* **31:** L20507.

Lewandowski, I. and Heinz, A 2003. Delayed harvest of Miscanthus – influences on biomass quantity and quality and environmental impacts of energy production. *European Journal of Agronomy* **19:** 45–63.

Lewandowski, I., Kicherer, A. and Vonier, P., 1995. CO_2-balance for the cultivation and combustion of Miscanthus. *Biomass and Bioenergy* **8:** 81–90.

Lewandowski, I., Clifton-Brown, J.C., Scurlock, J.M.O. and Huisman, W., 2000. Miscanthus: European experience with a novel energy crop. *Biomass and Bioenergy* **19:** 209–227.

Londo, M., Vleeshouwers, L., Dekker, J. and de Graaf, H., 2001. Energy farming in Dutch dessication abatement areas: yields and benefits compared to grass cultivation. *Biomass and Bioenergy* **20:** 337–350.

Maag, M. and Vinther, F.P., 1996. Nitrous oxide emissions by nitrification and denitrification in different soil types and at different moisture contents and temperatures. *Applied Soil Ecology* **4:** 5–14.

Marbe, A., Harvey, S. and Berntsson, T., 2006. Technical, environmental and economic analysis of co-firing of gasified biofuel in a natural gas combined cycle (NGCC) combined heat and power (CHP) plant. *Energy* **31:** 1614–1631.

Martin, S. and Seeland, G., 1999. Effects of specialisation in cattle production in harmful emissions. *Livestock Production Science* **61:** 171–178.

Matthews, R.B. and Grogan, P., 2001. Potential C-sequestration rates short-rotation coppiced willow and *Miscanthus* biomass crops: a modelling study. *Aspects of Applied Biology* **65:** 301-310.

Matthews, R.W., 2001. Modelling of energy and carbon budgets of wood fuel coppice. *Biomass and Bioenergy* **21:** 1–19.

McCracken, A.R., Dawson, M. and Walsh, L, 2006. Short rotation coppice (SRC) willow as an energy source and as an effective method for the bioremediation of wastewater streams. *In: Renewable Energy in Maritime Climates*. pp. 29–34, DIT, Dublin, Ireland.

McGettigan, M., Duffy, P. and Connolly, N., 2005. National Inventory Report 2005: *Greenhouse Gas Emissions 1990–2003 Reported to the United Nations Framework on Climate Change*. Environmental Protection Agency, Wexford, Ireland.

McGettigan, M., Duffy, P., Connolly, N. and O'Brien, P., 2006. National Inventory Report 2006: *Greenhouse Gas Emissions 1990–2004 Reported to the United Nations Framework on Climate Change*. Environmental Protection Agency, Wexford, Ireland.

McKay, H., 2006. Environmental, economic, social and political drivers for increasing use of woodfuel as a renewable resource in Britain. *Biomass and Bioenergy* **30:** 308–315.

Oenema, O., Velthof, G.L., Yamulki, S. and Jarvis, S.C., 1997. Nitrous oxide emissions from grazed grassland. *Soil Use and Management* **13:** 288–295.

Perttu, K.L., 1998. Environmental justification for short-rotation forestry in Sweden. *Biomass and Bioenergy* **15:** 1–6.

Perttu, K.L. and Kowalik, P.J., 1997. Salix vegetation filters for purification of waters and soils. *Biomass and Bioenergy* **12:** 9–19.

Raskin, N., Palonen, J. and Nieminen J., 2001. Power boiler fuel augmentation with a biomass fired atmospheric circulating fluid-bed gasifier. *Biomass & Bioenergy* **20(6):** 471–481.

Refsgaard, K., Halberg, N. and Kristensen, E.S., 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. *Agricultural Systems* **57:** 599–630.

Rice, B. and Quinlan, G., 2003. An estimate of fuel use and related emissions on Irish farms. *In: Agricultural Research Forum*. Conference held in Tullamore, Ireland. Teagasc, Ireland.

Rosenqvist, H., Aronsson, P, Hasselgren, K. and Perttu, K., 1997. Economics of using municipal wastewater irrigation of willow copice crops. *Biomass and Bioenergy* **12:** 1–8.

Rosenqvist, H. and Dawson, M., 2005a. Economics of willow growing in Northern Ireland. *Biomass and Bioenergy* **28:** 7–14.

Rosenqvist, H. and Dawson, M., 2005b. Economics of using wastewater irrigation of willow in Northern Ireland. *Biomass and Bioenergy* **29:** 83–92.

Rural Generation, 2004. Description and costs for willow planting on grass ley. Rural Generation, Derry, Northern Ireland. www.ruralgeneration.com. Accessed September 2007.

Savolainen, K., 2003. Co-firing biomass in coal-fired utility boilers. *Applied Energy* **74:** 369–381.

Scanlon, T.M. and Kiely, G., 2003. Ecosystem-scale measurements of nitrous oxide fluxes for an intensely grazed, fertilised grassland. *Geophysical Research Letters* **30:** 1852.

SEI (Elekrowatt-Ekono), 2004. *Co-firing with Biomass*. SEI, Dublin, Ireland.

Smith, P., Powlson, D.S., Smith, J.U., Falloon, P. and Coleman, K., 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biology* **6:** 525–539.

Tharaken, P.J., Volk, T.A., Lindsey, C.A., Abrahamson, L.P. and White, E.H., 2005. Evaluating the impact of three incentive programs in the economics of cofiring willow biomass with coal in New York State. *Energy Policy* **33:** 337–347.

Thorne, F.S., 2003. The Impact of the 'Mid Term Review' on Irish Tillage Farms. *Proceedings of The National Tillage Conference 2003*. Teagasc, Carlow, Ireland. p. 15–38.

Thorne, F.S., 2004. *Examining the Relative Competitiveness of Irish Agriculture (1996–2003/4)*. Teagasc, RMIS 5222. Teagasc, Ireland.

Thorne, F.S., 2006. Reform of the common market organisation for sugar: distributional impacts for Irish sugar beet producers. *Agricultural Research Forum*. Conference held in Tullamore, Ireland. Teagasc, Ireland.

Tillman, D.A., 2000. Biomass cofiring: the technology, the experience, the combustion consequences. *Biomass and Bioenergy* **19:** 365–384.

Unger, T., Ahlgren, E.O., 2005. Impacts of a common green certificate market on electricity and CO_2-emission markets in the Nordic countries. *Energy Policy* **33:** 2152–2163.

van den Broek, R., Faaij, A., van Wijk, A., Kent, T., Bulfin, M., Healion, K. and Blaney, G., 1997. Willow firing in retrofitted

Irish peat power plants. *Biomass and Bioenergy* **12:** 75–90.

van den Broek, R., Teeuwisse, S., Healion, K., Kent, T., van Wijk, A., Faaij, A. and Turkenburg, W., 2001. Potentials for electricity production from wood in Ireland. *Biomass and Bioenergy* **26:** 991–1013.

van Loo, S. and Koppejan, J., 2003. *Handbook of Biomass Combustion and Co-firing.* Twente University Press.

Venturi, P., Huisman, W. and Molenaar, J., 1998. Mechanization and costs of primary production chains for *Miscanthus x giganteus* in The Netherlands. *Journal of Agricultural Engineering Research* **69:** 209–215.

Venturi, P., Gigler, J.K. and Huisman, W., 1999. Economical and technical comparison between herbaceous (*Miscanthus x giganteus*) and woody energy crops (*Salix viminalis*). *Renewable Energy* **16:** 1023–1026.

Wells, C., 2001. *Total energy indicators of agricultural sustainability: dairy farming case study*. University of Otago, Otago, New Zealand.

Zan, C.F., Fyles, J.W., Girouard, P. and Samson, R.A., 2001. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. *Agriculture, Ecosystems and Environment* **86:** 135–144.

List of Abbreviations

BIG/CC	Biomass Integrated Gasification/Combined Cycle
CAP	(EU) Common Agricultural Policy
CER	Commission for Energy Regulation
CH_4	Methane
CHP	Combined Heat and Power
CMO	Common Market Organisation
CO_2 eq.	Carbon dioxide equivalent global warming potential
CSO	Central Statistics Office
DAF	Department of Agriculture and Food
DARD	Department of Agriculture and Rural Development, NI.
DCMNR	Department of Communications, Marine and Natural Resources
DEFRA	UK Department for Environment, Food and Rural Affairs
DM	Dry Matter
ESB	Electricity Supply Board
ETS	Emission Trading Scheme for CO_2
EU ETS	European Union Emissions Trading Scheme
FAPRI	Food and Agricultural Policy Research Institute
GHG	Greenhouse Gas
GJ/MJ	Gigajoule/Megajoule; $10^6/10^9$ joules of energy
GWP	Global Warming Potential
kWh	Kilowatt hour of useful energy, as electricity (kWh_e) or thermal (kWh_{th})
LCA	Life-Cycle Analysis
LCCA	Life-Cycle Cost Analysis
LCI	Life-Cycle Inventory
LHV	Lower Heating Value (also known as Net Calorific Value)
MBM	Meat and Bonemeal (agricultural waste product)
M€/Mt	Million euro/million tonnes
MW	Megawatt power capacity (energy per second)
NFS	National Farm Survey
NIR	National Inventory Report for air emissions (EPA)
N_2O	Nitrous oxide
NPV	Net Present Value
PSO	Public Service Obligations
RE-FIT	Renewable Energy Fee-In Tariff
SEI	Sustainable Energy Ireland
SFP	Single Farm Payment
SRCW	Short Rotation Coppice Willow
t.km	Tonnes multiplied by kilometres transported
WW	Waste Water

Appendix A Heating Calculations

Electric Heating Calculations

Based on tariffs implemented from 1 January 2007 (CER, 2006b).

Domestic

Based on Urban Nightsaver tariff, €140.16 standing charge not included, 80% heat load from night rate electricity.

4,250 kWh (20%) @ €0.1435/kWh:	€609.88
16,999 kWh (80%) @ €0.0705/kWh:	€1,198.43
VAT @ 13.5%:	€244.12
Total:	**€2,052.43**

=76.496 GJ electricity @ €26.83/GJ (€0.0966/kWh)

Commercial

Based on General Purpose Nightsaver Tariff, €160.60 standing charge not included,80% of heat from night rate, 20% from cheaper of two day rates (i.e. first block of more expensive day units attributed to other purposes).

42,498 kWh (20%) @ €0.1598/kWh:	€6,791.18
169,992 kWh (80%) @ €0.0695/kWh:	€11,814.44
VAT @ 13.5%:	€2,511.76
Total:	**€21,117.38**

=764.96 GJ electricity @ €27.606/GJ (€0.0994/kWh)

Gas heating calculations

Domestic

Based on Bord Gáis high user commitment residential tariff. According to this tariff, all gas used is charged at €0.05385/kWh, inclusive of VAT, and with no additional standing charges.

= 84.996 GJ delivered gas @ €14.96/GJ fuel (€0.0539/kWh)

Commercial

Based on Bord Gáis SME standard commercial tariff.

3,000 kWh @ €0.05376/kWh:	€161.28
3,001–7,500 kWh @ €0.04963/kWh:	€223.34
7,501–15,000 kWh @ €0.04548/kWh:	€341.10
15,001–236,100 kWh @ €0.04136/kWh:	€9,144.65
€12.12 monthly charge per meter:	€145.44
VAT @ 13.5%:	€1,352.13
Total:	**€11,367.95**

=849.96 GJ delivered gas @ €13.38/GJ fuel (€0.0482/kWh)

Appendix B Case studies

Woodchip CHP on the Brookhall Estate, Northern Ireland

In 1996, John Gilliland began a trial growing and utilising SRCW at Brookhall Estate, Derry, planting an initial 14 of 44 ha. SRCW woodchip is chip-harvested and dried on a grain-drying floor, prior to being fed into a gasifier. The gas is then fed into a conventional diesel engine (with a small proportion of diesel) used to drive a turbine producing 100 kW electricity. The electricity is sold to the grid, whilst the waste heat (from cooling water and exhaust) is utilised for heating the houses on the estate, and for drying grain and woodchips on the drying floor. Source: Boyd *et al.* (2000).

Rural Generation Ltd and Clearpower Ltd

From his experience establishing the SRCW trial at Brookhall, John Gilliland set up Rural Generation Ltd, a contracting consultancy company for SRCW cultivation, WW treatment, and woodchip distribution. In the Republic of Ireland, Clearpower, a company with a similar role, has begun operating, and distributes woodchip produced from over 50 ha of SRCW cultivation in the south-east (supplying some of the premises below). These companies compete with wood-pellet suppliers Balcas/Kerry Biofuels, who supply more expensive, but higher grade, pelleted wood fuels produced from timber-production sawdust.

Camphill Community, Jerpoint, Kilkenny

A wood-fuelled heating network was installed during construction of the new community premises, to serve one 9- and one 12-bedroom community house, one office building and one multi-purpose building. A 150 kW wood-fuel boiler, able to utilise woodchips containing up to 40% moisture, and convert wood energy into useful heat at up to 92% efficiency, was installed. Sixty tonnes of wood fuel are used annually, at a cost reduction of over 60% compared with kerosene. Total installation costs amounted to €85,500. Source: SEI (2006: http://www.sei.ie).

Kymijävi Power Station, Lahti, Finland

This CHP plant has a capacity of 167 MW_e and 240 MW_{th}, with an additional 47 MW_e from a combined-cycle gas

Inchydoney Island Lodge and Spa, Clonakilty, Cork

A wood-pellet boiler was installed at the lodge in conjunction with a new heat recovery system and solar panels. The total installation cost amounted to €300,000, but it is calculated that their annual fuel bill of €10,000 will be halved. Source: SEI (2006: http://www.sei.ie).

Woodchip CHP in Enköping, Sweden

Enköping, a town of 20,000 inhabitants, uses locally grown SRCW, forestry residues and sawdust to fire a CHP plant producing 55 MW heat supplied to the district heating system and 22 MW electricity. The SRCW includes 80 ha used for sewage sludge and WW treatment, absorbing 30 t N and 1 t P, which would otherwise have entered a nearby lake, annually. Source: Boyd *et al.* (2000).

Drax Power Station, Yorkshire

At 4,000 MW capacity, the Drax coal power station in west Yorkshire is Europe's largest coal power station. An energy-crop biomass co-firing strategy is actively being pursued, with local fuel processing trials of 1,100 ha locally grown SRCW under way, and a large grinder being integrated into the plant (to pulverise wood for combustion injection). The aim is to directly inject 10% (energy content) biomass, mainly wood from SRCW, into boilers. Drax can earn Renewables Obligation Certificates (ROCs) to compensate for the increased fuel costs. Under the UK's Renewables Obligation Order, co-fired biomass must originate and be comprised of at least 25% energy crops from 1 April 2009, 50% energy crops from 1 April 2010, and 75% energy crops from 1 April 2011. However, co-firing ceases to be eligible for ROCs after 31 March 2016. Drax requirements will amount to around 12,500 ha of energy crops by 2009, and 37,500 ha by 2011. Drax has also contracted local *Miscanthus* growers to supply biomass for co-firing. Source: Modern Power Systems (2006: http://www.modernpowersystems.com/story.asp?sectionCode=88&storyCode=2035784).

turbine, and is primarily fired by pulverised coal during higher loading, and natural gas during low summer loading. In 1997, an atmospheric circulating fluidised bed gasifier (ACFBG) was integrated into the plant to enable the conversion of solid biomass and waste material into gas for co-firing in the main boiler. Refuse waste from the area, comprised mainly of wood products but including cardboard, paper, plastics and tyres, is collected, fed into the gasifier, and the gas combusted in the CHP station to supply 15% of its annual output. Tests conducted since successful commissioning of the ACFBG in 1997 demonstrated reduced NO_x (by 5–10%) and SO_x emissions. Source: Raskin *et al*. (2001).