Energy Requirements and Environmental Impacts Associated with the Production of Short Rotation Willow (Salix sp.) Chip in Ireland

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Abstract:
Ireland, a member state of the European Union, has committed to the EU's Renewable Energy Directive target of 20% of overall gross energy consumption by renewables by 2020. In order to achieve this the Irish Government has committed to a target of 30% co-firing with biomass at the three State owned peat power generation stations to be achieved progressively by 2015. Short rotation forestry has received attention as a potential source of biomass for cofiring in recent years. Co-firing of short rotation coppice willow (SCRW) with peat at the power stations offers a way to reduce the carbon intensity of the electricity produced while concurrently reducing the reliance on peat. This study focuses on the environmental performance of the willow chip supply chain in Ireland in relation to energy demand and greenhouse gas (GHG) emissions by the use of life cycle assessment methodologies. Each step in the supply chain is examined; from willow cultivation, to harvesting, processing and transport, using Simapro 7.3 software. The functional unit of the system is 1 GJ of willow chips delivered to the end user. Results show that the production of 1 GJ of willow chips requires 60.9 MJ and causes the emission of 5.52 kg CO2-eq. Results indicate that the maintenance of the willow crop during production makes the highest contribution to the, impact categories studied requiring 31% of overall energy demand and emitting 53% of the GHGs emitted over the whole supply chain. This is due to application of synthetic fertilisers,production of which is highly energy intensive and utilises non-renewable fossil fuels. Direct chip harvesting is the second most energy intensive and polluting step, demanding 32% of energy and emitting 22% of GHGs. Sensitivity analysis highlights the effects of rod harvesting overall emissions. Transporting the chips 50 kilometres in a 16-32 tonne EUR 3 truck requires 30% of overall energy and contributes to 20% of GHG emissions.

Keywords: Short rotation forestry**,** Willow *Salix sp.***,** Energy ratio**,** Greenhouse gas emissions**,** Harvest methods

1 Introduction

In an effortto promote the use of bioenergy in Ireland and to contribute to meeting the EU renewable energy targets, the Irish Government set out to implement co-firing of biomass at the three peat-fired electricity generating plants owned by the state(DCENR, 2007). The co-firing targets are limited to cofiring 30% of the maximum rated capacity in any plant until 2017, 40% between 2017 and 2019, and 50% thereafter (2010).Three hundred kilotonnes of biomass will be required to achieve 30% co-firing at Edenderry power plant alone, requiring additional biomass feedstocks to be sourced.

Short rotation coppice willow (*Salix sp.)*(SRCW) has been cultivatedas an energy crop in Ireland which can help meet the biomass demand of the 3 peat-fired power plants. There are currently more than 800 ha of willow crops sown in Ireland. In 2010, 5,208 tonnes of willow chip were co-fired with peat in Edenderry power plant, representing 4.8% of total biomass co-fired. With the co-firing target increasing to 30% by 2017, a substantial increase in the area of energy crop plantations will be required.

The aim of this study is to evaluate the energy requirements and environmental impacts associated with the cultivation, harvest, and transport of willow (*Salix sp.)* for energyutilisation in Ireland. The paper presents detailedlife cycle inventory (LCI) data for willow cultivation in Ireland. The paper considers two different harvesting techniques; direct chip and whole rod harvesting. Cherubini et al. (2009) have recommended that the energy and GHG balances of biomass to energy systems should always be contrasted against fossil fuel systems. This allows comparison of the potential benefits/drawbacks of the bioenergy system in question. As such, the results of this LCA are compared to some common fossil fuels including coal and peat, feedstocks with which biomass is commonly co-fired in Ireland (Heller et al. 2004, Mann and Spath 2001, Sebastián et al. 2010, Styles and Jones 2008).

2 Materials and methods

The LCA software SimaPro v7.3.2 (Consultants, 2011) was used to construct the LCA model and undertake the impact assessment calculations.

2.1 Goal and scope

The aim of this study is to evaluate the energy requirements and GHG emissions associated with willow (*Salix sp.)* cultivation, harvest and transport. Different management practices based on two methods of harvesting, direct chip and whole rod, are analysed.The scenario with the highest energy ratio will be determined. As this study focuses on the production of biomass and transport to the end user gate it is thus considered a 'cradle to gate' LCA.

2.1.1 Functional unit

As the function of the system being studied is for energy use, and the results are to be compared with fossil fuels, the functional unit in this case is '1 GJ of energy contained in the willow biomass'.This allows the energy productivity of the system to be analysed in comparison with other sources of fuel (Goglio et al., 2012, Nemecek et al., 2011).

2.1.2 System description

All of the field activities, from land preparation, to maintenance, harvesting and transport have been considered, as can be seen in the system diagram (Figure 1). All of the inputs (material, fuel, energy) and outputs (product flow, and emissions to air, soil, water) for each of the unit operations in the supply chain are quantified and included in the LCA.

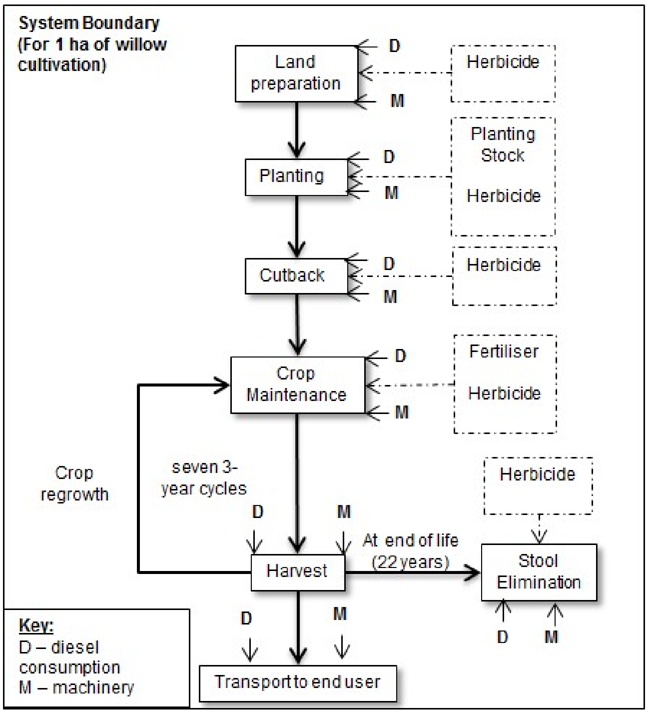

Figure 1: System diagram

2.2 Inventory analysis

Data specifically relating to willow production in Irish conditions is used wherever possible. Where this is not possible, standard data for willow production reported in the literature is used.The SRCW production cycle in this model is based on data from Teagasc Short Rotation Coppice Willow Best Practice Guidelines (Teagasc 2010), and other LCA studies(Heller et al. 2003, Jungbluth et al. 2007). This data describes the inputs required and machinery operations over the lifetime of the willow plantation (22 years). Table 1 outlines frequency of field operations over the lifetime of the crop.

Table 1: Summary of field operations

Field operation	Frequency of operation (per 22 year cycle)
Pre-ploughing herbicide	1
Plough	2
Disk	1
Plant	1
Roll	1
Harvest	7
Herbicide	8
Fertilise	7

Table 2 outlines the inputs over the lifetime of the cropping system.

Table 2:Data summary of inputs to cropping system

Plan	Input	Frequency (per 22 year cycle)	Application rate [kg/ha]	Total over life cycle [kg/ha]
Land preparation	Water	1	400	400
	Glyphosate	1	1.98	1.98
Crop Establishment	Cuttings	1	16500u	16500u
	Water	1	500	500
	Pendimethalin	1	1.09	1.09
Cutback	Water	1	200	200
	Pendimethalin	1	1.37	1.37
Maintenance	Water	7	200	1400
	Nitrogen	7	120	840
	Phosphorous	7	15	105
	Potassium	7	10	280
	Pendimethalin	7	1.37	9.59
Crop removal	Water	1	200	200
	Glyphosate	1	1.8	1.8

Table 3 outlines the data requirements for the LCA study, along with the data sources.

Table 3: Summary of data requirements and data sources

Data required	Data sources
Nursery data	Jungbluth et al., (2007)
Machinery type, fieldwork, chemical application rates	Teagasc, (2010), Heller et al., (2003)
Machinery manufacture, fuel consumption and emissions	Ecoinvent databases - Nemecek et al., (2007) and Spielmann et al., (2007), l'Environnement, (2007), Lechasseur and Savoie, (2005)
Chemicals production	Nielsen et al., (2003), Ecoinvent databases - Nemecek et al., (2007)
Yield data	Teagasc, (2010), Styles and Jones, (2008), Caslin, (2010), Garstang(2002)
Yield data	Ecoinvent databases - Nemecek et al., (2007), Cherubini et al., (2009), Heller et al., (2003), IPPC, (2006)
Carbon sequestration	Grogan and Matthews, (2002)

2.3 Life cycle impact assessment

The attributional LCA for willow cultivation in this case was carried out using CML 2001 (Guinée et al. 2002) and ecoinvent methods (Frischknecht et al. 2007). The following impacts are considered; global warming potential (GWP)(Guinée et al. 2002), and cumulative energy demand (CED).

In addition, Huijbregts et al. (Huijbregts et al. 2005) found that CED correlates well with most environmental life cycle impact categories and can be considered an appropriate proxy indicator for environmental performance. A further way to assess advantages of renewable energy systems may be to evaluate the pure energy ratio of the system. The term "energy ratio" is used to characterize relations between the energy input and output. Energy ratio is a ratio between the energy output and energy input according to the following equation;

$ER = Eo / Ei$ where;Eo - energy output,Ei - energy input,ER - energy ratio (Klvac 2011).

3 Results and discussion

The results of the LCA study are presented and discussed below. Figure 2 shows the percentage contribution of each of the life cycle stages to the overall impacts for each category for the base case scenario (direct chipping of willow grown using synthetic fertilizer and transported a distance of 50 km). The results clearly identify the hotpots in the production chain; maintenance, harvest and transport.These three steps in the supply chain contribute the largest share of impacts to each of the impact categories.These three steps are repeated for every harvest cycle throughout the life cycle, while the other steps are only carried out once. Maintenance of the willow crop is highly energy intensive, with energy required for the manufacture of synthetic fertilizers but also in diesel consumption in the farm machinery used in fertilizer application. Willow harvesting and transport are also highly energy intensive processes with high consumption of diesel in the chipper harvester and truck engine respectively, contributing to the high energy demand.

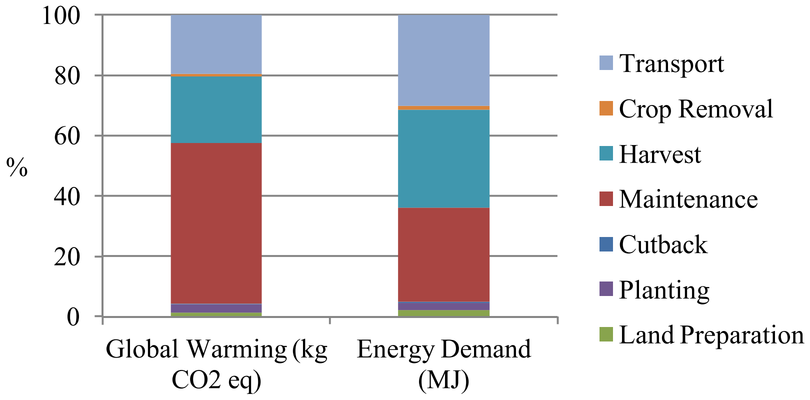

Figure 2: Percentage contribution of life cycle stages to each impact category

Table 4 quantifies the impacts associated with the production of 1 GJ of energy embodied in the harvested willow chips.

Table 4: LCA results AP, EP, GWP, CED per GJ of energy contained in the willow

Impact category	Unit	Land Prep.	Planting	Cutback	Maint-enance	Harvest	Crop Removal	Trans-port	Total
GWP	kg CO2 eq	0.08	0.15	0.01	2.93	1.21	0.05	1.08	5.52
CED	MJ	1.3	1.5	0.2	19.0	23.5	0.8	14.6	60.9

3.1 Energy demand and energy ratio

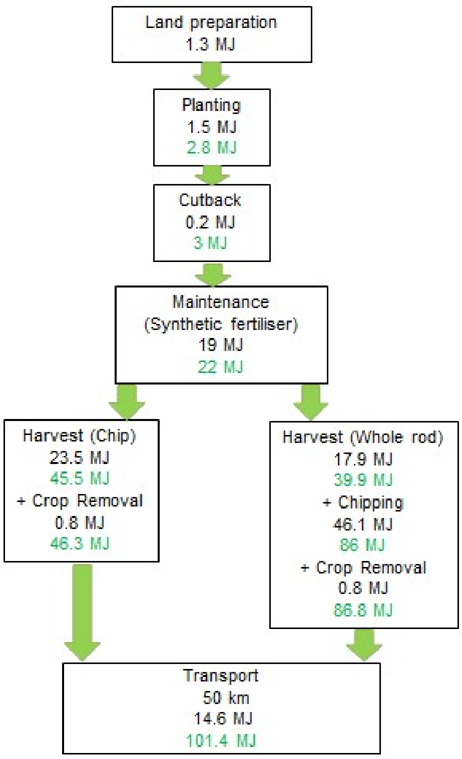

Figure 3: Energy flow diagram

Figure 3 shows the energy requirements of each step in the life cycle. Figures in black indicate the energy demand associated with each individual step, while figures in green represent cumulative energy demand along the production chain. The final figure indicates the cumulative energy required to produce 1 GJ of energy contained in the harvested willow.This highlights that although energy consumption in the rod harvester is lower than the direct chipper, this energy saving is significantly outweighed by the energy required subsequently to chip the rods.The energy ratio of the direct chip system is 16.4, with the energy ratio decreasing to 9.9 when direct chipping is replaced by rod harvesting and subsequent chipping. Heller reported energy ratios for willow production to be approximately 55 (Heller et al. 2003). These ratios assume drying of the biomass which increases the energy content of the material, hence increasing the energy ratio. In this study, the harvested willow is assumed to have a lower energy content as the material is exported from the farm to the power plant directly after harvest, allowing no time for drying. As such the energy ratios of the willow scenarios in this study are lower than other reported values (Mann and Spath 2001, Matthews 2001).

3.2 Global warming potential

Greenhouse gas emissions from the default scenario (willow chips, synthetic fertilizer and 50 km transport distance), amount to 5.52 kg CO_2-eq per GJ of energy produced. The manufacture of synthetic fertilizers is an energy intensive process, contributing to a large degree to the overall greenhouse gas emissions of the system. Direct chipping results in lower GHG emissions than rod harvesting followed by chipping, which emits 8.0 kg CO_2-eq per GJ of energy produced.

3.3 Comparison with fossil fuels

When comparing the energy ratio of the willow production scenarios studied, with those of conventional fossil fuels with which willow is commonly co-fired, the benefits of willow as a source of energy become apparent. Data on coal and peat supply were obtained from the ecoinvent database (Dones et al., 2007). The energy ratio of both willow chip scenarios is higher than both coal and peat which have an energy ratio of 2 and 5 respectively, implying that more energy is required to produce these fuels. Greenhouse gas emissions associated with willow production in both scenarios are lower than coal supply which emits approximately 12.28 kg CO2 eq per GJ of coal. GWP of peat production is lower than the production of willow.

4 Conclusion

The results from the LCA study show that the largest contributors to the impact categories considered; GWP and CED,are the maintenance, harvesting and transport processes. These steps utilise a large quantity of energy in machinery use, and in synthetic fertilizer production required for maintenance. The results clearly show that, while rod harvesting is less energy intensive than direct chipping, the subsequent chipping required increases overall energy use and GHG emissions. This result highlights the environmental benefits of direct chipping harvesting.When compared to conventional fossil fuels, coal and peat, the willow biomass system performs favourably in terms of energy requirements. Willow chip supply is preferable to coal supply in terms of GHG emissions. Overall the results of this study confirm the positive environmental and energy performance of the willow chip biomass system in Ireland.

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