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Forest Biomass Supply Chains in Ireland:
A Life Cycle Assessment of GHG Emissions and Primary Energy Balances

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Abstract:

The demand for wood for energy production in Ireland is predicted to double from 1.5 million m^3 over bark (OB) in 2011 to 3 million m^3 OB by 2020. There is a large potential for additional biomass recovery for energetic purposes from both thinning forest stands and by harvesting of tops and branches, and stumps. This study builds on research within the wood-for-energy concept in Ireland by analysing the energy requirements and greenhouse gas emissions associated with thinning, residue bundling and stump removal for energy purposes. To date there have been no studies on harvesting of residues and stumps in terms of energy balances and greenhouse gas emissions across the life cycle in Ireland. The results of the analysis on wood energy supply chains highlights transport as the most energy and greenhouse gas emissions intensive step in the life cycle. This finding illustrates importance of localised production and use of forest biomass. Production of wood chip, and shredded bundles and stumps, compares favourably with both other sources of biomass in Ireland and fossil fuels.

Keywords: woodchip, residues, stumps, energy, greenhouse gas (GHG), Ireland,

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Nomenclature:

OB – over bark

GHG – greenhouse gas

CTL – cut-to-length

WIT - Waterford Institute of Technology

LCA – life cycle assessment

odt – oven-dried tonne

GJ – giga joule

GWP – global warming potential

CED – cumulative energy demand

MJ – mega joule

SRCW – short rotation coppice willow

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1 Introduction

The EU Renewable Energy directive requires 16% of gross final energy consumption in Ireland to come from renewable resources by 2020. The contribution of renewable energy to overall energy demand reached 5.6% in 2010 [1], with biomass comprising 29% of this total. This biomass is comprised of wood and wood waste as thermal energy, with smaller contributions from electricity generated from biomass and biogas along with transport liquid biofuels [1].

Ireland's forests are an important source of biomass for the timber industry and for energy generation. At the beginning of the 1900s, forest cover in Ireland stood at only 1% of total land. However thanks to state afforestation programs this had risen to approximately 11% in 2011 [2], with the aim of achieving 17% forest cover by 2030 [3]. Overall, approximately 6% of total land in Ireland can be classified as productive forest land [4]. The demand for wood for energy production is predicted to increase from 1.5 million m^3 over bark (OB) in 2011 to 3 million m^3 OB by 2020 [5].

Sitka spruce (*Picea sitchensis*) is the most important and widely planted tree species in Irish forestry, occupying 52.3% of the total forest estate or 327,000 ha [6]. It is the dominant species planted during afforestation, accounting for around 60% of the national planting program since the 1970s [7]. Irish forestry is highly productive, with an average yield class for Sitka spruce of 17 $m^3ha^{-1}a^{-1}$ [8]. The mechanised cut-to-length (CTL) method predominates in Irish forestry systems, accounting for approximately 95% of harvesting [9]. Harvesting by the CTL system involves felling, delimbing, and crosscutting by the harvester, followed by forwarding to the roadside with the forwarder. Secondary haulage is carried out by road or rail.

Ireland has a large number of young conifer plantations that are approaching the age of first thinning [10]. Thinning of a forest plantation is a silvicultural operation which involves the removal of part of the crop in order to concentrate future volume growth on fewer and better quality stems [11]. Thinning reduces the time taken for trees to reach valuable sawlog size, and provides an additional source of biomass during the forest rotation [12]. The net realisable volume production by thinnings in Ireland is projected to increase from nearly 1 million m^3 over bark in 2011 to nearly 2 million m^3 over bark in 2028 [13], and as such can provide an important source of wood for the forest industry.

There is still a large potential for additional biomass recovery by harvesting of tops and branches and stumps which can be utilised for energetic purposes [14]. In Ireland, forest residues, i.e. tops and branches, tops of trees, and stumps, etc. have traditionally been left in the forest after clearfell. Occasionally some of the larger waste wood is removed as firewood for domestic consumption but this does not occur on any scale. The residues are used as a brash mat to improve trafficability of strip roads for the harvester and forwarder during timber extraction [15]. Interest in forest residue harvesting for energetic purposes has increased in recent years as demand has risen for bioenergy sources. Recent trials by Coillte, the state-owned forestry company, estimate that up to 80 green tonnes per ha of this biomass material can be recovered on suitable sites, depending on species, age, site type and wood assortments harvested [16]. It is estimated that raw material in the 'tip – 7 cm' category will increase from 48,000 m^3 in 2011 to 61,000 m^3 by 2020 [13]. However, due to environmental constraints and restricted soil types, this resource is only likely to be available on about 35% of harvest sites in Ireland [16].

There is no stump harvesting currently carried out on a commercial scale in Ireland. Research trials are being carried out by Coillte and Waterford Institute of Technology (WIT) on the feasibility and productivity of stump harvesting in Ireland. Stump harvesting results in increased intensification of forest management when compared to conventional systems with only above-ground biomass harvesting. Benefits of stump harvesting include; increased production of wood energy resources, reduced CO_2 emissions when compared with fossil fuels [17, 18], and improved site preparation and potential reduction of Heterobasidion [19]. The soil disturbance resulting from stump harvesting can also affect the forest soil carbon store by decreasing the amount of carbon stored in forest and thus causing indirect CO_2 emissions into the atmosphere [20, 21], and also influences forest nutrient stocks [19].

Understanding the environmental impacts of timber production and processing has been an important focus of research over the last number of years. The Scandinavian countries have been particularly active in this area, carrying out life cycle analyses of a range of wood products from roundwood, to residue bundles and stumps [22-28]. Production of wood chips in the US, the largest wood producer in the world, has also been studied [29]. In Ireland, aspects of timber production have been studied from an environmental point of view, mainly focusing on harvesting operations [30]. Consequently, there is a lack of research on environmental impacts of forestry production over the entire life cycle from seedling production, to harvesting, transport and processing.

Life cycle assessment (LCA) is a software tool that was used for this work to assess the environmental sustainability of wood energy production from a holistic perspective. However, when comparing LCAs reported by different authors and sources for apparently similar bioenergy systems in terms of originating biomass source, there can be a wide range of results in both the energy balances and greenhouse gas (GHG) emissions. These differences can be due to several factors; functional unit, system boundaries, allocation procedures, and management of raw materials [31].

The boundaries of LCA studies on forestry production frequently differ, making it difficult to compare results between different studies. The choice of system boundary also influences the completeness of the study. Some studies start at forest management (including seedling production) [22, 26], some are concerned only with harvesting [32]. It is recommended that the environmental system be included in any analysis [33], however this is only the case in a few studies [27, 34].

Another issue in LCA is the delineation of system boundaries to exclude the burdens associated with machinery production and forest road construction and maintenance. The energy embodied in the harvesting machinery can equal up to 40-50% of the direct process energy [33]. In addition, Heinimann [33] states approximately 60% of the overall environmental burdens of forestry production can be caused by road construction and maintenance, along with long-distance transport. As such, excluding these elements of the production chain from the system boundary could result in significantly underestimating the environmental impacts of wood energy systems.

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2 Materials and methods

2.1 Goal and scope

The aim of this study is to identify and evaluate the energy demand and greenhouse gas emissions related to the production of roundwood, wood chip, shredded bundles and shredded stumps from a Sitka Spruce stand in Ireland.

The functional unit of timber production systems varies depending on the end use of the material. In roundwood and pulpwood production systems where the wood is intended for industry use, the functional unit is normally a unit of volume (m^3) [22, 24, 26, 35]. When the end use of the timber produced is for energy generation, the functional unit changes accordingly. In this case, the functional unit concerns the energy content of the material, as such it is then defined as '1 MJ or MWh of forest fuel' [27, 34, 36]. Other functional units include area (ha) and mass (odt) [37]. In this study, two functional units are used to reflect the differing functions of the system i.e. roundwood production for wood products, and biomass production for energy generation. Using a measure of energy contained in the feedstock allows the energy productivity of the system to be analysed in comparison with other sources of fuel [38-40]. As such, one functional unit concerns mass and is defined as '1 odt (oven dried tonne) of solid (over bark) or 1 odt loose chips or 1 odt loose shredded residue bundle or shredded stump at the gate of the end user'. The other functional unit concerns energy content of the material and is defined as '1 GJ loose chips or 1 GJ loose shredded residue bundle or shredded stump at the gate of the end user' In the case of residue bundling, the bundles are shredded at the end user, this step is included in the analysis. It should be noted that the study does not consider carbon sequestration in the forest, nor does it include emissions of mineralized carbon due to the disturbance of the soil during stump lifting.

2.2 System description

This study examines a number of different scenarios for biomass recovery from forestry operations in Ireland. As thinning for energy, and residue bundling and stump removal for energy, are relatively new concepts in Ireland, this study examines a number of scenarios reflecting both traditional practices and new innovation for energy production. Figure 1 outlines the system boundary of the study. The scenarios are described in Table 1.

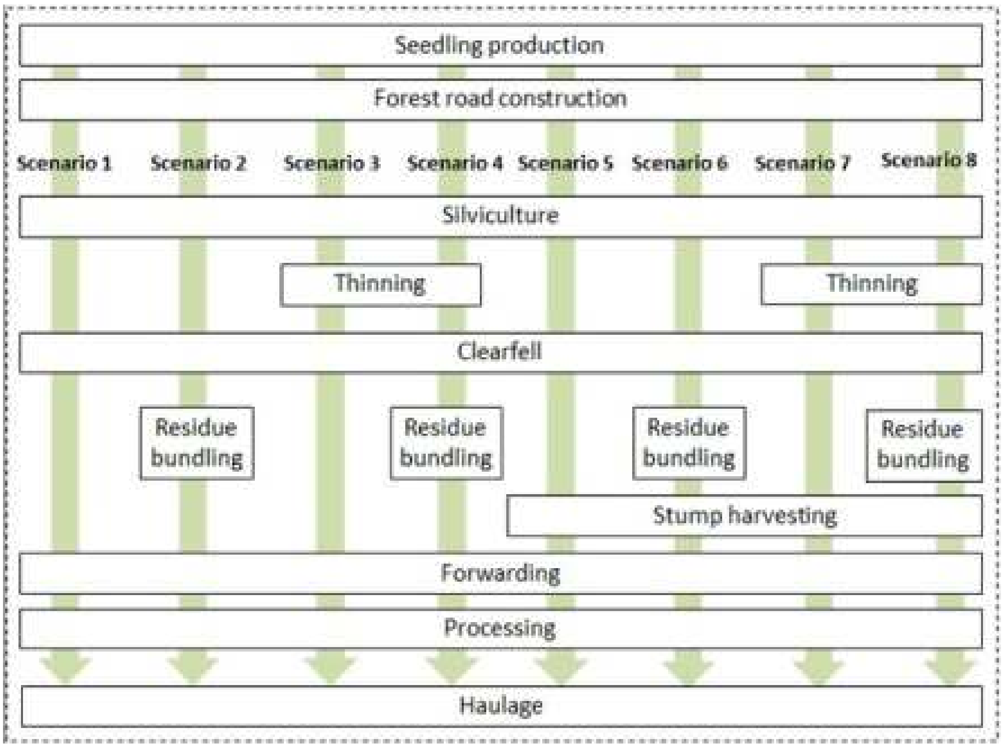

Figure 1 – System boundary.

- Scenario 1 assumes standard roundwood and pulpwood removal at clearfell. No thinning or residue/stump removal occurs. This reflects the standard log market with the additional assumption that all pulpwood is used for energy.
- Scenario 2 is also a no-thin scenario but residue bundling occurs after harvest.
- Scenario 3 incorporates a thinning regime while the residues are left on the forest floor.

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- Scenario 4 incorporates both thinning and bundling of harvest residues after clearfell.
- Scenarios 5-8 are identical to those from 1-4 with the addition of stump harvesting.

Seedlings are produced in nursery conditions. New forest roads are constructed to allow access to and from the afforested site. New roads are constructed to a density of 0.005 km/ha [37]. Road maintenance is also carried out before each harvesting event.

The site is prepared by mounding the soil with excavators. A small dose of herbicide is applied to control any remaining grass growth.

Once the forest stand is established, there is no intervention until the first thinning. This study also considers a no-thin scenario in which no biomass removal occurs until clearfell. The mechanised CTL method predominates in Irish forestry systems. The CTL system is also the most common system used in Ireland for thinnings and accounts for approximately 90% of thinnings undertaken [12]. Harvesting by the CTL system involves felling, delimbing, and crosscutting by the harvester, followed by forwarding to the roadside with the forwarder. Three assortments are produced by the CTL method; sawlog (> 20 cm diameter), stakewood/palletwood (13 – 20 cm diameter), and pulpwood (7 – 13 cm diameter). Increasingly, the pulpwood assortment is sold to wood fuel suppliers for chipping [11]. As such, for the purposes of this study, it is assumed that pulpwood will be used for energy production and is therefore termed ‘energywood’, while the sawlog and stakewood assortments will be termed ‘roundwood’ and used directly within the sawmilling industry.

In mechanised thinning, a harvester fells, delimbs and crosscuts the stem into various product assortments, e.g. pulpwood, pallet wood, stake wood and sawlog (usually based on the top diameter and length of the log). The material is then extracted to roadside by a forwarder.

Roundwood and energywood are forwarded to the roadside where roundwood is stacked during harvesting prior to transport to the end user. The energywood assortment is left to season at the roadside for at least one summer in order to reduce the moisture content prior to chipping. In this study the energywood is chipped at the roadside before being transported in chip form to the end user.

The remainder, termed ‘tops and branches’ or ‘forest residues’, are traditionally left in the forest after harvest. However, this study looks at bundling these residues in four of the eight supply chain scenarios considered. In these scenarios, residue is removed after clearfelling, as such there is one residue removal event in the life cycle. Harvest residues are collected and bundled using a dedicated bundler system. The bundles are harvested on a green basis and contain 0.33 tonnes per bundle at 60% MC [41]. The bundles are transported and are stored on-site at the end user and are shredded after a period of drying.

After clearfell, 42% of stumps are harvested using an excavator equipped with a stump harvesting head. The stumps are forwarded to the roadside where they are left to season for a number of months. This allows some of the dirt to fall off and a reduction in moisture content. The stumps are then shredded at the roadside and chips are blown straight into the trucks for transport.

Haulage is carried out by road over a distance of 100 km. This results in a 200 km roundtrip during which the outward leg is empty.

Table 1 – Description of scenarios

Scenario	Roundwood	Thinning	Residue bundling after clear-felling	Stump harvesting
1	x			
2	x		x	
3	x	x		
4	x	x	x	
5	x			x
6	x		x	x
7	x	x		x
8	x	x	x	x

2.3 *Data inventory*

This study mainly relies on data from Irish forestry operations and Irish forestry trials. Where there are gaps in the availability in this data specific to Ireland, other published data are used. The model is dependent on data from afforested sites in the Carbifor project [7]. Table 2 gives the chronosequence data for the Dooary (52°57’ N, 7°15’ W) site at age 14.

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Table 2 – Chronosequence data for Dooary site at age 14 [7]

Yield class (m^3 ha^{-1} yr^{-1})	Stem (ha^{-1})	Mean DBH (cm)	Mean Height (m)	Crown to height ratio	Top height (m)
20-24	2,400	13.6	7.6	0.41	9.83

Table 3 outlines schedule of events over the lifetime of the stand in both unthinned and thinned scenarios for 1 ha.

Table 3 – Schedule of events for unthinned and thinned scenarios (1 ha)

Scenario	Age	Event	Roundwood and energywood harvested (m^3)
Unthinned	41	Clearfell	983.73
Thinned	19	1st Thinning	44
	21	2nd Thinning	74
	25	3rd Thinning	75
	29	4th Thinning	70
	33	5th Thinning	70
	37	6th Thinning	70
	41	Clearfell	648.79

Seedling production data for Irish conditions were provided by Mick Doyle (personal communication) [42] with additional data from Aldentun [43]. A planting rate of 2,500 seedlings per ha was assumed according to Philips & Thompson [44]. The site was prepared in mounds using an excavator. Data on the excavator fuel consumption and productivity in Irish conditions was obtained from Lyons [45], while data on machinery production and maintenance is from the ecoinvent database [46]. A small dose of herbicide (0.06 kg of active ingredient per ha) was applied prior to seeding to remove any remaining grass growth according to Whittaker [37].

Data on materials required in road construction were obtained from the state forestry body, Coillte, [47] with additional data from the ecoinvent database [46]. A road density of 0.005 km/ha was assumed according to Whittaker [37].

Data on fuel consumption and productivity for harvesters, forwarder, and bundlers used in

Ireland were provided by Lyons [45]. Lubricant consumption for all forest machines was set at 6% of fuel consumption according to Berg and Lindholm [22]. Data on machinery production and maintenance is from the ecoinvent database [46]. Chipping of energy wood was modelled according to trials carried out by Kent et al. [11]. Fuel consumption of the chipper was provided by Lyons [45]. Data on bundling trials were obtained from Neri [41]. Data on stump trials were obtained from Coates et al. [48]. Data on fuel consumption and productivity of bundle and stump shredding was provided by the contractor involved in the bundling and stump trials [49].

Data on transport loads and fuel consumption are from field data [50].

In harvesting, approximately 5% of the value is lost [51] due to mechanical damage, processing defects, contamination with dirt, and deviations from the desired log dimensions [52]. Losses in chipping and shredding are also assumed to be 5%.

The Irish Dynamic Yield Model (GROWFOR) developed by COFORD [53], was used to estimate forest growth under the different scenarios.

2.4 Life cycle impact assessment

This study looks at two important categories in the evaluation of energy systems; global warming potential (GWP) and energy demand.

Global warming potential (GWP) is an important environmental impact to consider in the evaluation of renewable energy systems. GWP refers to the potential of the system to trap greenhouse gases in the atmosphere, leading to climate change. Gases which contribute to global warming include carbon dioxide, methane and nitrous oxide. GWP is expressed in kg CO2-equivalents [54].

Cumulative energy demand (CED) of a product or system characterises both the direct and indirect energy use throughout the life cycle. Both renewable and fossil energy are included in CED, but no product energy content [55]. It is a particularly important evaluation of bioenergy systems in order to ensure that more energy is not consumed than produced. CED is expressed in mega joules (MJ).

In addition, Huijbregts et al. [56] found that CED correlates well with most environmental life cycle impact categories and can be considered an appropriate proxy indicator for environmental performance.

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A further method of assessing 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 [57].

2.5 Allocation procedure

In a multi-output process, the environmental impacts and energy requirements must be apportioned between each valuable output. The ISO 14044 standard on Life Cycle Assessment [58] recommends avoiding allocation by expanding the system boundary to include the additional functions of the co-products, or by dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes. Where allocation cannot be avoided two methods are recommended; allocation by physical causality (mass or energy allocation), and allocation by socio-economic means, usually by economic value. In this study both mass allocation and economic allocation are used. The values used in the economic allocation procedure are outlined in Table 4.

Table 4 – Economic values for each material feedstock component

Component	Euro/odt
Roundwood	46.2
Wood chip	37.4
Shredded bundle	21.5
Shredded stump	25.1

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3 Results

3.1 Material feedstock production

Table 5 gives an overview of total material feedstock production in each of the scenarios. The table shows that implementing a thinning regime in the management of the forest stand increases the overall material feedstock production of the stand over its lifetime (41 years). Thinning increases the quantity of biomass available for energetic purposes. The bundling of residues and stump harvesting after clearfell also yields a significant quantity of biomass for use in energy generation.

Table 5 – Material feedstock production in oven dried tonnes per hectare for each scenario

	Sc 1	Sc 2	Sc 3	Sc 4	Sc 5	Sc 6	Sc 7	Sc 8
Roundwood (odt)	591.27	591.27	565.35	565.35	591.27	591.27	565.35	565.35
Wood chip (odt)	23.93	23.93	71.18	71.18	23.93	23.93	71.18	71.18
Shredded bundle (odt)	-	46.39	-	46.39	-	46.39	-	46.39
Shredded stump (odt)	-	-	-	-	41.15	41.15	41.15	41.15
Total for energy generation	**23.93**	**70.32**	**71.18**	**117.57**	**65.08**	**111.47**	**112.33**	**158.72**
Total for sawmill industry	**591.27**	**591.27**	**565.35**	**565.35**	**591.27**	**591.27**	**565.35**	**565.35**

When employing mass allocation in LCA, it is important to note that the impacts from the production of roundwood, wood chip and shredded bundles and stumps are allocated to each category based on the proportion each category contributes to the total mass produced over the production period. As such, the use of mass allocation determines the impacts of producing 1 tonne of biomass, regardless of the distinction between roundwood and chip or shredded bundle or stump. Table 6 outlines the global warming potential and energy requirements associated with production of 1 tonne of biomass in each scenario.

Table 6 – GHG emissions and energy demand per odt of material feedstock producted per scenario (mass allocation)

	Unit	Sc 1	Sc 2	Sc 3	Sc 4	Sc 5	Sc 6	Sc 7	Sc 8
GHG emissions	t CO2-eq	41	44	42	43	45	43	44	45
Energy demand	MJ	711	746	717	738	768	728	753	771

3.2 Energy use

Figure 2 outlines the contribution of each stage in the life cycle to the overall energy demand of each scenario on a hectare basis. The results show that transportation is the most energy intensive stage in the life cycle, accounting for 70 – 78% of overall energy requirements. This echoes Heinimann's [33] claim that long-distance transport and road construction, and maintenance, can account for a significant proportion of the overall burdens. Harvesting and forwarding is the second most energy intensive stage in each scenario (19 – 24% of overall energy requirements) due to the intensive use of large forest machinery.

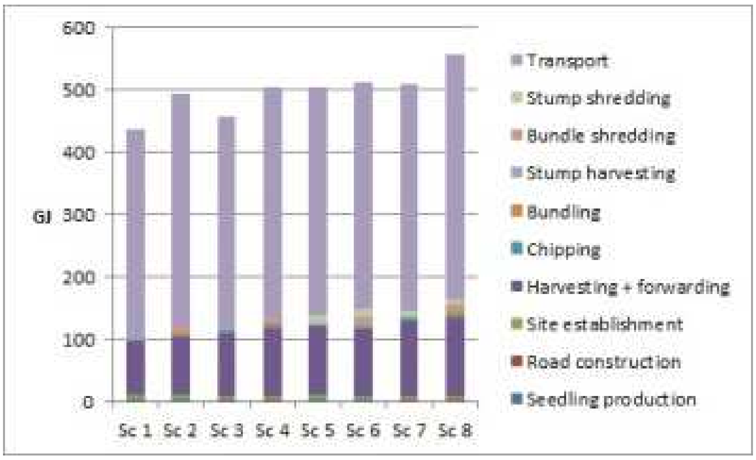

Figure 2 - Process contribution – energy demand per hectare for all scenarios

Additional interventions such as thinning and residue bundling, increases energy requirements due to the supplementary machinery operations required when compared to a no-thin or no-bundle scenario.

The results of the analysis when employing economic allocation of energy requirements are

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outlined in Table 7.

Table 7 – Energy demand (MJ) per odt of material feedstock produced in each scenario (economic allocation)

	Sc 1	Sc 2	Sc 3	Sc 4	Sc 5	Sc 6	Sc 7	Sc 8
Roundwood	717	781	733	782	796	782	790	837
Chip	581	633	594	634	645	634	641	678
Bundle	-	364	-	365	-	364	-	390
Stump	-	-	-	-	433	425	430	455

Using a gross calorific value of 19.2 GJ/odt for conifers [59], the energy ratios for the production of wood chip and shredded bundles and stump were calculated (see Figure 3 for results). The biomass bar represents the energy ratio of producing 1 odt biomass according to the results by mass allocation. The remaining bars use the economic allocation results. Shredded bundle production has the highest energy ratio in each scenario it is produced in, followed by stumps and finally wood chip.

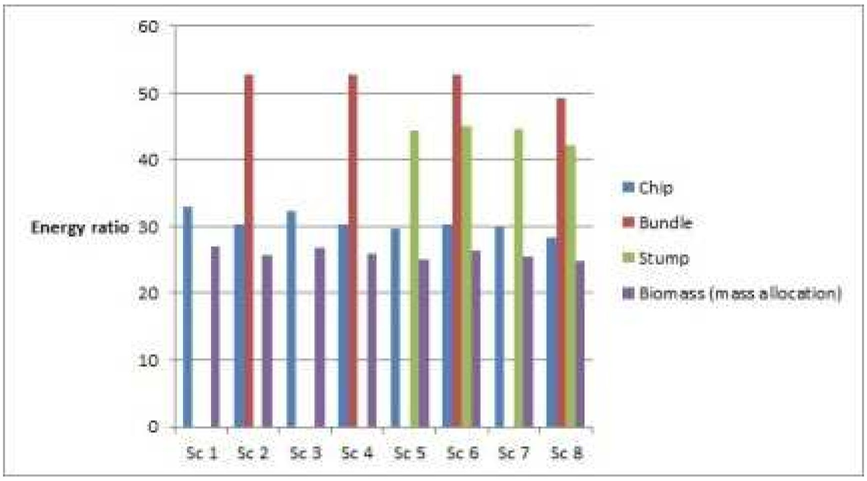

Figure 3 - Energy ratios of biomass production in each scenario – economic and mass allocation.

When employing mass allocation, the production of 1 GJ contained in biomass requires 37.1 to 40.1 MJ depending on the scenario. When employing economic allocation, 30.3 – 35.3 MJ are attributed to 1 GJ of wood chip, 19.0 – 20.3 MJ to shredded bundles, and 22.2 – 23.7 MJ to shredded stumps.

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3.3 *Greenhouse gas emissions*

Figure 4 displays the impacts associated with each step in the supply chain of each of the scenarios on a hectare basis. These results echo those of the energy analysis, again highlighting transportation as the major contributor (68 – 75%), followed by harvesting operations (21 – 26%).

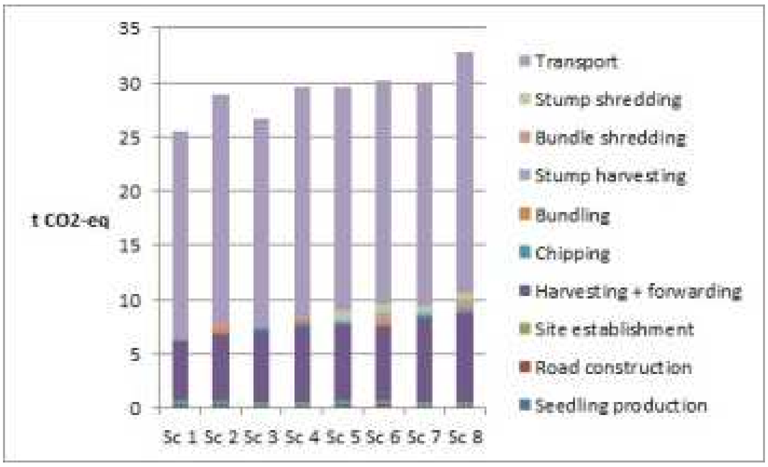

Figure 4 - Process contribution – GHG emissions per hectare for all scenarios

González-García et al. [60] reports emissions of 23.99 t CO2-eq from the intensive production of one hectare Douglas Fir in France. The analysis includes thinning and clearfelling but no residue recovery and is therefore similar to scenario 2 in Figure 4.

The results of the analysis when employing economic allocation of global warming potential are outlined in Table 8.

Table 8 – GHG emissions (kg CO_2-eq) per odt of material feedstock produced in each scenario (economic allocation)

	Sc 1	Sc 2	Sc 3	Sc 4	Sc 5	Sc 6	Sc 7	Sc 8
Roundwood	41.8	45.7	42.9	45.8	46.7	46.0	46.4	49.2
Chip	33.9	37.0	34.7	37.2	37.9	37.3	37.6	39.9
Bundle	-	21.3	-	21.4	-	21.4	-	22.9
Stump	-	-	-	-	25.4	25.0	25.3	26.8

When employing mass allocation, the production of 1 GJ contained in biomass emits 2.2 – 2.4 kg CO_2-eq per GJ depending on the scenario. When employing economic allocation, 1.8 – 2.1

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kg CO_2-eq are attributed to 1 GJ of wood chip, 1.1 – 1.2 kg CO_2-eq to shredded bundles, and 1.3 – 1.4 kg CO_2-eq to shredded stumps.

4 Discussion

This study aims to identify and evaluate energy demand and greenhouse gas emissions related to the production of roundwood, wood chip, shredded bundles and shredded stumps from a Sitka Spruce stand in Ireland. There is little research on the environmental impacts of increased harvest of forest biomass for energy generation in Ireland. This study builds on existing research by Klvac et al. [30] by considering the recovery of forest residues in addition to traditional roundwood production. The system boundary is also expanded to include the impacts from site establishment (including seedling production and road construction) to harvesting, biomass processing and transport.

The forest biomass resource is distributed over an extended geographical area, which makes transportation costly from an energy and economic point of view[61, 62]. Several studies have reported that transportation of forest biomass accounts for the majority of energy use and environmental impacts in forest biomass systems [25, 63, 64]. The results highlight that biomass transportation is the major contributor to both energy demand and GHG emissions, accounting for 70 – 78% of overall energy requirements and (68 – 75%) of GHG emissions. Ideally biomass demand centres could be located close to the source areas to reduce this affect.

Forest activities which require extensive use of large forest machinery such as harvesting and forwarding are commonly significant contributors to overall environmental impacts and energy use [22, 60]. The large quantities of fuel required during these processes result in substantial GHG emissions from fuel combustion. In this study, harvesting and forwarding are identified as the second highest contributor to energy demand (19 – 24%) and GHG emissions (21 – 26%). Biomass production is heavily reliant on fossil fuels in forest machinery and transportation vehicles, and thereby causes significant GHG emissions. A switch to more renewable fuels may positively affect the GHG performance of forest bioenergy systems.

In scenarios with higher biomass production, increased harvesting and forwarding, processing and transportation of biomass results in higher impacts per hectare and per GJ of biomass. As such, scenarios with higher impacts may appear to be the least favourable options; however, the potential for GHG mitigation by substitution of fossil fuels may increase as more biomass is available for energy generation.

Comparison of results with those of other LCA studies can be complicated by differences in system boundaries, technical systems, and geographical regions. Some studies start at forest management (including seedling production) [22, 26], some are concerned only with processes after harvesting [65].

Eriksson and Gustavsson [65] report energy requirements for wood chip, chipped bundle and stump production in Sweden of 10 MJ/GJ, 16 MJ/GJ and 24 MJ/GJ respectively (values derived from Fig. 4. Eriksson and Gustavsson 2010). These values are low in comparison to the results of this study as the boundary in Eriksson and Gustavsson [65] consider only energywood harvesting to processing and transport, but did not include site establishment or roundwood harvesting. An increase in transport distance from 45 km to 80 km resulted in an increase to 12.5 MJ/GJ for wood chip, 19.5 MJ/GJ for shredded bundle and 26 MJ/GJ for stumps (values derived from Fig. 4. Eriksson and Gustavsson 2010).

Lindholm et al. [25] also evaluated the production of chips from residues and stumps in Swedish conditions. Lindholm et al. (2010) reported energy requirements of 21 – 49 MJ/GJ of chip, and GHG emissions of 1.5–3.5 g CO2-eq/MJ chip. The higher end of these ranges is slightly higher than the results in this study. This may be down to geographical differences as average annual productivity is higher in Ireland than in Sweden. The average annual productivity of forest land in Sweden is 5.3 cubic metres per hectare (for Scots pine or Norway Spruce) [66]. The national average weighted yield class for Sitka spruce in Ireland is 17 cubic metres per hectare [8]. In addition, Lindholm et al. (2010) report an energy output/input ratio of chips from residues and stumps in the range of 21–48, however the method of allocation is not reported. This is similar to the energy ratio for the production of material feedstock when using mass allocation in this study but lower than the energy ratios obtained by economic allocation.

GHG emissions from chipped residue production in Finland were calculated by Wihersaari [27], however, the system boundary was limited to collecting, chipping and transporting the forest residues. As such, GHG emissions of 1.68 – 2 kg CO_2eq/GJ (values derived from Table

1 Wihersaari 2005), depending on harvesting and chipping methods and transportation distance, are higher than the GHG emissions estimated in this study.
Forest residue processing in the UK, a more similar geographical region to Ireland than the Scandinavian countries above, was analysed by Whittaker et al. [37]. The complete supply chain, from site establishment to processing and transport was investigated, as such; it is most similar to the analysis in this study. Whittaker et al. [37] reported GHG emissions of 5.3 kg CO_2eq/GJ of brash bales, and an associated energy requirement of 74 MJ/GJ. These values are higher than the results in this study for several reasons; in this study there are lower material requirements for road construction and maintenance, higher biomass yield is assumed, and transportation distance is higher.

In addition to wood biomass, the production of energy crops Miscanthus and short rotation coppice willow (SRCW) for energy generation is being encouraged in Ireland in order to reduce reliance on fossil fuels. The production of forest residues compares favourably with both Miscanthus and SRCW. Forest biomass produced in each scenario has a lower GHG impact than the production of SRCW chip which causes emissions of 5.84–11.65 kg CO2-eq/GJ depending on fertilisers applied, harvesting methods, and transport distances [67]. Similar forest biomass is significantly lower in GHG emissions than Miscanthus pellet production at 9.76 – 20.56 kg CO2-eq/GJ, also depending on the above factors [68]. The energy ratios of forest biomass supply chains are higher than both SRCW chip production (9.29 – 19.38), and Miscanthus pellet production [68]. As such, the study finds that the use of forest residues is less GHG and energy intensive than dedicated energy crops in Ireland.

Whilst forest biomass is tied to fossil fuel through the production and use of forest machinery and transportation, it nevertheless remains a superior energy source to fossil fuels. The energy ratios of all biomass scenarios are significantly higher than both coal and peat which have an energy ratio of 2 and 5, respectively [69], implying that more energy is required to produce these fuels.

GHG emissions associated with biomass production in all scenarios are significantly lower than coal supply which emits ca. 12.28 kg CO2-eq per GJ of coal [69]. GHG emissions from peat provision of approximately 2.27 kg CO2-eq per GJ of peat [69] are similar to GHG emissions of biomass production when mass allocation is employed. However, when emissions are allocated based on economic value, production of wood chip and forest residues causes lower GHG emissions than peat.

5 Conclusion

This study builds on research within the wood-for-energy concept in Ireland by analysing the energy requirements and greenhouse gas emissions associated with thinning, residue bundling and stump removal for energy purposes. To date there have been no studies on harvesting of residues and stumps in terms of energy balances and GHG emissions across the life cycle in Ireland. The study addresses that gap and expands the boundaries of analysis compared to previous studies in an Irish context. The results of the analysis on the life cycle of wood energy supply chains highlights transport as the most energy and GHG step. This finding illustrates importance of localised production and use of forest biomass. Production of wood chip, and shredded bundles and stumps, compares favourably with both other sources of biomass and fossil fuels.

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