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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<sup>3</sup> over bark (OB) in 2011 to 3 million m<sup>3</sup> 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

2  
3 The EU Renewable Energy directive requires 16% of gross final energy consumption in  
4 Ireland to come from renewable resources by 2020. The contribution of renewable energy to  
5 overall energy demand reached 5.6% in 2010 [1], with biomass comprising 29% of this total.  
6 This biomass is comprised of wood and wood waste as thermal energy, with smaller  
7 contributions from electricity generated from biomass and biogas along with transport liquid  
8 biofuels [1].

9 Ireland's forests are an important source of biomass for the timber industry and for energy  
10 generation. At the beginning of the 1900s, forest cover in Ireland stood at only 1% of total  
11 land. However thanks to state afforestation programs this had risen to approximately 11% in  
12 2011 [2], with the aim of achieving 17% forest cover by 2030 [3]. Overall, approximately 6%  
13 of total land in Ireland can be classified as productive forest land [4]. The demand for wood  
14 for energy production is predicted to increase from 1.5 million m<sup>3</sup> over bark (OB) in 2011 to 3  
15 million m<sup>3</sup> OB by 2020 [5].

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

25 Ireland has a large number of young conifer plantations that are approaching the age of first  
26 thinning [10]. Thinning of a forest plantation is a silvicultural operation which involves the  
27 removal of part of the crop in order to concentrate future volume growth on fewer and better  
28 quality stems [11]. Thinning reduces the time taken for trees to reach valuable sawlog size,

29 and provides an additional source of biomass during the forest rotation [12]. The net realisable  
30 volume production by thinnings in Ireland is projected to increase from nearly 1 million m<sup>3</sup>  
31 over bark in 2011 to nearly 2 million m<sup>3</sup> over bark in 2028 [13], and as such can provide an  
32 important source of wood for the forest industry.

33 There is still a large potential for additional biomass recovery by harvesting of tops and  
34 branches and stumps which can be utilised for energetic purposes [14]. In Ireland, forest  
35 residues, i.e. tops and branches, tops of trees, and stumps, etc. have traditionally been left in  
36 the forest after clearfell. Occasionally some of the larger waste wood is removed as firewood  
37 for domestic consumption but this does not occur on any scale. The residues are used as a  
38 brush mat to improve trafficability of strip roads for the harvester and forwarder during timber  
39 extraction [15]. Interest in forest residue harvesting for energetic purposes has increased in  
40 recent years as demand has risen for bioenergy sources. Recent trials by Coillte, the state-  
41 owned forestry company, estimate that up to 80 green tonnes per ha of this biomass material  
42 can be recovered on suitable sites, depending on species, age, site type and wood assortments  
43 harvested [16]. It is estimated that raw material in the 'tip – 7 cm' category will increase from  
44 48,000 m<sup>3</sup> in 2011 to 61,000 m<sup>3</sup> by 2020 [13]. However, due to environmental constraints and  
45 restricted soil types, this resource is only likely to be available on about 35% of harvest sites  
46 in Ireland [16].

47 There is no stump harvesting currently carried out on a commercial scale in Ireland. Research  
48 trials are being carried out by Coillte and Waterford Institute of Technology (WIT) on the  
49 feasibility and productivity of stump harvesting in Ireland. Stump harvesting results in  
50 increased intensification of forest management when compared to conventional systems with  
51 only above-ground biomass harvesting. Benefits of stump harvesting include; increased  
52 production of wood energy resources, reduced CO<sub>2</sub> emissions when compared with fossil  
53 fuels [17, 18], and improved site preparation and potential reduction of Heterobasidion [19].  
54 The soil disturbance resulting from stump harvesting can also affect the forest soil carbon  
55 store by decreasing the amount of carbon stored in forest and thus causing indirect CO<sub>2</sub>  
56 emissions into the atmosphere [20, 21], and also influences forest nutrient stocks [19].

57 Understanding the environmental impacts of timber production and processing has been an  
58 important focus of research over the last number of years. The Scandinavian countries have  
59 been particularly active in this area, carrying out life cycle analyses of a range of wood

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60 products from roundwood, to residue bundles and stumps [22-28]. Production of wood chips  
61 in the US, the largest wood producer in the world, has also been studied [29]. In Ireland,  
62 aspects of timber production have been studied from an environmental point of view, mainly  
63 focusing on harvesting operations [30]. Consequently, there is a lack of research on  
64 environmental impacts of forestry production over the entire life cycle from seedling  
65 production, to harvesting, transport and processing.

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

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

79 Another issue in LCA is the delineation of system boundaries to exclude the burdens  
80 associated with machinery production and forest road construction and maintenance. The  
81 energy embodied in the harvesting machinery can equal up to 40-50% of the direct process  
82 energy [33]. In addition, Heinemann [33] states approximately 60% of the overall  
83 environmental burdens of forestry production can be caused by road construction and  
84 maintenance, along with long-distance transport. As such, excluding these elements of the  
85 production chain from the system boundary could result in significantly underestimating the  
86 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<sup>3</sup>) [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

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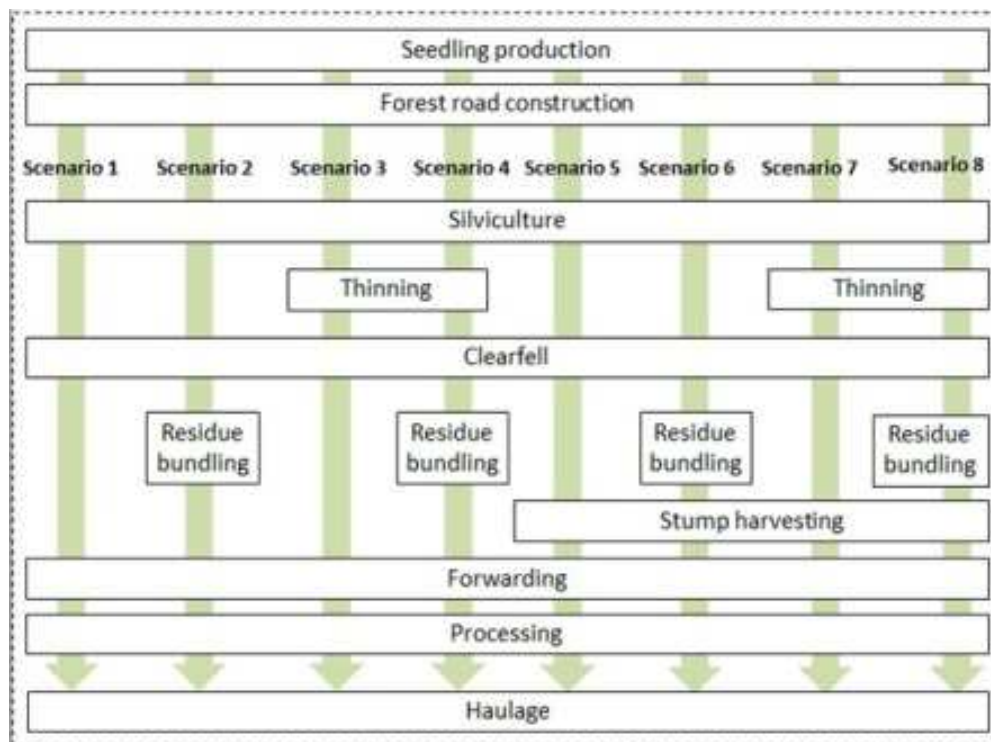
123 shredded at the end user, this step is included in the analysis. It should be noted that the study  
124 does not consider carbon sequestration in the forest, nor does it include emissions of  
125 mineralized carbon due to the disturbance of the soil during stump lifting.

126

## 127 2.2 System description

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

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

145

146 Seedlings are produced in nursery conditions. New forest roads are constructed to allow  
147 access to and from the afforested site. New roads are constructed to a density of 0.005 km/ha  
148 [37]. Road maintenance is also carried out before each harvesting event.

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

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

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

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

171 The remainder, termed ‘tops and branches’ or ‘forest residues’, are traditionally left in the  
172 forest after harvest. However, this study looks at bundling these residues in four of the eight  
173 supply chain scenarios considered. In these scenarios, residue is removed after clearfelling, as

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174 such there is one residue removal event in the life cycle. Harvest residues are collected and  
 175 bundled using a dedicated bundler system. The bundles are harvested on a green basis and  
 176 contain 0.33 tonnes per bundle at 60% MC [41]. The bundles are transported and are stored  
 177 on-site at the end user and are shredded after a period of drying.

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

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

185

186

**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

187

188

### 189 2.3 Data inventory

190

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

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196 **Table 2 – Chronosequence data for Doonary site at age 14 [7]**

Yield class (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	Stem (ha <sup>-1</sup> )	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

197

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

200

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

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

202

203

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

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

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

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

225 In harvesting, approximately 5% of the value is lost [51] due to mechanical damage,  
226 processing defects, contamination with dirt, and deviations from the desired log dimensions  
227 [52]. Losses in chipping and shredding are also assumed to be 5%.

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

230

#### 231 *2.4 Life cycle impact assessment*

232

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

235 Global warming potential (GWP) is an important environmental impact to consider in the  
236 evaluation of renewable energy systems. GWP refers to the potential of the system to trap  
237 greenhouse gases in the atmosphere, leading to climate change. Gases which contribute to  
238 global warming include carbon dioxide, methane and nitrous oxide. GWP is expressed in kg  
239 CO<sub>2</sub>-equivalents [54].

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

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

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248 A further method of assessing advantages of renewable energy systems may be to evaluate the  
249 pure energy ratio of the system. The term "energy ratio" is used to characterize relations  
250 between the energy input and output. Energy ratio is a ratio between the energy output and  
251 energy input [57].

252

### 253 *2.5 Allocation procedure*

254

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

264

265

**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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277 3 Results

278

279 3.1 Material feedstock production

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

286

287 **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
<b>Total for energy generation</b>	<b>23.93</b>	<b>70.32</b>	<b>71.18</b>	<b>117.57</b>	<b>65.08</b>	<b>111.47</b>	<b>112.33</b>	<b>158.72</b>
<b>Total for sawmill industry</b>	<b>591.27</b>	<b>591.27</b>	<b>565.35</b>	<b>565.35</b>	<b>591.27</b>	<b>591.27</b>	<b>565.35</b>	<b>565.35</b>

288

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

296

297

298

299

300 **Table 6 – GHG emissions and energy demand per odt of material feedstock produced per scenario (mass**  
 301 **allocation)**

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

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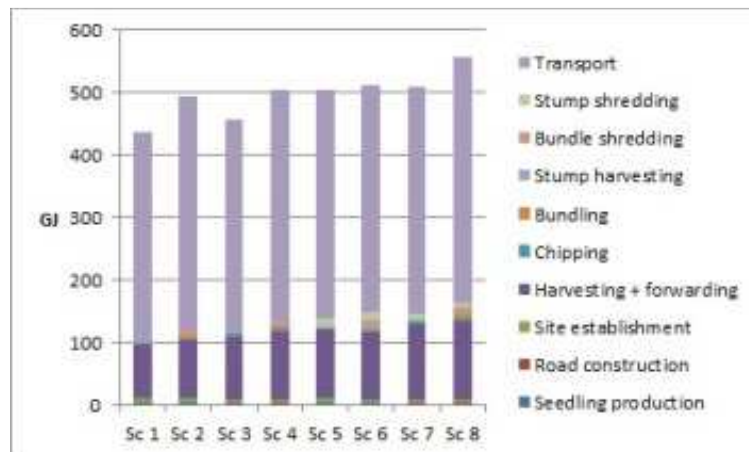
305

306 **3.2 Energy use**

307

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

315



316

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

318

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

322

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

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324 outlined in Table 7.

325

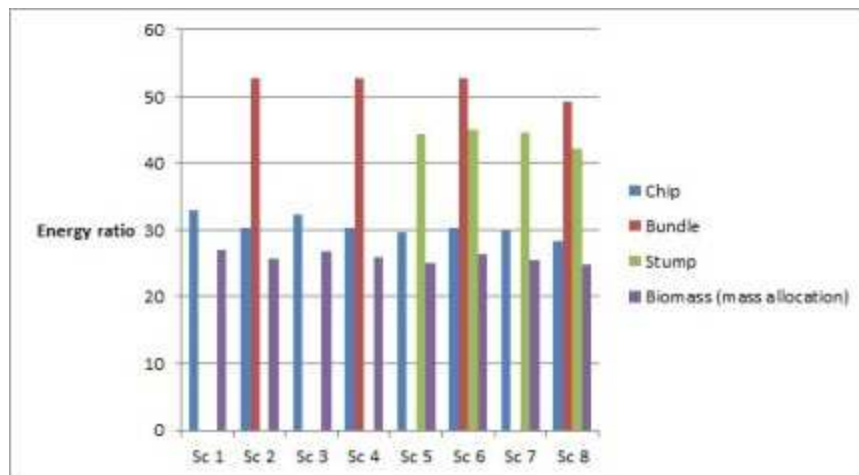
326 **Table 7 – Energy demand (MJ) per odt of material feedstock produced in each scenario (economic**  
327 **allocation)**

	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

328

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

335



336

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

339

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

344

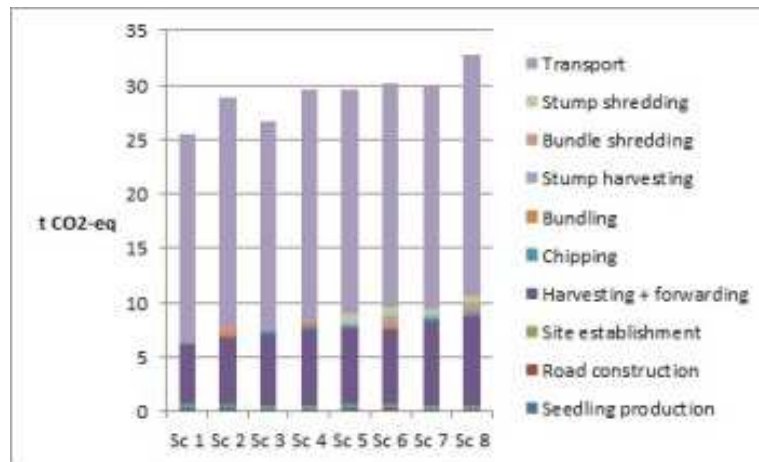
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345 3.3 Greenhouse gas emissions

346

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

351



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

353

354  
 355 González-García et al. [60] reports emissions of 23.99 t CO<sub>2</sub>-eq from the intensive production  
 356 of one hectare Douglas Fir in France. The analysis includes thinning and clearfelling but no  
 357 residue recovery and is therefore similar to scenario 2 in Figure 4.

358

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

361

362 **Table 8 – GHG emissions (kg CO<sub>2</sub>-eq) per odt of material feedstock produced in each scenario (economic  
 363 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

364

365 When employing mass allocation, the production of 1 GJ contained in biomass emits 2.2 – 2.4  
 366 kg CO<sub>2</sub>-eq per GJ depending on the scenario. When employing economic allocation, 1.8 – 2.1

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367 kg CO<sub>2</sub>-eq are attributed to 1 GJ of wood chip, 1.1 – 1.2 kg CO<sub>2</sub>-eq to shredded bundles, and  
368 1.3 – 1.4 kg CO<sub>2</sub>-eq to shredded stumps.

369

370

#### 371 4 Discussion

372

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

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

389 Forest activities which require extensive use of large forest machinery such as harvesting and  
390 forwarding are commonly significant contributors to overall environmental impacts and  
391 energy use [22, 60]. The large quantities of fuel required during these processes result in  
392 substantial GHG emissions from fuel combustion. In this study, harvesting and forwarding are  
393 identified as the second highest contributor to energy demand (19 – 24%) and GHG emissions  
394 (21 – 26%). Biomass production is heavily reliant on fossil fuels in forest machinery and  
395 transportation vehicles, and thereby causes significant GHG emissions. A switch to more  
396 renewable fuels may positively affect the GHG performance of forest bioenergy systems.

397 In scenarios with higher biomass production, increased harvesting and forwarding, processing  
398 and transportation of biomass results in higher impacts per hectare and per GJ of biomass. As

399 such, scenarios with higher impacts may appear to be the least favourable options; however,  
400 the potential for GHG mitigation by substitution of fossil fuels may increase as more biomass  
401 is available for energy generation.

402

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

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

415 Lindholm et al. [25] also evaluated the production of chips from residues and stumps in  
416 Swedish conditions. Lindholm et al. (2010) reported energy requirements of 21 – 49 MJ/GJ of  
417 chip, and GHG emissions of 1.5–3.5 g CO<sub>2</sub>-eq/MJ chip. The higher end of these ranges is  
418 slightly higher than the results in this study. This may be down to geographical differences as  
419 average annual productivity is higher in Ireland than in Sweden. The average annual  
420 productivity of forest land in Sweden is 5.3 cubic metres per hectare (for Scots pine or  
421 Norway Spruce) [66]. The national average weighted yield class for Sitka spruce in Ireland is  
422 17 cubic metres per hectare [8]. In addition, Lindholm et al. (2010) report an energy  
423 output/input ratio of chips from residues and stumps in the range of 21–48, however the  
424 method of allocation is not reported. This is similar to the energy ratio for the production of  
425 material feedstock when using mass allocation in this study but lower than the energy ratios  
426 obtained by economic allocation.

427 GHG emissions from chipped residue production in Finland were calculated by Wihersaari  
428 [27], however, the system boundary was limited to collecting, chipping and transporting the  
429 forest residues. As such, GHG emissions of 1.68 – 2 kg CO<sub>2</sub>eq/GJ (values derived from Table

430 1 Wihersaari 2005), depending on harvesting and chipping methods and transportation  
431 distance, are higher than the GHG emissions estimated in this study.

432 Forest residue processing in the UK, a more similar geographical region to Ireland than the  
433 Scandinavian countries above, was analysed by Whittaker et al. [37]. The complete supply  
434 chain, from site establishment to processing and transport was investigated, as such; it is most  
435 similar to the analysis in this study. Whittaker et al. [37] reported GHG emissions of 5.3 kg  
436 CO<sub>2</sub>eq/GJ of brash bales, and an associated energy requirement of 74 MJ/GJ. These values  
437 are higher than the results in this study for several reasons; in this study there are lower  
438 material requirements for road construction and maintenance, higher biomass yield is  
439 assumed, and transportation distance is higher.

440

441 In addition to wood biomass, the production of energy crops Miscanthus and short rotation  
442 coppice willow (SRCW) for energy generation is being encouraged in Ireland in order to  
443 reduce reliance on fossil fuels. The production of forest residues compares favourably with  
444 both Miscanthus and SRCW. Forest biomass produced in each scenario has a lower GHG  
445 impact than the production of SRCW chip which causes emissions of 5.84–11.65 kg CO<sub>2</sub>-  
446 eq/GJ depending on fertilisers applied, harvesting methods, and transport distances [67].  
447 Similar forest biomass is significantly lower in GHG emissions than Miscanthus pellet  
448 production at 9.76 – 20.56 kg CO<sub>2</sub>-eq/GJ, also depending on the above factors [68]. The  
449 energy ratios of forest biomass supply chains are higher than both SRCW chip production  
450 (9.29 – 19.38), and Miscanthus pellet production [68]. As such, the study finds that the use of  
451 forest residues is less GHG and energy intensive than dedicated energy crops in Ireland.

452

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

458

459 GHG emissions associated with biomass production in all scenarios are significantly lower  
460 than coal supply which emits ca. 12.28 kg CO<sub>2</sub>-eq per GJ of coal [69]. GHG emissions from

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461 peat provision of approximately 2.27 kg CO<sub>2</sub>-eq per GJ of peat [69] are similar to GHG  
462 emissions of biomass production when mass allocation is employed. However, when  
463 emissions are allocated based on economic value, production of wood chip and forest residues  
464 causes lower GHG emissions than peat.

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## 475 5 Conclusion

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

486

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## 509 6 References

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