Life Cycle Assessment of Biomass-to-Energy Systems in Ireland Modelled with Biomass Supply Chain Optimisation based on Greenhouse Gas Emission Reduction.

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Abstract

The energy sector is the major contributor to greenhouse gas emissions (GHG) in Ireland. Under EU Renewable energy targets, Ireland must achieve contributions of 40%, 12% and 10% from renewables to electricity, heat and transport respectively by 2020, in addition to a 20% reduction in GHG emissions. Life cycle assessment methodology was used to carry out a comprehensive, holistic evaluation of biomass-to-energy systems in 2020 based on indigenous biomass supply chains optimised to reduce production and transportation GHG emissions. Impact categories assessed include; global warming, acidification, eutrophication potentials, and energy demand. Two biomass energy conversion technologies are considered; co-firing with peat, and biomass combined heat and power (CHP) systems. Biomass is allocated to each plant according to a supply optimisation model which ensures minimal GHG emissions. The study shows that while CHP systems produce lower environmental impacts than co-firing systems in isolation, determining overall environmental impacts requires analysis of the reference energy systems which are displaced. In addition, if the aims of these systems are to increase renewable energy penetration in line with the renewable electricity and renewable heat targets, the optimal scenario may not be the one which achieves the greatest environmental impact reductions.

Highlights

- Life cycle assessment of biomass co-firing and CHP systems in Ireland is carried out.
- GWP, acidification and eutrophication potentials, and energy demand are assessed.
- Biomass supply is optimised based on minimising GHG emissions.
- CHP systems cause lower environmental impacts than biomass co-firing with peat.
- Displacing peat achieves higher GHG emission reductions than replacing fossil heat.

1   Introduction

The energy sector is the major contributor to greenhouse gas emissions in Ireland, accounting for 63% (37 Mt CO_2-equivalent) of total national greenhouse gas emissions (GHG) in 2012 [1]. The emissions from the electricity and thermal generation subsectors were 12.8 Mt CO_2-equivalent and 12.4 Mt CO_2-equivalent respectively [2]. Natural gas, coal and peat use account for the majority of GHG emissions from electricity generation at 4.8 Mt CO_2-eq (38%), 4.6 CO_2-eq Mt (36%), and 2.7 Mt CO_2-eq (21%) respectively [3]. The combined annual electricity output from the 3 state-owned peat-fired power plants is 370 MWe, which equates to 12% of Ireland's total primary energy requirement for electricity generation [4].

Ireland's specific requirements under the EU 2020 targets [5] are to achieve contributions of renewable energy of 40%, 12% and 10% to electricity (RES-E), heat (RES-H) and transport (RES-T) respectively by 2020 [6]. 'Renewable' in this case means energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases [5]. In addition to this, a 20% reduction in GHG emissions and a 20% increase in energy efficiency is to be achieved by 2020 [7]. Each EU country has set their own indicative national energy efficiency target which can be based on primary or final energy consumption, primary or final energy savings, or energy intensity [8]. With the aim of meeting these targets and reducing GHG emissions in line with the Kyoto protocol [9], the Irish Government has implemented co-firing targets for the 3 state-owned peat-fired power plants. Under these targets, biomass is to be co-fired with peat at a rate 30% of the maximum rated capacity until 2017, 40% between 2017 and 2019, and 50% thereafter [6]. In addition to this the government aims to have 800 MW of installed Combined Heat and Power (CHP) capacity by 2020, with particular emphasis on biomass fuelled CHP [10]. In 2012, the total renewable electricity penetration reached 19.6% with wind energy accounting for over 15.3% of all electricity generation in 2012, hydro accounting for 2.7%, and biomass only contributing 1.6% mainly from co-firing and landfill gas [2]. The renewable energy contribution towards the RES-H target reached 5.2% in 2012, with the use of solid biomass (wood) and renewable wastes (tallow) accounting for the majority (84%) of overall renewable heat consumption [2].

Solid biomass is the main source of bioenergy for both electricity and heat generation in Ireland. Indigenous sources of solid biomass include; forest wood chip and forest residues, wood chip and wood pellets from the wood processing industry, and energy crops (willow and miscanthus). The biomass resource base in Ireland is expanding in part due to state afforestation programs and government support for bioenergy crop production. The availability of wood fibre from forestry for energy generation in Ireland is forecast to increase from 1 million m^3 in 2011 to 1.5 million m^3 in 2020. In addition to this source of biomass, the Irish government is incentivising the production of bioenergy crops for use as a renewable source of energy through the Bioenergy Scheme which was introduced in 2007 [11]. It is estimated that the cultivation of willow and miscanthus

energy crops will expand to 6,000 ha by 2020, at the current price level [12]. As the potential supply of the indigenous biomass resources is limited, it is imperative to optimise the production, processing, and use of this biomass in energy generation to ensure optimal GHG emissions reductions compared to the reference fossil energy scenarios. Developing sustainable biomass supply chains depends on determining a number of key factors including; harvesting and processing techniques, transportation distances, and final energy conversion technology [13]. Final energy conversion technologies considered include co-firing in the existing peat-fired power stations and the development of new biomass CHP plants to potentially replace existing fossil heating plants in a decentralised approach to energy generation. These scenarios differ in conversion efficiency, biomass requirements, and plant location relative to the biomass resource. It is important to compare the environmental performance of each scenario to determine the optimal GHG emissions reductions and to determine the optimum biomass resource mix for each plant.

Life cycle assessment (LCA) is comprehensive sustainability assessment tool which can be used to analyse the environmental impacts of biomass-to-energy systems over the entire life cycle; from biomass production, processing, and transportation, to combustion [14]. By including the impacts from each stage life cycle, LCA can provide the environmental impacts of a number of scenarios based on selection of different production or processing techniques.

Supply chain planning in the bioenergy sector encompasses a wide range of complex decisions, from strategic to operational level, and these decisions are usually supported by optimisation-based decision support tools [15]. Where to locate power plants and how to supply biomass to each plant is known as a location-allocation problem, where the global objective is typically to minimise the supply chain cost [16].

1.1   LCA studies of biomass-to-energy systems

The majority of studies concerned with the LCA of co-firing have focused on co-firing biomass with coal [17-20]. A small number analyse biomass co-firing with peat, these studies are mainly limited to Ireland [21, 22]. A wide range of biomass feedstocks used in co-firing have been researched including; energy crops [20, 22-27], and agricultural and forest residues [28-32]. Assessment of the environmental impacts is limited to GHG emissions and global warming potential (GWP), and energy balance in many of the reviewed studies, with some expanding the analysis to look at additional impacts such as acidification potential (AP), and eutrophication potential (EP) [17, 20, 29, 30].

There is a wide range of literature pertaining to the LCA of CHP systems utilising a variety of biomass types including; willow [33-35], agricultural residues [36, 37], and wood residues [38-41]. Several impact categories have been considered in LCA of CHP systems, including; GWP, AP, EP, photochemical oxidation potential, abiotic depletion and energy use [42-44]. The nature of CHP systems with two useful energy outputs requires consideration of how to determine the environmental impacts of each product separately. Several different methods for dealing with the co-production of electricity and heat have been used. Allocation can be avoided by the use of system expansion where the electricity generated displaces the marginal electricity mix [36] or

electricity generated in utility plants [35]. There are a number of methods for the allocation of environmental impacts between each product of the CHP, including; allocation based on operational characteristics (grid electricity only, district heat only, credits for grid electricity, credits for district heat) [41], allocation based on thermodynamic properties such as exergy [33, 39, 40] and energy [38, 39, 41], and also allocation based on the economic value of the products [38, 39].

1.1.1   Optimisation and LCA

In recent years there has been increased interest in the use of spatial data in the determination of biomass resource availability with which to meet the energy requirements of existing energy systems or support the introduction of new biomass-to-energy systems [16, 45-47]. A number of studies have integrated such spatial modelling with life cycle assessment methodology with the aim of determining life cycle environmental impacts by linking the impacts of biomass cultivation and transportation with the potential or existing resource availability in the supply chain [48-51].

A number of studies have used mathematical programming in developing optimisation models in order to gain insight into the logistics of biomass supply chains and to improve the efficiency of these supply chains by maximising or minimising one or more parameters considering scarce resources   [52]. Typically, an optimisation problem is comprised of an objective function (linear or non-linear equation) expressed as a mathematical function of decision variables and other parameters that will be maximised or minimised according to the necessity of the problem, and a set of constraints (linear or non-linear inequalities or equations) [53]. Historically, these models have been used to optimise the economic performance of the supply chain, however recently efforts have been to include both environmental and societal impacts in the optimisation model [54, 55]. Several environmental impacts have been considered; some studies on carbon emissions [56, 57] and include energy analysis [58-60], while others have looked at an expanded range of environmental impacts [61, 62].

1.1.2   Carbon balance of bioenergy systems

Forested land contains a considerable store of carbon both above and below-ground [63], and are an important sink for atmospheric carbon on a global scale [64]. Forests contribute to reductions in atmospheric CO_2 in the atmosphere in numerous ways; through sequestration of carbon in biomass, soil and wood products, replacement of fossil fuel with wood energy, and through the use of harvested wood products [65]. There is debate regarding the most efficient method to reduce carbon emissions; by sequestration in forests, or by managing forests for wood extraction to replace fossil fuels in energy generation, and replacement of energy-intensive materials such as plastics and cement [66-71]. According the 'Marland principle', in-forest sequestration and forest bioenergy usage are equally valid means of lowering net carbon emissions with the choice between preserving the forest and harvesting it for bioenergy depending on; energy conversion efficiency, forest productivity, current status of land, and the time perspective used [72]. The type and carbon intensity of fossil fuel that is replaced with forest bioenergy is also important [73, 74].

The debate on the best use of forest resources has prompted an increase in research on the carbon balance of bioenergy systems based on residue removal [75-79]. Still, many LCA studies on bioenergy systems assume biomass 'carbon neutrality' or that the carbon taken in during biomass growth is equal to carbon emitted in combustion [38, 40, 80-82]. This approach may underestimate the impacts of bioenergy systems based on forest residues by failing to consider the impact of increasingly intensified harvests on soil and biomass carbon stocks [83, 84]. In conventional harvest systems, brash (tops and branches of trees) and stumps are left in-forest after clearfell, creating an additional input to the soil carbon stock. The removal of brash and/or stumps after clearfell reduces the additional input of carbon to the forest soil and may cause a decline in soil carbon stock [85, 86]. In turn, this reduction in soil organic matter input leads to reduced biomass productivity due to the role played by soil organic matter in maintaining biological fertility, chemical fertility, and physical fertility [87]. The removal of stumps and biomass containing large quantities of foliage and bark also leads to the depletion of soil nutrient stocks and causes changes in nutrient cycling which will lead to loss of long term productivity in the forest unless these nutrients are replaced [87, 88].

Indirect carbon dioxide emissions occur when carbon is released from the harvested brash and stumps immediately during combustion, instead of the residues being left in-forest emitting biogenic carbon from gradual decomposition [79, 85]. In the case of residue removal for replacement of fossil energy, carbon emissions from fossil fuel are avoided, however fossil carbon emissions do occur due to fossil fuel use in biomass harvesting and transportation. If the residues are left in-forest and allowed to decompose, an equivalent quantity of fossil fuel will be used instead, resulting in immediate fossil emissions [79]. It is important that these trade-offs be analysed for bioenergy systems to ensure net carbon reductions compared to fossil energy systems.

2   Materials and methods

2.1   Goal and scope

The aim of this study is to assess biomass resource availability for the year 2020, enabling the optimisation of biomass-to-bioenergy systems using LCA modalities through adjustment of the relative contribution of each biomass feedstock to the energy chain, specifically relating to biomass co-firing with peat at the 3 existing peat-fired power plants in Ireland, and biomass CHP systems. A co-firing rate of 50% is to be achieved in each of the power plants by 2020 [6].

2.1.1   System description

This study focuses on co-firing of biomass with peat in the 3 peat-fired power plants in Ireland; Edenderry Power Plant (P1), West Offaly Power Plant (P2), and Lough Ree Power Plant (P3), and sole biomass combustion in CHP plants. The co-firing power plant efficiency is approximately 37%, i.e. 37% of the primary energy supplied from the fuel is converted to electricity. The CHP systems achieve 90% efficiency. The indigenous

sources of biomass considered are pulpwood from Sitka spruce, forest residues, sawmill residues, and energy crops willow and miscanthus. The system diagram is outlined in figure 1.
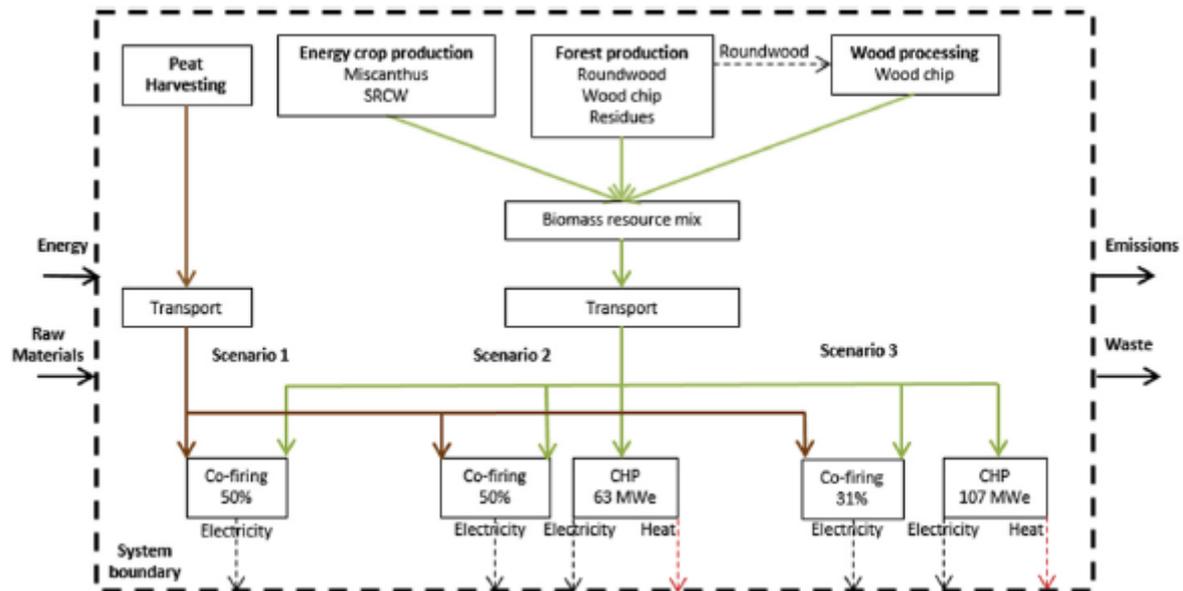
Fig. 1. System diagram.

Three biomass-to-energy systems scenarios (SC) are analysed in this study;

- Scenario 1 (SC1) – The potentially available biomass resources in 2020 are allocated to the 3 peat-fired power plants in order to meet the 50% (by energy) co-firing rate at each plant. The biomass supply mix to each plant is optimised to ensure minimal GHG emissions from production and transportation.
    - Reference scenario – 100% peat firing in each of the power plants.
- Scenario 2 (SC2) – The 50% co-firing rate as above applies to this scenario. In addition, 6 potential CHP plant locations are identified based on existing industry heat demands (from fossil fuels oil and coal). 63 MWe of biomass CHP capacity is installed to provide the equivalent heat output. The biomass sources suitable for CHP plants are; clean wood chip, forest wood chip, willow and miscanthus. Biomass supply to each plant is optimised to ensure minimal GHG emissions from production and transportation.
    - Reference scenario – 100% peat firing in each of the power plants. Industrial heat demand is met by fossil fuels and electricity is provided by the national grid.
- Scenario 3 (SC3) – Preference is given to allocate biomass a total of 15 CHP plants (107 MWe of installed capacity) – this is an additional 9 to the 6 plants identified in Scenario 2. The remaining biomass is allocated to the 3 co-firing plants, achieving a co-firing rate of 31%.

The three scenarios also consider Ireland's two wood-based panel (WBP) board mills competing for forest biomass when it comes to biomass allocation within the supply model. One of the mills (M1) produces medium-density fibreboard (MDF) and the second mill (M2) produces oriented strand board (OSB). The environmental impacts of production at these mills are not considered in the analysis.

The locations of the biomass supply, and demand locations; co-firing power plants, CHPs, and WBP mills, are shown in figure 2.
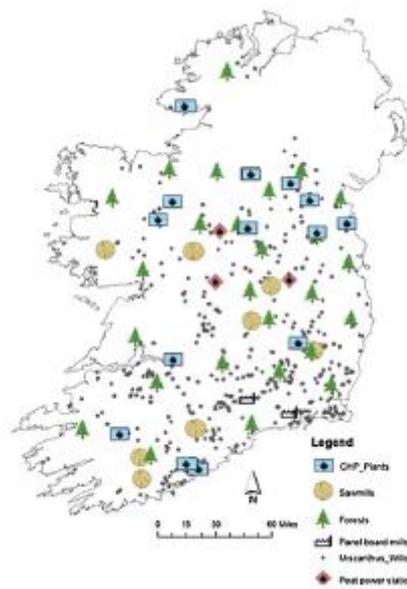
Fig. 2. Supply and demand location.

Description of the biomass supply chains;

- Forest biomass supply chains are described by Murphy et al. [31]. Roundwood and pulpwood are harvested by the cut-to-length system and are forwarded to the roadside. The pulpwood is left to season for at least one summer in order to reduce the moisture content prior to chipping and transportation by truck to the power plants. After harvest, the brash is left on the forest floor in order to allow the needles to fall off and to reduce the moisture content. The brash is bundled using a dedicated bundler system and transported by truck to the power plants where it is subsequently shredded.

  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 transported by truck to the power plants.

- Miscanthus supply chains are described by Murphy et al. [26]. Miscanthus is harvested on a yearly basis. The crop is mown and left in the field to dry before baling. The bales are subsequently transported 5 km to the farm yard where it is transferred to truck and delivered to the power plants. The bales are shredded prior to combustion.

- Willow supply chains are described by Murphy et al. [27]. Willow is harvested once every 3 years. Willow is harvested in rod form, it is then transported 5 km to the farm yard where the rods dry to 25% moisture content (MC). The rods are subsequently chipped, transferred to a truck and delivered to the power plants.

- Clean wood chip is produced as a co-product in the sawmilling process [32]. It is then transported by truck to the power plants.

The yield and properties of the biomass feedstocks considered in this study are outlined in table 1.

Table 1 Biomass data.

	Yield (odt.ha^{-1})	MC at harvest (%)	MC at delivery (%)	Bulk density (kg.m^{-3})	Gross Calorific Value (MJ.kg^{-1})	Net Calorific Value at MC (MJ.kg^{-1})
Bioenergy crops						
Miscanthus (per harvest)	11.5	30	20	-	18.3[a]	13.4
Miscanthus bale	-	-	-	150	-	-
Miscanthus chip	-	-	-	100	-	-
Willow (per harvest)	30	55	-	-	-	-
Direct chip			55	285	19.7[b]	7
Rod			25	150	-	13.2
Forest biomass						
Forest pulpwood chips	-	-	40	276	19.1[c]	10.5
Bundles	51	60	40	195	-	10.5
Shredded bundles	-	-	-	340	-	
Stumps	45	67	39	122	18.1[d]	
Shredded stumps	-	-	-	237	-	10.5
Sawmill co-products						
Clean wood chip			30	206	19.2[e]	12.6

[a] [89], [b] [90], [c] [52], [d] Billy Horgan Personal Communication, [e] [91].

2.1.2 Allocation

Allocation of environmental impacts is required in the supply chains producing multiple outputs; forestry (roundwood and energy products; wood chip, bundles, stumps) and sawmilling (sawnwood, chip, sawdust, bark). Allocation methods are discussed in more detail in the publications relevant to these supply chains [31]. In this study mass allocation between co-products is used when necessary, in line with ISO standards [92]. Allocation is also required in the CHP systems in determine the environmental impacts both heat and electricity production separately. Several different methods for dealing with the co-production of electricity and heat have been used. In this study allocation is carried out based on the energy of each product produced.

2.2 Data Inventory

The data required for in this can be broken down into 3 distinct areas; biomass resource assessment, life cycle assessment data, and the optimisation model. The data requirements for each area are discussed below.

2.2.1 Biomass resource assessment

Potentially available forestry resources are based on the Council for Forest Research and Development (COFORD) roundwood production forecast [93]. The roundwood production forecast estimates net realisable pulpwood volume in 2020 for each county in Ireland. The net realisable volume includes reductions for harvest loss, accessibility and crops unlikely to be harvested [93]. Sitka spruce accounts for 84% of this total volume [94]. Pulpwood logs are delivered to the WBP mills with an average moisture content (MC) of 56%, while pulpwood chip is delivered to the power plants at MC of 40%. The potentially available energy in pulpwood chip at this moisture content is shown in table 2.

Table 2 Total biomass availability for 2020 (TJ).

County	Pulpwood	Brash/Bundles	Stumps	Miscanthus	Willow	Total Biomass
Carlow	112	6	3	23	6	151
Cavan	319	18	11	4	103	455
Clare	1,238	70	42	3	0	1,353
Cork	1,870	106	56	98	14	2,143
Donegal	1,761	99	43	2	53	1,957
Dublin	57	3	2	3	5	70
Galway	1,295	73	31	29	6	1,434
Kerry	1,458	82	41	26	14	1,620
Kildare	136	8	2	23	89	257
Kilkenny	432	24	9	64	16	545
Laois	480	27	17	20	0	544
Leitrim	716	40	26	-	0	782
Limerick	586	33	15	101	0	735
Longford	247	14	6	3	33	303
Louth	33	2	1	3	21	60
Mayo	1,564	88	29	9	8	1,697
Meath	100	6	2	7	92	207
Monaghan	71	4	3	5	67	150
Offaly	340	19	11	10	35	416
Roscommon	586	33	19	9	7	654
Sligo	675	38	21	2	7	742
Tipperary	1,110	63	24	110	64	1,370
Waterford	609	34	13	41	7	705
Westmeath	264	15	6	18	87	390
Wexford	332	19	8	93	40	491
Wicklow	858	48	28	23	0	958
Total	**17,250**	**973**	**462**	**730**	**776**	**20,191**

It is assumed that a proportion of the 'tip to 7cm' assortment is used as brash for energy generation. Phillips [93] estimated a production of 58,000 m^3 brash in Ireland in 2020. The quantity of brash available is allocated to each county based on the proportion of total wood volume produced in that county compared to the total wood volume produced in the country. The brash is bundled at the forest, and delivered to the power plant at

40% MC where the bundles are subsequently shredded. The potentially available energy in brash at this moisture content is shown in table 2.

Research trials are being carried out by Coillte (Ireland's state-sponsored forestry company) and Waterford Institute of Technology (WIT) on the feasibility and productivity of stump harvesting in Ireland [31]. The average stump removal from the trial study sites was 45 odt per ha. The average volume of wood harvested on the stump trial sites was 478 m^{3}ha^{-1}. Therefore 0.094 odt of stump biomass is removed per m^3 clearfelled[1]. To extrapolate this to a national scale, the volume of clearfell per county was estimated from Phillips [93]and Coillte's Business Area Unit plans [95]. This allowed the calculation of the quantity of stump biomass available on all clearfell sites in 2020. Approximately 35% of clearfell sites are suitable for stump harvesting conversations [31]. Applying this percentage to the total quantity of stump biomass allowed the calculation of potentially available energy in stumps at a MC of 39%, as shown in table 2.

It is predicted that expansion of bioenergy crops to 2020 will remain at a low level with the current price level and incentives. Willow and miscanthus cultivation is predicted to expand to a total area of 6,000 ha by 2020 [12], which represents less than one percent of the total forested land in Ireland which stood at 745,456 ha in 2011 [96]. As of 2011, there were 441 ha and 2,812 ha of short rotation coppice willow (SRCW) and miscanthus respectively [97]. Difficulties have arisen with the co-firing of miscanthus as high levels of chlorine can lead to corrosion in the boilers[2]. In addition, miscanthus crops have been removed due to a lack of market demand, with 300 hectares of the crop removed in 2013 alone [98]. Therefore, in this work it is assumed that no co-firing of miscanthus occurs and miscanthus is only used in CHP applications. As such, it was assumed that miscanthus cultivation will remain at current levels (2011) and the expansion of energy crops will relate only to SRCW. The expansion of these energy crops is assumed to take place on land previously used for beef production and will not displace beef production as the production would be maintained by increasing stock density as stock densities on beef farms are low [99]. The potentially available energy in willow and miscanthus in 2020, at a MC of 55% and 20% respectively, is shown in table 2.

Conventional demand (roundwood used for processing by the sawmill and board processing industries) is predicted to increase from 3.456 million m^3 (overbark) in 2011 to 3.830 million m^3 (overbark) by 2020 [100], an increase of 0.374 million m^3. For the purpose of this study, it is assumed that this increase will be spread across each of the sawmills operating in the country based on the wood volumes processed in 2013. The availability of wood chip in 2020 was estimated based on the material balance in the sawmilling process for coniferous sawnwood from the UNECE [101]. Sawnwood represents 53% of timber throughput, with sawdust (11%), chip (35%), and losses (1%) making up the remainder. The potentially available energy in clean wood chip in 2020, at a moisture content of 30%, is shown in table 3.

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[1] Coillte representative. Stump harvesting. Personal communication. 24th October 2014.
[2] Bord na Mona Representative. Co-firing rates. 17th October 2014.

Table 3 Clean wood chip production 2020 (TJ).

Sawmill	Clean wood chip
S 1	949
S 2	1,265
S 3	585
S 4	388
S 5	220
S 6	289
S 7	379
S 8	236
Total	4,310

2.2.2 Life cycle assessment data

Comprehensive life cycle studies have been carried out on the production of each of the biomass feedstocks considered [26, 27, 31, 32].

The scope of the LCA studies on each of the biomass feedstocks include all processes along the value chain, including; biomass cultivation, harvesting, and processing (where required), and each of the studies focus on Ireland. All relevant inputs to, and outputs from, the system were considered in a life cycle inventory up to the point of the farm, forest, or sawmill gate. Inventory mass balances were summed and converted into environmental impacts. Environmental impacts were calculated and expressed based on the energy content (GJ) of the biomass produced.

Data on transport payloads and fuel consumption are from field data [89, 102] and is supplemented with data from the ecoinvent database [103].

Combustion emissions from co-firing and CHP systems are based on data from the Irish National Inventory Report [1]. Peat combustion is described in a previous study [104]. Data for fossil fuel combustion in the reference scenarios is from the econivent database [105, 106]. Data regarding the Irish electrical grid mix in 2020 is from Clancy and Scheer [107] and is combined with ecoinvent data [108].

2.2.2.1 *Carbon balance*

The total life cycle emissions associated with a bioenergy system are dependent on both the change in carbon stock of the system, and the emissions related to energy and material requirements during production, processing and transportation of the biomass. The total emissions can be calculated using the following framework based on McKechnie et al. [78] and Lindholm et al. [76]; $GHG_{Tot}(t) = \Delta FSC(t) + GHG_{Bio}(t)$, where $GHG_{Tot}(t)$ is the total emissions associated with the biomass, $\Delta FSC(t)$ is the change in forest soil carbon due to

biomass harvest for bioenergy, and $GHG_{Bio}(t)$ is the GHG emissions associated with bioenergy substitution for a fossil fuel alternative (all reported in tonne CO_2-equivalent (tCO_2-eq)) at time t.

The change in forest soil carbon, $\Delta FSC(t)$, is the difference in forest soil carbon stocks between harvest scenarios i.e. a 'reference scenario' without residue removal for bioenergy, and scenarios with residue removal for bioenergy. The change in soil carbon stock due to residue removal must be allocated to the biomass used in energy production.

The emissions from bioenergy production, $GHG_{Bio}(t)$, are linked to the life cycle inventory of the bioenergy production system, including material and energy use in; seedling production, site preparation, harvest and processing of the forest bioenergy. The LCI data for the forest energy products in this study are outlined by Murphy et al. [31].

In this study, the change in soil organic carbon stock is analysed for a number of different scenarios over 3 forest rotations (123 years). It is assumed that 25% of sites are newly afforested, while the remainder are previously forested sites. The initial soil carbon content of grassland prior to afforestation is 160 tC ha^{-1} [109], while the initial soil carbon content in the previously forested case is assumed to be that of the afforested sites after 2 rotations. The reference scenario reflects conventional forestry in Ireland i.e. all brash and stumps are left in the forest after clearfell. In the brash scenario, a proportion of brash (51 odt ha^{-1}) is removed after clearfell and used for energy generation. In the stump scenario, a proportion of stumps (45 odt ha^{-1}) are removed for energy generation. In the brash and stump scenario, both brash and stumps are removed in the same quantity as the previous two scenarios. Brash and stump removal is only suitable on 35% of harvest sites [31]. The results are presented for 1 hectare of forest land, as such bundle and stump removal is carried out on 0.35 ha of this land parcel.

The CO2FIX model developed by the European Forest Institute [110], was used to estimate the soil carbon stock changes of the different scenarios in the study. CO2FIX V.2 is an ecosystem-level model based on carbon accounting of forest stands, including forest biomass, soils and products [111]. The CO2FIX carbon accounting module keeps track of all fluxes to and from the atmosphere and determines the effects of the different scenarios on the soil carbon balance. The CO2FIX model was parameterised for Irish conditions using a number of sources. The stands analysed in this study are based on chronosequence data from the Carbifor project [112-114]. The Irish Dynamic Yield Model (GROWFOR) developed by COFORD [115], was used to estimate forest growth under the different scenarios. Soil carbon stocks of the grassland prior to afforestation were obtained from Eaton et al. [109]. Climate data for the study sites was obtained from Farrelly et al. [116].

Table 4 shows the soil carbon stock for each of the scenarios considered. At the end of 3 rotations (123 years), soil carbon stock has reduced by 0.5% when only brash is removed compared to the reference scenario. Stump harvesting reduces the soil carbon stock by 1.6%, and in the scenario where both brash and stumps are removed, soil carbon stock is reduced by 2.1%.

Table 4 Effect of residue removal on soil organic carbon stock on 1 ha of forest.

			1st rotation		2nd rotation		3rd rotation	
			Stump removal		Stump removal		Stump removal	
			No	Yes	No	Yes	No	Yes
Carbon stock (tC ha^{-1})	Brash removal	No	165.72	165.72	174.70	172.30	176.34	173.60
		Yes	165.72	165.72	174.07	171.62	175.38	172.56
ΔFSC (123 years) (tC ha^{-1})	Brash removal	No		-2.40		-2.74		-2.40
		Yes	-0.63	-3.08	-0.96	-3.78	-0.63	-3.08
ΔFSC (123 years) (%)	Brash removal	No				-1.4		-1.6
		Yes			-0.4	-1.8	-0.5	-2.1

The change in soil carbon stock is attributed to the residues removed during the 3 rotations. These values are added to the LCI data described by Murphy et al. [31] to give the total greenhouse gas emissions for biomass production in each scenario, see table 5.

Table 5 Life cycle GHG emissions from brash and stump production (kg CO_2-eq per odt).

	Residue type	GHG emissions from soil carbon stock changes	GHG emissions from cultivation and harvesting	Total GHG emissions
Scenario 2	Brash	23	14.21	36.29
Scenario 3	Brash	23	16.87	37.22
	Stump	74	16.87	88.22

2.3 Life cycle impact assessment

Environmental impacts considered include; acidification potential (AP) expressed in kg SO_2-equivalents, eutrophication potential (EP) expressed in kg PO_4-equivalents, and global warming potential (GWP) expressed in kg CO_2-equivalents. CML2001 methodology [117] was used in characterising environmental impacts. Ecoinvent methods [118] were used to evaluate the cumulative energy demand (CED), and expressed in MJ. The three impact categories and energy indicator were chosen as they are considered to be particularly relevant in the evaluation of bioenergy systems [26].

2.4 Optimisation model

The aim of the tactical and spatial optimisation model developed was to determine the optimal biomass supply that satisfies the energy demand at the power plant, and the CHP plants under the three different scenarios.

The model considers a one year planning horizon (2020). The model displays the results in a series of matrices including among others:

- Decision variables on tonnes and corresponding oven dry tonnes of each biomass material to be harvested from each supply point and supplied to each demand location.
- Energy content (GJ) of each biomass material supplied to the demand location.
- Number of truck loads delivered to the demand location.
- GWP from production of each type of biomass and the corresponding GWP from biomass transportation.
- Total transportation distances from each biomass supply point to each demand point.

2.4.1   Parameters of the model

The parameters used in this study were obtained from different sources and are outlined in previous studies [26, 27, 31] (table 6).

Table 6 Parameters used in optimisation model.

Parameters and conversion factors	Forest[a]				Miscanthus[b]		Willow[c]		Sawmill[d]
	Short wood logs	Pulpwood chip	Bundles	Stumps	Chip	Bales	Rod then chipped	Direct chipped	Woodchips
Bulk density (kg.m^{-3})	253	130	377	237	100	150	150	285	206
Moisture content (%)	56	40	40	40	20	20	25	55	30
Net Calorific Value at MC% (GJ.t^{-1})	7	10.5	10.5	10.5	13.4	13.4	13.2	7	12.6
Load weight at MC% (t)	27.19	17.29	23.69	22.52	9.5	14.25	14.25	27	19.6
Truck maximum legal payload (t)	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5
Truck maximum volume capacity (m^3)	69	95	78.2	95	95	78.2	95	95	95
Production impacts									
Global warming potential (kg CO$_2$-eq.t^{-1})	16.87	14.22	37.22	88.22	70.96	81.95	44.874	53.37	88.62
Acidification potential (kg SO$_2$-eq.t^{-1})	0.13	0.11	0.11	0.11	2.78	2.81	0.828	1.22	0.43
Eutrophication potential (kg PO$_4$-eq.t^{-1})	0.03	0.02	0.02	0.02	0.90	0.88	0.212	0.31	0.11
CED (MJ)	263.70	221.96	221.96	221.96	1,003.14	1,099.81	548.606	541.81	3,310.56
Transportation impacts									
Global warming potential (kg CO$_2$-eq.t^{-1})	0.116	0.136	0.106	0.110	0.230	0.190	0.095	0.161	0.123
Acidification potential (kg SO$_2$-eq.t^{-1})	3.59E-04	4.15E-04	3.32E-04	3.43E-04	6.70E-04	5.63E-04	3.03E-04	4.82E-04	3.79E-04
Eutrophication potential (kg PO$_4$-eq.t^{-1})	9.70E-05	1.09E-04	9.11E-05	9.35E-05	1.64E-04	1.41E-04	8.48E-05	1.23E-04	1.01E-04
CED (MJ)	1.98	2.27	1.83	1.89	3.62	3.05	1.68	2.62	2.08

Sources: a [31], b [26], c [27], d [32].

Two types of trucks were assumed for the haulage of the biomass to the demanding plants. Articulated trucks with 6 axles and a design gross vehicle weight (DGVW) of 46,000 kg to transport wood logs, residue bundles and miscanthus bales, and articulated box trailer trucks also with 6 axles and DGVW of 46,000 kg to transport shredded and chipped biomass. To calculate the number of truckloads necessary to supply the different types of biomass, average truck's volume and weight capacities were gathered in field studies carried out in Ireland by Sosa et al. [52].

2.4.2 Mathematical formulation

The objective function of the problem is to minimise the GWP from producing and transporting different types of biomass to all demanding points (Equation 1). The supply optimisation model was developed using linear programming (LP) and implemented using the What'sBest® solver package for MS-Excel. The mathematical formulation of the model includes sets, parameters, and variables used which are presented in table 7.

Table 7 Sets, parameters, and variables used in the mathematical formulation of the model.

Indices			
		CAP_c^{stump}	Supply capacity (odt) from stumps in county *c.*
c	County	CAP_c^{mis}	Supply capacity (odt) from miscanthus in county *c.*
s	Sawmill	CAP_c^{will}	Supply capacity (odt) from willow in county *c.*
p	Power plant	$CAP_s^{sawchips}$	Supply capacity (odt) from sawmill woodchips in sawmill s*.*
m	Board mill	Variables	
e	CHP plant	$GWPP_c^{fl}$	Global warming potential from producing *X* tonnes of pulpwood log in county *c.*
fl	Pulpwood logs	$GWPT_{c,m}^{fl}$	Global warming potential from transporting truckloads of pulpwood logs from county *c* to mill *m.*
fc	Pulpwood chips	$GWPP_c^{fc}$	Global warming potential from producing *X* tonnes of pulpwood chips in county *c.*
fb	Forest residue bundles	$GWPT_{c,p}^{fc}$, $GWPT_{c,e}^{fc}$	Global warming potential from transporting truckloads of pulpwood chips from county *c* to plant *p* and to CHP plant *e.*
fs	Forest stumps	$GWPP_c^{fb}$	Global warming potential from producing *X* tonnes of residue bundles in county *c.*

Symbol	Description	Symbol	Description
mb	Miscanthus bales	$GWPT_{c,m}^{fb}$	Global warming potential from transporting truckloads of residue bundles from county c to mill m.
mc	Miscanthus chips	$GWPT_{c,p}^{fb}$	Global warming potential from transporting truckloads of residue bundles from county c to plant p.
wdb	Willow dried chips		
wc	Willow chips		
sc	Sawmill woodchips	$GWPP_{c}^{fs}$	Global warming potential from producing X tonnes of forest stumps in county c.
Sets		$GWPT_{c,p}^{fs}$	Global warming potential from transporting truckloads of forest stumps from county c to plant p.
C	Set of counties $c \in C = \{1 \dots 26\}$	$GWPP_{c}^{mc}$	Global warming potential from producing X tonnes of miscanthus chips in county c.
S	Set of sawmills $s \in S = \{1 \dots 8\}$	$GWPT_{c,p}^{mc}$, $GWPT_{c,e}^{mc}$	Global warming potential from transporting truckloads of miscanthus chips from county c to plant p and to CHP plant e.
P	Set of power plants $p \in P = \{1 \dots 3\}$	$GWPP_{c,p}^{mb}$	Global warming potential from producing X tonnes of miscanthus bales in county c.
M	Set of board panel mills $m \in M = \{1 \dots 2\}$	$GWPT_{c,p}^{mb}$, $GWPT_{c,e}^{mb}$	Global warming potential from transporting truckloads of miscanthus bales from county c to plant p and to CHP plant e.
E	Set of CHP plants $e \in E = \{1 \dots 15\}$	$GWPP_{c}^{wdc}$	Global warming potential from producing X tonnes of willow dried chips in county c.
Parameters		$GWPT_{c,p}^{wdc}$, $GWPT_{c,e}^{wdc}$	Global warming potential from transporting truckloads of willow dried chips from county c to plant p and to CHP plant e.
$EC_{c,p}^{fc}$, $EC_{c,e}^{fc}$	Energy content of pulpwood chips produced in county c and delivered to the power plant p and/or to CHP plant e.	$GWPP_{c}^{wc}$	Global warming potential from producing X tonnes of willow chips in county c.

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http://dx.doi.org/10.1016/j.energy.2016.04.125.

$EC_{c,p}^{fb}$	Energy content of forest residue bundles produced in county c and delivered to the power plant p.	$GWPT_{c,p}^{wc}$, $GWPT_{c,e}^{wc}$	Global warming potential from transporting truckloads of willow chips from county c to plant p and to CHP plant e.
$EC_{c,p}^{fs}$	Energy content of forest stumps produced in county c and delivered to the power plant p.	$GWPP_{s}^{sc}$	Global warming potential from producing X tonnes of sawmill woodchips in county c.
$EC_{c,p}^{mc}$, $EC_{c,e}^{mc}$	Energy content of miscanthus chips produced in county c and delivered to the power plant p and/or to CHP plant e.	$GWPT_{s,m}^{sc}$, $GWPT_{s,p}^{sc}$, $GWPT_{s,e}^{sc}$	Global warming potential from transporting truckloads of sawmill woodchips from county c to mills m, to plant p and CHP plant e.
$EC_{c,p}^{mb}$, $EC_{c,e}^{mb}$	Energy content of miscanthus bales produced in county c and delivered to the power plant p and/or to CHP plant e.	$X_{c,m}^{fl}$	Tonnes of pulpwood logs harvested in county c, to be delivered at the mill m.
$EC_{c,p}^{wdc}$, $EC_{c,e}^{wdc}$	Energy content of willow dried chips produced in county c and delivered to the power plant p and/or to CHP plant e.	$X_{c,m}^{fc}$, $X_{c,p}^{fc}$, $X_{c,e}^{fc}$	Tonnes of pulpwood chips harvested in county c, to be delivered at mill m, power plant p, and CHP plant e.
$EC_{c,p}^{wc}$, $EC_{c,e}^{wc}$	Energy content of willow chips produced in county c and delivered to the power plant p and/or to CHP plant e.	$X_{c,p}^{fb}$	Tonnes of forest residue bundles harvested in county c, to be delivered at the power plant p.
$EC_{c,p}^{sc}$, $EC_{c,e}^{sc}$	Energy content of sawmill woodchips produced in county c and delivered to the power plant p and/or to CHP plant e.	$X_{c,p}^{fs}$	Tonnes of forest stumps harvested in county c, to be delivered at the plant p.
ED_p	Energy demand at power plant p.	$X_{c,p}^{mc}$, $X_{c,e}^{mc}$	Tonnes of miscanthus chips harvested in county c, to be delivered at the plant p and to CHP plant e.
TD_m	Oven dry tonne demand at mill m.	$X_{c,p}^{mb}$, $X_{c,e}^{mb}$	Tonnes of miscanthus bales harvested in county c, to be delivered at the plant p and to CHP plant e.
ED_e	Energy demand at CHP plant e	$X_{c,p}^{wdc}$,	Tonnes of willow dried chips harvested in

		$X_{c,e}^{wdc}$	county c, to be delivered at the plant p and to CHP plant e.
CAP_c^{pulp}	Supply capacity (odt) from pulpwood logs in county c.	$X_{c,p}^{wc}$, $X_{c,e}^{wc}$	Tonnes of willow chips harvested in county c, to be delivered at plant p and at CHP plant e.
CAP_c^{bundle}	Supply capacity (odt) from bundles in county c.	$X_{c,m}^{sc}$, $X_{c,p}^{sc}$, $X_{c,e}^{sc}$	Tonnes of sawmill woodchips harvested in county c, to be delivered at mill m, plant p, and at CHP plant e.

Objective function

$$\sum_{c\in C}\sum_{s\in S}\sum_{m\in M}\sum_{p\in P}\sum_{e\in E} (GWPP_c^{fl} + GWPT_{c,m}^{fl}) + (GWPP_c^{fc} + GWPT_{c,p}^{fc} + GWPT_{c,e}^{fc}) + \left(GWPP_c^{fb} + GWPT_{c,p}^{fb}\right)$$

$$+ \left(GWPP_c^{fs} + GWPT_{c,p}^{fs}\right) + \left(GWPP_c^{mc} + GWPT_{c,p}^{mc} + GWPT_{c,e}^{mc}\right)$$

$$+ \left(GWPP_{c,p}^{mb} + GWPT_{c,p}^{mb} + GWPT_{c,e}^{mb}\right) + \left(GWPP_c^{wdc} + GWPT_{c,p}^{wdc} + GWPT_{c,e}^{wdc}\right)$$

$$+ \left(GWPP_c^{wc} + GWPT_{c,p}^{wc} + GWPT_{c,e}^{wc}\right)$$

$$+ \left(GWPP_c^{sc} + GWPT_{c,m}^{sc} + GWPT_{c,p}^{sc}\right.$$

$$\left. + GWPT_{c,e}^{sc}\right) \hspace{4cm} (1)$$

Constraints

1. Demand at the plants (GJ), and demand at the panel board mills (odt).

Equation 2 and 3 ensure that the energy demand (ED) at the power plants (GJ) and the CHP plants is met by the different types of biomass. Equation 4 ensures that the forest products satisfy the tonnes demanded (TD) by the two board WBP mills.

$$\sum_{c\in C}\sum_{s\in S}\sum_{p\in P} X_{c,p}^{fc} * EC_{c,p}^{fc} + X_{c,p}^{fb} * EC_{c,p}^{fb} + X_{c,p}^{fs} * EC_{c,p}^{fs} + X_{c,p}^{mc} * EC_{c,p}^{mc} + X_{c,p}^{mb} * EC_{c,p}^{mb} + X_{c,p}^{wc} * EC_{c,p}^{wc} +$$
$$X_{c,p}^{sc} * EC_{c,p}^{sc} = ED_p \quad \forall p \in P \hspace{4cm} (2)$$

$$\sum_{c\in C}\sum_{s\in S}\sum_{e\in E} X_{c,e}^{fc} * EC_{c,e}^{fc} + X_{c,e}^{mc} * EC_{c,e}^{mc} + X_{c,e}^{mb} * EC_{c,e}^{mb} + X_{c,e}^{wc} * EC_{c,e}^{wc} + X_{c,e}^{sc} * EC_{c,e}^{sc} = ED_e \quad \forall e \in$$
$$E \hspace{4cm} (3)$$

$$\sum_{c\in C}\sum_{s\in S}\sum_{m\in M} X_{c,m}^{fl} + X_{c,m}^{fb} + X_{s,m}^{sc} = TD_m \quad \forall m \in M \hspace{2cm} (4)$$

2. Supply capacity.

These constraints refer to the maximum potential supply capacity of each supplying point. Equations 5 to 10 ensure that the biomass supplied to all demanding plants is lower than the maximum forecasted production capacity of each type of biomass.

$$\sum_{c \in C} \sum_{p \in P} \sum_{m \in M} X^{fl}_{c,m} + X^{fc}_{c,p} \leq CAP^{pulp}_c \quad \forall c \in C \quad Pulpwood \tag{5}$$

$$\sum_{c \in C} \sum_{p \in P} X^{fb}_{c,p} \leq CAP^{bundle}_c \quad \forall c \in C \qquad Residue\ bundles \tag{6}$$

$$\sum_{c \in C} \sum_{p \in P} X^{fs}_{c,p} \leq CAP^{stump}_c \quad \forall c \in C \qquad Forest\ stumps \tag{7}$$

$$\sum_{c \in C} \sum_{p \in P} \sum_{e \in E} X^{mc}_{c,p} + X^{mb}_{c,p} + X^{mb}_{c,e} \leq CAP^{mis}_c \quad \forall c \in C \qquad Miscanthus \tag{8}$$

$$\sum_{c \in C} \sum_{p \in P} \sum_{e \in E} X^{wdc}_{c,p} + X^{wc}_{c,p} + X^{wc}_{c,e} \leq CAP^{will}_c \quad \forall c \in C \qquad Willow \tag{9}$$

$$\sum_{c \in C} \sum_{m \in M} \sum_{p \in P} \sum_{e \in E} X^{sc}_{c,m} + X^{sc}_{c,p} + X^{sc}_{c,e} \leq CAP^{Sawchips}_c \quad \forall c \in C \quad Sawmill \tag{10}$$

3   Results

3.1   Optimisation model

The total demand of both the energy sector (co-firing and CHP plants) and the WBP manufacturing industry can be satisfied by the forecasted biomass supply in 2020; scenario 1 used 71.18% of the available biomass while scenarios 2 and 3 used 99.17% and 99.44% respectively. The total demand under the three scenarios was satisfied with different proportions of biomass types, see table 8.

Table 8 Optimised supply of biomass in each scenario, energy supply and percentage of available biomass used.

Biomass type	Energy supplied (TJ)			Percentage of available biomass used (%)		
	SC 1	SC 2	SC 3	SC 1	SC 2	SC3
Pulpwood	13,780	17,250	17,250	79%	100%	100%
Sawmill woodchips	2,556	4,310	4,310	59%	100%	100%
Willow	404	776	776	52%	100%	100%
Bundles	686	973	973	70%	100%	100%
Miscanthus	0	690	730	-	94%	100%
Stumps	13	298	324	3%	65%	70%
Total used	17,440	24,297	24,363			
Total available biomass	24,501	24,501	24,501			
Total biomass used (%)	71.18	99.17	99.44			

The model allocated biomass to each of the demand locations by combining the different biomass production and processing GHG emissions with the transportation GHG emissions and choosing the optimal combination for each plant. Figure 3 shows the GHG emissions from production and processing of the different biomass sources, and also the GHG emissions from the transportation of one tonne of the different biomass sources over one kilometre.
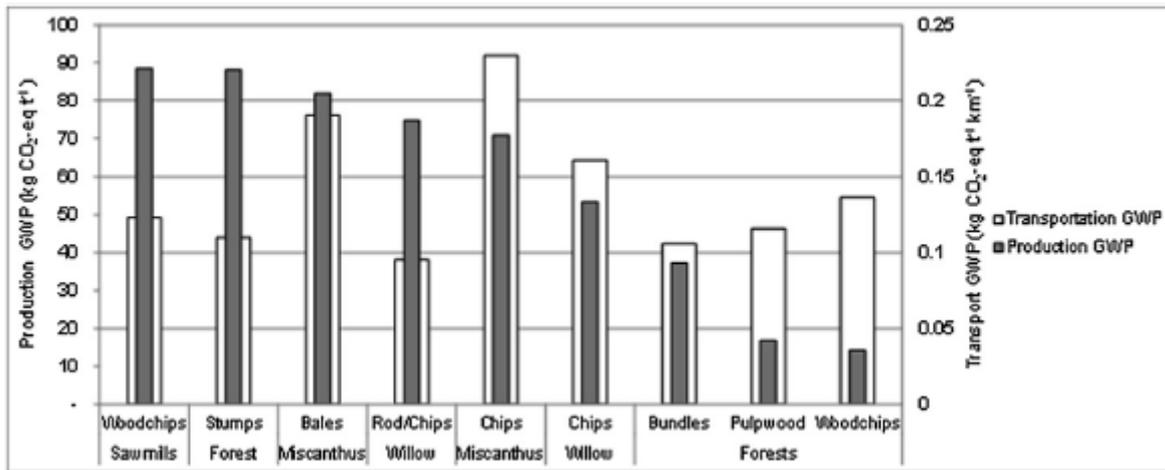
Fig. 3. Life cycle emission from producing-processing and transporting biomass.

In general, the model chose to satisfy the demand of the peat power stations, CHP plants and WBP mills with pulpwood in the form of logs and woodchips where possible due to the high availability of these sources of biomass and lower GHG emissions from production and transportation compared to other sources. The second highest quantity of biomass supplied was woodchips from sawmills. Wood chips from sawmills generate the highest GHG emissions in production compared to the other sources of biomass, however, the model allocates this material mainly because of demand restrictions, as the panel board mills required this type of biomass.

Beyond these sources of biomass, forestry residues (bundles) were allocated to the co-firing power stations and SRCW to the CHP plants as both have the lowest transportation GHG emissions. Lastly, stumps and miscanthus were allocated to the co-firing power stations and CHP plants respectively due to scarcity of the preferred biomass types.

Reducing the co-firing rate from 50% to 31% in scenario 3, resulted in a decrease in the number of biomass procurement areas required to fulfil the biomass demand at the peat power stations, from an average of 11 counties in scenario 1 to an average of 8 counties in scenario 3. On the contrary, the demand of each CHP plant was satisfied with an average of 3 procurement areas in scenario 2, and this increased to an average 17 procurement areas (counties) in scenario 3. Compared to scenario 2 the total transportation distance from supply points to the peat power stations was reduced by 10% in scenario 3 with an average roundtrip of 184 km; for the CHP plants the total transportation distance increased for the CHP plants by 35%, with an average roundtrip distance of 362 km.

Two types of trucks were used in biomass transportation; 6-axle articulated box trailer trucks used in the transportation of chips and shredded material, and 6-axle articulated trucks with skeletal trailers (including a self-loading crane) used to transport logs, forest bundles and miscanthus bales. The maximum truck payloads

were established based on Irish regulations, with a DGVW of 46,000 kg for 6-axle articulated trucks. The maximum volume capacity of the trailers was 95 m^3 in the case of box trailers and 69 m^3 in the case of skeletal trailers. The form of the material, MC, bulk density and gross calorific value of each biomass type had an impact on the gross vehicle weight (GVW) of the trucks; all the truckloads from the different biomass types were under the legal maximum GVW as the loads reached the truck's maximum volume before exceeding the legal maximum weight.

The high bulk densities of logs and sawmill woodchips (253 kg m^{-3} and 206 kg m^{-3} respectively), allowed highest payloads of all of the biomass resources, see figure 4b. On the other hand, the low bulk density of miscanthus both as chip (100 kg m^{-3}) and bale (150 kg m^{-3}) generated a negative impact on truck transport productivity. For the truck configurations used in this study, loading trucks to full volume capacity with miscanthus resulted in payloads with 18,000 kg under the maximum legal weight (figure 4a). The trade-off between bulk density and the calorific value at the delivered MC per biomass type affected the energy content per truckload delivered to the demand points. A fully loaded and heavier truck with biomass material does not necessarily imply that a high energy content is being delivered (figure 4b). The highest energy content per truckload delivered with skeletal trailers was obtained by residue bundles followed by miscanthus bales (250 GJ and 191 GJ respectively). In the case of box trailer loads the highest energy content was supplied by clean wood chips from sawmills and stumps (247 GJ and 236 GJ respectively). Miscanthus chips presented the lowest energy content per truckload (127 GJ). Despite this, the model chose pulpwood chips as the major biomass supply in the study due to its higher resource and closer availability to all demanding points, and its low production GHG emissions.
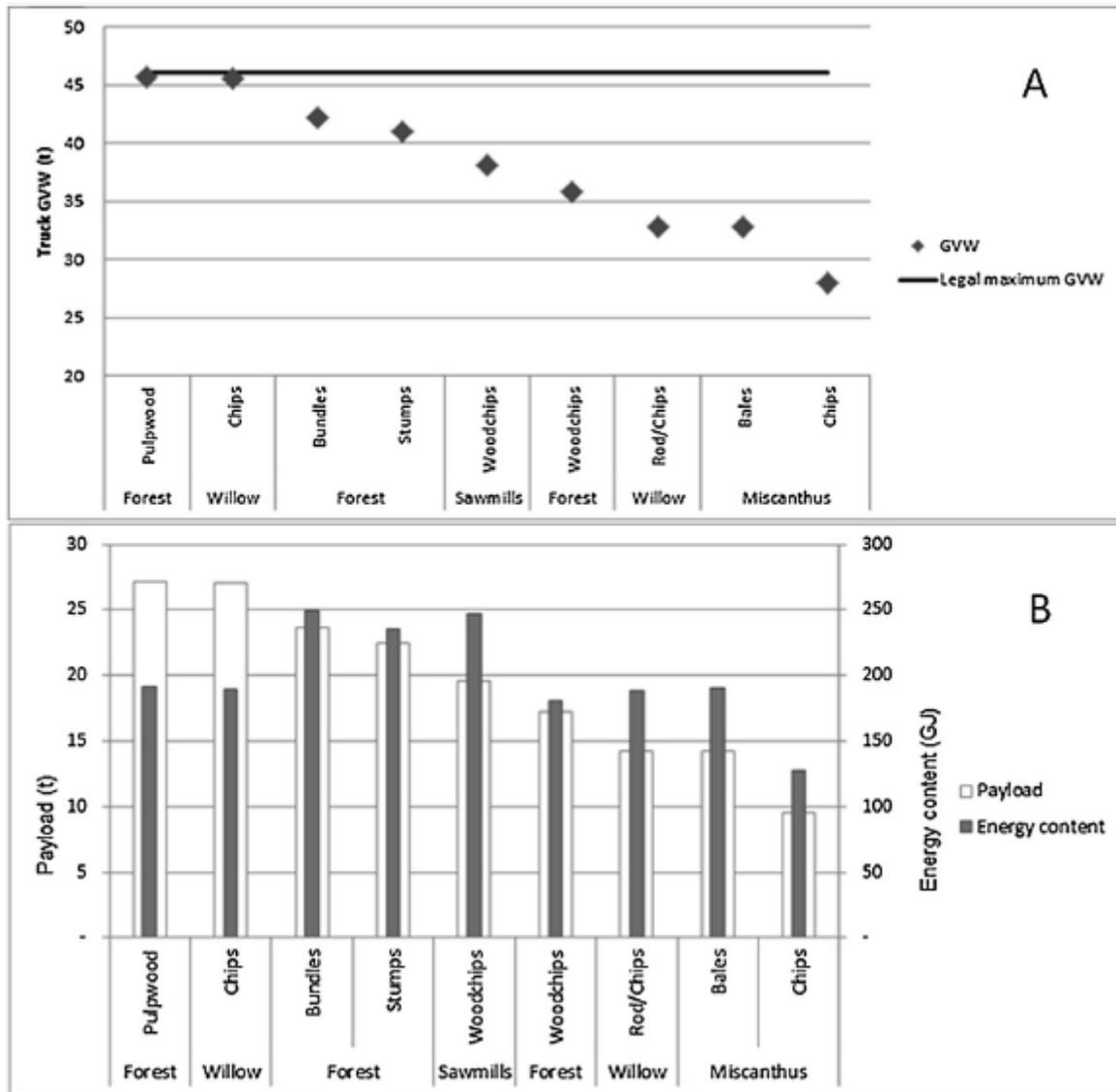
Fig. 4. a) Maximum legal truck GVW vs GVW per biomass type, b) Payload weight vs energy content per biomass type.

The total life cycle environmental impacts for each scenario are shown in table 9. The results show that SC 3 produces the highest environmental impacts but also produces the most energy. Similarly, SC 1 has the lowest environmental impact and produces the least amount of energy.

Table 9 Overall environmental impacts for each scenario.

Impact category	Unit	SC 1 Co-firing 50%	SC 2 Co-firing 50%	SC 2 63 MWe CHP	*Total SC 2*	SC 3 Co-firing 31%	SC 3 107 MWe CHP	*Total SC 3*
GWP	t CO_2-eq	1550894	1558451	54402	*1612853*	2101969	86940	*2188908*
AP	t SO_2-eq	553	561	323	*884*	616	454	*1069*
EP	t PO_4-eq	76	79	92	*171*	69	126	*195*
CED	GJ	2144165	2321744	1453006	*3774750*	1669743	2488518	*4158260*
Energy produced	MWh	2502024	2502024	666675 E[a] 1047632 H[b]	*4216330*	2502024	1127476 E[a] 1771748 H[b]	*5401248*

[a] Electricity, [b] Heat.

3.2.1 Environmental impacts of each of the scenarios per unit of electricity produced

Table 10 shows the environmental impacts of each of the scenarios per unit (MWh) of electricity produced. Co-firing at 50% in SC 1 produces lower GHG emissions than co-firing at the same rate in scenario 2. This is due to the biomass optimisation model considers only co-firing in SC 1 and as such co-firing has 'first choice' of the biomass available since there is no competing demand. On the other hand, biomass must satisfy both co-firing and CHP requirements in SC 2, and as such less desirable biomass (in terms of GHG emissions) is allocated to co-firing in comparison to SC 1. For SC 3, co-firing at 31% produces higher GHG emissions more peat must be combusted to achieve the same energy output. The CHP systems produce the lowest environmental burdens across all impact categories considered. Combustion emissions are vastly reduced compared to co-firing as biomass is the only fuel. Also, the efficiency of the co-firing system is approximately 37%, while the CHP system achieves 90% efficiency; as such less biomass is required in the CHP system to achieve the same energy output.

<p style="text-align:center">Table 10 Environmental impacts of electricity generation (per MWh$_e$).</p>

		SC 1	SC 2		SC 3	
Impact category	**Unit**	Co-firing 50%	Co-firing 50%	63 MWe CHP	Co-firing 31%	107 MWe CHP
GWP	kg CO_2-eq	619.9	622.7	32.4	839.6	30.4
AP	kg SO_2-eq	0.222	0.224	0.201	0.246	0.165
EP	kg PO_4-eq	0.031	0.031	0.056	0.028	0.045
CED	MJ	857	938	855	669	864
Biomass fuel requirement	GJ	4.9	4.9	4.0	3.0	4.0
Total fuel requirement	GJ	9.8	9.8	4.0	10.2	4.0
Co-firing rate	%	50	50	-	31	-

3.2.2 Contribution of life cycle stages to overall impacts

A breakdown of the contribution of each of the life cycle stages is shown in figure 5, including; biomass production, biomass transportation, peat harvesting and production, along with combustion and ash disposal.
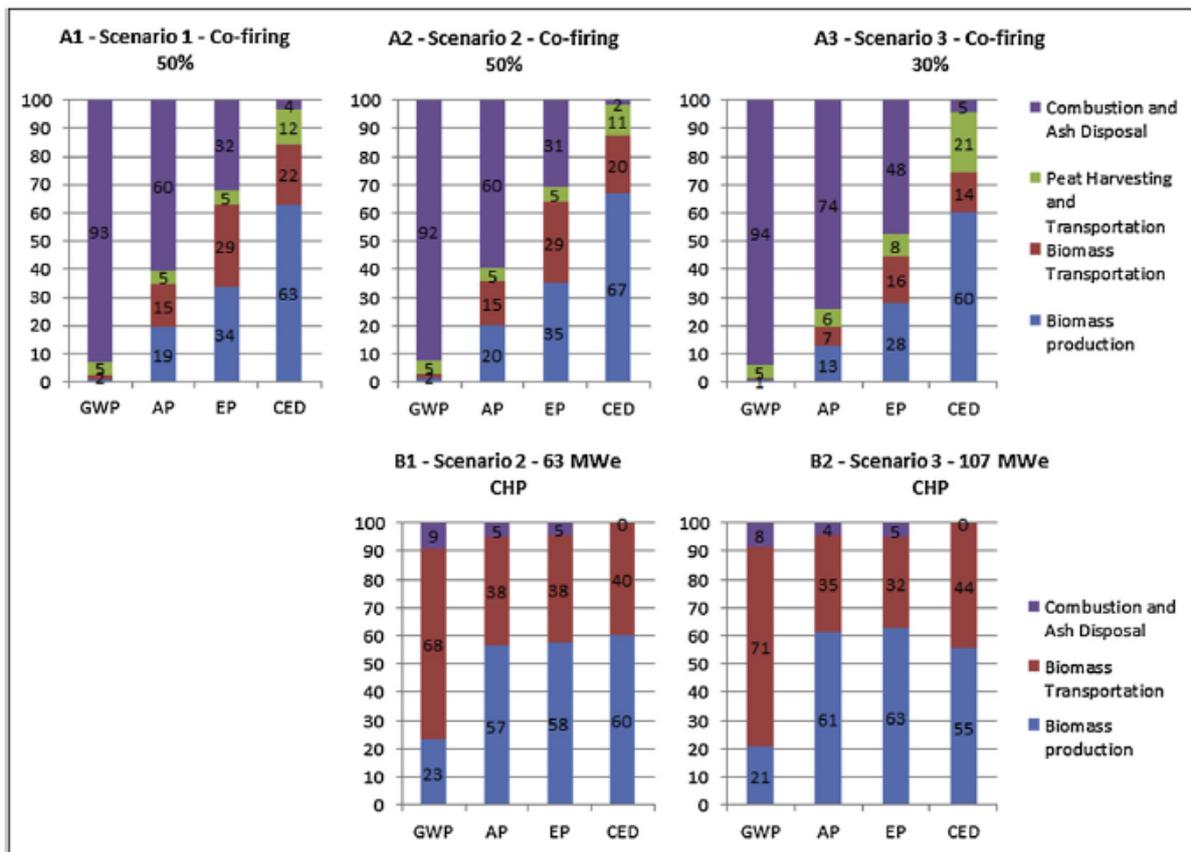
Fig. 5. Contribution of each life cycle stage to overall environmental impacts – A1 SC 1 Co-firing at 50%, A2 SC 2 Co-firing at 50%, A3 SC 3 Co-firing at 31%, B1 SC 2 63 MWe of installed CHP, B2 SC 3 107 MWe of installed CHP.

The results show that combustion and ash disposal produce the majority of emissions (92-94%) relating to global warming potential of the co-firing systems. The GHG emissions are mainly due to the carbon released during combustion but also to non-CO_2 emissions from peat and biomass combustion including methane (CH_4) and nitrous oxide (N_2O) emissions. Peat harvesting and transportation accounts for 5% of GWP, while biomass transportation accounts for 1-2%, and biomass production accounts for less than 1% of total life cycle GHG emissions.

Similarly, emissions from combustion cause the majority of acidifying potential in the co-firing systems (60-74%). Biomass production accounts for approximately 13-20% of acidifying emissions in co-firing systems, with the majority of emissions resulting from the application of fertilisers in energy crop production, and from emissions from fuel combustion in harvesting and processing machinery. Biomass transportation also accounts for a significant proportion of total acidifying emissions due to emissions from fossil fuel combustion.

Biomass production causes the majority of eutrophication emissions (28-35%) in the scenarios where a co-firing rate of 50% is achieved. These eutrophication emissions occur as a result of fertiliser use in energy crop

production, but also from fossil fuel combustion in harvesting machinery. Similarly biomass transportation contributes significantly (16-29%) to eutrophication emissions, again due to fossil fuel combustion in truck engines.

Biomass production accounts for approximately 60-67% of energy requirements in the co-firing systems, including embodied energy in the biomass. Biomass transportation accounts for 14-22% of total energy use. Peat harvesting and transportation account for 11-21% of overall energy requirements, depending on the scenario. The peat harvesting process is less energy intensive than biomass production, and in addition the peat is transported approximately 10 km from the harvest site to the co-firing plant, a significantly shorter distance than the biomass.

Combustion emissions are significantly reduced in the CHP systems, accounting for less than 9% of emissions in each impact category. Biomass transportation causes 68-71% of GHG emissions in CHP systems, with biomass production and processing accounting for 21-23%. On the other hand, biomass production causes the majority of acidification and eutrophication emissions, 57-61% and 58-63% depending on the scenario, respectively. As mentioned previously, the majority of these emissions are caused by fertiliser use in energy crop production, and from fossil fuel combustion in harvesting and processing. Similarly, fuel combustion in biomass transportation contributes to 35-38% and 32-38% of acidification and eutrophication emissions respectively.

Biomass production and processing (including embodied energy) represents the major energy requirement (55-60%) in CHP systems, with biomass transportation accounting for 40-44%, with the remainder required for ash disposal.

3.2.3 Comparison with reference scenarios

Table 11 shows the change in environmental impact of each scenario when compared to the relevant reference scenario. Co-firing scenarios are compared to peat firing only, while CHP scenarios are compared to the use of fossil fuels (light fuel oil, heavy fuel oil, and coal) required to produce the equivalent heat output and the use of the national grid to produce the equivalent electricity output. Co-firing at 50% in scenarios 1 and 2 one achieves a GHG reduction of 1.3 Mt CO_2-eq, while co-firing at 31% achieves a reduction of 0.76 Mt CO_2-eq. In addition to this, acidification potential is reduced in co-firing due mainly to a reduction in SO_2 emissions in combustion as peat combustion is reduced. However, eutrophication emissions increase in co-firing due to fertiliser use in energy crop production and fossil fuel combustion in processing and transportation.

Table 11 Change in environmental impacts for each scenario versus the relevant reference scenario.

Impact category	Unit	SC 1 Co-firing 50%	SC 2 Co-firing 50%	63 MWe CHP	Total SC 2	SC 3 Co-firing 31%	107 MWe CHP	Total SC 3
GWP	t CO_2-eq	-1,315,879	-1,308,322	-740,370	-2,048,692	-764,805	-1,254,250	-2,019,055
AP	t SO_2-eq	-208	-200	-3,744	-3,945	-146	-5,928	-6,074
EP	t PO_4-eq	+23	+25	-675	-650	+16	-1,106	-1,090
CED	GJ	+1,564,511	+1,742,090	-10,024,482	-8,282,392	+1,090,088	-17,161,048	-16,070,960

The use of 63 MWe of installed CHP capacity in SC 2 achieves a GHG emission saving of 0.74 Mt CO_2-eq due to the replacement of fossil fuels, while 107 MWe of installed CHP capacity in SC 3 achieves a GHG emission reduction of 1.25 Mt CO_2-eq. In addition, acidification and eutrophication potentials are reduced due to the reduction in combustion emissions from the replacement of fossil fuels with biomass. When total emissions savings from both the displacement of peat with biomass in co-firing, and the displacement of fossil fuels and the national grid mix with CHP are considered, SC 2 shows the highest emissions reductions in terms of GHG emissions. However, SC 3 achieves the highest reductions in each of the other impact categories considered.

3.2.4 Contribution to Ireland's renewable energy targets

The contributions of each scenario towards meeting the Irish renewable electricity and renewable heat targets are outlined in table 12, the RES-E target being 40%, and the RES-H target being 12%. Gross final consumption is projected to be 27,656 GWh by electricity and 58,371 GWh by heat by 2020 [107]. Renewable electricity generation in SC 1, co-firing at 50% at the 3 peat power plants, contributes 4.5% to the total gross final consumption, and contributes to 11.4% of the RES-E target for 2020. The addition of 63 MWe of CHP capacity in SC 2 increases the contribution towards gross final consumption by electricity to 7%, the highest of all scenarios, and gross final consumption by heat to 2%, meeting 17.4% and 16.8% of RES-E and RES-H targets respectively. Despite the increase in CHP capacity to 107 MWe in SC 3, overall contribution to gross final consumption by electricity decreases to 6.8% due to a drop in the co-firing rate to 31%. On the other hand, contribution to gross final consumption by heat increases to 6.8%, representing 46.6% of the RES-H target.

Table 12 Contribution of each scenario towards Irish renewable energy targets.

	SC 1		SC 2			SC 3		
	Co-firing 50%	Co-firing 50%	63 MWe CHP	Total SC 2		Co-firing 31%	107 MWe CHP	Total SC 3
Contribution to RES-E target (GWh)	1251	1251	667	1918		751	1127	1878
Contribution to RES-H target (GWh)	0	0	1048	1048		0	1772	1772
Contribution to RES-E target (%)	11.4	11.4	6.1	17.4		6.8	10.2	17.1
Contribution to RES-H target (%)			16.8	16.8			46.6	46.6
RES-E contribution to total energy (%)	4.5	4.5	2.4	7.0		2.7	4.1	6.8
RES-H contribution to total energy (%)			2.0	2.0			5.6	5.6

4   Discussion and conclusions

The results highlight the superior environmental performance of CHP systems compared to biomass co-firing systems. CHP systems produce lower GWP, AP and EP per MWh of energy produced compared to co-firing and also require lower inputs of biomass to achieve the equivalent energy output due to the higher efficiency of the CHP system. The efficiency of the co-firing plants is approximately 37%, whereas the biomass CHP systems are operating at 90% efficiency. As such, CHP systems represent the better use of biomass compared to co-firing when focusing on the technology.

However, it is also important to consider each of the scenarios in comparison with the reference scenarios (and technologies) which they are displacing in order to fully quantify the overall environmental benefits/burdens rather than analysing the system in isolation. Biomass replaces carbon intensive peat in co-firing at approximately 37% efficiency. The introduction of biomass displaces a significant quantity of carbon which would have been emitted during peat combustion. Biomass CHP systems replace fossil heating systems, light fuel oil, heavy fuel oil, and coal with thermal efficiencies of 95%, 95% and 80% respectively. Additionally, the electricity produced by the CHP systems displaces electricity from the national grid.

It is important to note that this study is based on the possible renewable energy generation from maximum utilisation of indigenous biomass resources. Any additional biomass energy generation would require the consideration of biomass imports.

The results show SC 2 (50% co-firing and 63 MWe CHP) achieves the greatest reduction in GHG emissions despite having lower installed CHP capacity than SC 3. Co-firing at 50% in SC 2 displaces 543,518 t CO_2-eq more than co-firing at 31% in SC 3. On the other hand, increasing installed CHP capacity from 63 MWe in SC 2 to 107 MWe in SC 3 results in the increased displacement of 513,880 t CO_2-eq. Overall, SC 2 displaces 29,637 t CO_2-eq more than SC 3. This finding highlights that although CHP systems cause lower environmental impacts when compared to co-firing systems, displacing carbon intensive peat combustion achieves superior GHG emissions reductions. Conversely, SC 3 is highlighted as the most promising in terms of reduction in the other environmental impacts considered; AP, EP and CED. In co-firing, AP is slightly reduced compared to peat-only due to a decrease in SO_2 emissions from displacement of a proportion of peat with biomass. In the case of EP, co-firing increases eutrophication emissions slightly due to fertiliser use in energy crop production, and from fossil fuel combustion in harvesting, processing and transportation. Similarly, energy requirements are increased in co-firing as biomass production and transportation is more energy intensive than peat harvesting. In scenarios where CHP is included, the reductions in AP and EP are most pronounced due to replacement of fossil fuels with high combustion and production acidification and eutrophication emissions with biomass producing lower impacts in these categories. In addition, biomass production is less energy intensive than fossil fuel production and this is reflected in the results.

However, if the aims of these systems are to increase renewable energy penetration in line with the RES-E and RES-H targets, the optimal scenario may not be the one which achieves the greatest carbon reductions. CHP systems have an advantage over co-firing as both electricity and heat are produced, displacing heat from other sources and electricity from the national grid. Scenario 3 produces the highest overall contribution to gross final consumption, and produces the highest quantity of renewable heat. However, the contribution to renewable electricity in this scenario is slightly lower than SC 2 due a decrease in co-firing from 50% to 31%.

The Irish Government has committed to both reducing GHG emissions and increasing renewable energy penetration in line with EU targets. This research has shown that the scenario for achieving maximum contributions to the renewable energy targets may not be the one which achieves the greatest carbon reductions. As such it is difficult to recommend the most promising scenario to policymakers as not one scenario shows highest environmental impact reductions and highest renewable energy penetration across the board.

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