

Managing the Moisture Content of Wood Biomass for the Optimisation of Ireland's Transport Supply Strategy to Bioenergy Markets and Competing Industries.

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Abstract

One of the measures taken by the Irish government to reduce National CO₂ emissions is the conversion of peat fired power plants to co-fire with alternative energy sources. The aim of this study was to analyse the supply of wood biomass (short wood) to the three peat power stations in Ireland and the impacts on the competing wood-based panel industries. The methodology includes the development of a spatial decision support tool based on Linear Programming (LP). It deals with a two year planning horizon, and includes moisture content (MC) management as a driving factor for the optimal allocation of woodchips and logs from thinnings and clearfells. Results show that the planned maximum 30% co-firing rate at the three peat power station could be met with the forecasted short wood availability from both the private and public sector. The costs of supply increased not only with higher demands, but also with tighter constraints on MC. Spatial distribution and operational factors such as efficiency in transportation and truck loading showed to be sensitive to changes in MC. The analysis shows the benefits of controlling the MC when optimising supply chains in order to deliver biomass to energy plants in a cost-effective manner.

Key words: Biomass allocation, competing demands, spatial distribution, moisture content, transportation supply optimisation, Ireland.

Highlights

- A linear programming model was developed to optimise wood biomass supply in Ireland.
- It uses moisture content to determine harvesting, chipping, storage and transportation costs.

- It analyses the supply of woodchips to the three peat power stations in Ireland, and the impacts on the competing wood-based panel industries demanding logs (short wood).
- Low wood moisture content increases supply cost due to longer transport distances and/or inclusion of more costly forest products.
- Optimal truck loads can be achieved by controlling wood moisture content.

1. Introduction

Currently, Ireland imports 85% of its energy needs and it is highly dependent on fossil fuels with oil as the main fuel source (45.4%), followed by natural gas (30.4%), coal (11.2%) and peat (6.1%). This makes the country vulnerable to supply disruptions, price changes, and also contributes highly to greenhouse gas emissions (Howley & Holland 2013). The reduction in greenhouse gas emissions agreed to in the Kyoto Protocol in December 1997 binds several countries to mitigate climate change, with the European Union setting targets to increase the share of renewable energy sources. Ireland has a 16% target for renewable energy sources by 2020. This goal must be met through an increase of 10% in the transport sector, 12% in the heat sector and 40% in the electricity sector (Department of the Environment Heritage and Local Government 2009).

The Irish government has undertaken to reduce national CO₂ emissions through a range of measures like the National Renewable Energy Action Plan (Department of the Environment Heritage and Local Government 2009). One of these measures is the conversion of peat fired power plants to co-fire with renewable biomass. It is expected that all Ireland's three peat power generation stations to be co-firing with 30% biomass. Peat-based power plants are typically located in the proximity of peat sources to reduce the logistic cost, transmission losses due to transportation (Hashim et al. 2014). Bord Na Mona (a semi-state company) is responsible for the mechanised harvesting of peat, it owns Edenderry peat power station (120MWe), and sells peat to other two power stations which are owned and operated by the Electric Ireland (which is the main electricity supplier in Ireland and also owns and manages the country's transmission grid). These plants are Lough Ree (100MWe) and West Offaly (150 MWe), and the total annual electricity output from these three peat power plants is 370 MWe, which equates to 6% of Ireland's totally primary energy requirement (TPER). Greenhouse gas (GHG) emissions from energy production as one of the major contributors to anthropogenic climate change (Bentsen et al. 2014). The burning of peat currently emits 2.8 million tonnes of CO₂ per annum which is equivalent to 4.1% of Ireland's GHG emissions (Devlin & Talbot 2014).

At present Edenderry Power is co-firing biomass at 22%, displacing around 283,375 MWh from peat by 2011, and is on target for 2015 (SEAI 2012). Achieving the 30% co-firing target implies the offsetting of 0.9 million tonne of peat with biomass, and will require an increased amount of wood biomass (Irish Forestry and Forest Products Association 2012).

Biomass plays an important part not only on the global response to the challenges on energy security, but also greenhouse emissions and climate change. Although it is not a complete solution, it can play an important role in the partial substitution of fossil fuel in energy supply (Yu et al. 2009). In Ireland, industrial biomass energy (with wood as the major source) accounted for 69% of all thermal renewable energy used in 2011, which corresponds to 2.9% of all thermal energy used in the country (Dennehy et al. 2012). Forestry is the largest biomass resource with over 744,000 hectares which equates to 10.6% of Ireland's land area, and further 17% expansion of forest cover is planned by 2030 (Forest Service 2012). Half of the estate's forests are less than 25 years old, with 53% of the forests being managed by Coillte (a commercial semi state company) and 47% managed by private owners (Casey 2012).

The biomass potential is constrained by its characteristic low energy density (energy per volume), widely dispersed occurrence, and seasonality of supply. Biomass resources are also often distributed in remote locations (Lam et al. 2010). These factors add complexities to the supply chain and can increase the cost of the technology required to convert biomass into useful sources of energy (harvesting, collection, transport, comminution and storage operations) (Rentizelas et al. 2009). The current costs of primary biomass fuels are also often higher than the cost of competing fossil fuels (Junginger et al. 2005). Compared to more traditional energy transport technologies like electricity and gas, there are fewer studies dealing with techno-economic modelling and optimisation of biomass supply chains (van Dyken et al. 2010).

Another constraint for the wood biomass industry is the competition on national and international markets for forest products. The use of wood biomass energy by commercial and domestic users has risen considerably in the last years. In 2012, 36% of the roundwood harvested in Ireland was used for energy generation (Knaggs & O'Driscoll 2013). This situation increases competing demands for small sized timber volume assortments which traditionally were used in the manufacture of wood panels and fencing materials (H Phillips 2011). In this scenario it is important that wood biomass resources are used as efficiently and cost effectively as possible, allowing forest owners and wood processors to reduce harvesting and transportation costs, optimally match wood to market needs, and capture more value (Murphy & Wimer 2007).

Supply chain planning in the forest product sector encompasses a wide range of complex decisions at different planning levels, which usually are made and supported with the assistance of optimisation-based decision support tools (D'Amours et al. 2008). Effective design, planning and management of forest biomass energy plants play a critical role in reducing the energy generation cost and making it a viable energy source (Shabani et al. 2014). Recent advances in computational tools have made possible to build mathematical models for analysis and optimisation of complex supply systems (Azadeh et al. 2014). Many approaches have been used to simulate and optimise specific biomass supply chains, to get a better understanding of the cost reductions that could result from the implementation of more efficient logistics operations while ensuring a reliable and sustainable supply of forest fuel (Rentizelas et al. 2009).

Where to locate power plants and how to supply forest biomass to each plant is a problem that is commonly approached through location-allocation modelling, where the global objective is to minimise the total transport cost, typically expressed as the product of demand and distance (Ranta 2005). Commonly, biomass production and transportation account for a significant part of the whole bioenergy costs. The key element is to obtain sufficient biomass quantities in order to satisfy the energy plant at the least cost (Panichelli & Gnansounou 2008).

A planning tool often used for tactical planning is Linear Programming (LP) (Frisk et al. 2010). LP is an optimal decision making tool in which the objective is a linear function and the constraints on the decision problem are linear equalities and inequalities. LP is a well suited method for solving allocation problems and has been widely used in determining forest biomass availability (Ranta 2005). It can be used also to find a destination of flow from supply points to demand points. Eriksson & Bjoerheden (1989) in Sweden presented one of the first studies on biomass allocation. Their study dealt with one power station and six areas supplying four biomass products (sawmill residues, logging residues, wood chips and tree sections). The aim was to satisfy the demand at the plant at minimum cost for a period of one year. With the use of linear programming (LP) they analysed different supply scenarios: chipping at roadside or at the plant, and transporting direct from to the plant or via terminals. They concluded that transportation costs constitute the most essential part of the total supply costs, and that contrary to practice the best scenario was to comminute (chipping) at the forests with direct haulage to heating plants instead of using terminals.

Mixed Integer Linear Programming (MILP) modelling was used by Gunnarsson et al. (2004) with the aim of supplying from different forests and sawmills to various heating plants while minimising forwarding, chipping, storing and transportation costs. One of the decision

variables included in the model was whether or not to acquire residues from forests and sawmills that were not owned by the supplying company. Monthly plans for forwarding, storage and chipping were also determined. Different scenarios were tested based on storage restrictions, increased demand, chipping capacity and including new terminals.

Another MILP model on the forest fuel supply network at national scale in Austria was designed by Rauch et al. (2010). The model includes decisions on transport modes (road, rail and ship), number of terminals and their spatial arrangement. Scenarios are formulated to study the impact of rising energy costs and route optimisation. Railway had a minor share in all scenarios because the initial transport is always done by trucks and the total transport distances are relatively short within Austria. The impacts of rising energy costs on procurement sources, combination of transport modes, and procurement costs were evaluated. Their results showed a 20% increase of energy costs resulting in a procurement cost increase of 7%, and an increasing share of domestic waterway transportation.

A study in Denmark presented a GIS-based method to determine the least costly strategies to allocate forest wood chips to energy plants in Denmark. The GIS used a cost-weighted distance to wood chip resources and the annual demand as decision parameters (Möller 2004). The model allocated each supply of wood chips to plants along the least-cost paths in terms of travel time, until the demand of each plant was met or the wood chip source is exhausted. Resource areas were mapped on a national scale and the cumulative and total costs of supply for each plant were calculated. The study suggested that allocation analysis with a network-based GIS is a suitable method to express the costs connected with matching local demand and supply (Möller 2004).

Combining geographic information systems (GIS) and Linear Programming has been studied by Kanzian et al. (2009) in order to optimise the supply through the use of terminals. In Austria wood energy supply is required constantly through the year especially in winter when conditions often make mountainous regions inaccessible. The authors developed a regional fuel wood supply network that included the optimal use of terminals by testing a number of different scenarios based on demand, upgrading of energy plants and inclusion of harvesting residues. Together with Eriksson & Bjoerheden (1989) and Gunnarsson *et al* (2004) the authors have concluded that direct supply (without the use of intermediate terminals) is the most efficient and economical way to supply fuels to heating and power plants. Although the use of terminals can improve the quality of the biomass by minimising the MC and therefore increasing the energy content, it does not pay off the cost of making them part of the supply chain (Kanzian *et al* 2009).

The problem of choosing the best locations for energy facilities or supply to existing facilities is commonly assessed without considering the site competition for the biomass resource; competition have only to a limited extent been analysed in quantitative studies (Murphy et al. 2012). Finding the best locations for several energy units taking into account the sites competitions for resources is not straightforward. When the material in the region is scarce, the energy facilities have to compete for the biomass resources in order to meet their own demand. Collection areas may overlap and biomass amounts supplied to the unit will not be available for the other one (Panichelli & Gnansounou 2008).

In some cases the problem consists on choosing simultaneously the supply to more than one demanding plant. How the adoption of Irish policies related to the 30% co-firing target for the three peat power stations impact on other industries demanding wood resources was studied by Devlin & Talbot (2014). A digital road network of Ireland was used to calculate the shortest distances from 18 sawmills supplying woodchips to 3 wood based panel mills and 3 peat power station. The aim of this transportation problem based on linear programming was to minimise transportation costs. Three scenarios were analysed for two years 2015 and 2030. Global optimisation for both sectors is important, but prioritising for the board and energy sector are equally important. Results indicated that transportation makes up roughly one third of the delivered cost of forest biomass, and that physical planning and market intervention (allocating biomass to the correct destination) could be just as effective as market subvention through incentives.

Moisture content is a key attribute of wood biomass, the reduction of the amount of water in wood reduces transportation costs (more wood and less water can be delivered per load) and increases combustion efficiency as less energy is required during combustion to evaporate water (Murphy et al. 2012). Therefore, to facilitate the drying process and thereby ensuring the availability of high quality fuel in the short term, supply chains for wood chips should be designed to also promote the natural drying of timber during the procurement processes, as a cost efficient method (Röser et al. 2011).

Acuna et al. (2012) developed a non-spatial linear programming decision support system called BIOPLAN. This model applied in Finland does not use terminals, so storing of the biomass material occurs at the roadside. BIOPLAN uses drying (MC) curves as the driving factor for the optimisation of supply chain costs. The authors investigated the effect of MC on storage, chipping and transportation costs of biomass material delivered to the energy plant under different MC constraints, supply chain and biomass covering scenarios.

Geographical Information Systems (GIS) can be useful tools for mapping the availability of biomass fuel resources per county, demand location and average transportation distances

from each county to the plants. An extended review of different approaches to wood biomass supply optimisation can be found in Rönqvist (2003); Troncoso and Garrido (2005); Wolfsmayr and Rauch (2014)

This paper presents an approach for selecting the least cost supply of wood for three peat power stations and two competing wood-based panel mills. The methodology uses a spatial linear programming-based decision support system that uses interactions between parameters such as wood moisture content (MC), dry matter, solid and bulk density and truck payload constraints.

2 Materials and Methods

2.1 Site description

A total of 3 peat power stations and two panel board mills were identified as the demand points for the wood delivered from public and private managed forests. The three peat power stations are located quite centrally in Ireland within a triangular area of approximately 1,414 square km (Devlin & Talbot 2014). Power plant 1 (P1) is Ireland's first large scale independent power station producing 120 MWe. Power plant 2 (P2) is the largest peat-fired power station; capable of generating 150 MWe of power, and Power plant 3 (P3) is the smallest, generating 100 MWe of power. The total annual electricity output equates to 6% of Ireland's totally primary energy requirement (TPER) (Devlin 2012).

Currently, co-firing rate with biomass in P1 is 22%, the plant demands approximately 210,822 m³ solid of biomass, 60% of which is transported as wood chips from the forests. The two other demanding points include wood-based panel industries, which demanded approximately 1.28 million m³ of wood fibre in 2012 (Knaggs & O'Driscoll 2013). Mill 1 (M1) produces medium-density fibreboard (MDF) and Mill 2 (M2) produces oriented strand board (OSB) (Figure 1)

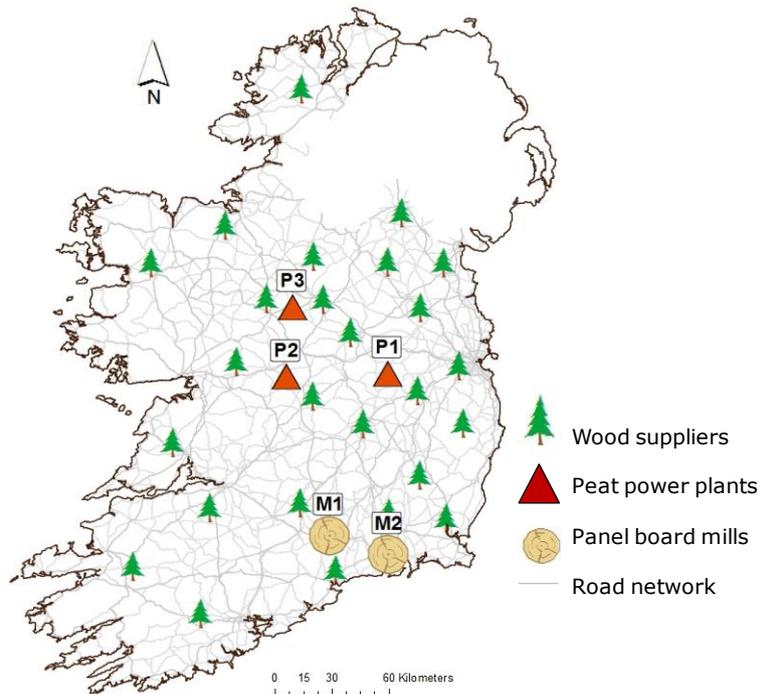


Figure 1 Supply and demand points, and road network used in the study.

2.2 Transportation distances for supply

Truck transport distances from supply to demand points were estimated using a digital road network of Ireland. The geometric road network created in ArcGIS was comprised of different road types (motorway, national primary, national secondary, regional and third class roads) represented as arcs connected by nodes.

Shortest routes from the centroid of each county to each peat power station and panel mill were determined using the Network Analyst extension of ArcGIS 10.1® and included in the optimisation model. Roundtrip distances were used assuming that trucks travelled loaded to the power plants and returned empty to the supply point (forest). Network Analyst uses the Dijkstra algorithm to find the least-cost paths based on distance, time or weighted cost. It uses the topological representation of the road network as arcs and nodes. Arcs hold attributes such as the road segment length and other attributes, and connect the road segments. For each resource location (county), this tool identifies the nearest node of the road network and computes the distance from the resource location to the nearest node. The centroid of each county was used as the pickup location due to the limited availability of detailed forest and forest roads maps for the private sector. More applications of the network

analyst tool can be found in other studies (Alfonso et al. 2009; Möller 2004; Panichelli & Gnansounou 2008).

2.3 Supply chains used for the analysis

For the application proposed in this paper, the potential availability of short wood was obtained from the Irish round wood production forecast (2011-2028), and it includes both the private and public (Coillte) forestry sector (Henry Phillips 2011). The short wood volume available per county was assumed to be produced from thinning and clearfell operations; the average percentages of both harvesting systems were obtained from the strategic management plans developed by Coillte (Coillte 2013). It was also assumed that the wood supplied to all the plants was delivered from Sitka spruce forests (*Picea sitchensis* (Bong) Carr.); this represents Ireland's most important timber species, accounting for slightly less than 60% of the forested area but more than 80% of the harvested volume (Murphy et al. 2012).

The production phases in this study include felling, forwarding, storage, chipping, and transportation. All the demand points required short wood in one of two forms: wood chips in the case of the peat power stations, and logs in the case of wood panel mills. Altogether, the analysis considered four supply chains which has been investigated in previous trials carried out in Ireland as part of the Forest Energy Programme (Kent et al. 2011):

Supply chain I (SCI) and II (SCII): Thinning operations producing a standard short wood (3 m) assortment with a minimum top diameter of 7 cm. Mechanical harvesting produces delimbed stems, leaving branches and any stem material less than 7 cm in diameters and 3 m length on the ground which usually form a brush mat on which the harvester and forwarder can drive to reduce soil disturbance. In SCI, chipping is carried out at the forest roadside by tractor or truck-drawn machines, which operate while stationary on the forest road, and are fed by a crane fixed to the tractor or truck. Woodchips are then directly transported to the power plants using walking floor trucks. In SCII, logs are directly transported to the panel board plants using articulated trucks.

Supply chain III and IV (SCIII, SCIV): Clear felling with mechanically harvesting equipment. This operation produces a range of wood products: sawlogs with a minimum diameter of 20 cm, pallet wood obtained from the mid-section of the log and has a small end diameter of 14 cm, and pulpwood with a diameter between 14 and 7 cm. In addition to branches, stem material of less than 7 cm in diameter is left on the forest area. In SCIII, chipping is carried

out at the forest roadside by tractor or truck-drawn machines as in SCI. In the case of SCIV, logs are directly transported to the panel board plants using articulated trucks (Figure 2).

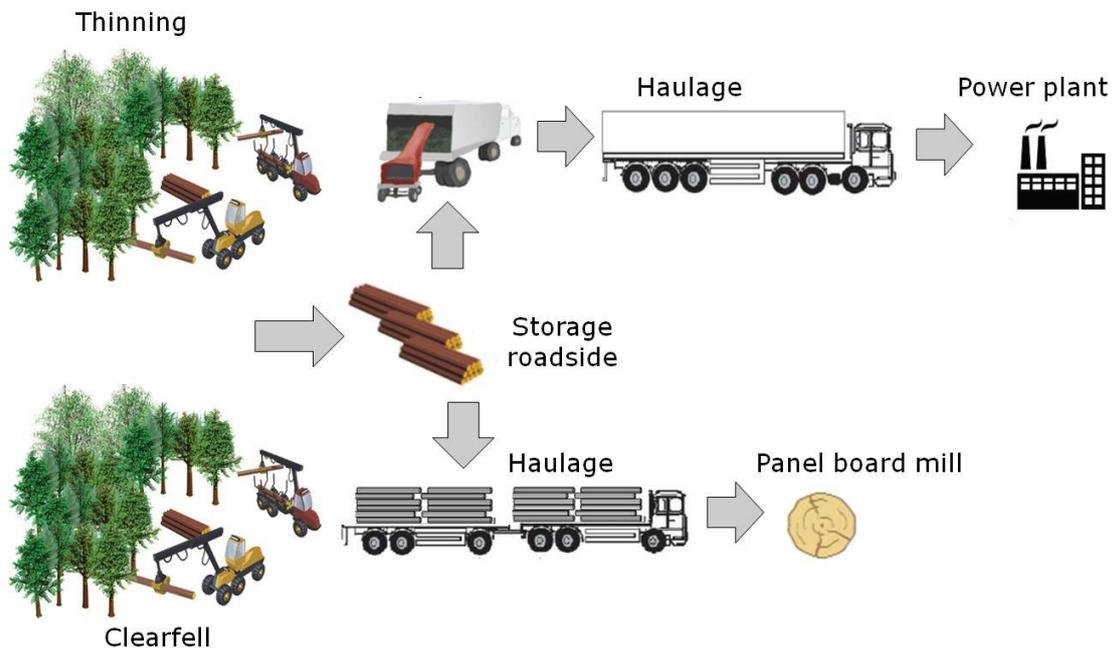


Figure 2 Summary of the supply chains used in the study.

2.4 Parameters of the model

The parameters used in this study were obtained from different sources (Table 1). The Forest Energy Programme in Ireland provided information on harvesting, forwarding and chipping costs. It also provided wood basic density, bulk density and bulk-solid volume conversion factor data (Kent et al. 2011). The net calorific value (NCV) for Sitka spruce was derived from European standards for biofuels (Alakangas 2011). Average volume and weight capacity of the trucks were collected in field studies carried out previously by the authors in Ireland.

Storage costs in the model are based on the assumption that there have been costs associated with harvesting and transporting the material to roadside and that these costs have been paid for at the time of harvest. Thus, storage costs are then the interest charge on the harvesting and transport to roadside costs since the wood owner incurs a delay due to storage in being reimbursed for these (Acuna *et al* 2012). An annual interest rate of 4.7% was used for the analysis based in Irish standards for short term projects (less than 10 years) (Department of Public Expenditure and Reform 2013). In addition, a woody biomass

loss due to storage was assumed to be 0.059 kg/m³ per year based on studies under Irish conditions (Olajuyigbe et al. 2011).

Table 1 Parameters and conversion factors used in the allocation model to determine energy content, number of truckloads, material loss from storage and storage costs.

Parameters and conversion factors	SCI	SCII	SCIII	SCIV
Net Calorific Value at 0% MC (GJ/t)	19.10	19.20	19.10	19.20
Basic density (kg/m ³)	377	377	377	377
Bulk density (kg/m ³)	130	252.59	130	252.59
Bulk/solid volume conversion factor	2.90	0.67	2.90	0.67
Truck maximum legal payload 6 axle (kg)	27,000	27,500	27,000	27,500
Truck maximum loose volume capacity (m ³)	95	69	95	69
Material loss rate (kg m ³ year)	0.059	0.059	0.059	0.059
Interest rate %/month	0.39	0.39	0.39	0.39

2.5 Drying curves

Murphy et al. (2012) developed a model that predicts daily moisture changes during drying periods on off-forest storage using daily climate information. In-forest seasoning of Sitka spruce under Irish weather conditions has been investigated by Kofman & Kent (2009) but monthly data during the two year planning period of the model were not available. Therefore, in-forest drying information for the model was based on a drying model developed by Sikanen *et al* (2012) (Figure 3).

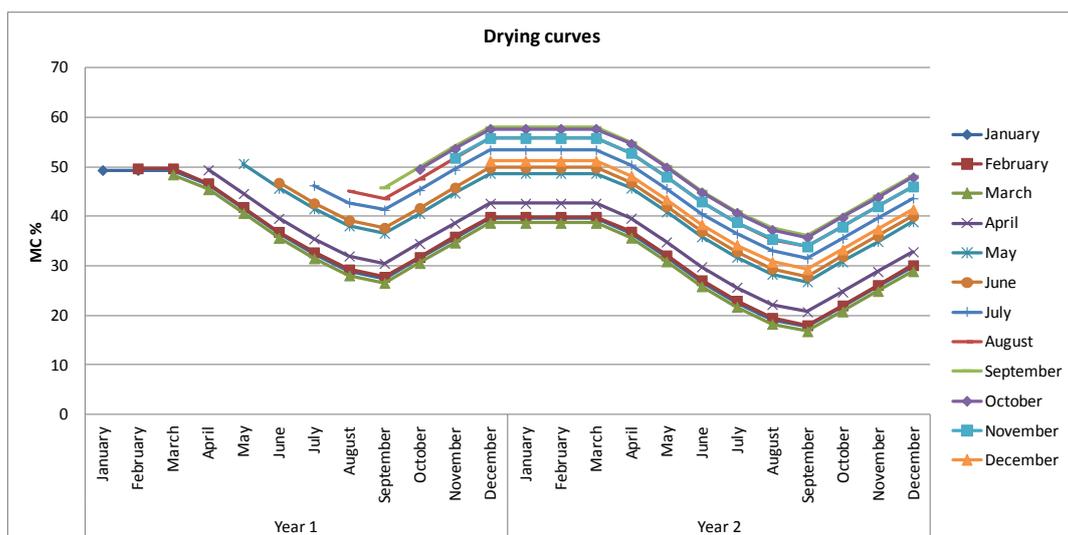


Figure 3 MC of biomass felled at different months and stored throughout the two year planning period (Sikanen et al. 2012).

2.6 Description of the model

The aim of the tactical and spatial optimisation model developed was to determine the optimal wood supply of shortwood that satisfies the energy demand of the three peat power stations and the competing demand of the two wood-based panel mills. The model considers a 2-year planning horizon where decisions on the volumes of wood to be harvested are made on a monthly basis (24 months). Storage of biomass materials at the roadside is allowed for a period of up to 24 months (from beginning of January year 1 to the end December year 2).

It is assumed that the woodchips produced from these materials are consumed during the same period (month) in which they arrive at the power plants. The energy content of the wood chips being supplied from the forests was determined using the MC from the drying curves, and must meet power plant's monthly energy demand (GJ). In addition, the transportation of wood chips and shortwood to the power plants and mills is performed by trucks with different configurations and volume capacities. The weight of the loads supplied and the number of truckloads to deliver the biomass was also calculated based on the wood MC.

The model displays the results in a series of matrices including among others:

- Decision variables on tonnes and corresponding solid volume of wood to be harvested in each period.
- Loose volume (LV) of wood chips produced at the roadside in each period.
- Weight of the wood (logs and woodchips) to be supplied to the peat plants and board panel mills.
- Number of truck loads delivered to the power plants and panel mills.
- Energy content of wood chips in gigajoules (GJ) arriving at the power plants.
- Harvesting, forwarding, chipping, storage, and transportation costs.

The model contains a list of assumptions and simplification:

- The fuel wood resource potential is uniformly spread over the forest area of each county.
- The costs of chipping are constant.
- The distance from each county to the plant is calculated based on the centroid of each county to each plant and mill.

2.7 Mathematical model

The supply optimisation model was developed using linear programming. The mathematical model uses sets, parameters, and variables are presented in Table 2.

Table 2 Sets, parameters, and variables used in the mathematical formulation of the model.

Term	Definition
<i>Set</i>	
$i, j = \text{periods}$	$i \in I = \{1 \dots 24\}, j \in J = \{13 \dots 24\}$
$c = \text{counties}$	$c \in C = \{1 \dots 26\}$
<i>Parameters</i>	
α, β	Conversion factors from m^3 solid to m^3 bulk for wood chips and logs, respectively
$EC_{i,j,c}^{th}, EC_{i,j,c}^{cl}$	Energy content for chips produced in period j and county c from thinning th and clearfell cl harvested in period i , respectively
$MC_{i,j,c}^{th}, MC_{i,j,c}^{cl}$	Moisture content of chips produced in period j and county c from thinning th and clearfell cl harvested in period i , respectively
$CH_{i,c}^{th}, CH_{i,c}^{cl}$	Harvesting and extraction cost ($\text{€}/\text{m}^3$ solid) for thinning th and clearfell cl , respectively, harvested in period i , at county c
$CS_{i,j,c}^{th}, CS_{i,j,c}^{cl}$	Storage cost ($\text{€}/\text{m}^3$ solid) for thinning th and clearfell cl , respectively, stored at the roadside or stump from period i to j ($i \leq j$) at county c
$CCH_{i,j,c}^{th}, CCH_{i,j,c}^{cl}$	Chipping cost ($\text{€}/\text{m}^3$ solid) for thinning th and clearfell cl harvested in period i and chipped at the roadside in period j at county c
$CTP_{i,j,c,p}^{th}, CTP_{i,j,c,p}^{cl}$	Transportation cost ($\text{€}/\text{m}^3$) of wood chips from thinning th and clearfell cl (loose volume), harvested in period i and transported to the energy plants p in period j from county c
$CTM_{i,j,c,m}^{th}, CTM_{i,j,c,m}^{cl}$	Transportation cost ($\text{€}/\text{m}^3$) of logs from thinning th and clearfell cl (stacked volume), harvested in period i and transported from county c to panel-board mill m in period j
$CAPC_c$	Supply capacity (m^3) from thinning th and clearfell cl in county c for the 2-year planning horizon

Table 2: Sets, parameters, and variables used in the mathematical formulation of the model
(continuation).

<i>Variables</i>	
$X_{i,j,c,p}$	Solid volume of shortwood (thinning) harvested in county c and period i , and stored at the roadside until period j for chipping at the roadside, to be delivered at the energy plant p
$Y_{i,j,c,p}$	Solid volume of shortwood (clearfell) harvested in county c and period i , and stored at the roadside until period j for chipping at the roadside, to be delivered at the energy plant p
$Z_{i,j,c,m}$	Solid volume of short wood (thinning) harvested in county c and period i , and stored at the roadside until period j for transportation, to be delivered at the panel-board mill m
$W_{i,j,c,m}$	Solid volume of short wood (clearfell) harvested in county c and period i and stored at the roadside until period j for transportation, to be delivered at the panel-board mill m
$X'_{i,j,c,p}$	$X_{i,j,c,p} * \alpha$ = Loose volume of chips from short wood (thinning) harvested in county c and period i , and stored at the roadside until period j for chipping and transport to the power plant p
$Y'_{i,j,c,p}$	$Y_{i,j,t,p} * \alpha$ = Loose volume of chips from short wood (clearfell) harvested in period i and county c , and stored at the roadside until period j for chipping and transport to the power plant p
$Z'_{i,j,c,m}$	$Z_{i,j,t,m} * \beta$ = stacked volume of short wood (thinning) harvested in county c and period i , and stored at the roadside until period j for transportation to the panel board mill m
$W'_{i,j,c,m}$	$W_{i,j,t,m} * \beta$ = stacked volume of short wood (clearfell) harvested in county c and period i , and stored at the roadside until period j for transportation to the panel board mill m

Objective function (FO)

The objective function of the model minimises total supply chain costs (€) including harvesting, storage, chipping and transportation (Equation 1).

$$\begin{aligned}
 FO = & \sum_{i,j,c,p} X_{i,j,c,p} * (CH_{i,c}^{th} + CS_{i,j,c}^{th} + CCH_{i,j,c}^{th}) + \sum_{i,j,c,p} X'_{i,j,c,p} * CTP_{i,j,c,p}^{th} + \sum_{i,j,c,p} Y_{i,j,c,p} \\
 & * (CH_{i,c}^{cl} + CS_{i,j,c}^{cl} + CCH_{i,j,c}^{cl}) + \sum_{i,j,c,p} Y'_{i,j,c,p} * CTP_{i,j,c,p}^{cl} + \sum_{i,j,c,m} Z_{i,j,c,m} * (CH_{i,c}^{th} + CS_{i,j,c}^{th}) \\
 & + \sum_{i,j,c,m} Z'_{i,j,c,m} * CTM_{i,j,c,m}^{th} + \sum_{i,j,c,m} W_{i,j,c,m} * (CH_{i,c}^{cl} + CS_{i,j,c}^{cl}) \\
 & + \sum_{i,j,c,m} W'_{i,j,c,m} * CTM_{i,j,c,m}^{cl} \quad (1)
 \end{aligned}$$

Constraints

Energy demanded at the power plants (GJ):

Equation 2 ensures that the monthly energy demand (ED) at the three power plants (GJ) in year 2 is met by the wood chips supplied from all the private and state forests (counties).

$$\sum_{i \leq j, c, p} X'_{i,j,c,p} * EC_{i,j,c,p}^{th} + \sum_{i \leq j, c, p} Y'_{i,j,c,p} * EC_{i,j,c,p}^{cl} \geq ED_j \quad \forall j \in J \quad (2)$$

Volume of wood demanded at the wood-based panel plants (m³):

Equation 3 ensures that the monthly volume demand (VD) for short wood at the two panel board mills is satisfied in year 2 by the logs supplied from all the forests (counties).

$$\sum_{i \leq j, c, m} Z'_{i,j,c,m} + \sum_{i \leq j, c, m} W'_{i,j,c,m} \geq VD_j \quad \forall j \in J \quad (3)$$

Minimum and maximum moisture content (MC %) of chips arriving at the power plant:

This constraint included in S1.2 and S2.2 ensures that the woodchips that arrive at the power plants meet the specified MC (Equation 4).

$$MinMC_j \leq \sum_{i \leq j, c, p} X'_{i,j,c,p} * MC_{i,j,c}^{th} + \sum_{i \leq j, c, p} Y'_{i,j,c,p} * MC_{i,j,c}^{cl} \leq MaxMC_j \quad \forall j \in J \quad (4)$$

Even production of wood chips and logs throughout the year:

An even volume of wood chips and logs is produced in years 1 and 2. This operational constraint allows for continuous work for harvesting and haulage contractors (Equation 5 to Equation 8).

$$\sum_{j \geq i, c, p} X_{i,j,c,p} = \sum_{j \geq i, c, p} X_{i+1,j,c,p} \quad \forall i \in \{1 \dots 11, 13 \dots 23\} \quad (5)$$

$$\sum_{j \geq i, c, p} Y_{i,j,c,p} = \sum_{j \geq i, c, p} Y_{i+1,j,c,p} \quad \forall i \in \{1 \dots 11, 13 \dots 23\} \quad (6)$$

$$\sum_{j \geq i, c, p} Z_{i,j,c,p} = \sum_{j \geq i, c, p} Z_{i+1,j,c,p} \quad \forall i \in \{1 \dots 11, 13 \dots 23\} \quad (7)$$

$$\sum_{j \geq i, c, p} W_{i,j,c,p} = \sum_{j \geq i, c, p} W_{i+1,j,c,p} \quad \forall i \in \{1 \dots 11, 13 \dots 23\} \quad (8)$$

Supply capacity from counties (m^3)

This constraint ensures that the biomass supplied to the plant is lower than the maximum potential supply capacity of each county (Equation 9). The total availability for short wood both from the private and public sector is forecasted to be around 1.5 million m^3 (Phillips 2011), with approximately 69.49% produced through clearfell and 30.51% through thinning (Coillte 2013). Table 3 shows the potential harvesting volume and percentage contribution of each county to the total available supply for the two year planning period.

$$\sum_{i \leq j, j, p} X_{i,j,c,p} + \sum_{i \leq j, j, p} Y_{i,j,c,p} + \sum_{i \leq j, j, m} Z_{i,j,c,m} + \sum_{i \leq j, j, m} W_{i,j,c,m} \leq CAPC_c \quad \forall c \quad (9)$$

Table 3 Potential harvesting supply available from each county forecasted during the planning period (Phillips 2011).

County	Potential supply (m^3)	Potential supply (%)	County	Potential supply (m^3)	Potential supply (%)
Meath	4,286	0.29%	Roscommon	49,879	3.33%
Louth	4,620	0.31%	Sligo	54,253	3.62%
Dublin	7,417	0.50%	Limerick	58,561	3.91%
Longford	9,134	0.61%	Leitrim	60,290	4.03%
Kildare	10,032	0.67%	Waterford	66,806	4.46%
Monaghan	10,907	0.73%	Mayo	89,202	5.96%
Carlow	15,346	1.02%	Wicklow	101,313	6.76%
Westmeath	16,121	1.08%	Clare	107,162	7.16%
Cavan	30,813	2.06%	Tipperary	108,424	7.24%
Offaly	32,565	2.17%	Donegal	108,866	7.27%
Wexford	35,666	2.38%	Kerry	110,392	7.37%
Kilkenny	40,033	2.67%	Galway	130,224	8.69%
Laois	43,653	2.91%	Cork	191,739	12.80%

2.8 Scenarios studied

Five scenarios were analysed based on different volume and MC of the wood demanded:

- Scenario S1: P1's demand increases its current 22% co-firing to the national target of 30%. P2 and P3 plants start co-firing at 10%. Meanwhile, the panel board mills (M1 and M2) demand must be also satisfied.
- Scenario S2: This scenario is similar to scenario 1, but in this case the MC of the biomass arriving at the power plants was constrained to be equal to or less than 40%. The demand at the panel board mills remains the same.
- Scenario S3: P1 meets the demand at the 30% co-firing target while P2 and P3 increase their demand so they co-fire at 15%. The demanded volume from the panel board mills remains the same.
- Scenario S4: Similar to scenario 3, but as in scenario 2 the biomass demanded at the peat plants must arrive with a MC equal of less than 40%. The demand at panel board mills remains the same.
- Scenario S5: The three peat power stations demand enough biomass to reach their 30% co-firing target. The demand from the panel mills remains the same.

6.2.9 Implementation of the model

The linear programming (LP) model was implemented using the What'sBest® solver package for MS-Excel. Once the tables and solver engine were setup, a Visual Basic program was written to execute the model.

3 Results and discussion

3.1 Supply to peat power stations and panel board mills

The demand from all the energy plants and mills under the five scenarios was satisfied with the available supply of short wood in Ireland. Approximately 64.6% of the potential supply can satisfy the demand in scenario S1 and S2. Scenarios S3 and S4 consumed 71.9% of the available supply, while in scenario S5 all the plants met their 30% co-firing target, and the demand on both panel mills was satisfied with approximately 94.2% of the available short wood supply.

The total demand under the five scenarios was satisfied with different proportions of short wood from clearfelling and thinning. In general, due to lower clearfelling harvesting costs, the model chose this material as the main supply source to both the power plants and the mills. Under unconstrained scenarios S1 and S3 all short wood delivered to the energy plants was delivered from clear cutting areas, whereas approximately 32.4% of the demand from the panel board mills was satisfied with short wood from thinnings. In order to provide enough material with low MC (scenarios S2 and S4) the model included the supply of wood from thinnings to the energy plants despite its higher harvesting costs. MC constraint scenarios S2 and S4 resulted in the allocation of wood volume from thinnings to energy plants (7.4% and 20.7% in each scenario, respectively). The proportion of wood from thinnings required to meet the demand at the panel board mills remained the same as in the unconstrained scenarios.

The model allocated wood from thinnings to the panel board mills because the high cost of harvesting thinnings can be offset by the chipping cost incurred if the thinning material is delivered to the energy plants. When co-firing increased in scenario S5, there was an increase in wood supply from thinning which satisfied 20.4% of the energy plants demand, and 40.3% of the panel board mills demand (Figure 4).

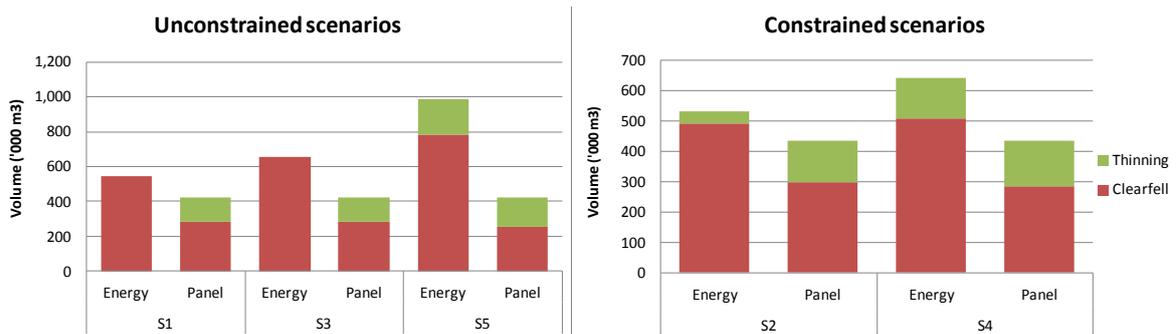


Figure 4 Volume supplied to power plants from thinning and clearfelling.

3.2 Costs of satisfying the increasing demand

Increasing the co-firing rate to 15% (S3) at the peat power stations P2 and P3 increased the supply chain costs by 17.3% in comparison to the 10% co-firing rate scenario (S1). Meeting the 30% co-firing target in all three peat power stations (S5) resulted in a 47.4% increase in supply chain costs in comparison to the 15% co-firing rate scenario. Naturally drying required to reach 40%MC resulted in higher overall supply chain costs when compared with the unconstrained scenarios. Co-firing at 10% (S2) resulted in 10.1% higher costs than S1, and co-firing at 15% (S4) had 21.2% higher costs in comparison with S3 (Figure 5).

Co-firing at 15% at the peat power stations (S3) did not affect the cost of supplying wood to the panel mills, while all the three plants meeting the 30% co-firing target (S5) increased the wood supply costs to the panel mills by 7.9%. Most of this increase in costs was the result of the higher volumes of wood from thinnings required to satisfy the panel mills demand. Constraining the MC of the biomass destined to the power plants increased the costs of supplying the panel mills by an average 3.8%, mostly due to longer transport distances (Figure 5).

The supply chain costs for the power plants under unconstrained scenarios S1 and S3 were comprised mainly of harvesting costs (avg. 57%), followed by chipping costs (avg. 18%), transportation (avg. 19%), and lastly storage costs (avg.1%). When constraining the MC of the wood biomass supplied to the power plant (scenario S2 and S4), harvesting, chipping, transportation, and storage costs accounted for 61%, 15%, 17%, and 3%, respectively (Figure 5). Constraints of wood MC did not affected the supply chain costs of panel mills, and they consisted mainly of harvesting (avg. 83%), transportation (avg. 16%), and storage (avg. 1%).

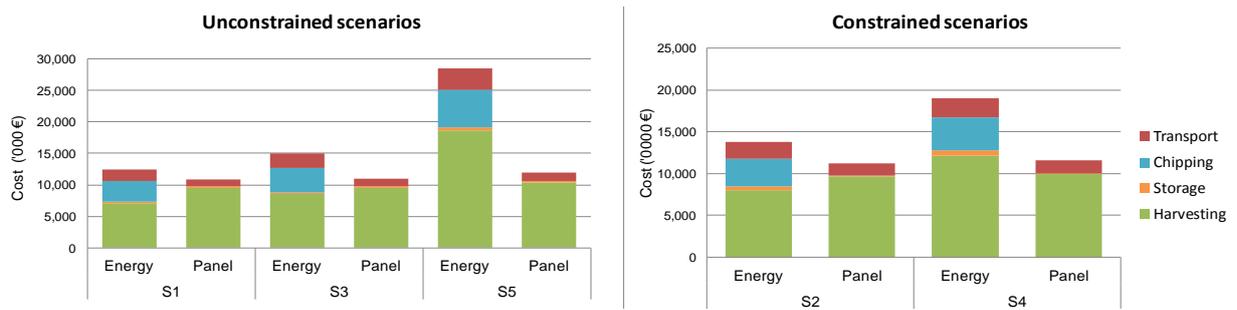


Figure 5 Supply costs to energy and panel plants for unconstrained and constrained scenarios.

In general, the major impact from constraining the MC of wood was associated with the increased storage costs in order to get drier wood, followed by an increase of harvesting costs as additional volume of wood from thinnings was required to be harvested in order to satisfy the increasing demand. Lastly, transportation costs increased as a result of the longer transport distances between the procurement areas with dry wood and the plants. Lastly, there was a reduction in chipping costs resulting from the lesser wood biomass that was harvested and chipped when the wood was dried at the roadside for longer periods.

A detailed analysis of the structure of supply costs revealed some differences between the constrained and unconstrained scenarios amongst the three energy plants, which was mostly associated with the size and demand of the plants. This result agrees with other studies which have showed that logistics management is pivotal to control costs as the scale of the plants increase. Bigger plants demand more material and results in bigger supply areas which in turn increases transport distances and costs (Dornburg & Faaij 2001). Also, both the yield of biomass per unit area and the location of the biomass have an impact on the optimum size and location of the power plants (Kumar et al. 2003).

Supply costs largely depend on the production system chosen (harvesting, storage, chipping, transport), the site characteristics and the transportation distances (Hall et al. 2001). Figure 6 shows how the cost structure of the supply chain varied between the three peat power plants when MC was constrained. For the 10% co-firing scenarios storage represented the major cost increase for all three plants when the MC was constrained, followed by harvesting costs, where for P3 increased only 1.8% in comparison with P1 and P2 (average increased harvesting cost of 14.3%). The change in harvesting cost for P3 was offset by the highest transport cost variation (26.7%) compared with P1 and P2 (11.7% and 6.8% respectively) (Figure 6A).

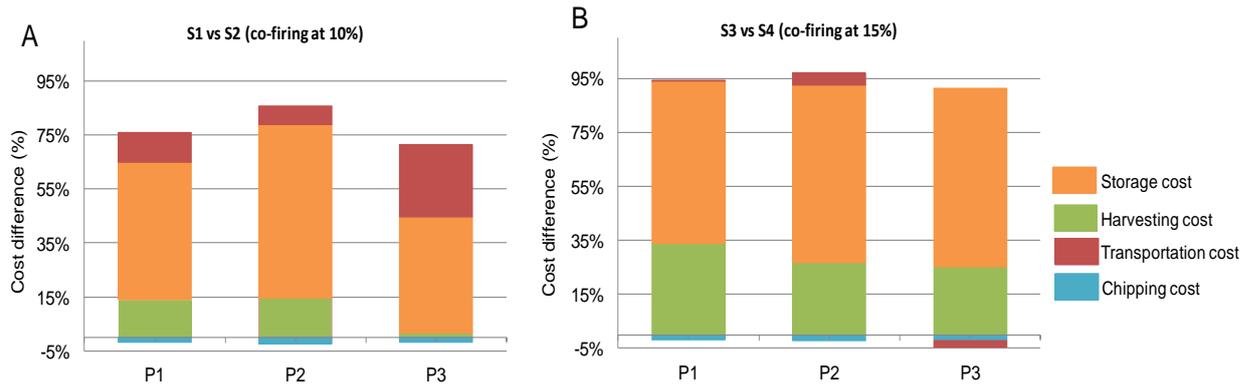


Figure 6 Supply chain costs differences between MC constrained and unconstrained scenarios, at A) 10% and B) 15% co-firing rate.

For a 15% co-firing rate, constraining the MC (scenario S4) resulted in a slight variation in supply costs between the three power plants. On the other hand, the combined effect of an increased demand and MC restrictions resulted in higher cost variation when compared to the 10% co-firing scenarios. Harvesting costs in P3 only increased by 1.8% when the MC was constrained (S2) under a co-firing rate of 10%, and by 25.2% when the co-firing rate was 15%. This was due to the inclusion of higher volumes of wood from thinnings, which reduced transportation costs by 2.1% as the result of shorter transport distances to P3 (Figure 6B). The cost variation between plants may depend on the technology used. In Cameron *et al* (2007), gasification had a lower power cost than direct combustion making it the most economic technology. Therefore, technology selection cannot be separated from an analysis of feedstock cost.

In this study the cost per unit of the wood delivered to both panel mills and energy plants increased with higher co-firing rates. However, the results of the optimisation model showed that the storage costs increased at a higher rate than the costs resulting from a higher demand at power plants. When the MC of wood biomass was constrained in scenarios S2 and S4 there was an average cost increase of 18% and 28.2% respectively. In the case of the energy plants, biomass supply chain costs were higher and more sensitive when calculated on a per weight basis (Table 4). The cheapest option usually tends to be the simplest system because each time the material is handled extra costs are added (Hall et al. 2001). In this case, the positive economic effect of transporting logs to the panel mills and not chipping them at the roadside was offset by the higher harvesting costs from supplying wood from thinnings.

Table 4 Average production costs of wood for biomass and panel plants.

Scenario	Energy plants			Panel mills
	€/m ³ solid	€/t	€/MWh	€/m ³ solid
S1	22.53	33.34	3.48	23.50
S2	25.37	40.66	3.84	23.64
S3	22.85	33.69	3.53	23.65
S4	29.27	46.95	4.44	23.55
S5	28.83	42.44	4.46	26.16

It is likely that the increasing demand for wood biomass will impact on the traditional forest sector. The magnitude of the impact will depend on wood availability, structure of the forest sector, technological development, political incentives and the development of energy prices. For example, the increase of energy prices in Norway will also increase the demand for wood-based bioenergy, affecting the conventional forest sector by reducing the production of particle board and pulp (Trømborg & Solberg 2010)

3.3 Spatial distribution

The feasibility and profitability of biomass to energy projects are highly dependent on the geographical location of supply and demand points (Noon & Daly 1996). The increasing demand of the power plants resulted in the model allocating biomass from longer distances and/or from thinnings. As co-firing rates increased from 10% to 15% in P2 and P3 (scenarios S1 and S3) there was a variation in the spatial distribution of wood biomass to all the other demand points. Larger demands of wood biomass also increased the number of procurement areas (counties) providing material to the power plants (P1: 17 to 19, P2: 2 to 3, and P3: 3 to 4 counties). This in turn increased the transportation distance by an average of 22.1%. Meeting the 30% co-firing target (S5) resulted in more counties delivering biomass to P2 and P3 (P2: 3 to 9 and P3: 4 to 7 counties respectively), and a 4.2% increase in haulage distance. On the contrary, the number of procurement areas delivering material to P1 decreased from 19 to 14 with a 24.2% reduction in haulage distance (Figure 7).

Procurement areas changed as the biomass MC was constrained in scenario S2 and S4. In scenario S2 there was an increasing number of supplying counties (P1: 17 to 21, P2: 3 to 5, and P3: 2 to 5 counties), with an average increase in haulage distance of 17.63%. In scenario S4 counties increased in P2 (4 to 6) and P3 (3 to 5), but counties supplying at P1 decreased from 19 to 18 with an average haulage distance increase of 7% (Figure 7).

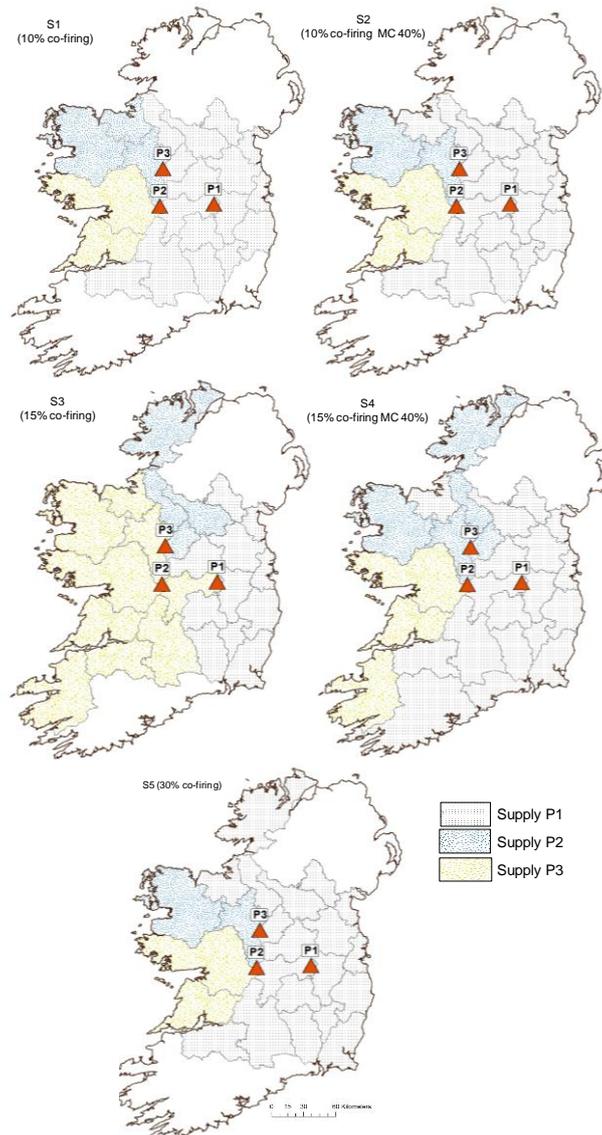


Figure 7 Spatial distribution of wood biomass with constrained and unconstrained MC.

Increasing the power plant demand for wood biomass had an effect on the spatial distribution of the short wood being delivered to the panel mills. An increase from 10% and 15% to 30% co-firing rate, reduced the number of counties supplying wood to M1 (9, 8 and 7 counties respectively), while the number of counties supplying to M2 remained the same (4 counties) (Figure 8). A reduction of counties supplying M1 is attributed to a higher proportion of wood from thinnings.

Constraining the MC of the wood biomass affected the spatial distribution of short wood distributed to the panel mills when co-firing increased to 15%. This resulted in the addition of new counties supplying wood biomass (8 to 9 counties to M1, and 4 to 12 counties to M2) (Figure 8).

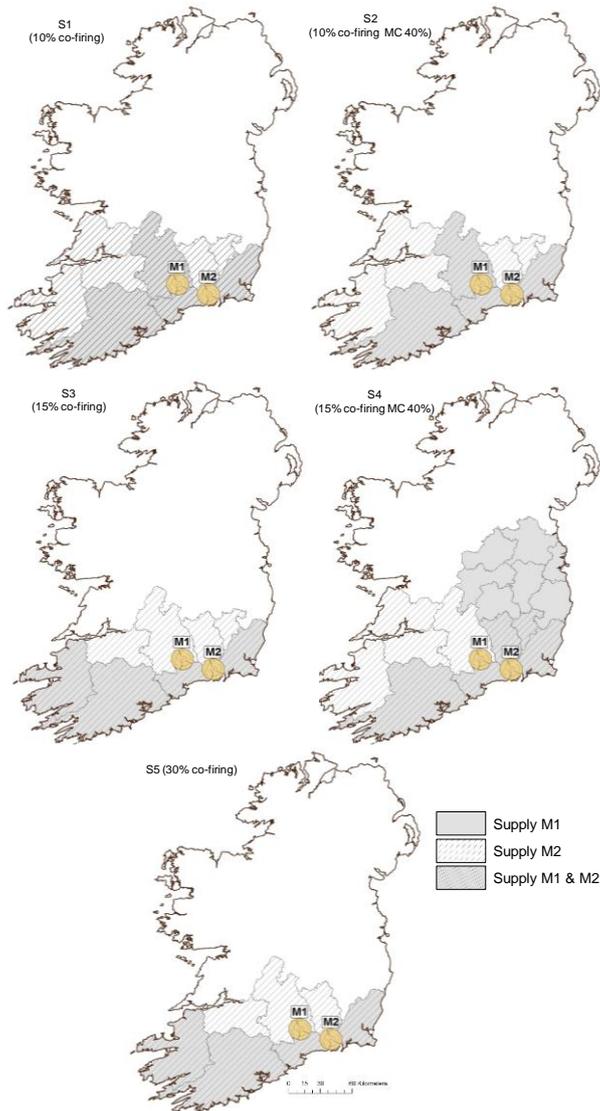


Figure 7 Spatial distribution of logs to panel mills by scenarios with MC constrained and unconstrained.

These results are confirmed by the findings of previous studies. In Möller (2004) a supply batch was allocated to the nearest energy plant, and when the resources in the vicinity of a plant were used, transport from more remote forests was allowed.

The spatial distribution of biomass varies when considering production technologies, multi-sources of biomass, and human accessibility to the biomass resource (Panichelli & Gnansounou 2008). In Freppaz et al. (2004) the type of biomass also played a role in how the demand was satisfied. For plants with lower thermal demands (less than 13 MW), the capacity of each plant was satisfied through the use of biomass being delivered from sites where harvesting was cheaper. For thermal demands greater than 13 MW, the biomass obtained both from harvesting and from waste of local production activities was not able to feed the overall demand of the plants. In this case, the model minimises the supply costs by

allowing transport from further distances in order to provide short wood from clearfellings, while in some cases it reduces the haulage distances to some power plants including a higher volume of short wood from thinnings (Freppaz et al. 2004).

3.4 MC changes

In all the unconstrained co-firing scenarios (S1, S3 and S5) the MC of the biomass supplied to the plants varied throughout the year, ranging from an average minimum MC of 45%, and a maximum of 52%. Lower clearfelling harvesting costs allowed for longer storage periods. This resulted in wood biomass from clearfellings presenting a MC lower (min. 40%, max. 48%) than that of the biomass from thinnings (min. 45%, max. 52%). Constraining the MC to a maximum of 40% (S2 and S4) resulted in a more uniform MC of the material arriving at the plants throughout the year, with a maximum MC of 40% and a minimum MC of 38% (Figure 9). The minimum MC in both scenarios was reached when the material was delivered to the power plants during the summer months.

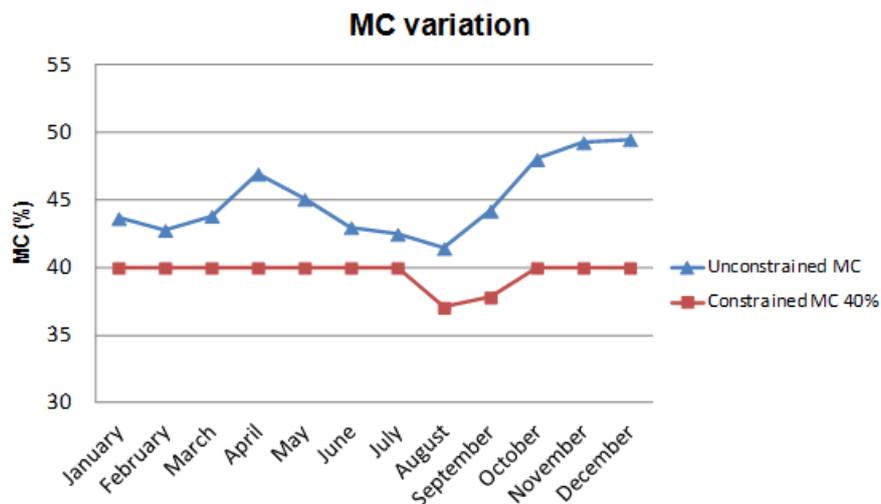


Figure 8 MC variation of wood biomass supplied to the power plants.

These results are confirmed by a previous study (Acuna et al. 2012) where under an unconstrained scenario wood biomass presented a much higher MC variation than in the case of MC constrained scenarios; with logging residues having overall a lower MC compared to whole trees and stem wood. The lower harvesting cost of whole trees allowed for longer storage times, which explains the lower MC values obtained.

Results also agreed with Talbot & Suadicani (2006) who point out that the MC is the most important controllable factor in determining transport efficiency. A high MC increases the weight and cost of the transported material, and leads to a higher forest fuel demand in

terms of the supplied volume. In addition, it increases the number of shipments needed and the volume of ash to be deposited at the end of the conversion process (Rauch 2010).

3.5 Storage

Storage time for the biomass supplied to the power plants averaged 7 months, with a maximum of 11 months and a minimum of 3 months for scenarios S1 and S3, respectively. When the co-firing increased to 30% in P2 and P3 (S5) storage changed to 12 months maximum and 2 months minimum, respectively. The solution in this scenario includes wood from thinning to satisfy the demand constraint, which is stored for a maximum and a minimum time of 9 months and 1 month, respectively. When the MC was constrained to 40% (S2 and S4) the storage time extended to an average maximum of 17 months and a minimum of 8 months.

Drying through storage increases wood's energy content and reduces the volume of wood to be harvested. Our results confirmed this latter effect showing an average reduction of 2% of the wood volume harvested, and an average 10.13% reduction on weight (Figure 10). Storage can also imply negative effects such as dry matter losses and added costs (Gallis 1996). Based on wood decay dynamic studies in Ireland (Olajuyigbe et al. 2011) found that only 0.01% of the material harvested was lost due to storage. Regarding the added cost from storage, section 3.1 shows that the maximum storage cost in this study accounted for only 3% of the overall supply chain costs.

In this study it was assumed that the wood biomass was uncovered, so the comparison of different storage methods was not analysed. Even so, different piling, covering and handling methods for storage at the plant and in-forest can have an effect on the MC change. For storage at the plant it is recommended to store biomass under roof and with as low initial moisture content and large particle size distribution as possible for minimal fuel losses (Anheller 2009).

For storage in-forest, to pile the wood in an open area along the forest road, covering the wood piles, and debarking stems partially proved to be an effective method to reduce moisture (Röser et al. 2010). It is important also to pay attention to the stacking method, wind and sun exposure. Studies under Irish conditions, showed that abrasion by wind, branch stubs, and sun exposure over time reduce the lifetime of the paper used to cover the piles, and some studies recommend paper covering to be applied in a depot where round wood is stored for shorter time periods (Kofman & Kent 2009). The benefits of increased combustion efficiency and price and reduced transportation costs due to storage must be weighed against increased handling costs (e.g., harvesting machines having to return to the

forest after drying to chip logs, or intermediate transport to an off-forest storage yard) (Murphy et al. 2012)

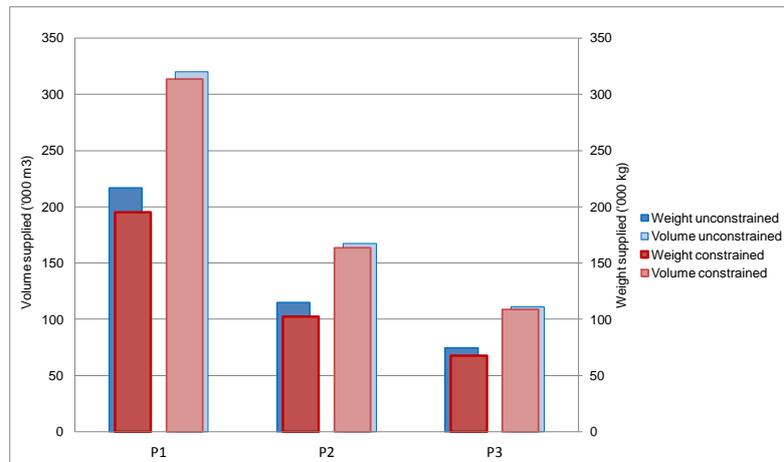


Figure 9 Wood biomass volumes and weights under unconstrained and constrained MC scenarios.

3.6 Transportation

Transportation distances from the forest areas to the peat power plants and the panel board mills varied. Under unconstrained scenarios S1 and S3 the average transport distances did not change, with an average distance of 86 km to the power plants and 83 km to the panel board mills. Constraining the MC (S2 and S4) increased the average transport distance to 100 km in the case of power plants and 124 km in the case of panel board mills. In scenario S5, these average hauling distances were reduced to 92 km and 90 km in the case of power plants and panel mills, respectively. The maximum transport distance for woodchips and short wood in S1 and S3 was 156 km, and 190 km in scenarios S2 and S4.

In addition, constraining the MC resulted in a variation on the size of the truck fleet. There was a reduction of 10.12% in the size of the fleet carrying wood chips and a 9.59% increase in the size of the fleet carrying logs to the panel mills. Tighter constraints on MC resulted in more volume of short wood been being stored for longer periods in order to reach the MC limit, maximise the volume per truckload and minimise transport costs.

Both biomass MC and demand affected the energy content per truck delivered to the plants. The highest energy (MWh) delivered per truckload was obtained in scenarios S2 and S4 where the MC limits were lower. The average maximum and minimum energy per truckload delivered in these two scenarios was 84 MWh, and 74 MWh, respectively. Scenarios with an unconstrained MC (S1 and S3) delivered a maximum of 78 MWh and a minimum of 63 MWh per truckload, while in S5 biomass was delivered with maximum and minimum energy

content per truckload of 73 MWh and 62 MWh, respectively. In this case, as demand and costs increased there was a reduction in storage times which resulted in material with lower energy content being delivered (Figure 11).

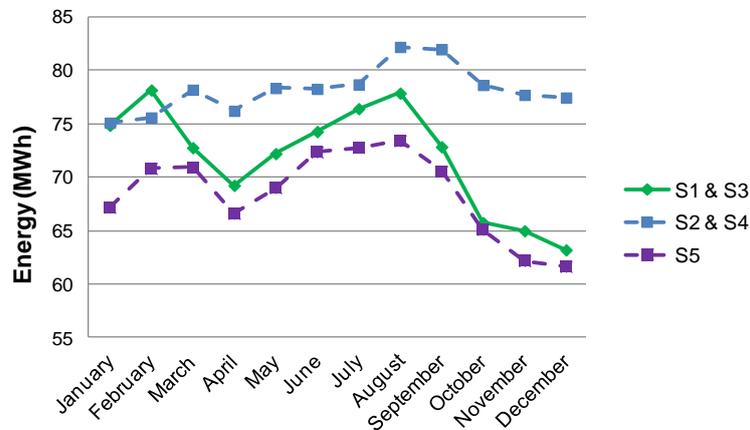


Figure 10 Energy content per truckload delivered to the power plants under the five scenarios.

Two types of trucks were used: articulated box trailer trucks with 6 axles carrying wood chips to the power plants, and 6-axle articulated trucks with skeletal trailers (including a self-loading crane) to transport logs to the panel board mills (Figure 12). The maximum truck payloads were established based on Irish regulations, with a maximum gross vehicle weight (GVW) of 46,000 kg for 6-axle articulated trucks. The maximum volume capacity of the trailers was measured in the field by the authors, and averaged 95 m³ in the case of chip trailers and 69 m³ in the case of log trailers.



Figure 11 Truck types used to haulage wood chips and logs.

The MC of the wood had an impact on the GVW of the trucks, especially in the unconstrained scenarios which presented a higher variability in MC. On average, trucks carrying logs moved 8,700 kg (5.47%) more than trucks carrying wood chips under a wide range of MC. The low bulk density of wood chips has a negative impact on transport productivity since loads reach the maximum legal dimensions of the truck and/or trailer before meeting the legal maximum payload weight. For the configurations used in this study, loading trucks with woodchips running at their maximum volume capacity resulted in payloads 12,159 kg under the maximum legal weight. As a solution to this problem, Talbot & Suadicani (2006) recommended raising and dropping the front end of the container 2–3 times in order to increasing the bulk density of the load by over 5% towards the maximum payload.

The situation is different when moving logs as this material has a higher bulk density in comparison with woodchips. In the case of logs transport, maximising the load implies to reach the full load volume capacity without exceeding the legal maximum weight. Trucks delivering logs to the panel mills and running at full volume capacity exceeded the legal maximum weight by up to 13,500 kg (Figure 13). In unconstrained scenarios (S1, S3 and S5) woodchips had a MC ranging from 45% to 52% which resulted in trucks running fully loaded with an average payload 2,900 kg lower than the legal limit. Constraining the MC (scenario S2 and S4) increased the weight underutilisation to an average of 6,738 kg.

A study in Sweden showed that trucks carrying woodchips and bundles could not be loaded to reach their maximum GVW (60,000 kg), as the maximum load was limited by the volume of the material. This occurred when the MC of chips and bundles decreased below 40.9% and 44.7%, respectively (Johansson et al. 2006).

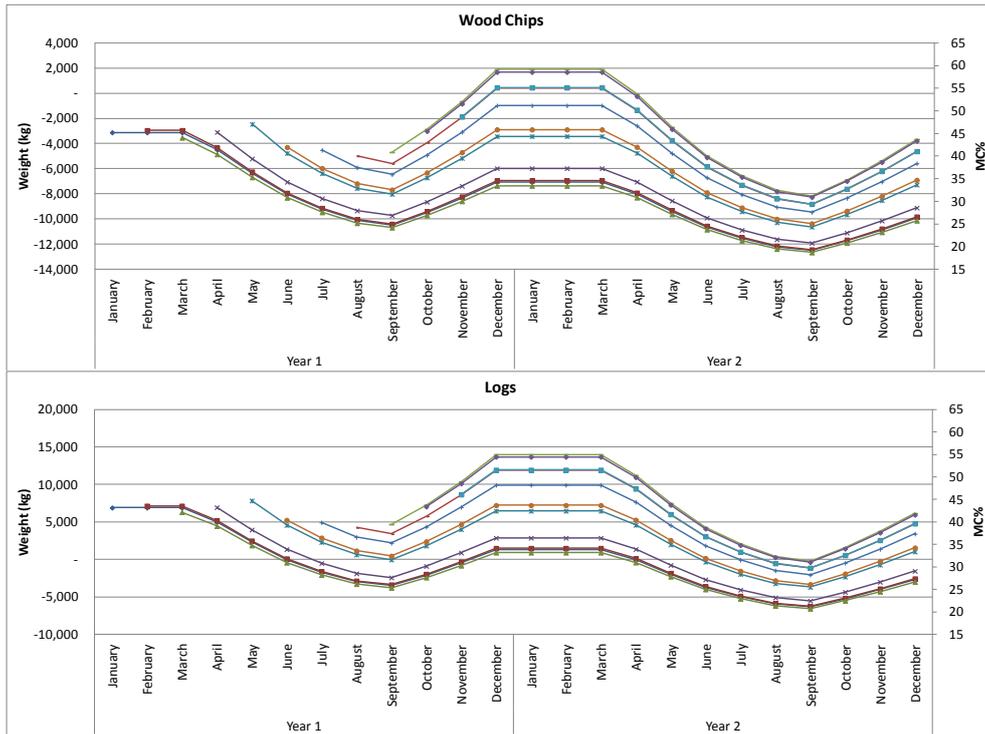


Figure 12 Payload changes in relation to trucks' GVW with wood at different MC.

4 Conclusions

This paper presents a tactical optimisation model based on linear programming, which in conjunction with drying curves can assist to make decisions on when and from which forest areas to harvest and chip roundwood, and for how long to store the wood materials at the roadside. The model also helps determine the best spatial allocation for the demanded wood products, and the number of trucks, including their volume and weight legal restrictions, in order to satisfy the demand at power and mill plants. The aim of this study was to analyse the increasing biomass utilisation strategies faced by the peat based electricity sector, and the impact of competing wood-based panel industries. The results show that both the 30% co-firing rate target required by all peat power plants and the demand from the wood-based panel industries can be satisfied with the forecasted potential short wood (pulpwood) volume available. Scenarios where the co-firing rate increased to a maximum 30% and MC was constrained affected the cost of supplying wood to the panel industries as more costly supply sources (thinnings) were needed to satisfy the demand.

The model selected short wood from clear cutting areas as the main source of biomass to supply both power plants and mills due to its lower harvesting costs. As demand increased and the peat power stations limited the MC of the biomass, the model included short wood produced from thinnings which resulted in greater overall supply costs. The model satisfied the energy demand with a combination of wood chips from thinnings and clearfells from

closer counties as well as with material from counties located at a longer distance from the power plant which resulted in an increased harvesting and transport costs

This study shows the benefits of managing MC when optimising wood supply chains. Naturally drying biomass at the road side can increase the efficiency of the power plants, and reduce the number of truckloads needed to meet the demand. In this study, storage costs accounted for 3% of the overall supply costs.

The combined impact and trade-offs associated with all these factors on supply chain costs are only possible to be investigated and analysed with the use of optimisation systems and decision support tools, whose application is critical to improve the decision making process in order to deliver biomass materials to energy plants in a cost-effective manner.

6.5 Acknowledgements

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