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Deriving Cooperative Biomass Resource Transport Supply Strategies in Meeting Co-Firing Energy Regulations: A Case for Peat and Wood Fibre in Ireland.

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Abstract

The Irish government has undertaken to reduce national CO_2 emissions through a range of measures put out in their Biomass Action Plan and the National Renewable Energy Action Plan. The conversion of peat fired power plants to co-fire with renewable biomass is one of these. This paper considers how the adoption of sweeping policies impact on other actors presently supplying or utilizing woody biomass resources. The SAWMILL sector (18 sawmills), BOARD sector, 3 board plants, and ENERGY sector (3 peat fired power stations) were included in a linear programming (LP) based transportation study. Specific transport costs between each residue producing sawmill and each board and energy plant were modeled and used in finding the minimum delivered cost for a number of scenarios. Scenario2015 represented the status quo, while Scenario2030 represented a situation with 30% co-firing with woody biomass equivalents in the energy plants. For each time horizon, the problem was solved from the perspective of society at large (GLOBAL), for the benefit of the board sector (BOARD) or with emphasis on minimizing the cost to the energy sector (ENERGY). The cost of transporting alternative sources of renewable energy was varied between € 100 and € 500 TJ^{-1}. Results showed how overall supply costs increase with increasing alternative energy cost, but also how the dynamics between sectors focus worked. The cost of transport to the Energy sector ranged from € 306 043 to € 996 842 in Scenario2015, while the increased demand in 2030 led to a range of between € 1 132 831 and € 4 926 040, depending on the alternative cost selected. For the Board sector, whose absolute demand remained constant, the total transport cost ranged between €868 506 and €3 454 916 in Scenario2015. The unchanged demand showed that the transport costs also remained the same for the 2030 Scenario, however, the optimization focusing on the Energy sector, increased the delivery cost to the Board sector by up to € 693 730 per year by 2015 and € 842 271 per year by 2030, indicating how intervention would be necessary if political ambitions of a 30% co-firing should happen without detriment to other important wood based industries.

Key Words

Co-firing; supply optimization; transport; linear programming; biomass; resource assessment; energy policy; Ireland.

Nomenclature

BNM	Bord Na Mona
c	Unit cost
CAN	Controller Area Network
CO2	Carbon Dioxide
D	Set of Demand
d	demand
D.G.V.W	Design gross vehicle weight
FMS	Fleet management system
GHG	Greenhouse gases
GJ	Gigajoule
Mm3	000 cubic metres
Mt	000 tonnes
Mwe	Megawatt of electric
NREAP	National renewable energy action plan
OB	Over bark
OBD	On-board diagnostics
P1	Peat Power Station 1
P2	Peat Power Station 2
P3	Peat Power Station 3
PP	Pulp
RES	Renewable energy sources
S	Set of sources
s	source
TJ	Terajoule
TPER	Total primary energy requirement
WBP1	Wood based panel mill 1
WBP2	Wood based panel mill 2
WBP3	Wood based panel mill 3
x	volume

1.1 Introduction

Ireland, like all EU 27 countries has a legal binding to the EU Directive 2009/28 EC which sets a target of 20% of all energy consumption to come from renewables by 2020 [1]. Ireland's contribution to this target is set out in the National Renewable Energy Action Plan which ensures that 16% of all national energy consumed by transport, electricity and heat will come from renewable sources by 2020 [2]. This will be achieved in the form of 40% electricity generation from renewable energy sources (RES), 12% for the consumption of heat and 10% for the transport sector.

In 2010 the main fuel sources for electricity generation in Ireland was comprised of natural gas (61%), coal (17.6%) and peat (10%). Other sources included wind (4.9%), fuel oil (2.1%), landfill gas, biomass and other biogas (1.5%) with the remainder being made up from electricity imports (0.8%) and 0.7% of gas oil and refinery gas [3].

Renewables in the fuel mix for electricity generation in total accounted for 7.4% in 2010 with 1.3% being biomass. Renewables in this scenario include wind, hydro, landfill gas, biomass and other biogas. In 2009 and 2010 the percentage of gross electricity consumption from renewables was 13.7% and 14.8% respectively (normalized). The target for Ireland in 2010 was 15% (which was effectively met) and the target for 2020 is set at 40%. Ireland is heavily dependent on imported fossil fuels with net imports of approximately 86% in 2010 of the total primary energy requirement (TPER) down from a peak of 90% in the year 2006. Ireland's overall energy use declined by 0.3% in 2010 mainly due to a contraction in the economy of 7% in 2009 followed by 0.4% in 2010 [4]

One main aspect of the NREAP (2010) is that the target of 30% co-firing for Ireland's 3 peat power stations that was set in the Energy White Paper (2007) [5] must still be achieved. To complete this initially, implies the offsetting of 0.9 Mt of peat with biomass. This paper looks at using a Linear Programming approach to analyse and provide the transport supply strategies necessary for optimal woody biomass allocation from the resource currently available in Ireland in order to meet the co-firing targets for two time horizons, 2015 and 2030.

1.1.1 Availability of Peat and Wood Fibre in Ireland

Currently, Edenderry Power which is owned by Bord Na Mona (BNM) is only co-firing biomass at present. Edenderry has a plant capacity of 128 MWe. BNM was established in 1946 to control and harvest the peatlands and is the only producer of peat for electricity in Ireland. Peatlands cover 17.2% of the land mass in Republic of Ireland, but not all of it is harvestable. The world's peat resource area is roughly 4 million km^2 which is 3% of the total land area. Peat consumption as a fuel is 17 Mt per annum with other countries such as Finland, Belarus and Sweden the main users. Currently only 0.34% of total peatland is used for energy peat production[6]

Resources suggest that at current production rates about 90 Mt (million tonnes) or 19 years of supply remains in Ireland [7], and there are concerns about their management [8] Total peat production in Ireland peaked in 1995 at 8.0 Mt. In 2011 it was 4 Mt. BNM sell peat to the other power stations which are owned and operated by the Electric Ireland (who are main electricity supplier in Ireland and also own and control the country's transmission grid). These plants are Lough Ree Power which has a plant capacity of 100 MWe and West Offaly Power with a plant capacity of 150 MWe. The total annual electricity output form these 3 peat power plants is 378 MWe, which equates to 6% of Ireland's TPER. BNM harvest approximately 4 Mt of milled peat over 20,000 ha of peatland annually, with 3.1 Mt used for power generation. Edenderry uses 1.0 Mt, Lough Ree burns 0.9 Mt and West Offaly 1.2 Mt. The remainder of peat is used for BNM's peat briquettes and garden compost which targets the domestic heating and horticultural sectors respectively. The burning of peat currently emits 2.8 Mt of CO2 / annum which is equivalent to 4.1% of Irelands GHG emissions. Edenderry Power is pro-active in the co-firing of biomass with a target of 0.3 Mt (30% target) set for 2015 and 0.5 Mt set for 2020. Note that the 2020 target is effectively a 50% co-firing rate. In 2011, 150,000 tonnes of biomass was co-fired with peat. To reach the 30% target for all stations implies 0.9 Mt of peat to be offset by biomass. This equates to 0.5 Mt of biomass according to Clancy, Breen et al. 2012[9][9]. However, average moisture content (MC) of peat is approximately 52% with an energy content of 7.95 GJ/t [10]. In energy terms, 0.5 Mt of biomass implies supplying it at an MC at 23% which is currently unlikely to happen. Average biomass MC currently in Edenderry is 50% which suggests approximately 0.9Mt of biomass needed to meet the target which is in line with the 30% target.

In 2008, Edenderry Power consumed 20 000 energy tonnes of biomass. By 2010, the tonnage was 110 000. This comprised of various biomass as outlined in table 1, with the majority of biomass coming from the forest based sector – woodchip, wood pellets, sawdust and willow chip.

Table 1 – Biomass consumed in Edenderry Power in 2010. [11].

Material	Weighed Tonnes (t)	Energy Tonnes / Peat Displaced
Forest Materials		
Woodchip	58,835	51,453
Wood pellets	9,202	20,391
Sawdust	12,409	9,168
Energy Crops		
Willow Chip	5,208	5,156
Miscanthus	1,187	1,979
Black Oats	48	99
Dry Materials		
Palm Kernel Shells	7,657	15,144
Almond Shells	2,199	4,452
Olive Pellets	125	269
Sunflower Pellets	40	82
Grape Meal	30	62
Soya Hulls	29	60
Total	**96,969**	**108,315**

Woody biomass will continue to dominate the mixture of materials for co-firing for the 2015 targets. The planned tonnages include willow increasing from 40 kt (000 tonnes) to 100 kt. Sawmill residues are to remain constant at 100kt in 2015 and 2020 while forestry thinnings increase from 50 kt to 100 kt.

1.1.2 Wood Fibre

Ireland forest cover equates to 10% of total land mass, with plan projections of 17% by 2030 [12].57% is state owned and operated by Coillte and 43% managed by the private owners. Ireland's forests are mainly comprised of 80% conifers and 20% broadleaves. In 2010, 2.88 million m^3 (Mm^3) of round wood was harvested. 2.7 million of this was utilized for processing while 199,000 m^3 was used in the firewood sector. 2.217 Mm^3 came from Coillte forests and 0.463 Mm^3 came from private forests [13]. In 2010, 34% of the total roundwood harvest in the Republic of Ireland was used for the production of biomass energy. This equated to 0.984 Mm^3, 0.079 Mm^3 of which was used for electricity generation in Edenderry (Table 2).

Table 2 – Use of forest based biomass in energy production in Ireland in 2010 [13].

Category	**000 m3 OB**
Forest-based biomass used for electricity generation by Edenderry Power	79
Forest-based biomass used for energy production and process drying in	
sawmills and wood-based panel mills	475
Pulp chipped for biomass use by commercial users	39
Domestic use of firewood	199
Short rotation coppice	1
Wood pellets and briquettes	121
Charcoal	2
TOTAL	**916**
Pulpwood chipped for pellet production	38
Sawdust used for pellet production	30
TOTAL	**984**
Roundwood harvest	
Roundwood available for processing	2708
Firewood harvest	199.00
TOTAL	**2907**
Forest-based biomass use expressed as a % of total roundwood harvest	**33.85%**

The overall demand for roundwood in Ireland is expected to increase from 4.295 Mm^3 in 2011 to 6.038 Mm^3 in 2020. Included in this figure is the demand of 1.589 Mm^3 for forest biomass for energy production in 2011. This figure is expected to increase to 3.084 Mm^3 in 2020. These figures can be broken down into exact demands from CHP, heat only and co-firing (Table 3).

Table 3 – Estimated demand for forest biomass for energy production in Ireland [13].

	2011	**2020**	**2011**	**2012**
	Estimated Demand			% of total demand
	000 m3 OB / annum			
Combined heat & power (CHP)	388	1550	24	50
Heat only	1092	1425	69	46
Co-firing	109	109	7	4
TOTAL	**1589**	**3084**	**100**	**100**

In energy terms, the demand in the Republic of Ireland will be 53 M GJ (based on scenario modeling by the Sustainable Authority of Ireland). Forest based biomass and wood residues are expected to supply 17% (or 9 M GJ) of this demand with the remainder coming from waste streams (17%), agricultural residues (15%) with purposely grown energy crops together with imported biomass making up the final 51%.

2.1 Biomass Supply Planning

Biomass supply planning invariably deals with the quantification of available volumes, harvesting and supply costs and the structuring of these on a comparative footing from which good business strategies can be derived. Due to the spatial distribution of natural resources, GIS analysis is often a pre-requisite and has been widely used in providing input data for supply modeling and biomass resource assessment [14-19]. In Japan, Kinoshita et al. 2009 [20] looked at how incorporating 25% more woody biomass in thermal power plants could be used to offset fossil fuel dependence and introduce CO2 mitigation techniques given Japan's large untapped forest cover of 68% (10.63 million Ha). Joutz [21] demonstrated the utility of representing biomass supply cost information, in the form of marginal cost curves, effectively providing the buyer with a market overview as well as a tool for consequence analysis or price negotiation. Walsh [22] elaborated on this method in applying a partial equilibrium model which considers choices in land use alternatives, crop productivity, and market prices, providing a tool that could support policy making through an iterative adjustment of the underlying assumptions.

The calculation of marginal supply cost curves can be based on varying levels of cost complexity, depending on the emphasis in the supply chain. The U.S. billion-ton assessment includes land cost, production costs, harvesting cost and primary transport cost – but has no geographic reference to specific conversion points [23]. This 'farm gate' approach is commonly applied in national or regional studies that aim to illustrate the extent of resource availability and potential [18, 24-26]. Viana et al. 2009 [16] looked at how the forest biomass allocation could meet the supply for 13 new electric power plants in Portugal as well as supplying 2 existing plants of 22 MW capacity. Results suggest that some form of cogeneration is needed as there is not enough biomass from logging residues alone. Nord-Larsen and Talbot [27] developed cost curves 'from farm gate' assuming a constant production cost and considering only secondary transport cost differences. However, both Bjørnstad [28] and Rørstad, Trømborg [29] provide examples of detailed calculations of harvesting costs, storage costs, comminuting costs and transport cost of four types of woody biomass to specific conversion plants in regional studies.

Examples of methodological approaches used in deriving supply cost curves range from ranking in the case of single conversion plants [21, 22, 30] through sequential ranking [31] to optimal allocation when multiple plants compete for the same resource [27, 29, 32, 33].

While Möller and Nielsen (2007) applied a continuous cover surface flow analysis, where each raster grid cell represented a transport cost, most studies utilise discrete vector data (such as road networks) in formulating the problem. Gronalt & Rauch [34] demonstrate a simple stepwise heuristic in selecting locations in a supply network and Bjørnstad [28] uses economic modeling to the same end. However, Linear Programming (LP) is a well suited method for solving these allocation problems [21] and has been widely used in determining optimal supply solutions, both in static [14, 27] and dynamic temporal dimensions [29, 35, 36]. Shabani and Sowlati 2012 [37] developed a dynamic mathematical nonlinear mixed integer LP model to solve the supply chain (supply, storage, production and ash management) of forest biomass for electricity generation in Canada. Interestingly, the model showed how the optimum solution generated more profit than the power plant was currently making.

Advantages of linear programming are the logical problem formulation, the efficient algorithms based on linear algebra, and the simultaneous provision of useful economic information on the elasticity of each variable with regard to the optimal solution.

3.1 Materials and Methods

3.1.1 Geographic Distribution of Supply and Demand Points.

The three peat power plants are located quite centrally in Ireland within a triangular area of approximately 1,414 square kilometres (sq km). The maximum buffer distance of 73 km is between P1 and P3. The shortest distance of 44km is between P2 and P3. Figure 1 shows a GIS map of geo-referenced locations compiled to include;

- 3 peat power stations
- 3 WBP mills
- Sawmills
- Peatlands
- County Boundaries
- Country Coastline

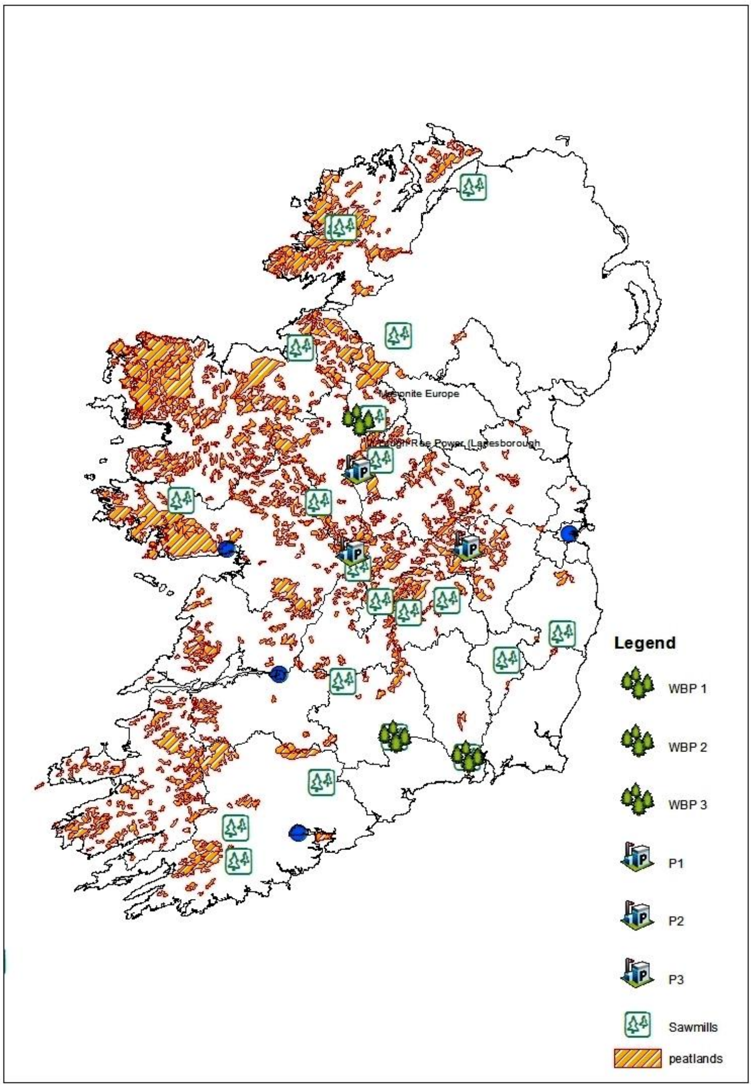


Figure 1 – GIS Peat Power station map of Ireland. Also includes Peatlands, Wood Based Panel mills and Sawmills.

A digital road network of Ireland was used within the GIS. This comprised of motorway, national primary, national secondary, regional and third class roads. The road network was represented as connections of 5917 nodes and 8941 links. The nodes represent the road intersections and the links represent homogeneous road segments. Geometric networks are built in the GIS model to construct and maintain topological connectivity for the road data in order to allow the path finding analysis to be possible. In GIS terms, topology defines the spatial relationships between features. This digital road network represents arc – node topology. The basic description of arc – node topology define the vertices (X and Y pairs) as the shape of the arc and the endpoint of each arc is termed a node. Arcs are only joined at nodes and each arc has 2 nodes – a “from” node and a “to” node. The ability to store these topological rules efficiently in terms of a digital road network (or any other type of network such as water mains and power lines etc.) is one of the essential functions of any GIS software. In ArcInfo 10.1, these types of networks are modelled with a geometric network. Geometric networks consist of edges and junctions that represent the arcs and nodes of the road network respectively. In order to carry out an analysis on the road network, geometric networks must be built. The utility Network Analyst Tool (NAT) cannot be used without a geometric network. The NAT is added to the GIS interface by simply customising the toolbars available. This toolbar is divided into 2 sections. The left side allows what network to work with, depending on whether there is more than one added to the map layer. The right side allows the set up to perform the trace operations on the currently selected network, in this case, determining the most logical route between point A and point B. The NAT uses edge flags and junction flags to represent the pick-up and destination point. Edge flags can only be used on the edges (arcs) and junction flags can only be used on the junctions (nodes). Edge and junction flags cannot be used interchangeably. Barriers can also be used to prevent the trace task from performing on a certain section of road, to avoid road closures or low bridges for example. Within the Analysis section of the NAT, the weights can be assigned. The value of the weights and what road features they represent are determined when building the geometric network. The “Find Path” trace operation was used in this analysis. As mentioned earlier, the flags that are placed on the network must be either all edge flags or all junction flags. A path cannot be found with a mixture of edge and junction flags. The Find Path trace task, by default, does not use weights. If no weights are assigned, the path found is simply the shortest path based on the number of edge elements in the path. The trace task is based on Dijkstra’s routing algorithm. The distances in kilometres (1 way) between supply points (sawmills) and demand points (peat stations and wood based panel mills) are used to build the transport costing matrix in table 4.

In total, 18 sawmills producing wood chips were identified as possible sources of mill residues for both electricity co-firing and the wood based panel (WBP) sector. Annual statistics on woodflow for the Republic of Ireland were obtained from Knaggs and O’ Driscoll, 2011 [38]. A WBP plant is also regarded as a potential market for these chips. The energy and board sectors are considered here. The energy sector includes 3 peat fired plants with staggered goals for co-firing with renewable biomass. The total demand volumes in solid cubic metres are detailed in table 4 with an assumed moisture content of 40% and an energy content of 7.3 GJ / m3 or 10.4 GJ / tonne [39]

P1 has a planned intake of biomass of 420,000 m^3 (300kt) in 2015, which equates to 30% of its intake of peat. This percentage value has been set by Irish legislation. This is planned to increase to 700,000 m^3 in 2020 when a 50% co-firing target is reached when approximately 500 000 t of peat needs to be replaced with an alternative fuel. It is anticipated that this figure will remain consistent for the 2030 analysis. For P2 and P3 there is no intake of biomass in 2015. The planned intake for P2 and P3 in 2030 is assumed to be 30% of its current peat consumption and is equivalent to 504,000 and 378,000 m^3 respectively. P2 and P3 plan to co-fire from 2019 onwards. Given that it will take P1 8 years to reach a 30% co-firing rate, the year 2030 is seen as a logical time horizon for this analysis.

The board sector includes 3 WBP mills. Two of the board plants source only chip directly from the available resource, while the other mill can include both woodchips and pulp. Sawdust is neglected in the analysis here as a mill residue for bioenergy, as it is primarily re-used by the sawmills as boiler fuel and the increasing wood pellet manufacture in Ireland. Table 4 outlines the problem summary together with the transport running costs to each of electricity plants together with the 2015 and 2030 total demand figures in energy terms per solid cubic metre for each of the energy plants (P1, P2 and P3) and the panel mills (WBP1, WBP2 and WBP3).

Table 4 – Problem summary - Matrix of Woodchip energy equivalents, sawmills, power plants, WBP mills and transportation costs (€ GJ^{-1}).

Sawmill	P1	P2	P3	WBP1	WBP2	WBP3‡	2015 Supply (GJ)	2030 Supply (GJ)
AA	0.31	0.31	0.19	0.52	0.13	-	868 830	868 830
AB	0.14	0.13	0.25	0.17	0.30	-	146 021	146 021
AC	0.22	0.20	0.09	0.42	0.02	-	36 028	36 028
AD	0.51	0.48	0.39	0.72	0.33	-	287 440	287 440
BA	0.49	0.52	0.41	0.73	0.36	-	475 999	475 999
BB	0.40	0.24	0.25	0.46	0.28	-	67 455	67 455
BC	0.26	0.19	0.30	0.10	0.38	-	130 308	130 308
BD	0.37	0.33	0.45	0.12	0.51	-	318 867	318 867
CA	0.08	0.15	0.21	0.19	0.28	-	36 028	36 028
CB	0.35	0.27	0.17	0.51	0.12	-	177 447	177 447
CC	0.17	0.26	0.31	0.19	0.37	-	17 172	17 172
CD	0.22	0.09	0.07	0.34	0.13	-	381 720	381 720
DA	0.16	0.03	0.16	0.22	0.23	-	146 021	146 021
DB	0.49	0.43	0.53	0.25	0.61	-	554 565	554 565
DC	0.49	0.48	0.37	0.70	0.31	-	36 028	36 028
DD	0.52	0.46	0.57	0.27	0.62	-	28 172	28 172
EA	0.16	0.10	0.21	0.17	0.28	-	20 315	20 315
EB	0.21	0.30	0.37	0.28	0.41	-	51 741	51 741
						∑	3 780 159	3 780 159
PP†	Var	Var	Var	Var	Var	Var		
Demand (GJ)								
2015	3 066 000	-	-	5 183 000	784 750	2 555 000	∑11 588 750	-
2030	5 110 000	3 679 200	2 759 400	5 183 000	784 750	2 555 000	-	∑20 071 350

†Prices for biomass from this source are varied between 100 – 500 € TJ-1

‡WBP3 uses only alternative pulp sources

3.1.2 Transport Costs

Table 5 details the standing costs per day and running costs per km for a 5 axle 42 000 kgs d.g.v.w. articulated truck and trailer in Ireland. These costings are the industry norm defined by the Irish Road Haulage Association [40].

Table 5 – Truck and Trailer standing and running costs for 5 axle articulated truck and walking floor trailer (92 m^3). Fuel consumption was measured by field experiment.

VEHICLE TYPE	42 000 kgs Artic	3 Axle Walking Floor
Cost Basis	Example	Example
Vehicle Cost	€79,000	€33,000
Depreciation Years	6	10
Average KMS Annually	120,000	40,000
Working Days Annually	240	240
Average Tyre Life KMS	70,000	60,000
Standing Costs per Day		
Wages	€38,307	€0
Depreciation	€13,167	€3,300
Road Tax	€2,330	€0
Insurance	€5,300	€302
Interest	€3,950	€1,650
Overheads per Vehicle	€14,497	€0
Standing Cost per Annum	€77,551	€5,252
Standing Cost per Day	€323	€22
Running Cost per Km		
Cost of 1 Litre of Fuel (net of vat)	€1.30	0
Litres per 100 Km's	38	0
Km's per litre;	2.7	0
Litre per km	0.38	0
Fuel Cost per Km	€0.48	0
Tyres	€0.05	€0.05
Maintenance / Repairs	€0.04	€0.06
Running Cost per Km	€0.57	€0.11
Summary Costs ONLY		
Standing Costs per Day	**€323**	**€22**
Plus Running Costs per Km	**€0.57**	**€0.11**

The total stand costs for truck and trailer amount to €345 / day. The total running costs amount to €0.68 / km and includes both truck and trailer running costs. In order to gather information on fuel consumption, a biomass truck was instrumented with engine diagnostic equipment. The FMS (Fleet Management System) cable is used to extract the engine diagnostic information through the hard wiring of the CAN_High and the CAN_Low. These must be connected into the CAN Bus from the FMS gateway on the truck's engine. The on board diagnostic (OBD) for the truck involved the installation of a GPS Blackbox with GPS tracker. The GPS antenna is positioned on the outer side of the dashboard so that it becomes visible through the front windscreen. The GSM / GPRS (Global System for Mobile Communications / General Packet Radio Service) magnetic antenna is fixed to the inside of the windscreen for optimum signal strength in order to send the information so that it can be viewed and analysed through a web browser. The average value for fuel consumption for roundtrip (both loaded and unloaded) recorded was 0.38 L / km and this is used in the costing's calculations

3.2 Optimisation Method

This is a typical transportation problem, allocating biomass (GJ equivalent) from each source *s (sawmills)* in a set of sources *S*, to each demand point d (pat power plants and wood based panel mills) in the set of demand points *D* at the lowest unit transport cost, *c,* for each unit volume *x*, and is considered highly suitable for solving with Linear Programming (LP) [41] The objective is then to minimize the objective function *Z* given in equation 1 as follows:

$$\min Z = \sum_{s=1}^{S} \sum_{d=1}^{D} c x_{sd}$$

Equation 1

The constraints being that the sum supplied from each source *s* to each destinations *d* (element of D) cannot exceed the total availability at the source (equation 2):

$$\sum_{d}^{D} x_{sd} \leq X_s \,, \forall s \in S$$

Equation 2

And secondly that the sum of volumes delivered from all sources to plant *d* must meet or exceed the requirements at that plant (equation 3):

$$\sum_{s}^{S} x_{sd} \geq X_d \,, \forall d \in D$$

Equation 3

Finally, non-negativity constraints ensure that the solution does not include infeasible (negative) allocations.

As there is not enough sawmill residue material to satisfy demand, a dummy resource (identified as pulpwood from Philips et al 2009 [12] at a considerably higher constant price (€ 5000 TJ^{-1}) was used in order to make the problem solvable. This dummy resource and its contribution to the objective function is identifiable in the post-optimality analysis where it is handled separately to avoid confounding the results. In the sensitivity analysis, it is recalculated at 5 discrete price levels (€ 100, € 200, € 300, € 400 & € 500 TJ^{-1}), representing the price range through the delivered cost of sawmill residues.

The problems were solved for each scenario using Microsoft Solver, which applies the simplex algorithm in a spreadsheet setting. MS Solver is a *what if* tool that finds the optimal (minimum in this analysis) supply cost (objective function) subject to the constraints mentioned in equations 2 and 3 above. The purpose of the optimization was to provide data for the analysis of wood fibre flow both in terms of a Global optimization (lowest common cost for both sectors), Energy sector optimization (lowest cost to the peat power plants), and a Board Sector (lowest cost to the panel mill sector). No optimizations were run for the benefit of individual plants within either sector.

3.2.1 Scenario Definitions

Three scenarios were analysed for each of two base years and both the energy and board sectors as follows:

Scenario2015 & Scenario2030

a. Global optimization (GLOBAL) = demands from the energy and board sectors are treated as being equally important.
b. Board optimization (BOARD) = the objective function prioritizes cost minimization in supplying the board plants while the energy sector is supplied with remaining biomass.
c. Energy optimization (ENERGY) = the objective function prioritizes cost minimization in supplying the energy plants while the board plants receive the remaining biomass. Plants P2 and P3 have no wood fibre demand in 2015.

4.1 Results

The three scenarios run for each time horizon (2015, 2030) solved feasibly due to the inclusion of an unlimited pulpwood supply at € 5000 TJ^{-1}. For Scenario2015, focus on a Global solution allocates the sawmill residues relatively equally between sectors with 268.9 km^3 to the Energy sector and 248.9 k m^3 to the Board sector (table 6). When the emphasis is placed on minimizing the delivered cost to the Board sector, all available sawmill residues are allocated to them (517.8 k m^3 to the Board and 0.0 k m^3 to Energy). The Energy sector sources only from the alternative biomass pool at a value of 420 k m^3. Finally, when the optimization was run for the benefit of the Energy sector, approximately 410 k m^3 of sawmill residues are allocated to them, while the board plants collectively receive 107.5 k m^3.

For Scenario2030, the total demand is increased from 1 587 500 m^3 to 2 749 500 m^3, an increase of 58% in a constrained market. This is in line with the predicted forecast of roundwood production in Ireland to 2028 where the net realizable volume of thinnings alone from the private sector and Coillte (public forest estate) will be 738 000 m^3 and 1166 000 m^3 respectively giving a total of 1904 k m^3 potential 'other' biomass direct from the forest sector [12].Focusing on a Global optimum resulted in 47.8% of Energy demand being met from sawmill residues while only 9% of the Board sector's demand comes from there. When the optimization focus is on minimizing delivered costs to the Board sector, all the sawmill residues are allocated to them as in Scenario2015, although this now makes up only 18.8% of the total demand, and 42.5% of the Board plant's requirements. When optimizing for the Energy sector in 2030, the distribution of allocation in absolute quantities is equivalent to that from Scenario2015, however their relative importance was diminished to 14.9% and 3.9% respectively.

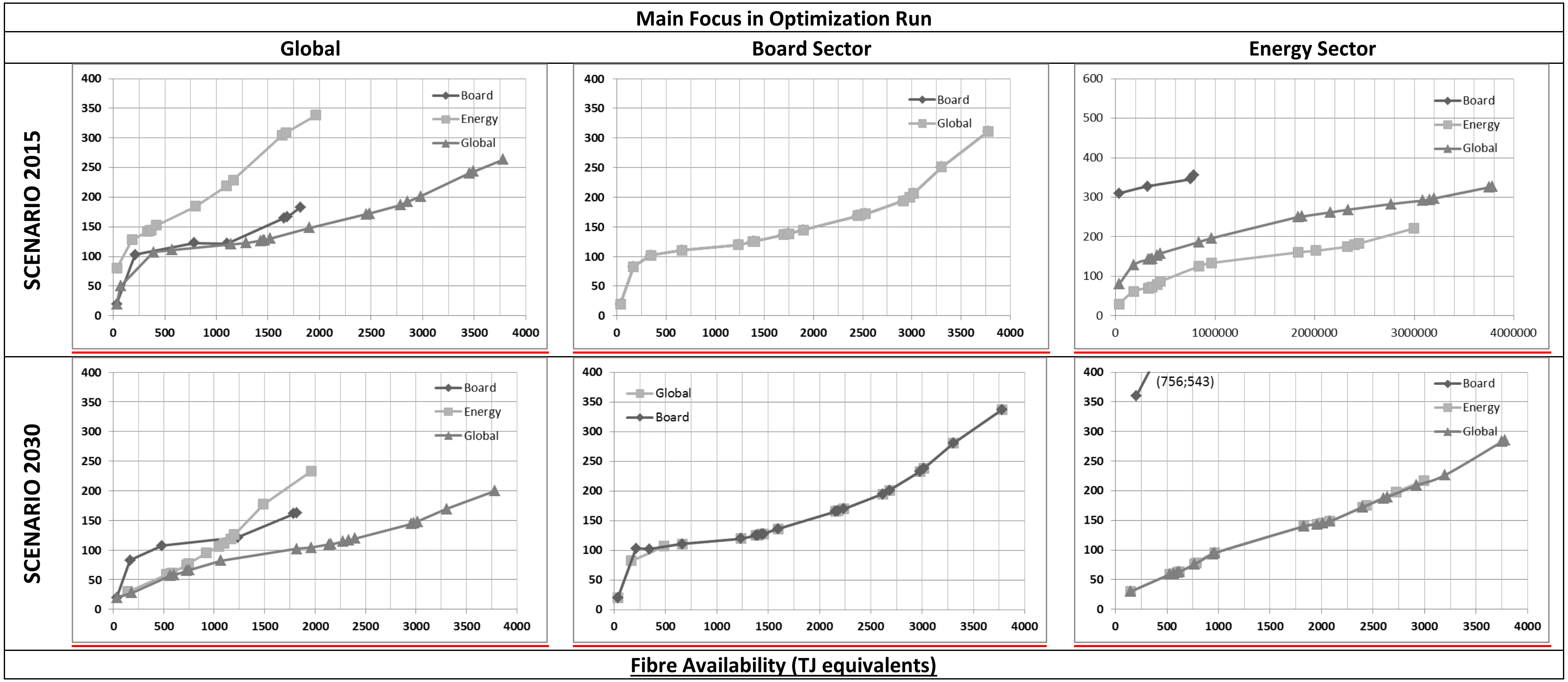
Table 6 - Volumes allocated under various scenarios in volumes (000 m^3 (%)).

Scenario	**To Sector**	**Biomass**	**MAIN FOCUS IN OPTIMISATION RUN**		
			GLOBAL	**BOARD**	**ENERGY**
Scenario2015	Energy	Residue	268.9 (16.9)	0 (0)	410.3 (25.8)
		Other	151.0 (9.5)	420.0 (26.5)	9.7 (0.6)
	Board	Residue	248.9 (15.7)	517.8 (32.6)	107.5 (6.8)
		Other	918.6 (57.9)	649.7 (40.9)	1 060.0 (66.8)
	Total 2015		**1 587 500**	**1 587 500**	**1 587 500**
Scenario2030	Energy	Residue	1 313.0 (47.8)	0 (0)	410.3 (14.9)
		Other	269.0 (9.8)	1582 (57.5)	1 171.7 (42.6)
	Board	Residue	248.9 (9.0)	517.8 (18.8)	107.5 (3.9)
		Other	918.6 (33.4)	649.7 (23.7)	1 060.0 (38.6)
	Total 2030		**2 749 500**	**2 749 500**	**2 749 500**

In addition to the static price and volume figures, the development of mean cost against incremental growth in transported energy units (mean supply cost curves) is given in Figure 2, for sawmill residues only. The two rows indicate the time horizons 2015 and 2030 respectively, while the columns show results depending on the sector focus in the optimization. These figures can be seen from the sawmill sector (supplier) viewpoint, as they show how the same total resource is reallocated dynamically, depending on the demand scenarios. The total combined availability of sawmill residues for all scenarios is 3 780 TJ (x-axes).
For Scenario2015 (row 1), the first diagram shows how a focus on the GLOBAL optimum allocates almost equal shares of the sawmill residues to the board and energy sectors, although the material is allocated to the board sector at a cheaper rate. For the energy sector, almost half the material comes at a marginal supply cost exceeding € 400 TJ^{-1} and ranging up to € 510 TJ^{-1}. This pulls the mean supply cost up significantly. For the energy sector run in Scenario2015, the board sector is only supplied with sawmill residues once the marginal cost, and here also mean cost, exceeds € 300 TJ^{-1}.

The Global series shows the mean supply costs when both the volumes delivered to the board and the energy sectors are ranked together in the same series. This is a proxy for mean supply cost for the whole scenario, as it always terminates at 3 780 TJ, and can be used to gain a rapid comparative overview of all scenarios. When focusing on BOARD, all sawmill residues are allocated to the board sector (no energy series which means the global is the same as board).

Figure 2 – Mean Supply cost curves for time horizons 2015 and 2030 and sector focus Global, Board and Energy.

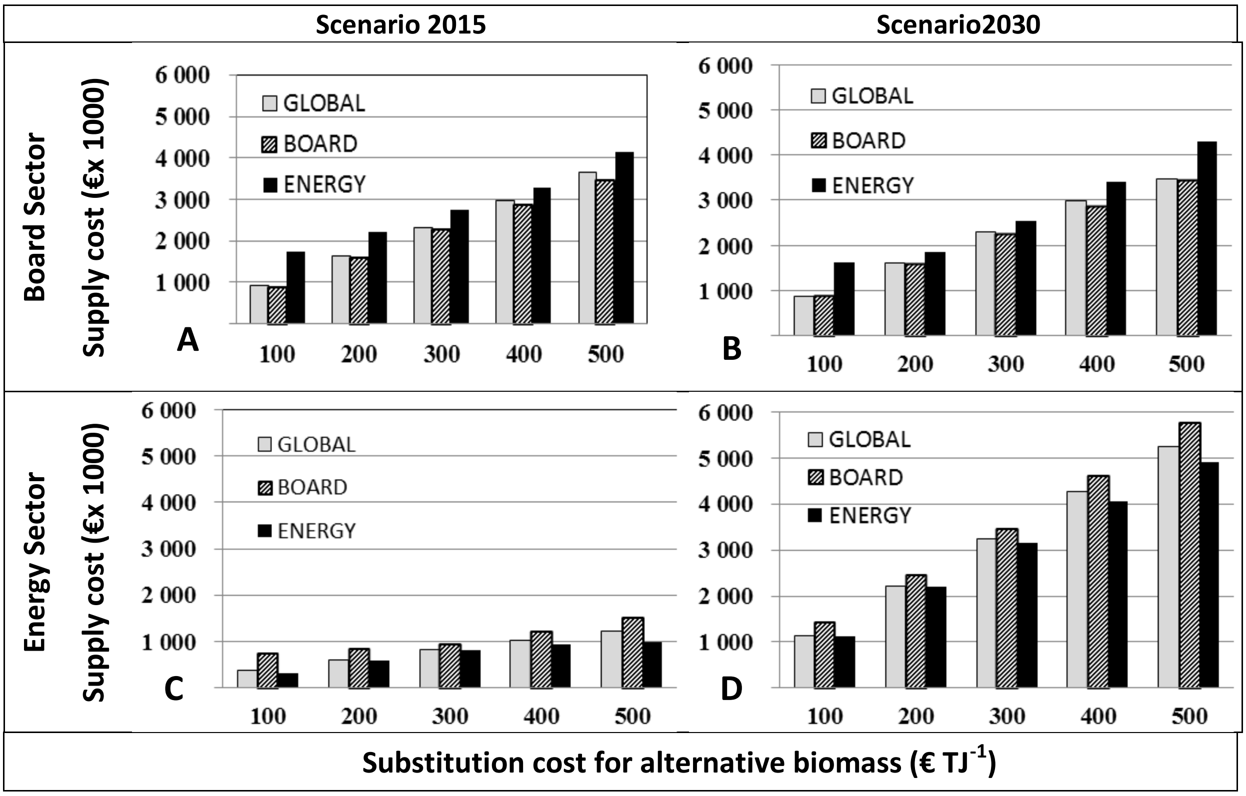


4.1.1 Supply Costs Including Sensitivity Analysis.

The volume allocations in Table 6 represent static solutions for 2015 and 2030. Here the focus has been on utilizing the existing sawmilling residues. The cost of the alternative biomass source 'other' was fixed at € 5000 per TJ, more than 10 times the price of residues, in order to prioritize the use of these. However, in order to evaluate the supply cost and sensitivity of the solution against a range of possible weighted mean prices of alternative biomass, optimisations were run using a transport cost for this between € 100 and € 500 TJ^{-1}. Figure 3 shows the development in supply cost within this range, and within and between the time horizons. The legends GLOBAL, BOARD, and ENERGY indicate which sector the optimization focused on minimizing the cost of supply for.

It can be seen how, when considering the Board sector (row 1), the supply cost increases sharply with increasing cost of alternative biomass. It can also be seen how, for each price category, the supply costs vary relative to one another, depending on whether the optimization was run for a Global best, for the benefit of the Board sector, or for the benefit of the Energy sector. Therefore, it can be seen how that in row 1 (Board sector) – the Board focused optimisation is always the cheapest and the Energy sector focused optimization is always the most expensive to the Board sector, and the Global optimum lies somewhere between these (Fig 3).

Figure 3 - The supply cost for the Board and Energy sectors, under different assumptions on the cost of alternative biomass.



While the scale (€ 6 000 000) is used in order to keep all scenarios in proportion, the visual impression underplays the extent of market distortion that is taking place. In figure 3[A] the GLOBAL focus at € 100 TJ^{-1} is € 65 568, and the ENERGY focus € 873 693 more costly than the optimal solution for the Board sector, BOARD. At € 500 TJ^{-1}, while the absolute cost of supply has now increased from € 868 506 (€ 100 TJ^{-1}) to € 3 454 916, the relative increase to the Board sector when focusing on ENERGY, is now only € 693 730, i.e. a total supply cost of € 4 148 646.

In figure 3[B] the GLOBAL focus at € 100 TJ^{-1} is € 6 224, and the ENERGY focus € 755 509 more costly than the optimal solution for the Board sector, BOARD. At € 500 TJ^{-1}, while the absolute cost of supply is the same as for Scenario 2030 at € 868 506 (€ 100 TJ^{-1}) and € 3 454 916 (€ 500 TJ^{-1}) the relative increase to the Board sector when focusing on ENERGY, is now € 842 271, giving a total supply cost of € 4 297 187.

When looking at the Energy optimisation in figure 3[A], the GLOBAL focus at € 100 TJ^{-1} is € 69 187, and the BOARD focus € 435 498 more costly than the optimal solution for the Energy sector, ENERGY. At € 500 TJ^{-1}, while the absolute cost of supply has now increased from € 306 043 (€ 100 TJ^{-1}) to € 996 842, the relative increase to the Energy sector when focusing on BOARD, is now € 536 158, i.e. a total supply cost of € 1 533 000.

In figure 3[B] the GLOBAL focus at € 100 TJ^{-1} is € 479, and the BOARD focus € 304 781 more costly than the optimal solution for the Energy sector, ENERGY. At € 500 TJ^{-1}, while the cost of supply for Scenario 2030 is € 1 132 831(€ 100 TJ^{-1}) and € 4 926 040 (€ 500 TJ^{-1}) the relative increase to the Energy sector when focusing on BOARD, is now € 848 008, giving a total supply cost of € 5 774 048.

Between Scenario2015 and Scenario2030, the total cost of supply to the Board plant remains constant when optimized under BOARD and is only marginally influenced by the large increase in demand for biomass from the Energy sector. Tables 9 and 10 show the level of compensation (€ TJ^{-1}) that would be required to either sector in neutralizing the competitive advantage that an optimization to the other sector – when compared with the GLOBAL focus.

Table 7 - Subsidy needed (€ TJ^{-1}) for scenario 2015 showing the 100 and 500 € TJ^{-1} variable price.

100	**GLOBAL**	**BOARD**	**ENERGY**
GLOBAL	-	20	20
BOARD	100	-	140
ENERGY	90	100	-
500			
GLOBAL	-	60	70
BOARD	40	-	170
ENERGY	30	80	-

Table 8 - Subsidy needed (€ TJ^{-1}) for scenario 2030 showing the 100 and 500 € TJ^{-1} variable price.

100	**GLOBAL**	**BOARD**	**ENERGY**
GLOBAL	-	0.00	0.00
BOARD	30	-	30
ENERGY	90	90	-
500			
GLOBAL	-	0.00	30
BOARD	30	-	70
ENERGY	40	100	-

From tables 7 and 8, the Global focus shows a level subsidy needed between both the Board and Energy Sector as is expected. The biggest decrease occurs when the optimization is for the Board sector when the focus is on Energy. For Scenario2015 and looking at the extremes of the variable cost of supply from 100 to 500 € TJ^{-1} it shows a subsidy of between 140 and 170 € TJ^{-1} needed when the Energy sector is getting less residues. This subsidy then decreases dramatically by 110 and 100 € TJ^{-1} for Sceanrio2030 mostly due to an increase in supply of 'pulpwood' biomass. Of note is the zero subsidy required for the Board sector on a Global focus in Scenario 2030 and also the 0 and 30 € TJ^{-1} subsidy for the Energy sector. This insight could play a role when determining prices for Renewable feed in tariffs (REFITS) and what the breakeven feed in price could be for all sectors for a competing biomass resource. Having looked at how the Global focus resolves the solution to having nearly no requirement for a subsidy, it paves the way forward for attempting an equal allocation of resources at the cheapest possible cost to society. The usefulness of the final data allows the development of a subsidy (€ TJ^{-1}) or level of compensation that would be required to either sector in neutralising the competitive advantage that an optimisation has over each sector. This connects with the concept of a REFIT scheme where the Irish Government currently pay biomass, wind power projects – but not for co-firing with peat for electricity generation.

5.1 Discussion

This study quantified the influence of biomass utilization strategy on the overall inbound transport cost to the Board and Energy sectors in Ireland – both for 2015 and 2030. Transport makes up roughly one third of the delivered cost of forest biomass and is therefore an important indicator of supply feasibility. An additional generic biomass resource, representing primarily pulpwood was sluiced into the problem in order to allow it to solve feasibly. The exact distribution and availability of the 'other' biomass was based on the 2028 forecasted net realizable volume of roundwood production in the form of thinnings from the private sector and Coillte [12] and were dealt with in a sensitivity analysis, at various levels of mean weighted delivered cost.

The Scenario2015 represented present conditions as closely as possible, and included the co-firing target that one of the energy plants was scheduled to have attained by that time. The optimized supply costs presented here are likely to be significantly lower than the sum of actual transport costs to six independent plants as few primary industries would cooperate or use mathematical programming on inbound logistics.

Scenario 2030 was considered to be sufficiently distant in time to include a situation where all 3 energy plants had attained the targeted 30% co-firing. Optimisation through mathematical programming, here Linear Programming, allows for the creation of supply cost curves. Furthermore, the output of shadow prices, upper and lower bounds, and slack and surplus on constraints all provide critical insight into the solution space. This paper took a sector wide perspective, and did not deal with the opportunity costs for each sawmill, boardmill or energy plant. At a sector level, it was shown that enough insight could be obtained for quantifying decisions on the magnitude and allocation of incentives, depending on the required impact. It also showed that physical planning and market intervention (allocating biomass to the correct destination) could be just as effective as market subvention through incentives, being both considerably cheaper for society, and lowering the carbon footprint of the respective industries through reduced transport. Devlin et al 2013 [42] showed how distance travelled for biomass transport has a direct correlation to truck CO2 emissions. So reducing distance travelled also reduces CO2 emissions. Gan and Smith 2005 [43] looked at how attempting to mitigate CO2 emissions could drive the economic potential of power generation from woody biomass versus coal. Depending on the price of coal and the emission taxes, logging residues could only be competitive.

Resources were allocated to the board and energy sectors on the basis of transport cost only. An equilibrium model that adjusts the price of the resources according to market dynamics could improve the validity of the solution, although it is difficult to assess whether this would accentuate or negate the differences found in this study. The CO_2 trade benefits of increased co-firing could have been used in justifying increasing costs [44] but this is left for *post hoc* analysis. Specifying the portfolio of alternative biomass to form, suitability, availability and cost would allow for more explicit solutions which would be of greater utility when optimizing at an individual plant level.

Finally, using the results of the data from the sensitivity analysis allowed the development of a subsidy which could be used as a value for renewable feed in tariffs (REFITS) to determine what a breakeven price would be for a competing biomass resource between each of the 3 sectors analysed. A subsidy of between 140 and 170 € TJ^{-1} is needed for Scenario 2015 when optimizing for the Board sector when the Energy sector is getting less residues. The subsidy decreases to 30 and 70

€ TJ^{-1} for Scenario 2030 mainly due to an increase in available pulpwood as an energy source for co-firing.

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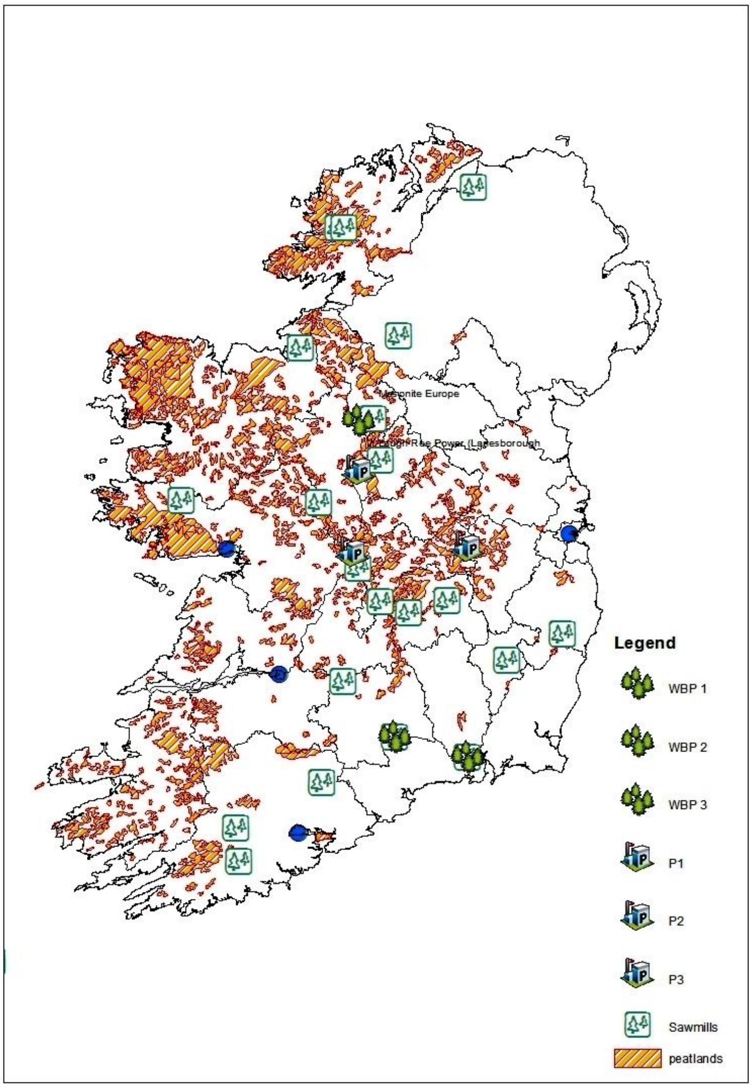

Figure 1 – GIS Peat Power station map of Ireland. Also includes Peatlands, Wood Based Panel mills and Sawmills.

Figure 2 – Mean Supply cost curves for time horizons 2015 and 2030 and sector focus Global, Board and Energy.

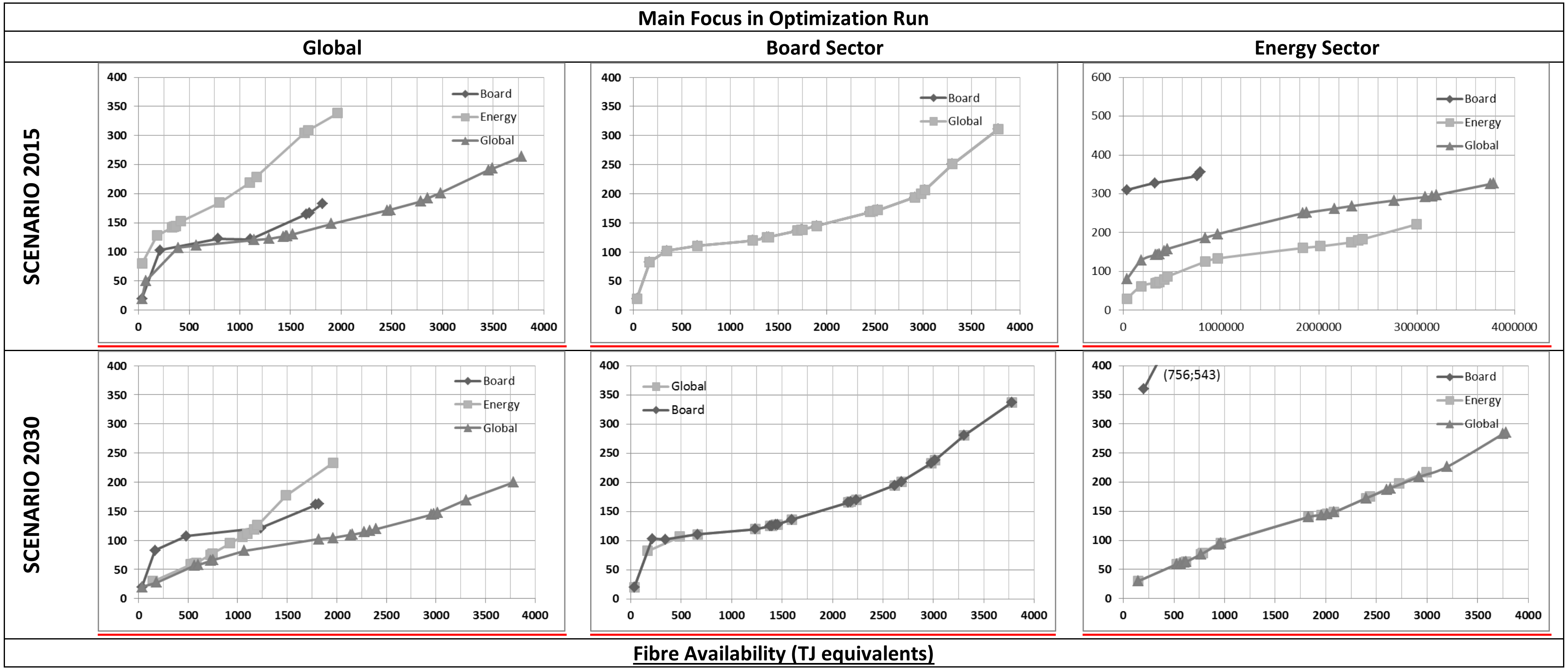

Figure 3 - The supply cost for the Board and Energy sectors, under different assumptions on the cost of alternative biomass.