BIOFUEL PRODUCTION IN EUROPE – POTENTIAL FROM LIGNOCELLULOSIC WASTE

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SUMMARY: The objective of this study is to analyze the biofuel potential in Europe from lignocellulosic waste (wood waste and paper and cardboard waste). Ethanol from fermentation and Fischer-Tropsch (FT) diesel from gasification are the two biofuels considered. As those biofuels are not yet commercially available, the optimal locations of the production plants have to be determined. The analysis is carried out with a geographic explicit model that minimizes the total cost of the biofuel supply chain. A mixed integer linear program is used for the optimization. The results show that ethanol production plants are selected in a majority of the studied cases. Ethanol plants are mainly set up in areas with a high heat demand and/or high electricity or heat price, whereas FT diesel production plants are set up in areas where the heat demand is low all year round. A high cost for emitting CO_2 as well as high transport fossil fuel prices favor the selection of FT diesel over ethanol production plants. With a CO_2 cost of 100 €/t_{CO2} applied, the biofuel production from waste can potentially meet around 4% of the European transport fuel demand.

1.INTRODUCTION

Demand for biofuels has increased considerably over the last decade, as is evidenced by for example the European Union (EU) target for renewable energy in the transport sector of 10% in 2020 (Dir 2009/28/EC, 2009). The main drivers have been high oil prices, security of supply and CO_2 emissions mitigation. During the last few years the criticism against biofuels, in particular first generation biofuels has increased, due mainly to issues related to competition with food production and potential negative environmental impact from biofuel production (Fargione et al., 2008, Searchinger et al., 2008). Second generation biofuels in general have lower specific land use requirements than first generation fuels, and can use non-food feedstock, such as various types of waste and forest residues. In order to reach the biofuel target for 2020 without substantial interference with other goals, it will likely be necessary to have a substantial share of second generation biofuels in the EU fuel mix.

Biofuel production plants will need to be very large to reach necessary efficiencies and economies of scale (Faaij, 2006). Large plant sizes increase the necessary feedstock supply area

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and put significant demands on the supply chain, which makes it necessary to carefully choose the geographic location of the production plants with respect to fuel demand and feedstock locations. In several second generation biofuel production routes a considerable part of the feedstock energy content can be used for co-production of other energy products, such as heat, electricity, lignin or biogas. Polyproduction gives an opportunity for higher total conversion efficiencies, but also puts additional requirements on the determination of the optimal biofuel production plant locations.

Many studies have focused their research on the use of waste for energy purposes at the national or regional level (see for example Münster and Lund, 2009, Münster and Lund, 2010 or Yassin et al., 2009). This study addresses localization of biofuel production on a European scale. The focus is on second generation biofuel using wood waste and paper and cardboard waste as feedstock, as a means to both increase the share of biofuel and decrease landfilling. The aim is to investigate the biofuel production potential from those wastes in the EU-27, under varying CO_2 costs, and to calculate the cost to meet the transport fuel demand with biofuels in different regions.

2. METHODOLOGY AND INPUT DATA

An optimization model is used to determine the location and size of the biofuel production plants, given the locations of feedstock and energy demand. The model minimizes the total cost of the entire supply chain of the studied system.

2.1 Geographical boundaries

The model incorporates the entire EU-27[1], the grid size is half a degree. In order to limit calculation times, the EU has been divided into eight regions.

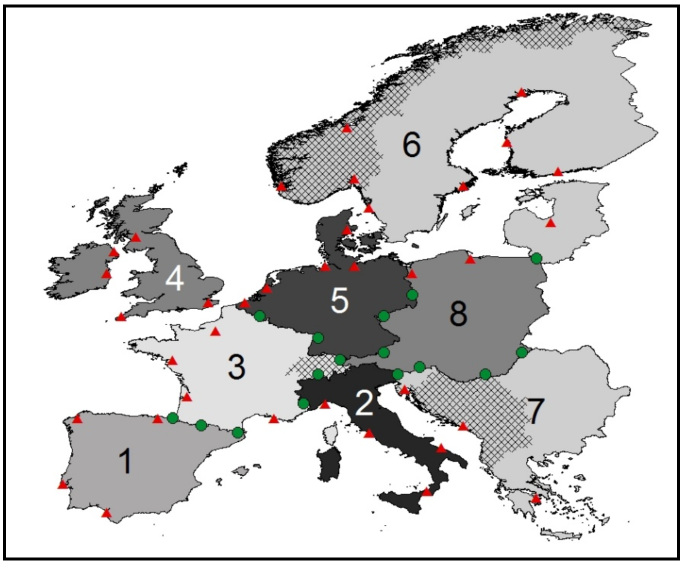

Figure 1. Region definition and location of the trade points. The red triangles represent the larger harbors and the green circles represent inland trade points. Feedstock and biofuel can be traded from one harbor to any other harbor, whereas inland trades can only occur at one specific inland trade point.

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[1] Malta and Cyprus have been excluded from the study.

As the model is based on transportation costs from one grid point to any other grid point, the eight regions have been delimited by natural borders such as mountains or water.

Within each region the distances between all grid points are calculated. Import/export of feedstock or biofuel between the regions can only take place at defined trade points, situated at major harbor locations or strategically located border points. Figure 1 shows those eight regions with the included trade points. The countries that do not belong to the EU-27 (cross dashed lines) are not considered as regards energy demand or waste supply, but trades are allowed through those countries.

2.2 Waste supply

Two lignocellulosic waste fractions are included – wood waste and paper and cardboard waste. Wood waste includes for example waste from the forest industry and from construction and demolition of buildings. Paper and cardboard waste includes for example collected waste as well as waste from pulp, paper and cardboard production. Data on the amount of waste for the individual EU member states in 2006 has been obtained from Eurostat, 2010. As a share of the total waste is already recovered, either for recycling or for energy recovery, only the share not currently reported as 'recovered' is assumed available for biofuel production.

The waste available is assumed to be dependent on the population of each grid point, with the per capita waste production assumed equal in all grid points for each country. In countries where a large amount of the total waste originates from the forest industry, in particular Sweden and Finland, this will result in an overestimation of the available waste in more populated areas and an underestimation of waste in more sparsely populated areas, where the forest industry is typically located. Figure 2 shows the distribution of available waste. For details of the waste data, see Wetterlund, 2010.

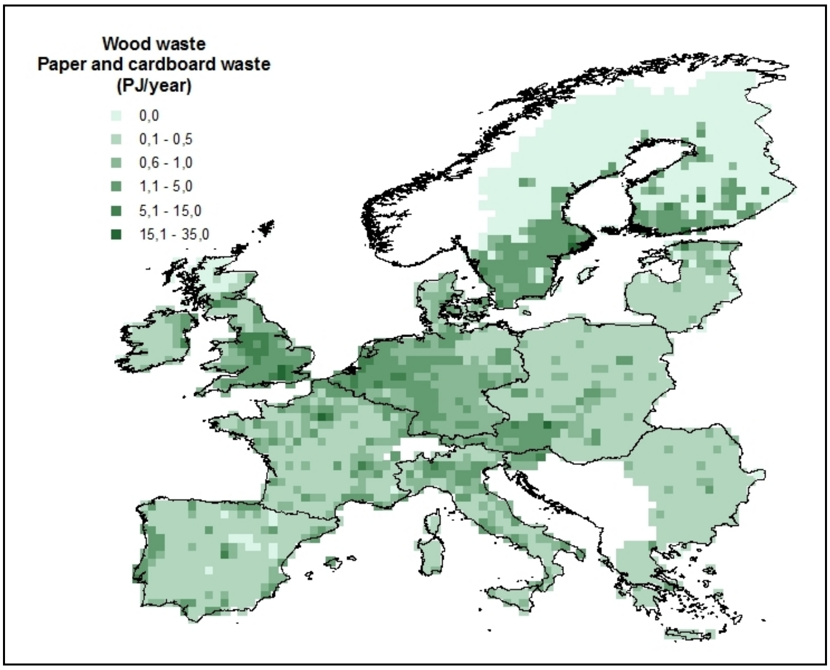

Figure 2. Amounts of wood waste and paper and cardboard waste available for biofuel production (PJ/year), 2006 (Eurostat, 2010).

2.3 Polyproduction technologies

Two different polyproduction technologies are considered – cellulosic ethanol via hydrolysis and fermentation and Fischer-Tropsch (FT) diesel via gasification, both with co-production of electricity and heat. Produced heat can either be sold for use as district heating or, if no heat demand exists close to the plant location, be wasted. Produced electricity is sold to the grid.

An annual operating time of 8,000 hours is assumed for both technologies. Scale effects have a strong impact on the costs of biomass conversion systems (discussed by e.g. Dornburg and Faaij, 2001, Sørensen, 2005). Investments costs are scaled using the general relationship:

$$\frac{Cost}{Cost_{base}} = \left(\frac{Size}{Size_{base}}\right)^{R}$$

where *Cost* and *Size* represent the investment cost and plant capacity respectively for the new plant, $Cost_{base}$ the known investment cost for a certain plant capacity $Size_{base}$, and *R* is the scaling factor. An overall scaling factor of 0.7, the average value for chemical process plants (Remer and Chai, 1990), is used. Process efficiencies are assumed constant over the entire scale range.

2.3.1 Ethanol production

Today ethanol for use as transport fuel is mainly produced from corn or sugarcane, with much interest in development of production processes utilizing cellulosic feedstock. Focus is primarily on agricultural residues, but production from various wood feedstock is also under development. Ethanol production from lignocellulosic material demands pre-treatment in order to separate the cellulose and hemicellulose from the lignin, typically using hydrolysis (enzymatic or acidic). Here a process using dilute acid hydrolysis is considered. The lignin and the biogas co-produced in the process are used to produce heat and electricity. Heat not used internally can be delivered for use as district heating. Key data is given in Table 1, while a detailed process description can be found in Leduc et al., 2010.

2.3.2 Fischer-Tropsch diesel production

Fischer-Tropsch (FT) fuels are synthetic hydrocarbons that are fully compatible with existing fossil fuel infrastructure and vehicles. Today FT fuels are produced from coal or natural gas. FT production from biomass feedstock is still not commercial, but research and development is being conducted (see e.g. CHOREN, 2010, Tijmensen et al., 2002).

Table 1 - Input data for the polygeneration technologies. Investment costs have been adjusted to €2009 using the Chemical Engineering Plant Cost Index (CEPCI). All efficiencies concern dry feedstock (lower heating value).

Key parameters	*Unit*	*Ethanol*[a]	*FT diesel*[b]
Base plant capacity	MW	372	300
Base investment cost	M€	490	304
Operating and maintenance cost	% of total investment cost	7.7	4.2
Biofuel efficiency		0.29	0.45
Electrical efficiency		0.20	0.06
District heating efficiency		0.32	0.06

[a] Hansson et al., 2007, Leduc, et al., 2010.

[b] van Vliet, et al., 2009, van Vliet, 2010.

Several potential production routes exist, incorporating different gasification technologies, cleaning and upgrading, and synthesis. Here a production route based on oxygen-blown gasification in a pressurized fluidized bed gasifier, followed by slurry phase FT synthesis and heavy paraffin conversion is selected. Electricity is co-produced in a combined cycle, using off-gas from the FT synthesis as fuel for the gas turbine and heat from the gas turbine and from the synthesis reactor in the steam cycle. Low-grade heat can also be recovered from the process and exported for use as district heating. Key input data is given in Table 1. For a detailed process description, see van Vliet et al., 2009.

2.4 District heating

Data on district heating in the EU in 2003 has been obtained from Werner, 2006 and Egeskog et al., 2009. The total national district heating demand is used to calculate the per capita heat demand for each country. No data on individual district heating systems has been collected. Instead the per capita heat demand is assumed to be equal in all grid points for each country, and the district heating systems are described on a nationally aggregated level. As discussed by Egeskog, et al., 2009, the heat that could be replaced by the heat from biofuel production depends on a number of system specific factors, such as heat load, current production mix and age structure of the existing heat production plants. Since the aim of this study is to give a broad view of the potential in EU for domestic biofuel production, no consideration is given to individual district heating systems.

It is assumed that all fossil heat, from combined heat and power (CHP) plants as well as from heat-only boilers (HOBs), can be replaced by heat from the biofuel production plants. Figure 3 shows the distribution of available heat sinks. As can be seen, the largest potential for heat deliveries is located in region 5, 7 and 8. The reason is that those regions have both relatively large national district heating systems and a large share of fossil heat today. Countries with large district heating systems with a large share of for example renewables and waste heat, such as Sweden and Finland, thus constitute much smaller heat sinks. Ireland, Spain, Italy and Greece have no or very little district heating.

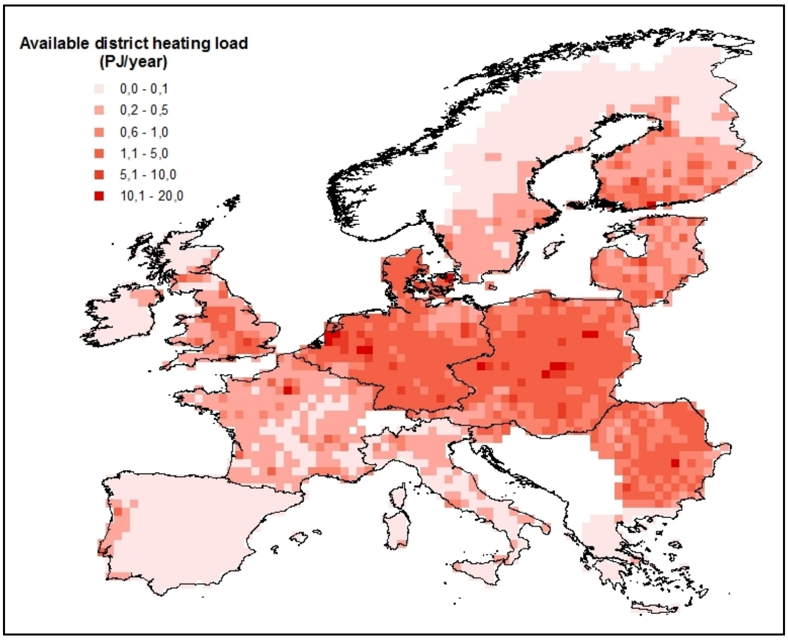

Figure 3. Modeled available district heating load (PJ/year), 2003 Egeskog, et al., 2009, Werner, 2006.

Table 2 - District heating load distributions used. Three seasons of equal length are applied. Load data from Bennstam, 2008, Chinese and Meneghetti, 2005, Sigmond, 2010.

Part of EU	*Season 1*	*Season 2*	*Season 3*
North[a]	49%	35%	16%
Central[b]	60%	32%	8%
South[c]	82%	12%	6%

[a] Denmark, Estonia, Finland, Latvia, Lithuania, Sweden.

[b] Austria, Belgium, Bulgaria, Czech Republic, France, Germany, Hungary, Ireland, Luxembourg, Netherlands, Poland, Romania, Slovakia, United Kingdom.

[c] Greece, Italy, Spain, Portugal, Slovenia.

A simplified heat load duration curve is applied, with the year divided into three seasons of equal length. To accommodate for variance in annual load distribution at different latitudes, three different load curves are used; one representing the northern EU countries, one representing the central and one representing the southern countries. The load distributions are summarized in Table 2.

The heat distribution distance limit is set to 50 km. Costs for investments in district heating distribution technology are not included. Details of district heating data and assumptions can be found in Wetterlund, 2010.

2.5 Transportation and distribution

2.5.1 Transport of waste and biofuels

Three transportation technologies for waste and produced biofuel are included; truck, train and boat. Base transportation costs are obtained from Börjesson and Gustavsson, 1996, and adjusted to take into account differences in heating values and feedstock moisture contents, as well as currency development since 1996. The transportation costs applied are presented in Table 3.

A network map of roads, rails and shipping routes is used to calculate transportation routes and distances d between the supply points and the production plants, as well as between the production plants and the demand points. This has been described in detail in Leduc, 2009 and Leduc et al., 2010.

2.5.2 Distribution and dispensing of biofuels

All gas stations are assumed to be able to handle biofuel distribution, after certain alterations to the existing equipment. The dispensing costs for FT diesel and ethanol are assumed equal, at 0.24 €/GJ (Leduc, 2009).

Table 3 - Transport costs in €/TJ for feedstock and biofuels. d is the transport distance in km. (Börjesson and Gustavsson, 1996).

Energy carrier[a]	*Truck*	*Train*	*Boat*
Waste (wood, paper and cardboard)	$192+4.32d$	$406+0.602d$	$465+0.246d$
FT diesel	$55.5+1.23d$	$170+0.265d$	$186+0.0594d$
Ethanol	$91.0+2.02d$	$280+0.436d$	$306+0.0975d$

[a] Waste is assumed to have the same heating value as forest residues, 18.5 GJ/ton (lower heating value, dry feedstock) and a moisture content of 20%. Heating value of FT diesel is 44.0 GJ/ton and of ethanol 26.8 GJ/ton (Edwards et al., 2007).

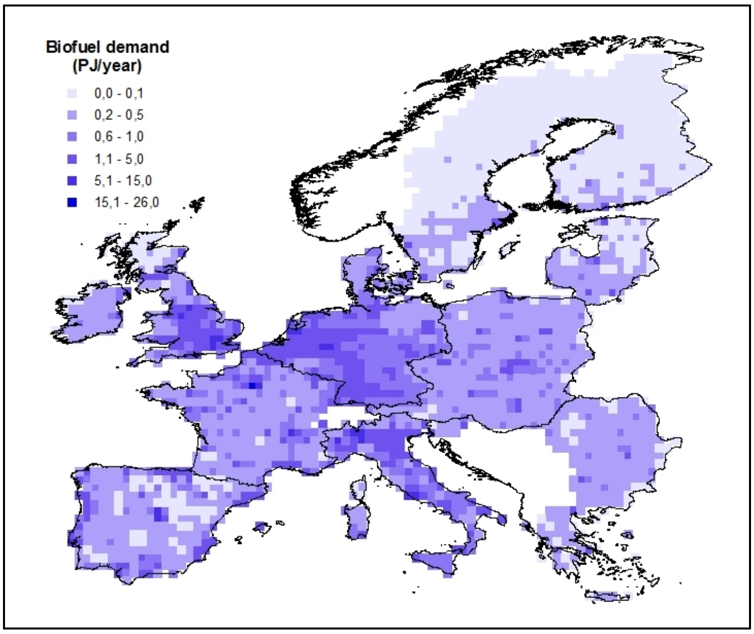

Figure 4. Biofuel demand at 10% biofuel share (PJ/year), 2005 (European Commission, 2008).

2.6 Transport fuel demand

The total energy demand in transport (public road transport, private cars and motorcycles and trucks) in the EU was 12 EJ in 2005, with an estimated increase to 15 EJ in 2020 (European Commission, 2008). This means that in order to meet the target of 10% renewable energy in transport, 1.2-1.5 EJ biofuel could be needed. If all wood, paper and cardboard waste not already recovered or recycled is used for biofuel production, it could cover 3-4% of the total 2005 fuel demand. If also all waste already used is assumed available for conversion into biofuels, a total of 5-8% of fossil transport fuels could be replaced.

Here the transport fuel demand for 2005 is used. The per capita fuel demand is assumed equal in all grid points of each country. Figure 4 shows the biofuel demand at a 10% share. In the model, any fuel demand not possible to be met by biofuels is met by fossil transport fuels. For details on the fuel demand data, see Wetterlund, 2010.

2.7 CO_2 emissions

The model considers CO_2 emissions from fossil fuels and from transportation of feedstock and biofuels. Each GJ of biofuel produced is assumed to replace 1 GJ of fossil transportation fuel[1], thus displacing 78 kg of CO_2 (Uppenberg et al., 2001).

Concerning heat, all fossil district heating is assumed replaceable, as mentioned in Section 0. Thus, heat delivered from the polyproduction plants is assumed to replace heat corresponding to the average fossil district heating mix for each country. Likewise, produced electricity is assumed to replace country mix electricity. CO_2 from biomass is not included, as it is assumed that the CO_2 emissions released when combusting the biomass based waste are balanced by CO_2 uptake in growing trees.

CO_2 emissions related to transportation of feedstock and biofuels are given in Table 4. Country specific CO_2 emissions for heat and electricity are given in Table 5.

[1] Average emission for petrol and diesel, with no country specific differences considered.

Table 4 - CO2 emissions from transportation in gCO2/km/GJ of feedstock and biofuels (European Commission, 2010).

Energy carrier[a]	*Truck*	*Train*	*Boat*
Waste (wood, paper and cardboard)	3.27	1.67	0.859
FT diesel	1.10	0.562	0.289
Ethanol	1.81	0.922	0.474

[a] Waste is assumed to have the same heating value as forest residues, 18.5 GJ/ton (lower heating value, dry feedstock) and a moisture content of 20%. Heating value of FT diesel is 44.0 GJ/ton and of ethanol 26.8 GJ/ton (Edwards, et al., 2007).

District heating emissions are calculated from reported country district heating mixes[1] (Uppenberg, et al., 2001, Werner, 2006). Electricity emissions are end-user life cycle emissions for national grid mixes (European Commission, 2010).

2.8 Energy prices

The energy prices assumed in this kind of study will naturally affect the results to a large extent. Today the energy prices in the different EU member states are highly diversified, with for example the electricity price in the country with the highest price (Italy) being more than three times the price in the country with the lowest price (Estonia).

Since it is very difficult to predict future prices in all the EU states, country specific energy prices for 2009 are used in this study. Sensitivity analysis of the influence of harmonized energy prices for the entire EU is also performed (see section 0). Table 5 shows the country specific energy prices used. The purchase price for all waste feedstock is assumed to be 0 €/GJ.

2.9 Optimization model

The problem is an ordinary Mixed Integer Program (MIP) and can thus be solved using standard MIP techniques (Wolsey, 1998). The model was developed in the commercial software GAMS using the solver CPLEX (McCarl et al., 2008). The MIP model has previously been used in studies of smaller regions at the country level (Leduc et al., 2008, Leduc, et al., 2010 or Schmidt et al., 2010), but has in this study been further developed to incorporate the entire EU.

Compared to the previous versions of the model, in this study it is possible to trade either the feedstock or the biofuel between the eight regions. The trades between the regions are based on the transportation costs of the commodities. The feedstock can be transported from one supply point to either a production plant or to a trade point (harbor or inland trade point, see Figure 1) of the same region. The biofuel can be transported from one production plant to either the demand point or to a trade point of the same region. The feedstock or the biofuels can then be shipped from one harbor to any other harbor of a different region, or from one inland trade point to the inland trade point opposite the region boarder only. The amount of commodity traded at one trade point is limited by an upper bound. This trade limit is assumed to be the same for all trade points in Europe and kept constant in this study.

[1] The share of the national mix that could be replaced by heat from polyproduction plants.

Table 5 – Country specific energy prices (€/GJ) and CO_2 emissions from displaced fossil energy (kg_{CO2}/GJ).

	Energy prices (€/GJ)[a]			*CO_2 factors (kg_{CO2}/GJ)*[b]	
Country	*Transport fuel*	*District heating*	*Electricity*	*District heating*	*Electricity*
Austria	11.9	17.0	35.2	73.7	87.3
Belgium	12.6	13.1	34.6	50.1	109
Bulgaria	11.4	6.9	19.0	41.5	242
Czech Rep.	12.9	11.4	26.1	64.8	214
Denmark	13.5	19.9	28.1	43.8	208
Estonia	11.9	6.9	18.9	23.4	432
Finland	13.5	9.4	23.6	80.7	135
France	12.0	13.5	22.4	78.8	39.3
Germany	12.3	15.8	34.8	43.7	187
Greece	13.9	10.3	32.6	31.0	311
Hungary	12.9	10.7	32.7	51.3	175
Ireland	12.4	7.5	43.1	105	234
Italy	13.9	19.0	65.6	39.4	186
Latvia	12.5	9.9	26.6	53.2	152
Lithuania	12.6	10.5	20.7	74.9	51.4
Luxembourg	12.8	13.1	41.1	30.0	159
Netherlands	12.7	13.1	36.4	19.3	195
Poland	12.2	8.8	24.3	57.5	316
Portugal	13.5	7.5	33.0	23.5	210
Romania	12.7	6.7	21.8	26.3	275
Slovakia	12.6	9.9	35.5	76.9	89.2
Slovenia	12.0	10.3	28.0	81.1	158
Spain	13.3	0.0	34.3	39.8	176
Sweden	11.8	15.5	24.1	114	29.9
UK	11.3	7.5	34.0	41.0	173

[a] Transport fuel prices are average pump prices without taxes for petrol and diesel in 2009 (European Commission, 2010). District heating prices are national estimated consumer price averages without VAT for 2003 (Werner, 2006), currency adjusted to $€_{2009}$. Heat sell prices are assumed to be possible at 50% of the consumer price. Electricity prices are average end-user prices without taxes (domestic customers) in 2009 (Eurostat, 2010).

[b] European Commission, 2010, Uppenberg, et al., 2001 and Werner, 2006.

A detailed description of the model can be found in Leduc, 2009 and Wetterlund, 2010.

The model minimizes the total cost of the supply chain which is defined as:

$$(\text{Total cost}) = (\text{Supply chain cost}) + (\text{Supply chain emissions})*(CO_2 \text{ cost})$$

The supply chain cost includes:

- feedstock cost, collection cost and transportation cost to the production plant,
- production plant: set up and biofuel production costs,
- biofuel transport cost to the gas stations,
- income from the co-products (i.e. heat, power),
- feedstock/biofuel transportation from one region to another,

- fossil fuel cost for transport.

The supply chain emissions include:

- emissions of fossil CO_2 from feedstock and biofuel transportation,
- emissions from additional transport fossil fuel use,
- offset emissions from replaced fossil transportation fuel, electricity and heat.

The emissions are weighted by a CO_2 emission cost, for example a CO_2 tax or tradable emission permits.

The model will choose the least costly pathways from one set of feedstock supply points to a specific production plant and further to a set of biofuel demand points. The final results of the optimization problem would then be the location of a set of plants, the different trade flows between the regions of both feedstock and biofuels, and the costs of the supply chain.

2.10 Scenarios

In the base scenario (scenario 0) the CO_2 emission cost is set to 0 €/t_{CO2} for all regions. Country specific energy prices given in Table 5 are used. All existing fossil district heating is assumed replaceable. The model is next run with different CO_2 cost settings for one region at a time (scenarios 1-8).

Table 6 - List of the scenarios modeled.

Scenarios	*CO_2 cost €/t_{CO2}*	*Fossil fuel price factor*	*Energy prices*
S0 (base scenario)	0	1	base
S1	100 (region 1 only)	1	base
S2	100 (region 2 only)	1	base
S3	100 (region 3 only)	1	base
S4	100 (region 4 only)	1	base
S5	100 (region 5 only)	1	base
S6	100 (region 6 only)	1	base
S7	100 (region 7 only)	1	base
S8	100 (region 8 only)	1	base
S9	100 (all regions)	1	base
S10	0	1	harmonized, weighted average[a]
S11	0	1	harmonized, min[b]
S12	0	1	harmonized, max[c]
S13	0	0.5	base[d]
S14	0	0.8	base[d]
S15	0	1.2	base[d]
S16	0	2	base[d]
S17	0	1	no heat revenue

[a] Transport fuel price 12.5 €/GJ, heat price 6.1 €/GJ, electricity price 32.1 €/GJ.

[b] Transport fuel price 11.3 €/GJ, heat price 3.3 €/GJ, electricity price 18.9 €/GJ.

[c] Transport fuel price 13.9 €/GJ, heat price 9.9 €/GJ, electricity price 65.6 €/GJ.

[d] Fossil transport fuel price is multiplied by a price factor, all other energy prices are kept at base levels.

Those scenarios reflect the impact of a CO_2 cost on the biofuel supply costs and biofuel production for a particular region, which would be hard to identify if all regions had the same CO_2 cost (scenario 9). To analyze the impact of energy prices, a number of scenarios with varying energy prices are also included. In scenarios 10-12 the energy prices are assumed harmonized in all the individual EU member states, with different price levels (average prices, prices corresponding to the lowest current prices, and prices corresponding to the highest current prices). In scenario 13-16 only the fossil fuel price is varied, while all other prices are kept at country specific base levels. Finally, in scenario 17 the influence of the possibility to sell heat is examined, by setting the heat revenue to 0 €/GJ. The different scenarios are summarized in Table 6.

3. RESULTS AND DISCUSSION

3.1 Biofuel production plant location

Large scale biofuel production plants over a capacity of 25 $t_{biomass}$/hour have been considered. For all the scenarios presented in this analysis, all the production plants reach the maximum capacity set at 100 $t_{biomass}$/hour.

Figure 5 shows the resulting plant positions in the base scenario (scenario 1). As can be seen, a majority of the production plants are set in central Europe, in or close to region 5. Region 5 has indeed the largest share of the total biofuel demand in EU (26%). The production plants in the neighboring regions 4 and 8 are located close to harbors or inland trade points, with a substantial part of the biofuel production being exported to region 5, but also with exports to regions 2 and 7. Only three production plants are set in region 1. As Figure 5 shows, all three plants are FT diesel plants, which can be explained by a very low heat demand in this region. In the plant locations in the other regions either the heat demand or the electricity price is high, which favors ethanol production.

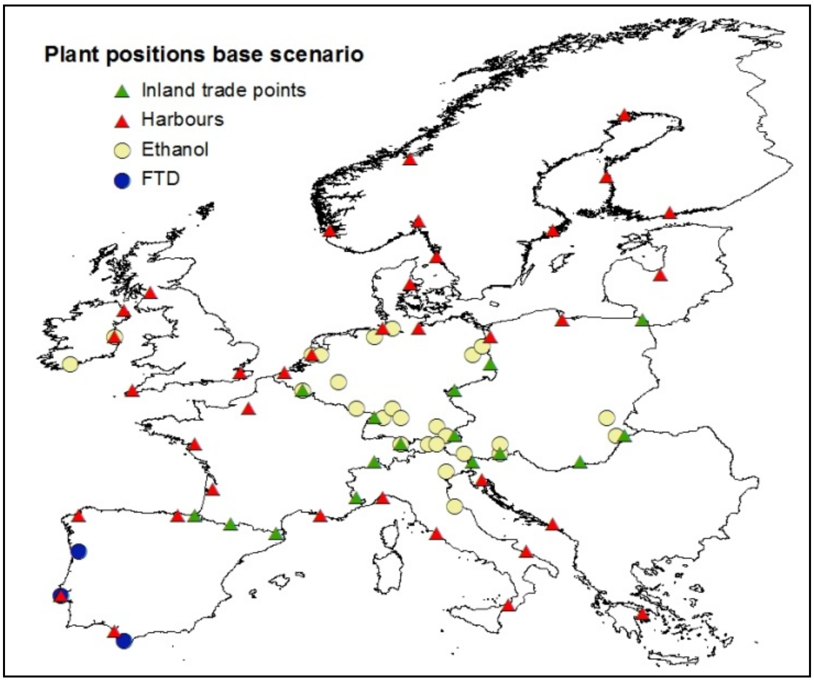

Figure 5. Resulting polyproduction plant positions (blue and yellow circles) in the base scenario. Harbors (red triangles) and inland trade points (green triangles) also shown.

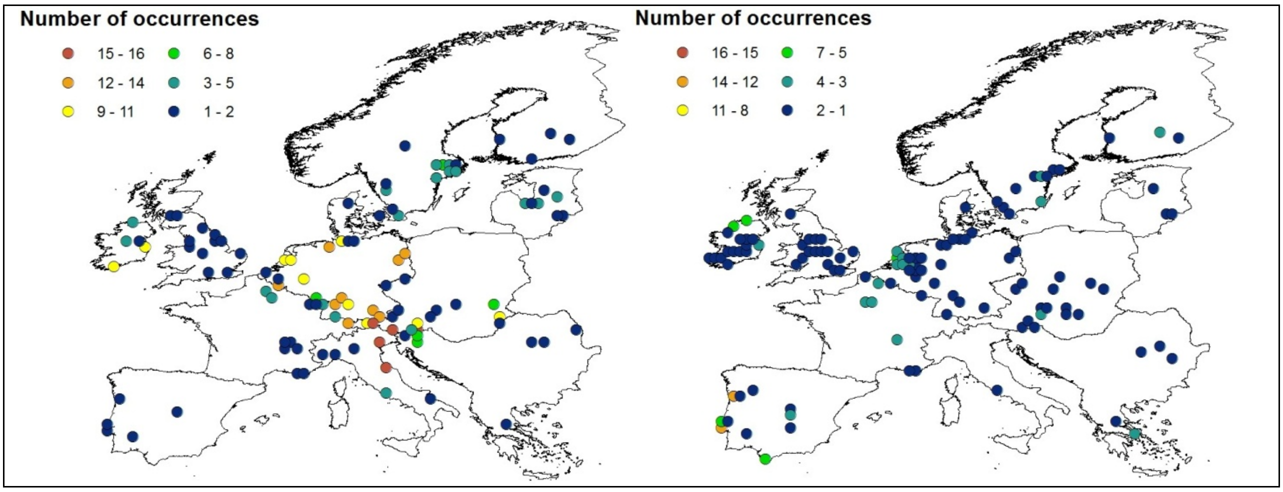

Figure 6. Number of occurrences for the ethanol production plants (left) and FT diesel production plants (right) from all scenarios.

Figure 6 shows the resulting positions from all the scenarios with their number of occurrences, for both ethanol and FT diesel production plants. The ethanol production plants are mainly located in Italy, Austria and Germany where they in some locations occur in 12-16 out of 18 scenarios (Figure 6, left). The optimal locations of ethanol production plants are primarily determined by factors related to the co-products (heat and electricity), such as electricity and heat prices, and size of heating demand.

Table 7 - Number of production plants per region and technology in each studied scenario (ethanol production plants / FT diesel production plants).

Scenario	*R1*	*R2*	*R3*	*R4*	*R5*	*R6*	*R7*	*R8*
S0	– / 3	2 / –	–	2 / –	14 / –	–	–	8 / –
S1	– / 5	2 / –	–	2 / 1	14 / –	–	–	8 / –
S2	– / 3	5 / –	4 / –	5 / 1	14 / –	–	2 / –	8 / –
S3	– / 4	5 / –	– / 5	4 / 1	14 / –	–	1 / –	8 / –
S4	– / 4	2 / –	–	– / 17	14 / 1	1 / –	2 / –	9 / –
S5	– / 4	2 / –	4 / –	2 / 1	– / 17	2 / –	2 / –	8 / –
S6	– / 4	2 / –	–	2 / –	15 / –	11 / 6	–	8 / 1
S7	– / 4	2 / –	–	3 / 1	14 / –	–	2 / 1	9 / –
S8	– / 3	2 / –	2 / –	2 / 1	14 / –	2 / –	2 / –	1 / 8
S9	– / 5	4 / –	– / 5	1 / 15	5 / 12	10 / 8	1 / 4	4 / 6
S10	–	1 / –	4 / –	–	11 / 1	5 / 4	1 / –	9 / –
S11	–	–	– / 1	–	–	–	–	–
S12	5 / –	3 / –	5 / –	16 / –	16 / –	20 / –	5 / –	10 / –
S13	–	2 / –	–	–	–	–	–	5 / –
S14	–	2 / –	–	–	13 / –	–	–	7 / –
S15	– / 3	2 / –	– / 2	2 / 14	9 / 5	– / 4	1 / 2	7 / 2
S16	– / 4	2 / 1	– / 5	– / 15	– / 15	10 / 7	– / 3	4 / 5
S17	– / 2	2 / –	–	2 / 1	– / 7	–	–	– / 2

Italy has indeed the highest electricity price in Europe, Germany has a high heat demand with fairly high heat prices, and both heat and electricity prices are relatively high in Austria.

From Figure 6 (right) it can be noticed that the number of occurrences for FT diesel production plants is highest (between 12 and 14 in some locations) in region 1. The heat demand in this region is very low all year long, which makes FT diesel production plants more profitable compared to ethanol production plants.

Table 7 summarizes the number of production plants that are set up per region and scenario for each of the biofuel production technologies. Noteworthy is that the occurrence of FT diesel production plants in several regions increases when a CO_2 cost is imposed in that region (see for example scenario 4, region 4), or when the fossil fuel price increases (see for example scenario 16, region 5). This is discussed further in section 0.

From scenario 1 to 8, a CO_2 cost was set to 100 €/t_{CO2} for one region at a time. In scenario 9, all the regions have the same CO_2 cost of 100 €/t_{CO2}. When a CO_2 cost is applied it becomes increasingly beneficial to substitute fossil fuel for biofuel. Thus, more production plants are built in the regions where such a cost is applied. As the objective function is defined, the higher the price of fossil fuel, the higher the total cost will be. Therefore to minimize the objective function, more biofuel needs to be produced to compensate this increase in price, as is evidenced by the results for scenario 15 and 16.

3.2 Biofuel supply costs at varying CO_2 costs

It has been described in Section 0 that the biofuel demand of a specific location can be met either by biofuel produced in the same region, or by biofuel traded from other regions. If a production plant is set up or not is determined by the biofuel production cost in that location compared to the cost of biofuel imported from other regions. Thus an average biofuel supply cost can be calculated for each region.

Figure 7 presents the biofuel supply cost for each region in scenario 0 to 9. The costs vary significantly between the regions as well as between the scenarios, ranging from -25 €/GJ to 38 €/GJ. The biofuel supply costs in regions 2, 5 and 8 are in general negative due to revenues from the co-products. Region 2 has the highest electricity price in Europe, which outweighs high transportation costs. Region 5 has a high demand for heat, fairly high heat prices and low transportation costs, due to good feedstock availability in the region. In region 8 the plants are mainly located in Austria (see Figure 6) where both heat and electricity prices are relatively high.

As can be seen in Figure 7, the biofuel supply costs reached in region 1 are stable at around 13 €/GJ, and are virtually not affected by any CO_2 cost obligation. The reason for this is that region 1 does not trade either feedstock or biofuel with other regions, which makes the in-region production very stable over scenarios. When a CO_2 cost is applied for the region more plants are set up and more biofuel delivered, which increases the biofuel supply cost slightly.

When a CO_2 cost is applied for region 2, 3, 4, 5 and 8 a significant increase of the biofuel supply cost can be noticed. This is mainly due to a shift from ethanol to FT diesel production, which leads to increased production costs due to lower co-production of heat and electricity.

Very high costs are observed for region 6 and 7 in scenario 4 and 3 respectively. For the two scenarios the total amount of biofuel produced within the region is exported towards the region where a CO_2 cost is applied. The regions where a CO_2 cost is set need to import as much biofuel as possible to the lowest possible cost, in order to substitute more fossil fuel. The two export regions (6 and 7 respectively) then have to import biofuel at higher costs. Meanwhile those two regions are less affected when a CO_2 cost is applied to them. In region 6 large amounts of waste feedstock are located close to the biofuel demand, which minimizes the need for biofuel import. For region 7 very few production plants are set up and the main source of biofuel supply is imported from the neighboring regions.

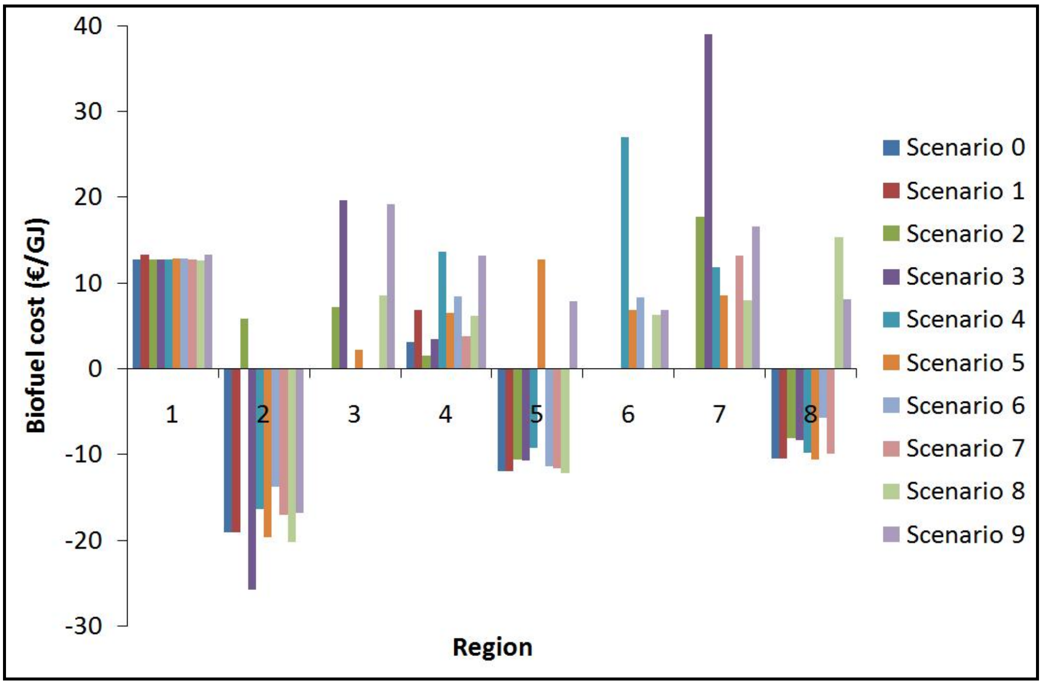

Figure 7. Average biofuel supply cost in €/GJ per region for scenarios 0 to 9.

3.3 Biofuel share

As mentioned in section 0, the maximum potential of biofuel (ethanol or FT diesel) from waste is around 3-4% (depending on production technology) if all waste not currently recovered is converted into biofuels. Figure 8 shows the resulting share of biofuel of total transport fuel demand in the EU for a selection of the studied scenarios. The figure also shows how large the share of FT diesel is of the total biofuel production.

In the base scenario the biofuel share is only about 1%, with a low share of FT diesel. The highest total biofuel share is reached when all regions are subject to a CO_2 cost (scenario 9). Indeed, in this case the biofuel share reaches almost 4%, which implies that close to all available waste is used for biofuel production. The preferred production technology shifts from ethanol to FT diesel, which allows for a higher biofuel production from the same amount of feedstock.

Two scenarios with harmonized energy prices in the entire EU are shown in Figure 8; one with average prices and one with prices corresponding to the current highest prices in EU. With average prices (scenario 10) the biofuel production naturally shifts from regions with individual energy prices higher than the average prices, to regions with lower individual prices. This is particularly noticeable for region 1 and 2 (decrease) and region 6 (increase). The total biofuel production in EU increases slightly, and so does the FT diesel share. With high harmonized prices (scenario 12) the total biofuel share increases significantly, compared to the base scenario. Due to the very high electricity price (66 €/GJ) the production also shifts entirely to ethanol. A 2.8% biofuel share from ethanol also implies that almost all available waste is used.

In scenarios 14-16 only the fossil transport fuel price is varied. In scenario 14 the fuel price is decreased by 20%, which naturally causes a decreased biofuel production, and a shift away from FT diesel. Scenarios 15 and 16 have increased transport fuel prices (20% and 100% respectively). An increased fuel price could be viewed as a representation of a case with targeted biofuel support policies, such as feed in tariffs, tax reduction or biofuel certificates. The biofuel share consequently rises significantly, as does the share of FT diesel.

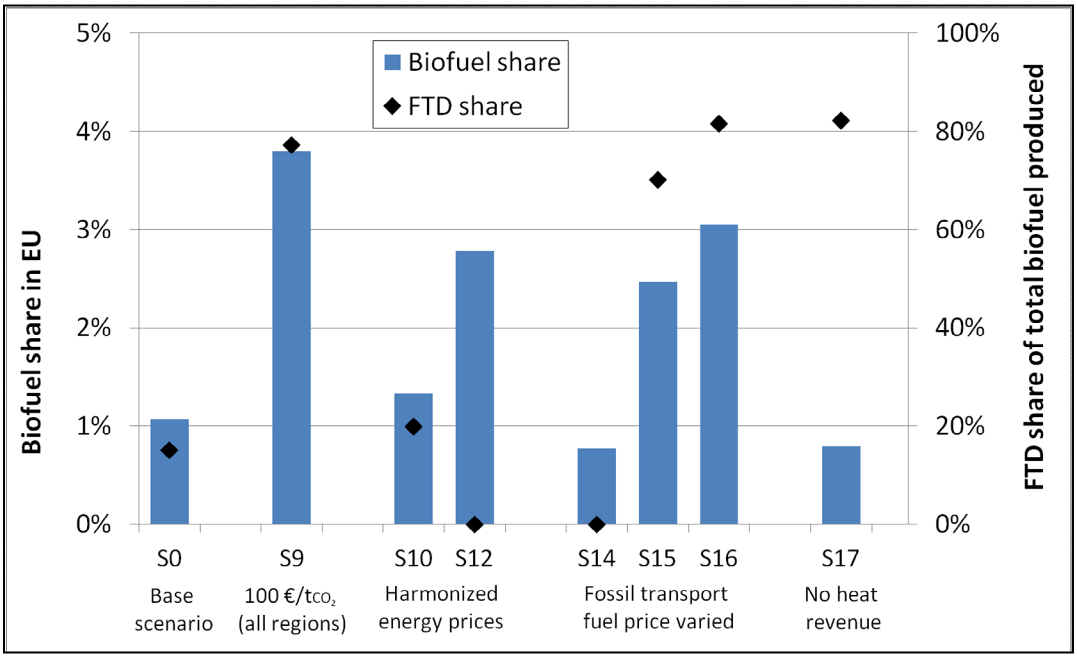

Figure 8. Biofuel share of total transport fuel demand and FT diesel share of total biofuel production in a number of scenarios (The numbers do not include biofuel already on the market).

When waste heat does not generate extra revenue to the plants (scenario 17) the biofuel production cost in most of the major biofuel producing regions (4, 5 and 8) increases significantly. This causes a substantial decrease in the total number of production plants in the EU, with the few installed production plants located at hot spots with high biofuel demand and good waste availability. However, as the preferred technology also shifts towards FT diesel, the drop in total biofuel production is not very distinct. Only in region 2 and 4 where the ratio between the electricity and the transport fuel price is particularly high, ethanol remains in place.

4. CONCLUSIONS

This study has presented the development of an already existing model to a larger scale. The optimal locations of biofuel production plants have been determined based on cost minimization for the EU-27, which has been divided into eight regions. The model generates solutions for each region, and allows trades of feedstock or biofuel between those regions. Two kinds of biofuel have been studied, ethanol and FT diesel, both of which can be produced from wood waste and paper and cardboard waste.

In many scenarios, ethanol is the preferred biofuel choice, due to the high incomes from the co-products. Ethanol production appears to be interesting in regions where the heat demand is high (like Germany), or electricity or/and heat costs are high (like Austria or Italy), whereas FT diesel production appears interesting in regions where the heat demand is lower all year round (like Portugal or Spain).

Sensitivity analyses have been carried out with a CO_2 cost applied region wise, as well as with varying transport fossil fuel, electricity and heat prices. The CO_2 cost has a significant impact on both the costs and the technology choice. With a CO_2 cost of 100 €/t_{CO2}, FT diesel production plants are preferably selected, potentially entailing an increased biofuel supply cost, depending of the region considered. High electricity or heat price favors the production of ethanol, whereas an increase of the price of transport fossil fuel increases the selection of FT diesel production considerably, due to the higher biofuel conversion efficiency.

By applying a correct policy tool (i.e. CO_2 tax or biofuel subsidy), biofuel from lignocellulosic waste can potentially meet 4% of the European transport fuel demand.

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