Proceedings from the LCA XIII International Conference 'Fulfilling LCA's Promise',
October 1-3, 2013, Orlando, FL, United states

Incorporating life cycle impact assessment in mathematical model to optimize strategic decisions in biomass-for-bioenergy supply chains

Annelies De Meyer[1,*] Joana Almeida[1] Wouter Achten[1] Bart Muys[1] Dirk Cattrysse[2]
Jos Van Orshoven[1]

[1] Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, 3001 Leuven, Belgium
[2] Centre for Industrial Management / Traffic & Infrastructure, KU Leuven, Celestijnenlaan 300A, 3001 Leuven, Belgium

Abstract

LCA is widely applied to compare multiple scenarios of supply chains in all the variety of operations needed for handling and transporting biomass. Due to the large number of product and operation types, supply chain planning requires choosing the best alternative combination of products and operation types in a decision environment with specific, pre-defined objectives.
To ensure a comprehensive evaluation of the biomass-for-bioenergy supply chain, all operations from crop harvest to delivery in conversion facilities are identified in a cradle-to-gate life cycle inventory. Each operation is characterized by attributes related to energy use, economic cost and GHG emissions. Then, the mixed integer linear programming model is applied to define the strategic design with the maximal cumulative energy output, the maximal cumulative profit or the minimal cumulative GHG emissions determined through life cycle impact assessment. The approach is applied to a supply chain of low input high diversity biomass in Belgium.

Keywords: Biomass, LCA, LCI, Strategic optimisation, Mixed integer linear programming
*Corresponding author: annelies.demeyer@ees.kuleuven.be

Introduction

The global energy consumption is expected to grow by 53 % between 2008 and 2035 (from 532 EJ to 812 EJ) (EIA, 2011) and may further boost greenhouse gas (GHG) emissions (IPCC, 2007), depletion of fossil resources and geographic energy dependency (Cherubini and Strømman, 2011). To counteract these trends, the potential of alternative and renewable energy sources is investigated which can simultaneously mitigate climate change and reduce the dependency on fossil sources (Cherubini and Strømman, 2011). Among these energy sources, bioenergy is anticipated to play a dominant role (IPCC, 2011) owing to the versatility of biomass, the possibility to store and convert it to energy on-demand (Rentizelas et al., 2009).

A variety of barriers and uncertainties regarding the international trade and sustainable and efficient production of biomass resources and bioenergy are hindering the use of biomass as an energy source (Bravo et al., 2012). The high handling and logistics costs related to biomass-for-bioenergy (B4B) supply chains are among the most decisive hurdles (Rentizelas et al., 2009). These costs cannot be avoided since they are indispensable to deal with the typical characteristics of biomass (e.g. spatial fragmentation, seasonal and weather related availability, high moisture content, low energy content and low bulk density) (Gold and Seuring, 2011; Rentizelas et al., 2009; Wee et al., 2012).

To support the development of a strong bioenergy sector, these barriers need to be overcome and sustainable bioenergy pathways need to be assessed. Operations research (OR) is regularly applied for defining the optimum biomass supply chain strategies in a decision environment with different kinds of objectives (De Meyer et al., in review). These OR models are able to define (a) the optimal biomass type to be converted, (b) the best way to transport, pre-treat and store biomass at operational, tactical and strategic level and/or (c) the optimal use of the conversion technologies (Wee et al., 2012). In order to identify the trade-offs between product and operation types and to account for all impacts generated throughout a bioenergy product's life-cycle (Godard et al., 2013), a comprehensive approach is required. However, a review of the existing optimization models has pointed out that most available OR models are case specific and address a definite part of the supply chain only incorporating far from all interrelationships and interdependencies between the operations considered in the supply chain (De Meyer et al., in review).

Life cycle assessment (LCA) is widely applied to profile the environmental impact of various kinds of bioenergy products (Cherubini and Strømman, 2011). Resorting to LCA, multiple scenarios of supply chain strategies can be compared in all the variety of biomass types and operation types needed for handling and transporting biomass (Cherubini and Strømman, 2011). As such LCA has the potential to provide the required comprehension when studying complex supply chains. Nevertheless, the large number of product and operation types in a B4B chain requires a decision environment to define the optimal supply chain strategy among the different alternatives (Halog et al., 2013).

This paper demonstrates the incorporation of life cycle impact assessment into a mathematical model aimed to optimize strategic decisions in the B4B supply chain in a comprehensive way. This model is linked to a geographic information system (GIS) to visualize and post-process the results (De Meyer et al., 2012). To illustrate the possibilities and functionalities, the methodology is applied to a (simplified) B4B chain supplying biomass derived from low input high diversity (LIHD) systems in the Limburg province (Belgium).

Methodology

To ensure a comprehensive evaluation of the B4B supply chain, a life cycle inventory (LCI) is performed, identifying all possible product and operation types. It also accomplishes the collection of data on material flows and costs in all phases of the life cycle (Davis et al., 2009). Then, the mathematical model is applied to define the optimal scenario of B4B supply in a decision environment with different kinds of product and operation types and pre-defined, conflicting objectives.

Life cycle inventory

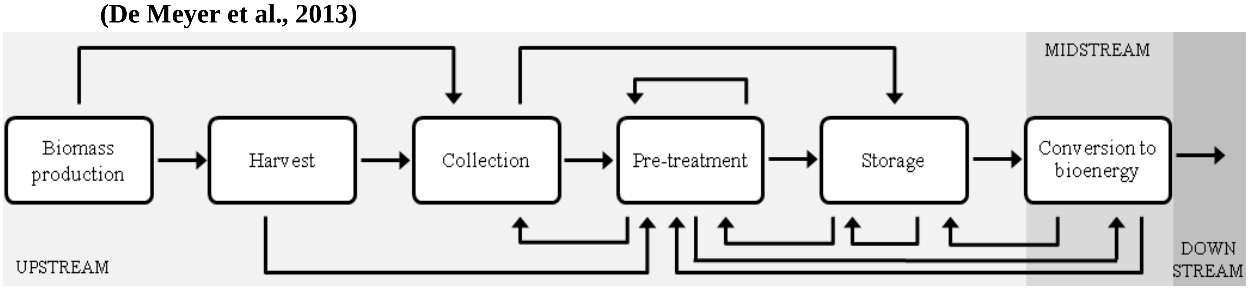
In the present study, a generic cradle-to-gate analysis of the B4B supply chain distinguishes six key operations from the point of harvesting raw materials to the delivery of the products to the conversion facility: i.e. biomass production, harvest, collection, pre-treatment, storage and conversion to bioenergy. Figure 1 schematizes the sequence of operations in the B4B supply chain in which the conversion operation is considered as a black box with input of biomass and output of bioenergy and by-products. Because the operations take place at different locations, products must be transported and transshipped. The interrelationships and interdependencies between products and operations and between operations mutually increase the degree of complexity of the supply chain. Based on the conceptual model in figure 1, a generic and flexible data model has been developed to store the data needed in the optimization model (De Meyer et al., 2012). This data model can be used to describe all (or most) biomass supply chains and attributes and attribute values can be easily changed, added or deleted (De Meyer et al., 2012). To define the B4B chain to be optimized, users identify the considered product and operation types.

Once the product system has been defined the required data are collected inventorying energy inputs, costs and emissions to the environment for all processes involved in the life cycle (Davis et al., 2009). As such, each product and operation type in the database is characterised by attributes related to energy use, economic cost and GHG emissions (indicated by the Global Warming Potential (GWP) calculated with IPCC’s Fourth Assessment Report’s factor for 100 years). These attributes determine the cumulative energy output, the cumulative economic profit and the cumulative GWP of the complete supply chain. Data collection and assumptions are based on databases such as ecoinvent® (Ecoinvent Centre, 2007), as well as peer-reviewed literature and expert opinions.

Mathematical optimization model

Based on the product and operation types and the attribute values defined in the LCI (and stored in the database), the mathematical model optimizes the strategic design of the complete upstream segment of the bioenergy supply chain (Figure 1). The upstream segment covers the operations from biomass production to conversion, while the midstream segment considers the conversion process itself and the downstream segment encompasses storage of bioenergy and distribution to customers (An et al., 2011).

Figure 1 Conceptual model representing the sequence of operations in the biomass supply chain (a box corresponds with the operation and an arrow indicates the product flow between operations) (De Meyer et al., 2013)



In this context, optimization of the upstream segment refers to the simultaneous selection of (1) the optimal location, technology and capacity of storage, pre-treatment and conversion facilities and (2) the optimal path and transport mode to allocate raw biomass materials, intermediate products and by-products from production sites to operation sites and between operation sites (De Meyer et al., 2013).

The mathematical model defines the optimal design according to one out of three objectives; i.e. an economic objective, an energetic objective and an environmental objective. These objectives are determined as the cumulative annualized energy output, cumulative annualized profit and annualized cumulative GWP and are calculated based on the results of the LCI. The economic and energetic objectives are similar in which the "gain" depends on the amount of energy produced by the conversion facilities and the "loss" is defined by the required inputs for handling and transporting products and managing operation sites and equipment. The annualized cumulative GWP only considers the emissions during handling and transporting the biomass and management of storage and conversion sites.

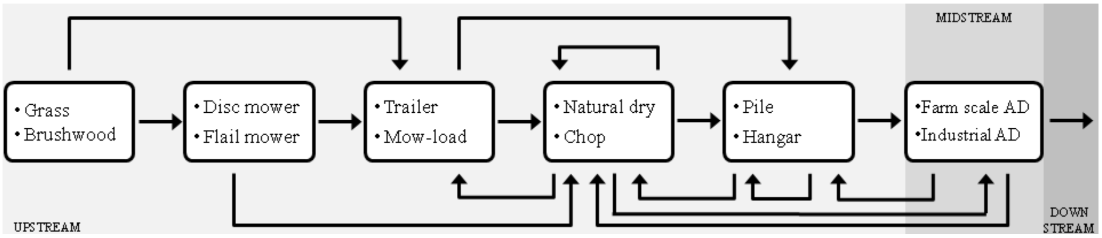
The model is designed as a transshipment problem in which biomass production sites correspond to supply nodes allowing harvest, collection and pre-treatment operations (Winston, 2003). The storage sites are the transshipment nodes to store (and potentially pre-treat) raw biomass materials, intermediate products and/or by-products. Conversion sites match with demand nodes hosting pre-treatment, storage and conversion operations. In addition, by-products (e.g. digestate) can re-enter the supply chain for subsequent conversion to bio-energy or for alternative use (e.g. soil fertilizer). Between nodes product flow and transportation occurs.

The mathematical model is developed as a mixed integer linear programming (MILP) model in which binary and integer variables determine whether or not a storage or conversion facility with specified type and capacity is open at a location, and whether or not a harvest, collection or pre-treatment operation is performed at the biomass production site, a storage site and/or a conversion site. Continuous variables define the product flows between the different sites and operations. A variety of constraints defines the supply chain restrictions (e.g. mass balances, capacity of equipment and facilities) and the interrelationships and interdependencies between operations. An extended description of the MILP model is given in De Meyer et al. (2013).

Limburg case study

To illustrate the possibilities and functionalities of the presented approach, the optimal strategic design is determined for a B4B supply chain in which the biomass is derived from low input high diversity (LIHD) biomass systems in the Belgian province Limburg (2422 km²). In LIHD systems (e.g. (semi-) natural grasslands, heathlands) regular mowing with removal of clippings is vital to maintain or enlarge the nature value (Bervoets, 2008). Increasing attention goes to the possibility to use LIHD biomass to meet the increasing demand of (bio-)energy (Bervoets, 2008).

Figure 2 The product and operation types defining the B4B supply chain to be optimized in this use case (AD = anaerobic digester)



Life cycle inventory

First, all product and operation types are characterised in a cradle-to-gate inventory to define the B4B supply chain to be optimized (Figure 2). Two product types, i.e. grass and brushwood, are distinguished. The location of the biomass production sites is derived from a biological value map (Vriens et al., 2011) by selecting the sites with grass or brushwood of at least 50 ha (Figure 3). This results in 46 biomass production sites (36167 ha of grass and 2536 ha of brushwood). Thirteen storage sites (piles or hangars) are considered which are located near a highway access point, at an intersection where transshipment between tractor and truck is required to allow further transport or near areas where several biomass production sites are gathered (Figure 3). The four anaerobic digesters registered by the Flemish compost organization (VLACO) are selected. The industrial anaerobic digester (IAD) is located in the north-east of Limburg, while the three farm scale anaerobic digesters (FAD) are more scattered over the area (Figure 3). The values of the attributes are adopted or derived from a variety of scientific publications (o.a. Bervoets, 2008; Suurs et al., 2002), LCA databases and energy statistics (Appendix 1).

Figure 3 Biomass supply network in Limburg province (without Voeren) as analyzed in the use case (Vriens et al., 2011, Vlaco, 2011, TeleAtlas BV, 2003) (adopted from De Meyer et al., 2013)

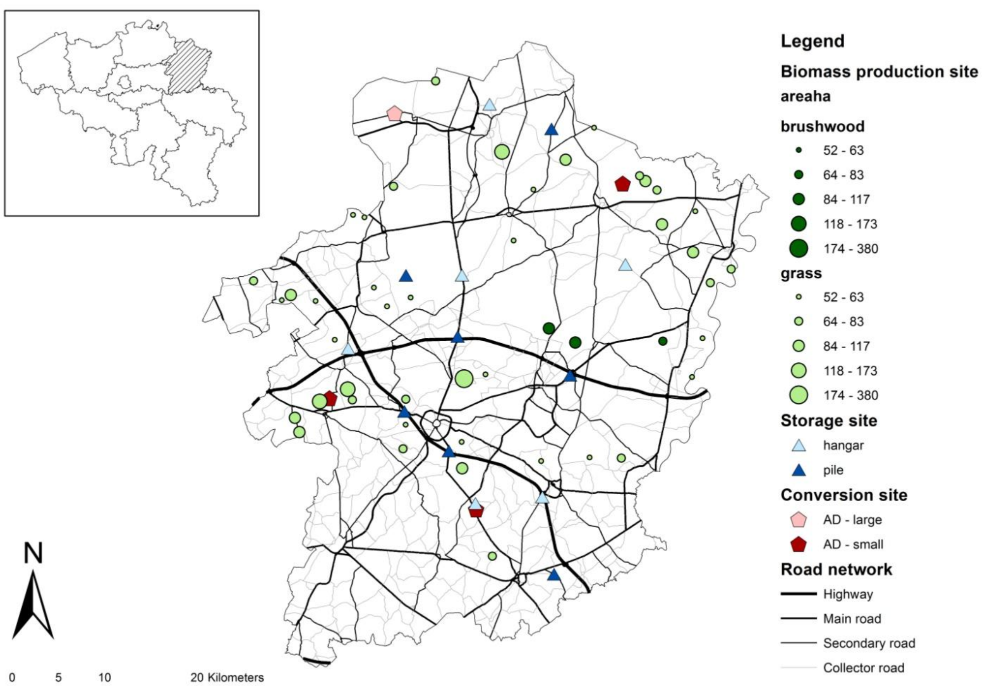
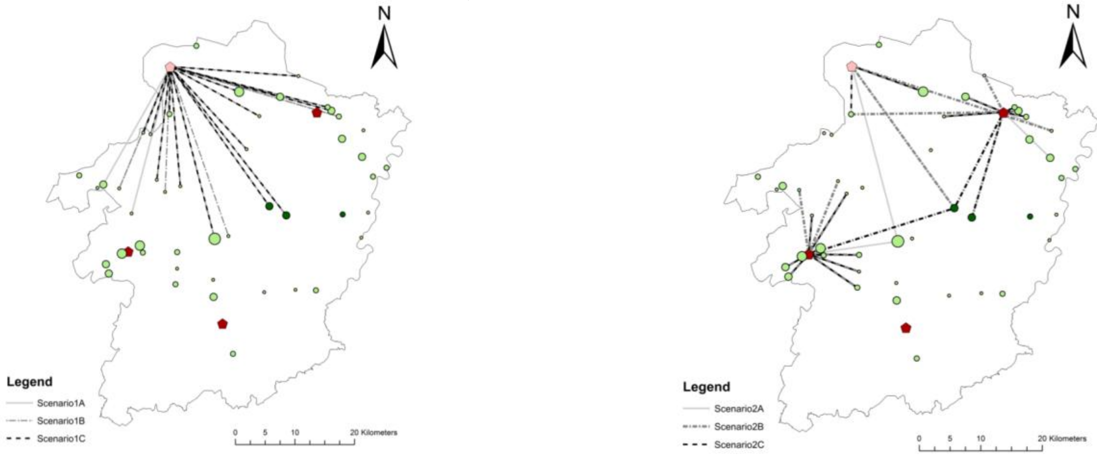


Figure 4 Visualization of the location – allocation result of scenario 1 and scenario 2 (adopted from De Meyer et al., 2013)



Mathematical optimization model

Two scenarios are analyzed to investigate the differences in strategic design due to centralized (scenario 1) and distributed (scenario 2) production of bioenergy. Scenario 1 optimizes the design accounting the attribute values summarized in appendix 1 considering one IAD and three FAD. In scenario 2 all four conversion facilities are transformed to a FAD with an electric capacity of 8000 MWh. This is expected to force the mathematical model to consider a distributed production of bioenergy.

Each scenario is optimized according to the 3 objectives; i.e. maximal energy output (A), maximal profit (B) and minimal GWP (C). Since Belgium is obliged to produce 13% of its final energy consumption from renewable (according to the EU Renewable Energy Directive) and biogas comprises 8% of the produced renewable energy (www.energiesparen.be) this scenario analysis assumes that at least 7536 MWh of heat (~27130 GJ) and at least 15137 MWh of electricity (~54493 GJ) are retrieved from biomass. The results of the scenario analysis are summarized in table 1 and visualized in figure 4.

Table 1 Summary of the results of the scenario analysis (cfr. De Meyer et al., 2013)

	SCENARIO 1			SCENARIO 2		
	Energy (A)	Profit (B)	GWP (C)	Energy (A)	Profit (B)	GWP (C)
Total E_{out} (GJ y^{-1})	**117049**	111624	106307	**118407**	112284	108885
E generated (GJ y^{-1})	140868	140868	129062	140269	140269	129821
E used (GJ y^{-1})	23819	29244	22755	21862	27985	20936
Total profit (€ y^{-1})	6022147	**6047466**	5485617	6200654	**6259865**	5720363
Total income (€ y^{-1})	6920412	6920412	6340401	6888077	6888077	6375026
Total cost (€ y^{-1})	898265	872946	854784	687423	628212	654663
Total GWP (kg CO_2 eq y^{-1})	1878906	1957138	**1866087**	1438876	1531820	**1429287**
Biomass	BW: 2 GR: 17	BW: 2 GR: 17	BW: 2 GR: 13	BW: 2 GR: 19	BW: 2 GR: 20	BW: 2 GR: 17
Storage	0	0	0	0	0	0
Conversion	1 IAD	1 IAD	1 IAD	3 FAD	3 FAD	3 FAD
Harvest	Flail	BW: flail GR: disc	Flail	Flail	BW: flail GR: disc	Flail
Collection	Mow-load	BR: Mow-load GR: trailer	Mow-load	Mow-load	BR: Mow-load GR: trailer	Mow-load
Pre-treatment	Chop at CL	BR: chop at BPS GR: chop at CL	Chop at CL	Chop at CL	BR: chop at BPS GR: chop at CL	Chop at CL
Transport	Truck	Tractor Truck	Truck	Truck	Tractor Truck	Truck
Calculation time (s)	48	21	19	366	24	12

Because the capacity of the IAD easily meets the assumed heat and electricity demand, in scenario 1 all biomass is centralized and transported to the IAD (Figure 4). The selection of the IAD is also influenced by the constraints defining the required moisture content of the biomass mixture in the digester. The IAD allows a maximum moisture content of 80% which has the advantage that no additional drying of biomass is required. This contrasts with the FAD, which requires additional drying operations to meet the maximum moisture content of 65%. The additional drying can result in other harvest, collection and pre-treatment operations and perhaps additional storage operations. These extra operations bring along additional energy inputs, costs and emissions. Furthermore, the allocation pattern differs depending on the objective to be optimized, mainly due to the differences between the effects of the transport attribute values (energy input, cost and GWP).

Scenario 2 shows that three out of four FAD are included in the supply chain to meet the heat and electricity demand. In comparison to scenario 1, more biomass production sites are harvested to meet the required minimum biomass input at each facility. As in scenario 1, the harvested biomass production sites are located in the vicinity of the selected conversion facilities (Figure 4). In some cases, the biomass from one site is allocated to several conversion facilities. In the case of brushwood, the biomass is usually divided over several conversion facilities to reduce the moisture content of the digested biomass mixture. In comparison with scenario 1, scenario 2 results in a higher cumulative energy output, a higher cumulative profit and a lower GWP. This likely owes to the decentralized conversion of biomass, which reduces the transport distances resulting in lower amount of energy consumed, money spent and GHG emitted (Table 1).

In both scenarios storage facilities are not included in the design strategy. This is mainly due to the extra cost to manage the storage site to be higher than the cost to transport the products directly to the conversion facility, related to the relatively small scale of the use case. Furthermore, the energetic and environmental objectives result in the same supply operations, while the economic objective distinguishes operations for grass and operations for brushwood. In addition to the difference in transport type, the different harvesting, collection and pre-treatment operations explain that the cumulative energy output and cumulative profit in the solutions of objectives A and B differ while the amount of energy and income generated by the conversion facilities are equal (Table 1).

Discussion and conclusion

To support the selection of the optimal combination of product and operation types among many alternatives, this paper combines a mathematical model that optimizes strategic decisions in the (future) B4B supply chain with life cycle impact assessment and GIS.

To illustrate the approach, two scenarios are analyzed to optimize a simplified B4B supply chain of LIHD biomass.

Since the attribute values adopted or derived from literature resources are often burdened by uncertainties, the results indicate a direction of change between scenarios, rather than presenting exact values. The main critical point in the implementation of this approach is the difficulty to identify reliable quantitative values for the various model attributes in the LCI analysis. Therefore, progress in other fields of research in order to provide more reliable quantitative information is a critical factor in the performance and the applicability of the presented model in real situations.

The scenario analysis and the experiences with this methodology indicate that the mathematical model can be applied to determine the most optimal biomass-for-bioenergy supply chain considering a range of alternative product and operation types. It indicates that the model is an inspiring tool to investigate the consequences of policy decisions and investment options, such as introducing new biomass materials or additional conversion facilities.

In addition, the model can be calibrated so as to meet determined biofuel environmental certification goals. It can also be improved by including further information on the life cycle of biomass, such as land use and land use change which remain on the forefront of the debate on sustainable bioenergy. Furthermore, the mathematical model can be elaborated to combine multiple objectives simultaneously in the optimization process incorporating all elements of sustainability. Indeed, the combination of mathematical optimization with life cycle impact assessment and GIS opens up possibilities for not only low-impact supply chain design but also low-land use change-related impact biofuel design. This is an important feature on the onset of measures such as the certification for Low Indirect Impact Biofuels.

Acknowledgements

Annelies de Meyer's research is funded by a Ph.D. grant of the Agency for Innovation by Science and Technology (IWT) in Flanders, Belgium.

Joana Almeida holds a Ph.D. grant from the Portuguese Foundation for Science and Technology (FCT).

References

An H., Wilhelm W.E., Searcy S.W. (2011): Biofuel and petroleum-based fuel supply chain research: A literature review. Biomass and Bioenergy, 35(9), pp. 3763-3774.

Bervoets K. (2008): Nieuwe perspectieven voor beheerresten. Natuurpunt & Vlaamse Overheid.

Bravo M.D.L, Naim M.M., Potter A. (2012): Key issues of the upstream segment of biofuels supply chain: a qualitative analysis. Logistics Research, 5(1–2), pp. 21–31.

Cherubini F., Strømman A.H. (2011): Life cycle assessment of bioenergy systems: state of the art and future challenges. Bioresource technology, 102(2), pp. 437–51

Davis S.C., Anderson-Teixeira K.J., DeLucia E.H. (2009): Life-cycle analysis and the ecology of biofuels. Trends in Plant Science, 14(3), pp. 140 – 146.

De Meyer A., Cattrysse D., Rasinmäki J., Van Orshoven J. (in review): Optimisation methods for the design and logistics of biomass-for-bioenergy supply chains: A literature review. Renewable and Sustainable Energy Reviews.

De Meyer A., Cattrysse D., Snoeck M., Van Orshoven J. (2012): Generic data model to represent the biomass-to-bioenergy supply chain logistics. Proceedings of the International Conference of Agricultural Engineering. Valencia, Spain, July 8-12 2012.

De Meyer A., Cattrysse D., Van Orshoven J. (2013): A mixed integer linear programming model for the strategic optimisation of biomass-for-bioenergy supply chains. Proceedings of the 21th European Biomass Conference & Exhibition. Copenhagen, Denmark, June 3-7 2013.

Ecoinvent Centre (2007): ecoinvent data v2.0. ecoinvent reports No. 1-25. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland. Retrieved from: www.ecoinvent.org.

EIA (2011): International Energy Outlook 2011. U.S. Energy Information Administration.

Godard C., Boissy J., Gabrielli B. (2013): Life-cycle assessment of local feedstock supply scenarios to compare candidate biomass sources. GCB Bioenergy, 5, pp. 16 – 29.

Gold S., Seuring S. (2011): Supply chain and logistics issues of bio-energy production. Journal of Cleaner Production, 19(1), pp. 32–42.

Halog A., Bortsie-Aryee N.A. (2013): The Need for Integrated Life Cycle Sustainability Analysis of Biofuel Supply Chains. In Z. Fang (eds.): Biofuels – Economy, Environment and Sustainability. InTech, pp. 197 – 216.

IPCC (2011): IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom.

Rentizelas A.A., Tolis A.J., Tatsiopoulos I.P. (2009): Logistics issues of biomass: The storage problem and the multi-biomass supply chain. Renewable and Sustainable Energy Reviews, 13(4), pp. 887–894.

Suurs R., Faaij A., Hamelinck C., Börjesson P., Nilsson L. (2002): Long distance bioenergy logistics. An assessment of costs and energy consumption for various biomass energy transport chains. Report NWS-E-2002-01. Utrecht University, Department of Science, Technology and Society.

Tele Atlas BV (2003): Skeletbestand (MultiNet) vector 2003.3. ’s-Hertogenbosch, the Netherlands.

VLACO (2001): Data - Overzicht vergunde capaciteit 2011 (.xls). Mechelen, Belgium.

Vriens L., Bosch H., De Knijf G., De Saeger S., Guelinckx R., Oosterlynck P., Van Hove M., Paelinckx D. (2011): De Biologische Waarderingskaart. Biotopen en hun verspreiding in Vlaanderen en het Brussels Hoofdstedelijk Gewest. Instituut voor Natuur- en Bosonderzoek, Brussel, Belgium.

Wee H.M, Yang W.H., Chou C.W., Padilan M.V. (2012): Renewable energy supply chains, performance, application barriers, and strategies for further development. Renewable and Sustainable Energy Reviews, 16(8), pp. 5451–5465.

Winston W.L. (2003): Operations Research: Applications and Algorithms (4th edition). Stamford, Cengage Learning, Inc.

Appendix 1

Attribute values characterizing the raw biomass types

		Grass	Brushwood
MC	(%)	75	45
LHV	($MWh\ Mg^{-1}$)	0.811	0.687
HBP	($Mg\ ha^{-1}\ y^{-1}$)	2.1	3.5

Attribute values characterizing the harvesting types

		Disc mower	Flail mower
CAP^h_{max}	($m^3\ y^{-1}$)	11 000	15 000
v^h	($km\ h^{-1}$)	8	11
w^h	(m)	2.82	1.80
E^h	($GJ\ h^{-1}$)	0.103	0.142
P^h	(€ h^{-1})	30	35
GHG^h	($kg\ CO_2\ eq\ h^{-1}$)	8.88	12.21

Attribute values characterizing the collection types

		Trailer	Mow-load
CAP^g_{max}	($m^3\ y^{-1}$)	18 000	15 000
Product loss	(%)	5	1
E^g	($GJ\ Mg^{-1}\ km^{-1}$)	4.29	0
P^g	(€ $Mg^{-1}\ km^{-1}$)	0.47	0
GHG^g	($kg\ CO_2\ eq\ Mg^{-1}\ km^{-1}$)	0.303	0

Attribute values characterizing the storage types

		Pile	Hangar
Product loss	(%)	15	2
E^s_{man}	($GJ\ m^{-3}$)	0.00	0.28
P^s_{man}	(€ m^{-3})	0.50	1.95
GHG^s_{man}	($kg\ CO_2\ eq\ m^{-3}$)	0.20	1.82

Attribute values characterizing the conversion types

		Farm scale	Industrial scale
Thermal capacity	(MWh_{th})	28 800	51 686
Electric capacity	(MWh_e)	24 000	43 072
Thermal efficiency	(%)	47	52
Electric efficiency	(%)	34	38
Min particle size	(mm)	1	1
Max particle size	(mm)	3	3
Min moisture content	(%)	50	60
Max moisture content	(%)	65	80
Min product input	($Mg\ y^{-1}$)	19 000	115 000
Max product input	($Mg\ y^{-1}$)	24 000	150 000

Attribute values characterizing pre-treatment types

		Natural dry	Chop
Product loss	(%)	5	0
E^c_{man}	($GJ\ Mg^{-1}$)	0	0.18
P^c_{man}	(€ Mg^{-1})	0.5	4.00
GHG^c_{man}	($kg\ CO_2\ eq\ Mg^{-1}$)	0.05	0.55

Attribute values characterizing the harvested, intermediate products and by-products

	MC (%)	LHV ($MWh\ Mg^{-1}$)	BD ($Mg\ m^{-3}$)	BP ($Nm^3\ Mg^{-1}$)	PS (mm)
Disc GR	75	0.811	0.08	180	150
Flail GR	75	0.811	0.11	180	50
Flail BW	45	0.687	0.13	340	50
Dry GR (disc)	55	2.003	0.06	155	150
Dry GR (flail)	55	2.003	0.09	155	50
Dry BW	25	3.416	0.11	300	50
Chop GR	75	0.811	0.18	180	1.5
Chop BW	75	0.687	0.22	340	1.5
Dry chop GR	55	2.003	0.15	155	1.5
Dry chop BW	25	3.416	0.18	300	1.5
Digestate	90	-	1.00	-	3
Dry digestate	40	1.111	1.10	-	3

Abbreviations:
MC = moisture content
LHV = lower heating value
BD = bulk density
BP = biogas production
PS = particle size
GR = grass
BW = brushwood
E = energy use
P = economic cost
GHG = greenhouse gas emission
CAP = capacity