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A framework with an integrated computer support tool to assess regional biomass delivery chains

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Abstract In this paper, we first provide a brief overview of other decision support tools for bioenergy and assess to which extent the integrated tool central in this paper is different and novel. Next, a description is given of the tool, the different models used and the functionalities. The working of the tool is then illustrated with three case studies based in the northern part of The Netherlands. The computerised tool is meant to support the communication process between stakeholders to come to the implementation of regional biomass delivery chains. It helps to create a quick and common understanding of optimal biomass use in a region. Although the tool has been applied only to bioenergy chains, other biochemical and biomaterial chains are also suitable to be incorporated. The three case studies presented include a conventional sugar beet bioethanol production chain, an advanced *Miscanthus* bioethanol conversion chain and a straw-based electricity chain. The main conclusions are that optimal biomass use for non-food purposes from a sustainability and resource-efficient perspective depend on many different factors specific to the conversion chains. For example, the green house gas (GHG) emission and mitigation potential of a sugar beet-based bioethanol chain requires careful organisation particularly on the primary biomass production and transport, while in a straw-based electricity chain, the largest efficiency gains can be reached in the conversion part. Land use change (LUC) to sugar beet generally causes more negative environmental impacts than LUC to *Miscanthus*. This applies to both GHG efficiency, soil organic carbon content and emissions of nitrogen to surface waters. At the same time, it becomes clear that the different scenario assumptions can be very influential, particularly on the final economic performance of a chain. Overall, it is clear from the cases that the users understand much better under which circumstances and through which mechanisms the designed chains can become profitable and can become more environmentally sustainable.

Keywords Biomass delivery chains · Sustainability · Resource efficiency

Introduction

The use of renewable energy sources may help to reduce greenhouse gas emissions, to mitigate climate change, to

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bring down energy import dependency, and provide additional employment and income opportunities. These factors have all contributed to the setting of general binding targets for renewable energy as specified in the 'Directive on the promotion of energies from renewable sources' (Directive 2009/28/EC) as part of the EU Climate and Energy Package. At the same time, the EU's *Roadmap to a resource efficient Europe* (EC 2011) establishes resource efficiency as the guiding principle for EU policies in all sectors. Enhancing resource efficiency means 'findings ways to achieve more at lower costs to the environment and reducing the amount of resources used to meet our needs and reducing the environmental impacts—on water, air, soil and biodiversity' (EEA 2013). For biomass use for non-food purposes, particularly for bioenergy, this implies that optimal understanding of resource-efficient use of biomass needs to be created before regional biomass chains can be established. Furthermore, it also implies that biomass use for energy is not the only pathway to consider. Uses of biomass in biorefinery applications in which several products for the biobased economy are produced including bioenergy and biofuels but also new biomaterials and biochemicals should be encouraged.

The EurObserv'ER (2011) figures illustrate impressive growth rates across the three bioenergy sectors in recent years. In spite of this growth, these figures must be considered against the relatively low bioenergy shares in most EU27 member states. One can clearly question whether these growth rates will be sufficient to reach the 2020 RED targets. On the other hand, there is still a very large untapped indigenous biomass potential. Recent results from the Biomass Futures project (2012) show that the EU biomass potential ranges between 375 and 429 MTOE depending on the sustainability criteria applied. This could in theory cover at least 2.5 times the amount of biomass that is needed to realize the total bioenergy demand as set in the NREAPs for 2020. However, in the demand analysis performed in Biomass Futures project with the RESolve model (Lensink and Londo 2009), it is predicted that only a part (37 %) of domestic biomass supply could actually be exploited by 2020. This is due primarily to lack of clearly focused policies and support measures at regional level that can promote efficient resource mobilisation. Given current incentives and wider cost-benefit ratios for bioenergy production, practically no use is made of agricultural residues (e.g. straw, cuttings and prunings, manure) nor of additionally harvestable stem wood potentials.

Most key global outlooks and scenarios expect that biomass will be an important renewable source for bioenergy, biofuels, biomaterials and biochemicals in the next 50 years (e.g. IEA BioT42 2012). The potential global supply of biomass for these purposes is very large. However, although the biomass potential is large, the bulk of this potential still awaits active development. The actual volume of biomass supply depends on and will vary with the timing in adoption of efficient agricultural management, rate of population growth and other trends. Also, land use changes (LUC), land use management and sustainable integrated biomass production for non-food purposes need to be aligned with regional conditions. Ecological and socioeconomic conditions will vary from place to place and the selection and implementation of biomass production chains (for both regional and world markets) is therefore a regional issue.

To realise the ambitious NREAP targets and a further decarbonisation of our economy requires a regional spatial planning process that includes the setting up of regional biomass delivery chains that turn potentially available biomass into actually available biomass. However, tapping into the regional potential is quite difficult because new biomass delivery chains require high investment costs, integration of activities and collaboration between different and unfamiliar stakeholders (Langeveld et al. 2010a). Furthermore, there is a risk that biomass production competes with other land use types, increasing the pressure on land and other natural resources. This could mean that its final environmental implications are more negative then positive. In addition, the spatial fragmentation of different biomass sources complicates the design and assessment of environmental implications and economic viability of new biomass delivery chains.

For The Netherlands, it has so far been proven difficult to set up biomass delivery chains, due to a variety of factors such as policy and legislative issues, availability of resources and high costs (Langeveld et al. 2010b). A recent project commissioned by the European Commission identified barriers for development of bioenergy production at European farms (Pedroli and Langeveld 2012) and showed that biomass availability was certainly not the main problem when developing bioenergy activities. Instead, the barriers reported, although very diverse per region, were high investment costs, low profitability, uncertainty about profitability, and long and complicated procedures to get access to subsidies and/or permits. Such types of barriers could be taken away if the stakeholders involved get a better understanding of the alternative options for biomass delivery chains particularly on their economic and environmental performance. The framework with the tool presented in this paper can provide this understanding and can therefore support the sustainable mobilisation of biomass use for non-food purposes at regional scales. With the tool, stakeholders will obtain a joint understanding of the environmental and economic performance of different biomass chains designed by themselves.

In this paper, we first provide a brief overview of other decision support tools for bioenergy and assess to which

Table 1 Titles, weblinks and main characteristics of other decision support tools for bioenergy chain evaluation

System + weblink	Description	Aspects of chain covered by tool	Type of user interaction	Developed by
Biobased Economy Route Kaart: http://www.biobasedeconomy.nl/routekaart/	Tool gives overview of chains that make up the Biobased Economy. It gives an attractive and informative visual overview of all the chain nodes and technological processes involved	Visualises a nodal network including pre-treatment, conversion routes, intermediate and final products produced. For sll technological aspects, there is also explanatory description	Web-based public tool: Informative and attractively presented, no possibility to design own chain.	Droge and Drimmelen, Schwandt Infographics and Food and Biobased Research-Wageningen UR
BIORAICE tool: http://bioraise.ciemat.es/bioraise/intro.aspx	Provides a calculation of biomass resource availability (agricultural and forestry primary, secondary and tertiary resources) for Spain, Portugal, France, Italy and Greece	The up-stream part of the chain is covered in terms of estimates of available biomass and costs	User can choose a location on the map and a distance from a certain point (or within a certain predefined region) and tool calculates for that combination the biomass availability and costs of bringing the biomass to a central point	CIEMAT, CEDER, BIOMA, SUDOE, Spanish Ministry of Economy. Application developed by: Tercera Fase Software, S.L.U
Biograce tool: www.biograce.net	The biofuel greenhouse gas emission calculation tool. Calculation based on the methodology in Annex V of the Renewable Energy Directive (RED) (2009/28/EC)	The tools allows to: use individual input numbers, calculates direct emissions including N_2O field emissions, emission savings, improved agricultural management mitigation gains. 22 default biofuel pathways included in the tool	Users can use the Biograce tool to calculate their own GHG emission. The user can define own standard values, add process steps and set up new biofuel production chains	Agentschap NL, ADEME, BIOENERGY 2020 + GmbH, BIO Intelligence Service, EXERGIA, IFEU, CIEMAT, STEM, LBST. The project was financed by Intelligent Energy Europe
Waste to Biogas Tool: http://epamap21.epa.gov/biogas/index.html	This tool is an interactive map with overview of organic waste producers	Covers the producers of biogas and the potential end-users in terms of address, type of activity	A user can enter an address or city (in the USA) and select search criteria. Search can also be reversed so that producers of biogas can search end-users	U.S. EPA Pacific Southwest Region
Interactive map of biomass conversion plants in the USA: http://maps.nrel.gov/transatlas	The map gives overview of location of different bioenergy conversion plants	Location and type of renewable energy conversion installations in USA	The user can choose the types of renewable production facilities to see on the map. By clicking on a location, an overview is provided of the number and type of other conversion installations in near distance	National renewable Energy Authority USA
BioSAT tool: http://biosat.utk.tennessee.edu/BioSAT/index.html	Web-based economic decision-making framework for agricultural and forestry biomass. Provides supply chain cost and logistics for cellulosic biomass markets and products. It covers part of the USA	Biomass availability (agricultural and forest biomass), costs including for logistics	User can get overview for preselected area and biomass type what supply options and costs are and what opportunities/constraints exist for mobilising the biomass	Center; The University of Tennessee; North Carolina State University; Oak Ridge National Laboratory; U.S. Department of Energy; U.S. Department of Transportation; and U.S. Endowment for Forestry and Communities
Biomass Geo-Wiki: biomass.geo-wiki.org	A Platform built on Google maps to visualise, analyse and further improve environmental data sets in terms of biomass availability	Only the biomass availability is in the tool. The tool cover the whole world	Users are provided with an instant global overview of available datasets, overlaid on the Google Earth platform to obtain a quantified overview of terrestrial biomass availability in uniform units. Users can also upload own data	GEO-WIKI TEAM consists of IIASA, University of Applied Sciences Wiener Neustadt and University of Freiburg

Table 1 continued

System + weblink	Description	Aspects of chain covered by tool	Type of user interaction	Developed by
BeWhere: http://www.iiasa.ac.at/web/home/research/modelsData/Bewhere/BEWHEREl.en.html	Techno-economic model that optimises the location of bioenergy production plants based on the minimisation of costs and emissions of supply chains. Considers already existing production plants, and if feedstock availability and cost allows, new production plants can be set up	Location and type of existing and new renewable energy conversion installations, total bioenergy mix, related costs and GHG emissions and mitigations	Delivers users the number and location of new production plants, the optimal technology selected, costs of each segment of the supply chain, bioenergy potentials, avoided emissions at the regional, national or EU level	IIASA

extent the integrated tool central in this paper is different and novel. In 'Approach, methods and models' section, a description is given of the tool, the different models used and the functionalities. The functioning of the tool is then illustrated in 'Case studies' section with 3 case studies. The paper ends with main conclusions and a discussion.

Existing models and decision support tools to facilitate the use of biomass

Many tools exist to help decision-making in complex and often contrary issues. Facilitating spatial planning and decision-making can profit from the use of models and methodologies (Herwijnen et al. 2002). Weighing of non-quantifiable issues can either be done in a pragmatic way by researchers or by using procedures for participative consensus-based stakeholder decision processes (Cuppen 2010). Participative processes are receiving increasing attention, especially in issues of general interest on a higher abstraction level (such as in the development of a more carbon neutral regional economy). On a project or local level, such a methodology might be a too heavy instrument to use. Therefore, in this study, we only developed an integrated tool that provides stakeholders with objective information and understanding to use in the stakeholder decision process they are involved in. Such a more direct pragmatic methodology is easier to apply at project level.

The development of integrated (web-based) tools that facilitate the employment of biomass for bioenergy and other purposes is not new. There are several examples of such tools of which a selection is presented in Table 1. There are tools aimed at providing a better overview of where and how much biomass there is. Examples of such tools are the BIORAICE, BioSat and the Biomass GeoWiki tools (see Table 1, also for references). The first two also include economic information on the costs of the biomass. Both are rather sophisticated tools which enable the calculation of different types of biomass use from preselected points on interactive maps. The Biomass GeoWiki operates at a global scale and provides a platform to add and use data on biomass availability all over the world. The BIORAICE and BioSat tools are part of a user interface providing the user access to several other informative sources of information that go beyond biomass potential availability and which are presented in report and text format.

Another type of tool is the 'Waste to Biogas Tool' and the 'Interactive map of biomass conversion plants in the USA' (see Table 1, also for references) both developed in and for the USA territory. Both tools are aimed to support economic operators (potential investors) in finding the right locations for their installations away from competitors or to create synergies with other operators for biogas production e.g. or use of biowaste for biogas production or use of (rest)heat. A tool that goes one step further is the BeWhere tool developed by IIASA for the EU territory (see Table 1). It enables the identification of optimal locations for new installations, taking account of already existing installations. For the new installations, it helps to design the conversion pathway by optimising towards costs and GHG emissions; especially this last step is novel in comparison with the other tools discussed.

A rather unique tool is the 'Biobased Economy Route Map' (see Table 1) which is designed particularly to provide a better understanding of the different types of industries and technological aspects of biomass delivery chains that make up the biobased economy. It goes beyond energy production and is particularly aimed at production of bio-products and chemicals. The information contained in the tool is informative, and the user can decide himself which chains to view and which details to read. There is no option to assess the feasibility of such a chain in relation to biomass availability in a particular geographical location.

The Biograce tool is different in the sense that it offers a very specific support to economic operators that are involved in the development of a biofuel production chain in the EU. Biofuels delivered to the EU biofuel targets have to comply with the minimal mitigation requirements as specified in the EU Renewable Energy Directive (RED 2009/28/EC). The Biograce tool enables the user both to further design and specify a chain and to make a calculation of the full life cycle emission of green house gas (GHG) in their biofuel chain.

From this overview, we conclude that most tools provide understanding and support in setting up biomass delivery chains by addressing and facilitating only one or a few of the many aspects that need to be taken into account when setting up a biomass delivery chain. The aspects covered can be biomass availability, presence of existing installations in order to find locations where there is room for new developments, technological characteristics of conversion pathways or GHG emissions for the whole biomass delivery chain. Support of both i) the design of a biomass delivery chain and ii) the assessment of the biomass delivery chain impacts in terms of environmental and economic implications is not yet integrated in most tools. The only tool that facilitates design taking account of cost and GHG impacts is the BeWhere tool. In that respect, BeWhere and the tool presented in this paper are rather similar. However, the tool in this paper provides more possibilities for impact assessment particularly in relation to environmental impacts taking account of detailed land use changes and GHG emissions. Overall, it can be concluded that the integrated biomass chain design and evaluation tool presented in this paper is unique. At the same time, we also see that focus on only one aspect of the biomass delivery chain also enables a more sophisticated analysis of this single aspect. In this respect, it can be concluded that the integration of different already existent tools in one framework would be very useful. A first step towards integration of different tools and models within a framework was exactly the goal when developing the tool presented in this paper.

Table 2 Overview of indicators (parameters) for logistical and economic performance of the chain

Data group	Parameter
Output simple chain calculation	Calculation number
	Biomass chain name
	Scenario name
	Scenario policy variant
	Scenario year
Total throughput [ton dm]	From sources
Revenues and costs [euro]	Heat revenues
	Electricity revenues
	Purchase costs
	Storage costs
	Transport costs
	Loading/unloading costs
	Pre-treatment costs
	Drying costs
	Conversion costs
Energy returns and use[GJ]	Heat returns
	Electricity returns
	Energy used for purchase
	Energy used for storage
	Energy used for transport
	Energy used for loading/unloading
	Energy used for pre-treatment
	Energy used for drying
	Energy used for conversion
GreenHouse Gas avoided and emission [ton CO_2-equivalents]	Heat GHG avoided
	Electricity GHG avoided
	GHG emission for purchase
	GHG emission for storage
	GHG emission for transport
	GHG emission for loading/unload ing
	GHG emission for pre-treatment
	GHG emission for drying
	GHG emission for conversion

Approach, methods and models

The developed framework with the support tool allows for design and assessment of economic and environmental performance of a biomass delivery chain. Design steps include selection of a predefined future scenario, chain type and biomass type, and a location for the conversion installation. The tool in the framework computes where the required amount of biomass for the specified biomass chain is to be harvested (in a circle around the chosen location) and calculates the costs of the required biomass, taking account of transport needs. Next, the costs and revenues of the biomass end product are computed, as well as the avoided and used amount of energy, and greenhouse gas (GHG) of the chain (see Table 2). If the specified biomass delivery chain is based on locally produced crops, it implies that the current land use will be changed as existing crops maybe partly replaced by (other) biomass crops. The impacts on the environment due to this land use change are computed as well. The results may vary per scenario, due to differences in input parameters for economic, technical and policy conditions. Although predefined scenario parameters are provided for 2020 and 2030, they can be changed by the user. In this study, only the impacts in 2020 are presented and impacts assessed by comparing against the situation in 2010 (Fig. 3).

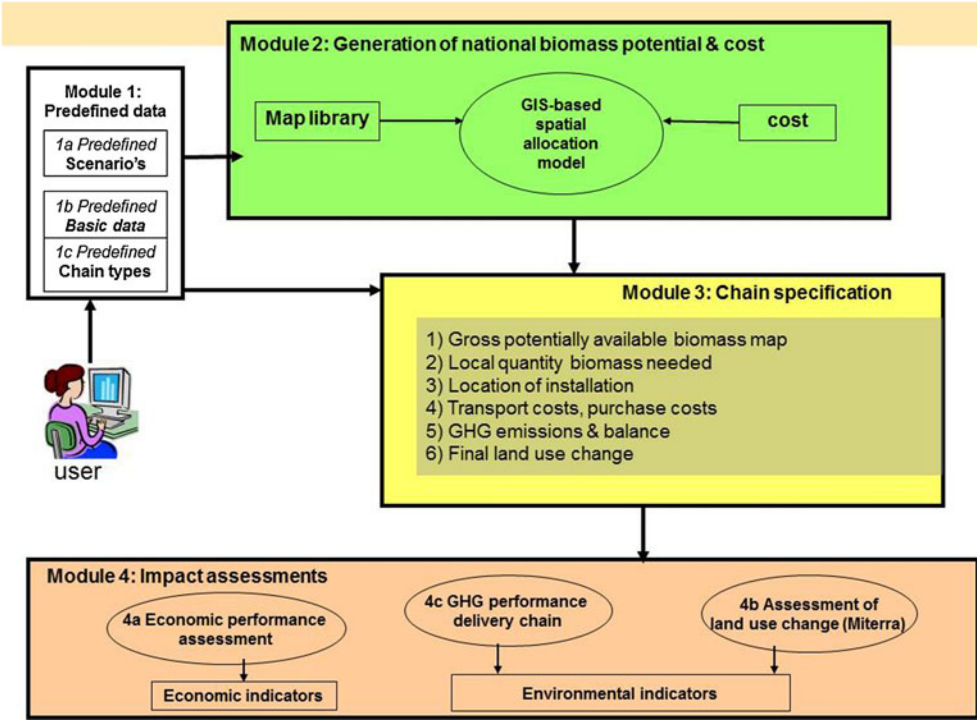
A schematic overview of the framework is given in Figure 1. The framework consists of four main modules which are further explained in the next.

Pre-defined data

In Module 1 (*Predefined data*), data can either be defined by the user, or they are already predefined in the framework (for biomass chains included in the framework). These predefined data are used as a starting point for design, spatial implementation and impact assessment of the biomass chain. There are three groups of predefined data: chain type characteristics, basic data on the chain and scenario characteristics. As to the chain type characteristics, the tool offers detailed information on predefined biomass conversion technologies, size and biomass type(s) (including the parameter values that are used for the assessments).

Further specifications of the chain enable the user to select a location for power production e.g. and (optionally) locations of point-sources for biomass (like harbours) by pin-pointing the location on a map. The user can also specify the maximum production costs of the biomass to be harvested from the local area, the percentage of the potentially available harvested biomass that will be used in the conversion chain and the amount of additional biomass to be purchased from a point source (e.g. a harbour). It is also possible to select a map with areas that must be excluded from harvesting (e.g. a future expansion of a town or a nature reserve area). When the biomass chain has been specified, the user can start the calculation of costs and distances. In several iterations, the framework computes the radius required to 'harvest' the required amount of

Fig. 1 Schematic overview of tool



biomass for the selected chain within a circle around the installation and the production costs of the harvested biomass.

Scenarios

For the definition of scenario in the tool, the IPCC-SRES scenarios were used as a basis. These scenarios have already been used in several studies such as Eururalis (Eickhout et al. 2007), ATEAM (Verboom et al. 2007) and IPCC assessments (IPCC 2000). The scenarios are developed along two extreme axes.

A1 Global Economy	B1 Global Co-operation
A2 Continental Market	B2 Regional Communities

On the horizontal axes, the assumed role of government is expressed making up the extreme of high and low regulation. On the vertical axes, the scale level (global or regional) of interventions and regulations is expressed. For this study, we have chosen to work with only two of the four resulting scenarios:

1. A1. Global economy
2. B2. Regional communities

For these two scenarios, three policy variants were defined covering low, base and high policy intervention. By introducing these variants per scenario, the differences between the scenario situations are more smoothed over a full continuum. Furthermore, according to these 3 policy variants, additional policy driving forces are specified that influence the way future biomass delivery chains can be implemented in terms of obligations and restrictions.

The reason to only choose two extreme scenarios and three policy variants is that more combinations would lead to an exponential number of assessment results for bioenergy chain implementations and effects. These could not be handled by the model assessments and the end-users of the system any way.

In the Global Economy scenario (A1), market-based solutions are the most efficient way to achieve strong economic growth and optimise demand and supply of goods, services and environmental quality. This scenario is basically fitting to a free market situation. The demand for biomass remains rather modest compared to RC scenario. With regard to nature conservation and other sensitive areas, some level of protection measures remain, depending on the policy intervention variant.

The Regional Community scenario (B2) is characterised by intensive regulation and a more closed market concept with limited market influence. It assumes that self-reliance, environmental stewardship and equity are the keys to sustainable development and local communities being the cornerstones of society. These conditions are favourable for the production of biomass, but competition for land with agriculture and nature conservation is stiff. Legislation on nature conservation and other sensitive areas is generally strict but varies per policy intervention variant. The overall increases in yields are expected to be more limited, compared to GE scenario because of stricter sustainability criteria.

In relation to production of bioenergy within Europe, it means in general terms that in the Global Economy situation, it can be expected that the market dictates most strongly where biomass and bioenergy will be produced. It can thus be expected that this will mainly come from outside the EU, while in the Regional Community situation, the choice will be towards more self-sufficiency in terms of both food and energy leaving more room for domestic production of biomass and bioenergy.

The framework tool displays a description of the scenarios and allows to view the parameter values per scenario that are used in the framework tool. The user can choose the scenario and policy variant he wants to use for the assessment of the chain. The user may also choose to specify a scenario himself. This can be done by adapting (a selection of) the existing scenario parameters according to his own judgement.

Economic viability of regional biomass production: Net Present Value (NPV)

For conventional crops, e.g. wheat or maize, data on the current production quantities, cost prices and locations can be used. For future biomass crops, e.g. willow or *Miscanthus*, potential biomass maps have to be developed based on assumptions on future shifts in land use and cropping systems. For this tool, inputs are needed in terms of maps showing at the minimum future potential biomass dispersion patterns based on e.g. current land use and cost calculations. A more sophisticated approach with a Net Present Value (NPV) calculation was also tested in van der Hilst et al. (2010) as a proxy to estimating the farmer's response. The NPV represents the future income minus the cost. The NPV method enables the comparison of the value of different cash crops over a long period of time. With this method, an economic value comparison can be made between rotational arable crops which deliver a harvest one or more times a year and perennial crops which start to deliver return only after a couple of years while most cost for establishing a plantation need to be made in the first year. The time horizon of the comparison is assumed to be the same as the rotation length of the perennial crop (15–20 years). The discount rate used reflects interest rates of a combination of long- and short-term loans (Houtsma 2008).

Calculations of NPV have also been made for different scenarios (as described in the former). Several scenario-specific factors influence the cost and also the NPV of which the most important are oil price which influences the price of diesel for mechanisation but also of fertilisers. Other factors of influence are labour cost, policy interference (e.g. support) and technical development.

Based on van der Hilst et al. (2010), the current framework includes cost calculations for the most common arable rotations in The Netherlands, and for perennials like *Miscanthus* and willow for the current and the scenario situations. The cost related to crop production generally include four main categories of expenses:

- land cost;
- field operation cost (contractor, machinery, labour and diesel costs);
- input cost (seeds, fertilizers and pesticides);
- fixed cost (insurance, soil sample assessment, etc.).

The benefits of crop production are the revenue from:

- selling the main product;
- selling the co-product(s);
- Common Agricultural Policy subsidies for crop production.

For the cost and NPV calculations which are spatially explicit account is taken of detailed spatial circumstances like land use and soil suitability. The current land use and the soil suitability for both current crops and potential biomass crops are mapped using a Geographical Information System (GIS) at a resolution of 100 m. For the feedstock production and costs calculations, the soil suitability is taken into account for seven soil suitability classes (see van der Hilst et al. 2010). The link between soil suitability class and the Dutch soil map is based on the work of Brouwer and Huinink (2002) and van Bakel (2007).

Yield statistics provided by CBS/LEI (2007) and De Wolf and van der Klooster (2006) were used to make average yield estimates per soil suitability class by taking into account the relative share of soil suitability class per crop for current land use. This step results in two maps (per biomass type): (1) the yields and (2) the production cost of the potential biomass within The Netherlands. In the current framework, both maps can be used to choose a suitable location for the installation and to identify the final locations of dedicated cropping.

Generation of national biomass potential maps

The current tool within the framework is implemented in Visual Basic, using ArcInfo workstation for the execution of grid map operations (cell size 100 × 100 m, an ArcGis MapComponent to display maps) and Excel for a flexible user interface and for data exchange between the different models and components. For each biomass supply chain type, a separate Excel sheet is created that calculates the economic and environmental performance of the chain. Excel can also be used independently to view the results and to compare results of different sessions with the framework tool. The ArcMap application (ESRI) is used to store and view maps in the map table.

The support tool is fed with information from a map library with different biomass sources, cost and other data layers. These are all used to create technical–economic potential maps of biomass resources given chain and scenario specifications. In several iterations, the framework then computes what radius is feasible to ‘harvest’ the required amount of biomass for the selected supply chain around the installation and what the production costs of the harvested biomass will be. For the calculation of the transport kilometres and related costs, the average road density network factor for the north of The Netherlands is taken. When applied to more peripheral and mountainous regions, the application should take account of the real road network as many rural places in the world are not as accessible as is the case in The Netherlands.

First, the biomass quantity within a circle of 10 km around the installation is assessed, taking account of predefined maximum biomass price to be paid and the preselected share of biomass available for this chain (e.g. 10, 20 %, etc.). Based on the biomass demand of the installation and the average biomass density in the first circle, a second, third, and fourth, etc. concentric circle is constructed until sufficient biomass is found.

Logistical chain design and spatial implementation of the chain

The biomass delivery chain consists of two parts: the conversion unit and its corresponding network. The conversion unit is characterised in three dimensions: (1) economical requirements (net return), (2) required biomass type and (3) required biomass quantity. These three dimensions are quantified by several (sub)variables, e.g. type of energy produced (electricity, heat and biofuels), and other products (e.g. chemicals), conversion technology, size of the conversion unit, expected amount of imported biomass, investments costs for the conversion units and price per energy unit. The network consists of the following categories: biomass sources, collection points and conversion units (Fig. 2).

Based on a biomass supply map, a grid structure is applied to the map, where the different sources relate to a specific grid cell. For each grid cell and biomass source

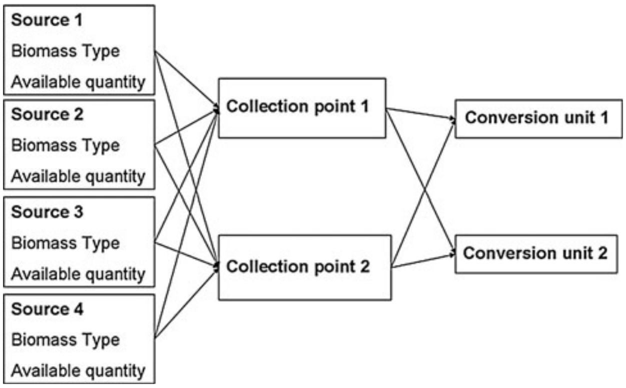


Fig. 2 Network structure showing biomass sources, collection points and conversion units

combination, the amount of biomass per biomass type, the purchase price and the distance to collection points and conversion units are generated. Pre-treatment of biomass (e.g. wood-chipping), although not incorporated in the present chains in the framework, can take place in any of the three categories.

When the feedstock extraction patterns of the conversion unit(s) are known in terms of amount and type of biomass per grid cell, the biomass allocation pattern within a grid cell has to be determined, after which the impact on environment and the cost and returns can be assessed.

Impact assessment

The interactions between a biomass delivery chain and the regional conditions have a strong influence on the actual environmental and socioeconomic performance of biomass chains. As the spatial variation of determining parameters of impacts on biomass chains is significant, impacts should preferably be assessed spatially explicitly. The GIS module in the framework provides spatially explicit information on current land uses and new land uses, resulting from a biomass chain implementation. The changes in land use and in the related management are the start of the environmental impact assessment. The cost of biomass, transport and pre-treatment and conversions cost and returns on output are the basis for the economic performance calculation.

Land-based environmental impacts

For the land-based environmental impact assessment, the MITERRA model (Lesschen et al. 2009; van der Hilst et al. 2012) is used to assess the environmental impacts of biomass production at postal zone level. MITERRA simulates the N and P balance, air emissions of ammonia (NH_3), nitrogen (N_2O, NO_X) and methane (CH_4), leaching and runoff of nitrogen (NO_3) and changes in soil and biomass carbon stocks. The main input data of the model are crop areas, livestock numbers, crop yields and fertilizer use. Crop yields were obtained at province level from The Netherlands Bureau of Statistics (CBS) ('oogstraming' data). The MITERRA model follows the methodology proposed in the IPCC (2006) guidelines to calculate GHG emissions due to the cropping of a biomass crop and the land use change (LUC)-related emissions. GHG emissions due to LUC are caused by changes in soil and biomass carbon stocks. In addition, LUC affects nitrogen (N_2O emission) due to changes in fertilizer and manure application and drainage of organic soils. N_2O soil emissions consist of direct N_2O emissions from managed soils related to different N sources (manure, grazing, mineral fertilizer, crop residues and cultivation of organic soils) and indirect N_2O emissions due to N leaching and N deposition. N leaching is calculated by multiplying the N surplus with a leaching fraction derived from Fraters et al. (2007). Soil nutrient surpluses are calculated from the total nutrient input (manure, mineral fertilizer, deposition and N fixation) minus the removal by harvested crop products.

Within the framework, the following outputs are included: GHG emission from fertilizer production, carbon emissions (CO_2) from fuel use, GHG emission from cultivation (soil N_2O emission + CO_2 from peat soils), carbon (CO_2) emission from changes in soil organic carbon (SOC), total GHG emission from agriculture (including livestock), nitrogen (N) soil surplus, phosphate (P) soil surplus, nitrogen (NO_3) concentration in leaching water, ammonia (NH_3) emission from agriculture and soil organic carbon (SOC) stock changes (upper 30 cm). For changes in SOC, the default IPCC stock change factors were applied in combination with region-specific SOC reference stocks. In line with IPCC (2006), a time horizon of 20 years is assumed to reach a new equilibrium after LUC. For further details on how these indicators are estimated, see van der Hilst et al. (2012).

The amount of fuel (diesel) used per crop is calculated based on the field operations data as used in the cost calculations ('Pre-defined data' section). The CO_2 emission is calculated by multiplying the amount of diesel by the CO_2 emission factor of 2.71 kg CO_2 per litre diesel. The average GHG emission for fertilizer production is calculated based on data of Brentrup and Pallière (2009). For the 2020 scenarios, it is assumed that the best available technique (BAT) would be standard.

For 2020, the amount of applied fertilizer is calculated according to balanced fertilisation. Balanced nitrogen fertilisation provides fertilizer and manure according to the crop nitrogen demand, after accounting for nitrogen inputs via atmospheric deposition, mineralisation and biological nitrogen (N_2) fixation. All

Table 3 Results for straw case in different combinations of scenarios, policy intervention levels and straw extraction rates

Chain	Electricity and heat—straw					
Scenarios	2010 Current situation/2020 Global Economy (GE)/2020 Regional Community (RC)					
Policy intervention	Current situation, low intervention, high intervention					
% biomass use	50 and 20 % of the total straw potential					
Scenario	Current situation	Current situation	2020 GE	2020 GE	2020 RC	2020 RC
Policy intervention	Current situation	Current situation	low	low	high	high
% biomass use	50 %	20 %	50 %	20 %	50 %	20 %
Radius around installation	19.18 km	40.64 km	16.18 km	33.94 km	17.97 km	39.16 km
Price electricity (€/GJ)	50	50	40	40	75	75
Economy (K€/jr)						
Total revenues	5,226	5,226	4,279	4,279	7,593	7,593
Total cost	4,338	4,554	4,063	4,206	5,385	5,640
Profit	888	672	215	72	2,209	1,953
Energy (MJ/jr)						
Total energy	258	258	258	258	258	258
Total energy use	15	19	15	17	15	19
Energy profit	243	239	243	241	243	239
Emissions GHG (Kton CO_2 eq.)						
GHG emissions avoided	24	24	24	24	24	24
Total GHG emissions	1	1	1	1	1	1
Net GHG avoided	23	23	23	23	23	23
% Mitigation[a]	96 %	96 %	96 %	96 %	96 %	96 %

[a] Net GHG emissions avoided as compared to fossil alternative

environmental impacts calculated in the MITERRA module are presented at an aggregate level for the whole chain but can also be presented at a spatially explicit level in maps in which comparisons can be made with the current land use situation to present the changes in emissions.

Economic and logistical performance assessment

In order to make a final evaluation of the chain performance, indicators are produced on the economic and GHG impacts of the whole chain. Beside the land-based environmental impacts, as discussed in the former section, performance of the downstream part of the chain also needs to be included in the evaluation. For this, all parameters in Table 3 are calculated which are used to assess the final performance indicators of the chains.

Case studies

Several regional biomass chains were elaborated within the project. Here, we discuss three cases of biomass chains that have been assessed for the Northern provinces of The Netherlands.

Case 1: Straw to electricity case

In an early stage of development of the framework, a case study was assessed using straw based on current land use in The Netherlands. The bioenergy chain consisted of two possible locations for a conversion unit requiring 30,000 ton dry matter (DM) to produce 110,000 GJ electricity. The optimisation target was to maximize the profit margin of the conversion unit by choosing the best location. The biomass supply map was based on the straw production of the three most dominant cereals in 2006. At the moment, straw in The Netherlands is partly harvested and sold by farmers to e.g. cattle or horse owners. It was assumed that only a part of this amount (either 20 or 50 %) would be available for bioenergy production. Based on the straw supply map, the model optimized the chain for the profit margin and generated a straw withdrawal pattern.

Withdrawal patterns are based on supply per grid cell, distance and feedstock price. The withdrawal pattern of straw for the electricity chain is fairly condensed and located in the direct vicinity of one conversion unit that was chosen by the optimisation. In competition with this conversion unit, the second conversion unit was not economically viable. The results for this chain in the different scenario situations show that in the Global Economy scenario revenues/profits of bioenergy will be lower, while in Regional Communities scenarios, these will be higher because of subsidies. Energy use will be higher when only 20 % of the straw is used as feedstock in this chain, due to longer average transport distance. This also leads to higher GHG emissions.

Case 2: Second-generation bioethanol from *Miscanthus*

The results of van der Hilst et al. (2010, 2012) obtained with parts of the framework show that the cultivation of *Miscanthus* is not competitive with current cropping systems on Dutch soils classified as 'suitable'. On less suitable soils, the return on intensively managed rotational crops is lower, and perennial crops achieve better NPVs than currently used rotational crops. The minimum feedstock production costs are 5.40 €/GJ for *Miscanthus*. Ethanol from *Miscanthus* (24.00 €/GJ) might become a cheaper option than ethanol from sugar beet (27.00 €/GJ), but the cost of bioethanol production from domestically cultivated crops is still not competitive with gasoline (12.30 €/GJ) production under current circumstances (see van der Hilst et al. 2010 for further details).

There are large spatial variations in environmental impacts of *Miscanthus* (see Fig. 3). For most impacts, *Miscanthus* can have both positive and negative effects. The GHG balance is dominated by the change in soil organic carbon (SOC), but also soil N_2O emissions are lower because of lower fertilizer inputs as compared to most rotational crops. SOC generally increases when current land uses are converted to *Miscanthus* cultivation, except for areas dominated by organic soils. On the other hand, second-generation bioethanol requires a considerable amount of chemical inputs which causes significant GHG emissions in the downstream part of the chain.

Case 3: First-generation bioethanol from sugar beet

The results of van der Hilst et al. (2010, 2012) obtained with parts of the framework show that sugar beet for ethanol cannot compete with current cropping systems in terms of return per hectare. In addition, the minimum cost of feedstock production of 9.70 €/GJ cannot complete with other domestically produced types of biomass (for example *Miscanthus*) or with biomass imported from abroad. The cost of bioethanol from sugar beet (27.00 €/GJ) is not competitive with gasoline (12.34 €/GJ) production under current circumstances.

The assessment of the environmental performance of bioenergy crops shows that there are large spatial variations in environmental impacts. Land use change (LUC) to sugar beet generally causes more negative environmental impacts than LUC to *Miscanthus*. This is especially the case for the (wet) pasture areas dominated by peat soils. The GHG balance is dominated by the change in soil organic carbon (SOC) especially when pastures are converted to sugar beet production. In addition, first-generation bioethanol requires considerable energy inputs for steam production which cause significant GHG emissions. Due to the relative high fertilizer requirements, the nitrogen (NO_3) concentration in leaching water will increase when arable land is converted to sugar beet cultivation (see Table 4).

Discussion and conclusions

The development of the framework with support tool in this project has confirmed that a lot of practical knowledge, existing models, and data can be captured in a framework enabling an integrated view on both environmental and economic performance of new biomass delivery chains. The support tool can be used in an iterative process with stakeholders and researchers. Frequent application of the framework by advisors in the design and assessment of a new biomass delivery chains can lead to a further improvement and wider applicability of the framework.

The application of the case studies showed in a comparative way the impacts of the chain in different scenario situations and at different biomass withdrawal rates. For the straw to electricity case, it became clear what the difference in profits is in a pure market situation and one with higher CO_2 credit prices and feed in tariffs.

In the *Miscanthus* and the sugar beet to ethanol cases, it is shown that *Miscanthus*-based ethanol is a cheaper option than ethanol from sugar beet. However, both are still too expensive to compete with fossil-based gasoline in the current situation and with bioethanol from abroad. As to environmental aspects, it is shown that direct impacts of a land use change from rotational crops to *Miscanthus* are generally positive both in terms of GHG emission, because of an improvement in the soil organic carbon content, and in terms of a decline in soil N_2O emissions. On the other hand, second-generation bioethanol requires a considerable amount of chemical inputs which causes significant GHG emissions in the downstream part of the chain. Land use change (LUC) to sugar beet generally causes more negative environmental impacts than LUC to *Miscanthus*. This applies to both GHG efficiency, soil organic carbon content and emissions of nitrogen to surface waters. In addition, first-generation bioethanol requires considerable energy inputs for steam production which cause significant GHG emissions which makes the downstream part of the chain of sugar beet-based ethanol even more inefficient compared to the *Miscanthus* based route.

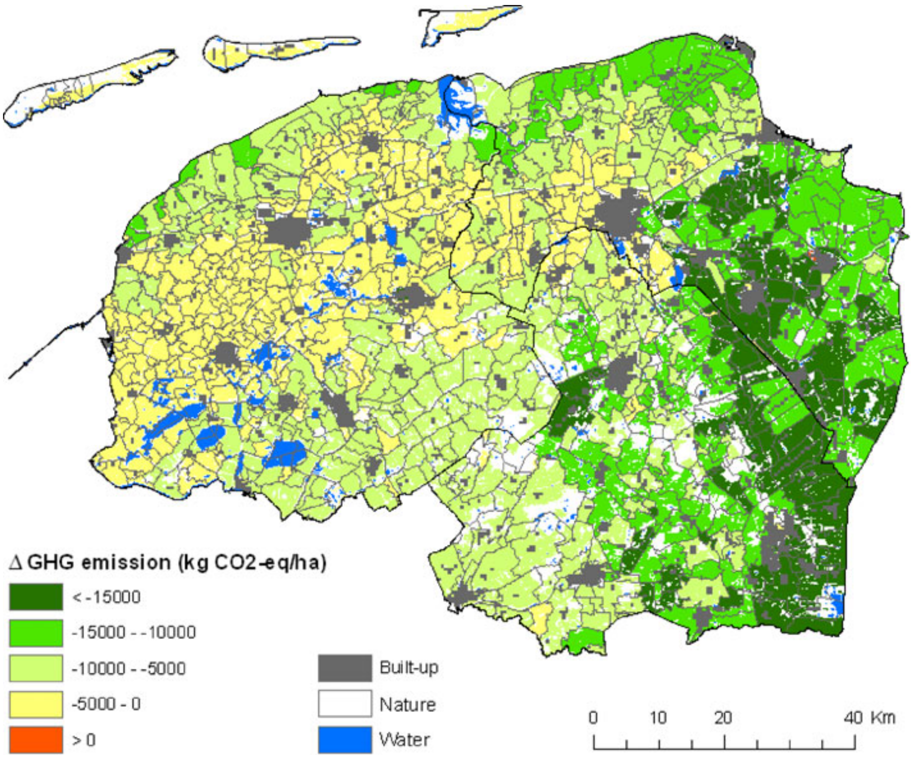


Fig. 3 Changes in GHG emissions when current land use is converted to Miscanthus

Table 4 Environmental effects of the entire sugar beet bioethanol chain

Environmental effects of total chain in ton CO_2-equivalent		
	GHG during cultivation	Totals
GHG emissions from fertiliser production	190	37,504
GHG emissions from fuel consumption for crop mechanisation	2,349	
GHG emission from cultivation (soil N_2O emission + CO_2 from peat soils)	34,965	
	GHG after cultivation	
GHG emission for storage	0	63,609
GHG emission for transport	29,566	
GHG emission for loading/unloading	87	
GHG emission for pre-treatment	0	
GHG emission for drying	0	
GHG emission for conversion	33,956	
	Total GHG emission	101,113
	Total GHG avoided	Net GHG avoided
ethanol GHG avoided	132,587	31,474
% mitigation (net GHG avoided versus total GHG avoided)		23.74 %

Other environmental indicators due to direct land use change (as compared to current land use)		
1,000 kg N	Change in nitrogen soil surplus due to land use change	−1.26
1,000 kg P	Change in phosphorus soil surplus due to land use change	0.02
1,000 kg NH_3–N	Change in ammonia emission due to land use change	0.00
1,000 kg CO_2	CO_2 emission from changes in soil carbon due to land use change	89
1,000 kg CO_2	Net difference in GHG emissions resulting from land use change	1,515

Overall it is clear from the three cases that the users understand much better under which circumstances and through which mechanisms the designed biomass chains can become profitable and can become more environmentally sustainable.

The current tool is restricted for use within The Netherlands and contains only a limited set of data, scenarios, chain types and biomass types. To use it in practical situations, it is necessary to add or change data (mostly in mapped and table format), scenarios and other chain and biomass types. This also implies that new input data such as quantity and cost maps of new biomass types will need to be produced and incorporated. Although no special knowledge is required to use the current support tool, experts on bioenergy chains and on the used software will be required to adapt the tool for use in practice.

Any additional design and impact assessment criterion and new biomass conversion technologies to be added to the framework require new knowledge (translated into formalised knowledge rules) and data to be incorporated. This can be a time-consuming process. In the current support tool, no account was taken during the allocation of a new installation of for example planning restrictions, the presence of already existing installations, presence of the (receiving) power grid and noise pollution. All these aspects could be incorporated technically, but require detailed mapped data input and additional allocation algorithms. As for the latter, it is advisable to first look at already existing applications that cover these aspects. Incorporation of other existing applications under the current framework should therefore be carefully considered and collaborations established.

The development of the framework support tool also confirmed that not all knowledge and data can be captured in a formalised framework environment. This especially applies to social criteria (Kalf 2011). However, this is not necessary as design and practical implementation of biomass delivery chains needs the involvement of many stakeholders in a wider communication process. The tool can be supportive in this interaction process with stakeholders, especially through provision of quick and better understanding of the spatial, environmental and economic consequences of a large range of choices that need to be made to come to a final chain designing and practical implementation in a region.

Overall, it can be concluded that the framework with the support tool presented here is novel in that it integrates the wide range of support and information needed when developing regional biomass delivery chains. These range from support in finding the available biomass sources, definition of the supply chain, chain design in terms of choice of biomass type, conversion technology and scale and related logistical implications and evaluation of the environmental and economic performance of the chain. No tools have been identified until now that integrate all these support functions. There is, however, large scale for collaboration with other tool developers to improve and further extent the functions of the integrated tool without re-inventing the wheel.

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