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Development of a land-use component for an integrated model of the German biogas system

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Abstract: Germany is one of the biggest producers of biogas in Europe. Biogas can either be combusted in highly efficient combined heat and power units to produce electricity and heat, or upgraded to biomethane for injection into the natural gas grid. As political conditions encourage the installation of new biogas plants, their number and capacity is expected to grow significantly in the next few years. In Germany, energy crops play an important role for biogas production. Due to their relatively low energy content transport distances from the field to the plants are a crucial issue for the efficiency of the biogas system. In order to simulate the interaction of the different processes involved in the biogas system, an integrated model has been developed at the University of Kassel. This article describes the development and testing of one of its central components: a land-use model to simulate the cultivation of crops and grassland management for biogas production under a set of different spatial constraints. First simulation experiments indicate that the model calculates plausible area demands for energy crops used for biogas production.

***Keywords**:* Biogas system, land-use, integrated modelling

1. INTRODUCTION

In Germany, the production of biogas for electricity generation has grown dramatically in the past few years. From 2004 to 2008 the overall capacity of installed biogas plants has increased almost sixfold and reached 1.435 GW_{el} while their number has doubled to more than 4.100 [Thrän et al., 2009]. This development was mainly triggered by the introduction of subsidies for using agricultural commodities as substrate for biogas production. According to Scholwin et al. [2008], 47 % of the substrates (by mass) in use are energy crops, which may account for about 78 % of the electrical energy generated by biogas. The most important energy crop is silage maize (79%), followed by grass silage (8 %), cereal silages (7 %) and grains (6 %). Other important substrates are slurry and organic wastes.

A number of factors put the use of land for production of biogas in a preferable position to biofuels such as ethanol: (1) a wide range of substrates can be used for producing biogas [Amon et al., 2007a], (2) the energy yield for biogas (from maize silage) is far greater (16.600 GJ/km²) than for ethanol from wheat (6.000 GJ/km²) or rapeseed oil (4.500 GJ/km²) [KTBL, 2006], (3) the use of the digestate as a high quality fertilizer [Amon et al., 2007b] supports the closing of the nutrient cycle in the cropping system and (4) the potential of avoiding greenhouse gas (GHG) emissions increases immensely, if slurry from livestock farming is used as coferment. Finally, biogas can either be combusted in highly efficient combined heat and power units to produce electricity and heat, or upgraded to biomethane for injection into the natural gas grid. For both conversion pathways GHG savings in the transportation sector (with optimized engines) are greater than savings using other biofuels such as bioethanol [Campbell et al., 2009].

As current political and legislative conditions in Germany encourage the installation of new biogas plants, their number and capacity is expected to grow significantly in the next years. However, competition to food crops and the use of agricultural land for nature conservation and urbanization will be limiting factors in this development. Concerns about expected

odorous emissions of biogas plants and objections against a landscape dominated by tall-growing maize crops may restrain the expansion of the biogas sector. In 2007 the area for growing renewable resources in Germany reached about 20.000 km², of which an estimated 4.000 [FNR, 2007] to 5.500 km² [Scholwin et al., 2008] produced energy crops for biogas. This accounts for 3.4 - 4.6 % of the arable land, respectively. Different studies have identified a future potential ranging from 30.000 [EEA, 2006] to 56.000 km² [Thrän et al., 2005] for renewable resources, or 25 – 47 % of the arable land, with a growing share of crops for biogas, as the currently dominating area of rapeseed for biodiesel has already reached its peak at about 10.000 km². Due to the generally low energy content of the substrates used for biogas production, transport distances are a major factor determining the profitability of a biogas plant.
The different processes involved in the generation and utilization of biogas and their linkages constitute the biogas system [Lantz et al., 2007]. In order to analyse the effectiveness and sustainability of these systems, often methods from the field of Life Cycle Analysis (LCA) are used [e.g. Börjesson and Berglund, 2007] to model the incorporated energy and material flows. This approach has two disadvantages. First, it does not account for the dynamic nature of processes and, second it only indirectly addresses the spatial distribution of the system's components. As an alternative proposal the prototype of a dynamic spatially explicit model of the German biogas system has been developed at the University of Kassel. This article describes the development of one central component of this model: a land-use model to simulate the cultivation of crops and pasture as substrate for biogas production under a set of spatial constraints. The following section first gives an overview of the architecture of the integrated model. After that, the structure and a prototypic application of the land-use model is presented and discussed.

2. INTEGRATED MODELLING OF BIOGAS SYSTEMS

The current situation of modelling biogas systems is characterized by a large number of singular models representing different aspects of the process of biogas generation and utilization. Application fields of these models include the cultivation of energy crops, the biochemical procedure of biogas generation and the utilization of the digestate as well as logistic processes, in particular the ensilage as storage process and transports between cultivated areas, storages and the biogas plant. Here a wide range of modelling methods is applied. The modelling of cultivation of energy crops includes a spatial database as well as calculation and simulation models inter alia for land use and energy yield. Continuous simulation is used to model processes such as the biogas generation or the treatment of residual material. Finally, discrete event simulation is the most suitable method for logistic processes where dynamics of discrete objects, e.g. transport and harvest vehicles, has to be modelled. Moreover, discrete event simulation is a valuable tool for the discretized modelling of continuous processes such as stock characteristics of silos.

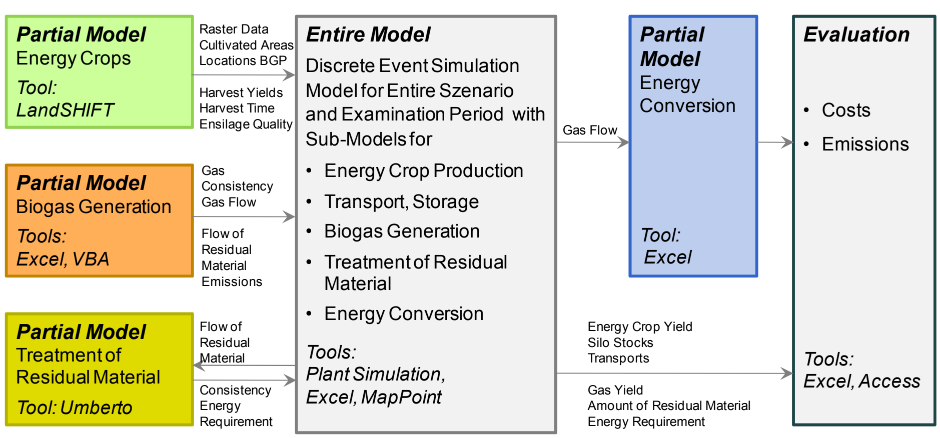

Figure 1. Model pipeline of biomass conversion

In principle, all these models serve well to address the specific problems they were developed for, and can give answers and predictions with sufficient accuracy. However, they cannot predict the entire behaviour of a biogas system as they model only details of the whole system and their system boundaries are based on assumptions. To model the entire biogas system it is necessary to bring these models together. Basically, there are two ways to do this. On the one hand, one can model all aspects of the entire system within one single, new model; on the other hand, it is possible to couple the existing (validated) models of subsystems by well-defined interfaces. This integration of simulation models requires both the exchange of data and the time synchronization of the dynamic models.
The modelling approach of the University of Kassel puts the discrete event simulation model of the entire biogas system in the centre of a data pipeline. This model gets data and parameters for its configuration from partial models that represent the different subsystems of the biogas system. Furthermore, it provides result data that can be used for model evaluation (see Figure 1).

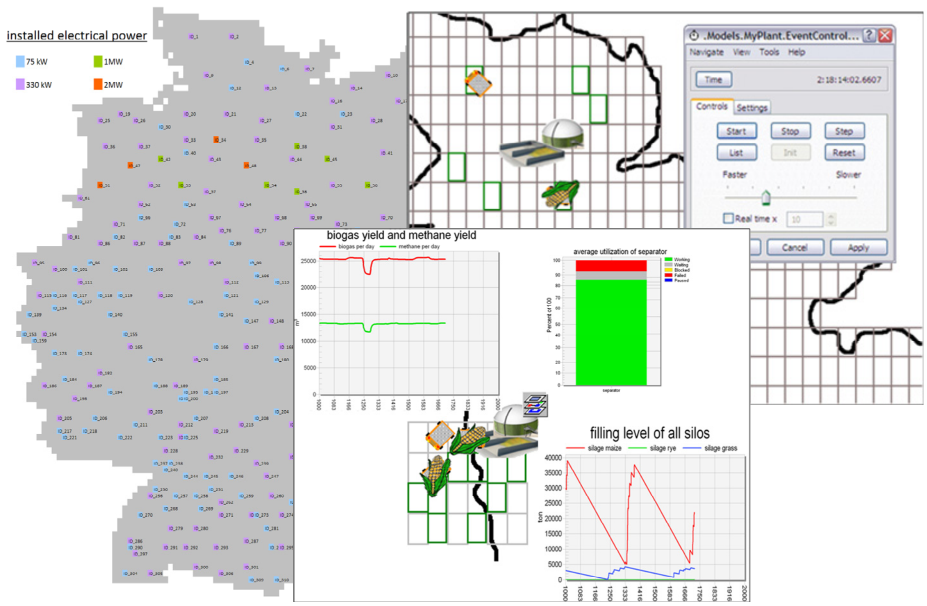

Figure 2. Simulation model of biomass conversion in Germany

The dynamic integrated model of the entire system (hereafter "BioSys model") was built up utilizing the simulation tool Plant Simulation. The model enables researchers not only to model single biogas plants and their surroundings, but also, based on a raster map, the partly automated modelling of any German region (see Figure 2). The regional model includes areas reserved for cultivation of energy crops, installed biogas and energy conversion plants and, where applicable, waste treatment plants as well as a logistics network including transportation and storage (see Figure 2) [Jessen et al., 2009]. For the configuration, the BioSys model gets data from connected upstream partial models by well-defined interfaces in form of Microsoft Excel sheets. These include inter alia size of raster elements, allocation of cultivated areas as well as harvest data from partial model "energy crops", data regarding gas flow and consistency from partial model "biogas generation" and data regarding flow of residual material and its consistency from partial model "treatment of residual material". The results of the BioSys model, e.g. dynamic characteristics of gas yield and content of silos or transports within simulation period, are lead to a specific module for statistic evaluation. The current BioSys model is the basis of a holistic examination of biogas systems. In the following the modelling of energy crop production within the partial model "energy crops" as well as its results, which are used as input parameters for the BioSys model, are presented.

3. SPATIAL SIMULATION OF ENERGY CROP PRODUCTION

3.1 Input data

The assessment is carried out for Germany on the uniform geographic raster with a cell size of 5 arcmin (~7km x 7km), which is also used by the BioSys model. Each raster cell is characterized by a dominant land-use type, an area fraction that is occupied by settlement structures as well as data on terrain slope, road infrastructure and nature conservation area. Furthermore, it includes information about biomass productivity in terms of crop yields and net primary productivity (NPP) of grasslands. The spatial input data is prepared using the GIS software package ArcGIS 9.2. The initial land-use map for the year 2000 is based on the CORINE CLC2000 land cover database from the European Environment Agency (EEA). The fraction of settlement area is derived from the population density map by Klein-Goldewijk et al. [2005]. Slope data is based on the HYDRO1k dataset from the US Geological Service, while information on road infrastructure is based on the VMAP level 0 dataset. The location of nature conservation areas is taken from the World Database on Protected Areas (http://www.wdpa.org). Biomass productivity is calculated by the LPJmL model [Bondeau et al., 2007]. LPJmL produces output on a 30 arcmin raster, which is then assigned to the 5 arcmin cropland and grassland cells located within each 30 arcmin cell (see section 3.2). According to Weiland [2003] almost 98% of all biogas plants in Germany use combined heat and power plants for the utilization of biogas. Data on the installed electrical power of biogas plants was available on the level of EU NUTS 3 administrative units in the year 2007 [Scholwin et al., 2008], distinguishing four different classes with upper limits of: (i) 1000 kWel, (ii) 10.000 kWel, 20.000 kWel and 40.000 kWel. In order to be able to take into account the location of biogas plants in our later analysis, we have introduced the concept of "virtual biogas plants" (hereafter VBP). For each NUTS 3 unit one VBP is located on the grid cell in its geographic centre. It is assumed that its installed electrical power is equal to the medium value of the respective class, i.e. if unit which falls into class 2, it receives a VBP with 5.500 kWel. The sum of the installed electrical power of all VBPs amounts to 1.150 MW_{el} which is about 5% less than the data provided by Scholwin et al. [2008], who estimate an amount of 1.232 MW_{el}.

3.2 Simulation of crop yields and grassland NPP

LPJmL is a process-based model to simulate global vegetation dynamics and the associated carbon and water fluxes on 30 arcmin raster cells. Agricultural land-use productivity is simulated through the consideration of crop functional types (CFTs), either rainfed or irrigated, representing the world's most important annual field crops. Moreover, LPJmL's crop module simulates sowing dates, crop phenology, crop growth and carbon allocation at a daily time step. All four processes respond to climate variables such as precipitation, temperature and insulation. A comprehensive evaluation of LPJmL's performance for the simulation of crop yields, crop phenology and carbon-fluxes is presented by Bondeau et al. [2007]. For our assessment, the model is applied to calculate rainfed and irrigated crop yields for the most important energy crops maize and rye as well as the NPP of managed grasslands. This means that simulation runs for these CFTs are done for all raster cells within Germany.

Table 1. Characteristics of different substrates for biogas production.

	Dry mass content [%][2]	Conversion harvested part to whole plant[1]	Energy content [kWh/t fresh mass][2]
Maize	35%	1.5	323
Rye	35%	1.3	274
Grass	35%	1.0	293

[1]Kim and Dale [2004]; [2]KTBL [2007]

Model results for maize and rye are dry mass grain yields. These are converted to fresh mass silage (whole plant) yields using the factors for dry matter (dm) content and ratio of harvested part to whole plant shown in Table 1. For grassland it is assumed that the whole harvested biomass is used for silage production.

3.3 Spatial allocation of agricultural land-use

We use the LandSHIFT model [Schaldach and Koch, 2009] to calculate the spatial allocation of crops and grassland used for biogas production. It relies on a "land use systems" approach that describes the interplay between anthropogenic and environmental system components as drivers of land-use change. Central model elements are land-use activities that simulate the land-use decision making of different sectors such as settlement, crop cultivation and grazing on a 5 arcmin raster. Each activity performs two processing steps. First the suitability of each raster cell is calculated with a multi-criteria analysis (eq. 1). In the following step a specified demand for a good (e.g. crop production) or service (e.g. housing) is allocated to the most suitable raster cells.

$$\psi_k = \underbrace{\sum_{i=1}^{n} w_i \, p_{i,k}}_{suitability} \times \underbrace{\prod_{j=1}^{m} c_{j,k}}_{constraints} \qquad , with \sum_i w_i = 1, \quad and \;\; p_{i,k}, c_{j,k} \in [0,1] \qquad (1)$$

For this study we have implemented a new land-use activity for the spatial allocation of energy crops and grassland (Figure 3). The implemented algorithm iterates over all the 316 VBPs and allocates energy crops to the cells in the geographic neighbourhood (n-order Moore) of the respective VBP to fulfil its energy demand. The maximum neighbourhood searching radius is set following Walla and Schneeberger [2008] in relation to the installed electrical power.

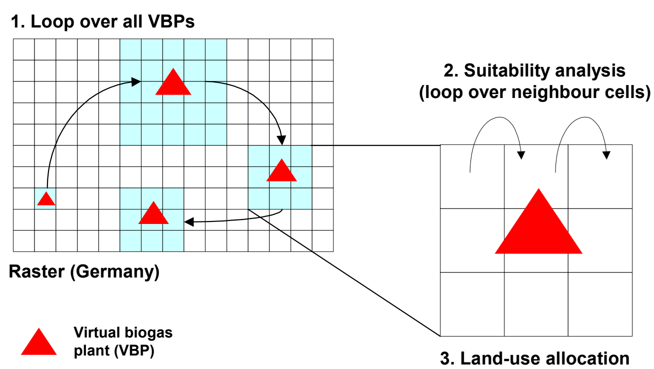

Figure 3. Processing steps of the model algorithm of the land-use component.

For each VBP the installed electrical power is translated to an energy demand to be provided by biogas. In the first step the suitability of each neighbourhood cell is determined. The multi-criteria analysis considers three factors, which have been identified as important for bioenergy plantations by Hellmann and Verburg [2008], all having the same weight (w1 = w2 = w3 = 0.333): terrain slope (p1), crop yield (p2) and available road infrastructure (p3). We assume that higher slope lowers suitability due to negative implications for the use of agricultural machinery and a higher erosion risk while higher crop yields lead to an increased suitability as well as a better road infrastructure does. Furthermore, suitability decreases linearly with distance from the analysed VBP. This effect is expressed by the constraint c1. A further constraint c2 excludes nature conservation areas from being used for the cultivation of bioenergy crops.
In the second step production of energy crops or grassland is allocated to the most suitable cells until the energy demand of the VBP is fulfilled. The energy production of each selected cell is based on the yield and biogas-specific energy content of the allocated crop type (or grassland) (Table 1). In the current version of the algorithm only cells classified as cropland in the initial land-use map are used for crop production. In order to conserve soil carbon stocks and to avoid an additional carbon debt in the sense of Fargione et al. [2008],

grassland and semi-natural vegetation (e.g. forests) cannot be converted. Grassland cells that are located within the neighborhood of a VBP are automatically used to fulfill the energy demand. Agricultural management takes place in a 3-year rotation period, i.e. only 1/3 of a cropland cell area can be used for an energy crop in each year. For each cell a decision is made between silage maize and rye silage production. The cultivation of maize has priority while rye is only used in case of maize yields below a threshold of 38t fresh mass, which is 5% below the yield level classified as low by KTBL [2007].

3.4 Interface to the integrated biogas model

The model output comprises raster maps with the location of energy crops and grassland used as substrate for biogas generation as well as information on the amount of production on each cell in metric tons. This data is further processed before it is handed over to the integrated model. In order to account for the year to year variability of crop and grassland yields, for each cell a 20-year time series of yields and harvest dates is stochastically generated. The statistical distribution function is derived from the census data for the respective crop between 1995 and 2005 and the available sources for harvest dates. The interface to the integrated model is realized as a set of 3 Microsoft Excel tables: (1) A list of raster cells where the VBPs are located, (2) a list of cells where energy crops and grassland are grown including yields and harvested area, and (3) their assigned VBP. Additionally this list includes for each cell the newly calculated time series on crop production and harvest dates. Based on this information the integrated model is able to simulate transport and storage processes between agricultural production sites and a VBP.

4. MODEL EXPERIMENT

We have designed two simulation experiments. The aim of experiment 1 is to provide a first plausibility test of the simulation results generated by the newly developed land-use activity. For the simulation we use data on the installed electrical power of biogas plants for NUTS 3 units in the year 2007 (status quo) provided by Scholwin et al. [2008]. For translating this information into VBP level energy demands we assume that each plant operates 80 % of the time of the year. Furthermore it is assumed that 15 % of the substrate (mass) is provided in form of manure, representing an energy fraction of 1.9%. These values are about half of the threshold value defined in the German law on renewable energies (EEG) for future bonus payments to the plant operator and therefore is a relatively conservative assumption. Other substrates such as biotic waste are not considered in this test run.

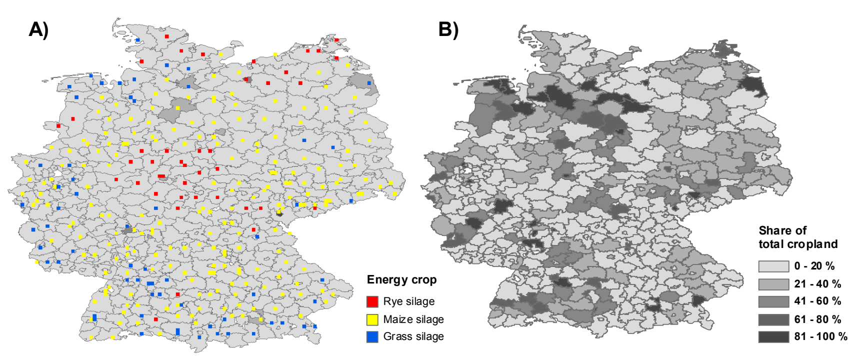

Figure 4. Simulation results for (A) status quo: locations of energy crops and their percentage of total cropland in each Nuts 3 unit and (B) scenario: % energy crops of total cropland in each Nuts 3 unit.

The simulated area of energy crops in Germany amounts to 6.260 km² with 3.810 km², 900 km² and 1.550 km² of silage maize, rye silage and of grassland, respectively. The total simulated area therefore exceeds the estimates of Scholwin et al. [2008] of up to 5.500 km² by 14 %. Figure 4 shows the spatial distribution of cultivation of energy crops.

In experiment 2 (scenario) an eightfold increase of the size of each VBP is assumed to explore possible spatial limitations of the cultivation of energy crops. All other assumptions are the same as in experiment 1. The model result shows an increase of cultivated area to 43.750 km² equaling 26 % of the total agricultural and 37 % of total cropland area in Germany. We further find that the demand of 31 VBPs could not be fulfilled due to the lack of suitable cropland in their neighborhood (Figure 4). Most of these plants are located in Saxony (11) and Lower Saxony (10), followed by Baden-Württemberg (6) and Bavaria (4).

5. DISCUSSION AND CONCLUSION

The article describes a newly developed component of a spatially explicit land-use model to simulate the cultivation of energy crops in Germany. The modified land-use model contributes to the integrated dynamic simulation of processes in the German biogas system and helps to realize the coupling of environmental processes (e.g. crop growth) with technical processes (e.g. transportation of the substrate and electricity generation from biogas). Furthermore, it also takes into account the location of biogas plants into the land-use decisions, comparable to the approach presented by Hellmann et al. [2008].

In the first simulation experiment we could demonstrate that the developed land-use activity produces relatively plausible results. One reason for the overestimation of area needed for the cultivation of energy crops is the lack of data for the use of other substrates for biogas generation. Major source of uncertainty is the regional availability of slurry and organic waste. Here more detailed regional data would be necessary to achieve more realistic results. The second simulation experiment illustrates that there is still a large potential for the expansion of biogas production in Germany. It also becomes obvious that the linear up-scaling approach we used leads into regional problems to fulfill the given demands. In order to produce more reliable results, another model component needs to be developed for the spatial allocation of additional biogas plant capacities. Other uncertainties that have not been taken into account by this study are increasing yield by the introduction of new crop varieties and the possible effect of climate change for plant growth conditions and water availability for irrigation.

The developed model has a relatively coarse spatial resolution and due to the lack of more detailed data it does not consider individual biogas plants. This leads to a highly idealized representation of the real-world system. Nevertheless, the model captures the most important processes of land-use decision making and can be applied to both finer scale raster datasets and more detailed plant location data without major modifications. Beside these spatial constraints, the major simplifications of this study are twofold: (1) Economical competition between biogas crops and other crops (in the way as signalled by Thrän and Kaltschmitt [2007]) is not considered but instead it is assumed that biogas crops are always given priority on one third of the available cropland area of a raster cell. This limitation could be overcome by introducing economic aspects of agricultural decision making into the suitability analysis. (2) Agricultural management in terms of fertilizer use and ploughing are not considered by the model. Furthermore, the LPJmL runs were summarized for the time period 1991 - 2000. The effect of inter-annual variability of climate variables such as temperature and precipitation on irrigation water requirements and crop yields is taken into account only in the post-processing step. Improvements of the land-use model should therefore also include the application of a more detailed crop/grassland model.

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