Abstract

In the framework of the EU FP7 project EnerGEO (Earth Observation for Monitoring and Assessment of the Environmental Impact of Energy Use) sustainable energy potentials for forest and agricultural areas were estimated by applying three different model approaches. Firstly, the Biosphere Energy Transfer Hydrology (BETHY/DLR) model was applied to assess agricultural and forest biomass increases on a regional scale with the extension to grassland. Secondly, the EPIC (Environmental Policy Integrated Climate) – a cropping systems simulation model – was used to estimate grain yields on a global scale and thirdly the Global Forest Model (G4M) was used to estimate global woody biomass harvests and stock.

The general objective of the biomass pilot is to implement the observational capacity for using biomass as an important current and future energy resource. The scope of this work was to generate biomass energy potentials for locations on the globe and to validate these data. Therefore, the biomass pilot was focused to use historical and actual remote sensing data as input data for the models. For validation purposes, forest biomass maps for 1987 and 2002 for Germany (Bundeswaldinventur (BWI-2)) and 2001 and 2008 for Austria (Austrian Forest Inventory (AFI)) were prepared as reference.

The output of BETHY/DLR, EPIC and G4M was used as input for the energy scenario-models REMIX (Renewable Energy Mix for Sustainable Electricity Supply in Europe, developed and operated by DLR-TT), TASES (Time And Space resolved Energy Simulation, developed and operated by Research-Studio, Salzburg) and BeWhere (a techno-economic model developed by IIASA and Ludwig university and operated by IIASA). The EPIC modelling results for agricultural areas are input to TASES and REMIX. G4M also provided input data for TASES on a global scale starting with the year 2000 and ending in 2050 with 10 years steps.

The main conclusions from the Biomass Pilot are:

1) It is possible to calculate biomass energy potentials for wood and agricultural crops by applying BETHY/DLR, EPIC or G4M models for Europe (1x1 km²) and the globe (0.5° x 0.5°).
2) The outcomes of biomass energy models are sensitive to input data by 40% or more. This is a consequence of biological sensitiveness to factors that determine growth such as weather, soil, species and cultivation. Collecting more and better input data is therefore essential.
3) Intensive effort was put on validation activities for all three models as well as a model intercomparison. For agricultural and forested areas all models showed significant linear relationship with reference data (R² up to 0.95).
4) Remote sensing data can be used for generating some input data for biomass potential modelling such as weather and land use data.
5) Remote sensing data have to be further developed before a differentiation can be made between different species and crops or biomass stacks can be modelled.

1. Biomass modelling using BETHY/DLR

The Biosphere Energy Transfer Hydrology Model (BETHY/DLR) is the theoretical framework to estimate NPP (= net primary productivity) for agricultural, grass land and forested areas. It is a special soil-
vegetation-atmosphere-transfer (SVAT) model that models photosynthesis, and takes into account environmental conditions that affect it. SVAT models track the plant-mediated transformation of atmospheric carbon dioxide into energy-storing hydrocarbons such as sugars, a process known as carbon fixation.

The process of photosynthesis is parameterized following the combined approach of Farquhar et al (1980) and Collatz et al (1992). Dark and light reactions of photosynthesis are calculated on leaf level and treated separately. With this approach the photosynthesis rate can be limited either by light availability or the carboxylation enzyme Rubisco, the key player in the Calvin cycle that fixes carbon. Because of their significant differences in their carbon fixation physiologies so-called C3 and C4 plants are distinguished in BETHY/DLR. C4 plants such as sugar beet and corn can fix more atmospheric carbon dioxide at higher temperatures than can C3 plants such as barley and wheat.

To extrapolate photosynthesis from leaf to canopy level, the canopy structure, and the soil-atmosphere-vegetation interaction is taken into account. For closed and open canopies (forests, shrubs, grassland and crops) the photosynthetic rate depends on the Leaf Area Index (LAI). Self-shading is considered by reducing the photosynthetic rate from canopy top to soil using the “two-flux scheme” of Sellers (1985) with three canopy layers.

Besides photosynthesis, other energy transfers, such as heat fluxes between vegetation and the atmosphere and the cooling effect of evapotranspiration, are also considered. Furthermore the soil heat flux and the storage of heat in the canopy is taken into account. The coupling of these processes is of great importance, since temperature-dependent photosynthesis transforms light energy into chemical energy, and finally into carbohydrates, using water and CO2.

The water cycle is also modelled and included in the interaction scheme. Three reservoirs are considered: soil water, snow, and “skin” or “intercepted” water on leaves and other parts of the vegetation, which change in time and space. Soil water is available for vegetation, while evapotranspiration from vegetation and evaporation from soil determine the water loss to the atmosphere. Water limitation is modelled by calculating the demand for evapotranspiration using the approach of Monteith (1965) with the criteria of Federer (1979), assuming that evapotranspiration cannot be greater than the limit set by the soil water supply and the water uptake of a plant’s roots. Thus when considering the dynamic interaction of, for instance, the soil water balance and photosynthesis, the natural behaviour of vegetation can be reflected, which is the motivating idea of the SVAT approach.

Autotrophic respiration is modelled in BETHY/DLR as the sum of maintenance respiration and growth respiration. Maintenance respiration is limited by vegetation-specific dark respiration rates. Growth respiration is assumed to be a constant fraction of NPP.

BETHY/DLR is driven by remote sensing data from SPOT-VEGETATION, meteorological data from the European Center for Medium-Range Weather Forecast (ECMWF), and additional static datasets, as a land cover information (GLC2000), a soil map (HWSD) and an elevation model (ETOP05).

The model output of BETHY/DLR is given as a time series of NPP in daily steps, at the resolution and projection of the land cover classification. For this study the Global Landcover Classification 2000 (GLC2000) with a 1km² resolutions is used. Integrating the yearly time series will result in yearly accumulated NPP which is first converted to straw potentials using simple allocation rules (root-to-shoot and yield-to-straw ratios) and then transferred to energy potentials using species-specific lower heating values.

1.1 Validation

Three validation and model comparison exercises were carried out during the project period. A validation exercise on the accuracy of BETHY/DLR for agricultural areas was performed (Tum and Günther (2011)). Our method yielded high coefficients of determination (R2 up to 0.74) allowing strong conclusions to be drawn about model validity. For German districts, BETHY/DLR substantially underestimated the NPP (17%), whereas for Austrian districts a slight overestimation (8%) was observed. In areas where
the land cover classification (GLC2000) provided insufficient information (particularly in the Alps), modelled NPP was significantly underestimated (even to zero), producing high discrepancies between modelled NPP and empirical data in those regions. This indicates that a spatial resolution of 1 km² is insufficient to describe the heterogeneous small-scale structure of mid-European land use practices. A validation exercise on the accuracy of BETHY/DLR for forest areas (Tum et al. (2011)) showed linear regressions of estimated above-ground biomass increment from modelled NPP (CAI) against the empirical data from the NFI (MAI). It was also shown that BETHY/DLR underestimates the net increment of above-ground biomass for both deciduous and coniferous trees. The R² values of 0.74 and 0.76 for deciduous trees indicate a high degree of correlation, however. The correlation for coniferous trees is even stronger, with R² values of 0.95 and 0.93, but the underestimation is also higher here. In order to quantify the predictive accuracy of BETHY/DLR’s NPP estimates, the root mean square error (RMSE given in Mt*NUTS1-1*y⁻¹) was calculated for all four panels; for deciduous trees the RMSE is 1.53 (2000) and 1.48 (2001), and for coniferous trees, 1.87 (2000) and 1.93 (2001). A comparison of EPIC and BETHY/DLR results to different input data (meteorological and land cover datasets) was carried out for the Marchfeld region (Austria) (Tum et al. (2012)). Both process models show a congruent pattern to changes in input data. The annual variability of NPP reaches 36% for BETHY/DLR and 39% for EPIC when changing major input datasets. However, EPIC is less sensitive to meteorological input data than BETHY/DLR. The ECMWF maximum temperatures show a systematic pattern. Temperatures above 20°C are overestimated, whereas temperatures below 20°C are underestimated, resulting in an overall underestimation of NPP in both models. Besides, BETHY/DLR is sensitive to the choice and accuracy of the land cover product.

1.2 Conclusion

In summary it can be concluded that NPP, sustainable straw energy potential and sustainable forest energy potential can be derived from BETHY/DLR. Compared to recently published straw potential values our method yields reasonable high coefficients of determination (R² up to 0.78) combined with a slight overestimation (up to 12%), allowing strong conclusions to be drawn about the usability of the presented method. In areas where the land cover classification (GLC2000) provided insufficient information (particularly in the Alps), modelled NPP was significantly underestimated (even to zero), producing high discrepancies between modelled NPP and empirical data in those regions. This indicates that a spatial resolution of 1 km² is insufficient to describe the heterogeneous small-scale structure of mid-European land use practices.

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In the framework of EnerGEO BETHY/DLR has been validated and data for the years 2000 – 2007 and 2010 are available with a spatial resolution of 1x1 km² for Europe. These data sets have been delivered to the energy models used in EnerGEO and to G4M (yields).

2. Biomass modelling and prediction using EPIC

The EPIC (Environmental Policy Integrated Climate) model was used to assess agricultural side products (straw) on a European and global scale. EPIC was originally developed by a modelling team of the
USDA to assess the status of U.S. soil and water resources (Williams, 1985) but continuously expanded and refined to allow simulation of many processes important in agricultural land management. EPIC is run in Austria at both the University of Life Sciences in Vienna (BOKU) and at International Institute for Applied Systems Analysis (IIASA) in Laxenburg. EPIC was calibrated by IIASA to meet their own needs. The model is not open-source in the true sense of the word, and is available to interested research groups.

The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient and carbon cycling, pesticide fate, plant growth and competition, soil temperature and moisture, tillage, cost accounting, and plant environment control. EPIC operates on a daily time step and can simulate plant growth for hundreds of years. The spatial resolution of EPIC is adjusted to Homogeneous Response Unit (HRU) assuming that weather, soil, topography, and management systems are equal and homogeneous in the HRU. Heterogeneous landscapes can be modelled by identifying a reasonable number of representative HRUs. For the European run the model resolution was set to 1km², for the global run to 10km x 10km. EPICs primary output is the crop yield for more than 20 species. However for our EnerGEO study only the six (barley, grain maize, oats, rapeseed, rye and wheat) crops which yield straw as a side product were used.

The input data for EPIC are weather (precipitation, minimum and maximum air temperature, and solar radiation), physical and chemical soil parameters describing the soil layer with depth, topography (field size, slope length and steepness) and management practices (e.g. planting day, harvesting day, harvesting index, date and depth of each tillage operation, scheduling options for timing and rate of irrigation water, fertilizer, lime, pesticide, grazing, and drainage systems). Remote sensing derived products used by EPIC are a land cover / land use map (GLC2000) and topographic information as altitude, slope length and steepness.

### 2.1 Conversion to Bioenergy potentials

The output of EPIC “dry matter yield (t*ha⁻¹)” is converted to bioenergy potential (PJ) for both the European (1km²) and global (10km²) runs using the following steps:

- Convert dry matter yield (t*ha⁻¹) to current yield (t*ha⁻¹) using crop specific conversion factors
- Convert current yield to straw yield (see harvest factors residual/grain Krausmann et al. 2008). Used conversion factors for Western Europe – as these are most conservative.
- Convert to energy equivalent (select only 20% of straw yield, multiply by 14.05 MJ*kg⁻¹ from Zeller et al (2011))
- Convert to total PJ per cell using area grid and % cropland area
- For global run only: Apply factor of 2 to NA, SA, EU and Australia. This calibrates the bioenergy potential to that of Europe derived from EPIC/BETHY (1km European Model).

Global EPIC runs showing the bioenergy potentials of six crops (barley, grain maize, oats, rapeseed, rye and wheat) were performed during EnerGEO for the past (1961-1990) and the future (2030, 2050 and 2090) at 10km² resolution. CO₂ concentrations change over time in the forecast runs as listed below (Source: http://www.ipcc-data.org/ddc_co2.html BERN CO₂ concentrations were used). The CO₂ fertilization effect is also included in the model:

- 1960-1990: 316..352 ppm (values dynamically change up to the 1990 value)
- 2026-2035: 444 ppm (value for 2030)
- 2046-2055: 522 ppm (value for 2050)
- 2086-2095: 754 ppm (value for 2090)
2.2 Validation / Evaluation

General comparisons of EPIC results to other model outputs have been made during EnerGEO. We have compared our EPIC 1km² results to those derived from the BETHY/DLR model across Europe, with a good level of agreement (0.68 < R² < 0.97). Following this, global EPIC results were compared against those of the European results from BETHY on a country scale. For example Table 1 shows a comparison between BETHY/DLR and EPIC for Germany, France and Spain.

The different temporal extends of BETHY/DLR and EPIC are due to their individual model setups. BETHY/DLR’s results are available on annual basis, whereas EPIC’s results was only available as average for a 30 years period. Results as presented in Table 1 can be seen as conservative estimate and are within the currently accepted range of bioenergy potentials (Zeller et al, 2011).

Furthermore, a comparison of the BETHY/DLR and EPIC models was made in a case-study over Austria. Agreement between the two models is generally high – but is strongly dependent upon the different input datasets in the models (Tum et al, 2012).

Table 1 Comparison of modelled bioenergy potentials of BETHY/DLR (2000-2007) and global EPIC (1961-1990). Values are given in energy units (PJ) per country and year, for Germany, France and Spain.

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<tr>
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<tbody>
<tr>
<td>Germany</td>
<td>250-389</td>
<td>395</td>
</tr>
<tr>
<td>France</td>
<td>388-624</td>
<td>555</td>
</tr>
<tr>
<td>Spain</td>
<td>321-426</td>
<td>358</td>
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2.3 Discussion and Outlook

Currently we are developing a methodology to provide improved crop yield estimates by integrating satellite data (higher resolution and temporal frequency biophysical parameters) and seasonal weather forecasts into the crop model EPIC. These yield estimates will be linked with socio-economic variables such as caloric availability and poverty indicators. Long term socio-economic impacts of climate change will be modelled under different scenarios by integrating climate forecasts into EPIC.

Furthermore, the impact of different policy scenarios related to land use changes and changes in commodity prices will be studied by coupling the EPIC crop model with the land use change model GLOBIOM.

Finally, the specification of locations for biomass production areas can be performed in the future. However this requires information on both supply and demand. At this stage, with both EPIC and G4M (see below) bioenergy potential results, we are providing future supply scenarios. In order to determine where to locate new areas of biomass production we need to consider demand, and require another set of models. One such model is the BEWHERE model of IIASA. Furthermore, the TASES model of RSA, which ingests the outputs of bioenergy potential from EPIC, could be used to identify new locations.
3. Biomass modelling and prediction using G4M

The Global Forest Model (G4M) was used to calculate theoretical energy potentials for forests on a European and global scale. G4M was developed at IIASA and predicts the annual above ground stem-wood increment and stocking biomass. Currently the species beech, birch, fir, larch, oak, pine and spruce are parameterised. The model can estimate the current rotation time (time between afforestation to final harvest) assuming a normal forest out of a biomass map and a given yield. It is also possible to use observed age structures to initialize a forest. As management it is possible to select a target rotation time, if thinning is done or not and which species are regenerated. Furthermore it is possible to let the model chose the rotation time by itself with the task to either have the highest wood growth rate or to have the highest biomass in the forest. For the European run the model resolution was set to 1km², for the global run to 0.5° x 0.5°.

G4M needs a yield description as an input parameter as e.g. NPP, which was supplied by model results of BETHY/DLR. G4M needs in addition the current forest and species cover, the stocking biomass or the stand density, the age structure if available and the management target. To estimate sustainable energy potentials for forests we assume that only the mean annual increment of above ground woody biomass can be used for energy purposes, meaning: only this equivalent amount of wood can be harvested from a stand. In a second step lower heating values, giving specific energy potentials per kilogram biomass, are used to transfer the data. For the forest areas only theoretical-sustainable potentials are estimated.

On a European scale G4M estimates energy potentials of 9.3 EJ for forests of Europe and on global scale energy potentials of 170 EJ for forests. Tropical forests and savannahs, as reported in the World Wild Fund for Nature (WWF) terrestrial eco regions map are excluded from the estimation of energy potential because it is recommended that these areas should not be used for energy production.

3.1 Validation

G4M was validated on forests around Harz –Germany and on inventory points in Lower-Austria and Styria. Estimates from G4M compared with measured increments from the German (BW12) and Austrian forest statistics (AFI) showed coefficient of determination in the range around 40% – 70%.

3.2 Discussion and outlook

The validation shows that G4M is able to describe 40%-70% of the observations. Taking into account that the observations include some random variation caused by measurement errors the correlations are high. Anyway the estimates depend to a large part on the input data. If for example the used NPP estimates are too low it can be expected that also the estimated wood increments will be too low. The energy supply from forestry depends on the usage of wood. If wood is burned with high water content typical the energy which can be used will be much lower compared to the same wood which has low water content. It also should be taken into consideration that for providing the wood also energy will be consumed. This energy consumption depends e.g. on the level of wood transformation.

The model estimates in Europe seems to be acceptable as they are close to forest inventory observations. For the tropics currently the estimates are hard to validate because there is a huge range of uncertainties. There exist some reports indicating that harvests in the tropic will be in the range of 1-2 m³ha⁻¹y⁻¹ other report increment rates of more than 100 m³ha⁻¹y⁻¹. In the future some effort should be spend to reduce this huge range of uncertainties of the potentials from the tropics as long as they will be used for providing bioenergy.

Currently we are providing bioenergy potentials for Europe (1km² resolution) and the globe (0.5°x0.5° resolution). These will be available via the EnerGEO Portal.

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Bibliography


