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Acronym:  
**CenBio**

Centre name:  
**Bioenergy Innovation Centre**

Start date of centre: 2009-03-01  
Duration: 8 years

**D5.2.28**  
**Collection of Journal Paper Abstracts**

Revision: **Final**

Due date of delivery: 2014-02-28  
**Actual submission date: 2014-01-06**

Organisation name of lead partner for this deliverable:  
**SINTEF Energy Research**

Project co-funded by the Research Council of Norway		
Dissemination Level		
PU	Public	
RE	Restricted to a group specified by the consortium	X
CO	Confidential, only for partners of the consortium	



Deliverable number:	D5.2.28
Deliverable title:	Collection of journal paper abstracts
Lead partner:	SINTEF ER
Work package:	WP5.2 Dissemination

Classification	
	<b>Article</b> (peer-reviewed), <b>Journal:</b>
	<b>Article</b> (popular science)
	<b>Conference paper</b> (published)
	<b>Conference presentation</b> (incl. posters)
	<b>Media Contribution</b> (e.g. feature article, interview, participation in radio/TV programme)
	<b>Technical Report</b>
	<b>Chapter in book</b>
	<b>Book</b> (PhD-dissertations, monographs)
	<b>Post doc</b> report
	<b>Master</b> report
<b>X</b>	<b>Other</b> (please specify)

Status of deliverable		
Action	By	Date
Submitted (lead author)	Stine Lund Davanger, SINTEF ER	20.12.2013
Verified (lead partner)	Alexis Sevault, SINTEF ER	20.12.2013
Approved (if applicable)	Executive Board	06.02.2014

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Abstract
<p>This document gathers the abstracts of all journal papers published (or "in press") written within CenBio since the start of the Centre.</p> <p>The abstracts are organized first by sub-project (SP), then by year of publication.</p> <p>Links to the journal webpage and the document in the eRoom are systematically given.</p> <p>This document is meant to be updated at least twice a year, to include the abstract of the new published articles.</p>

Revision history			
Date	Revision	Author(s)	Comments
2013-12-20	Final	Alexis Sevault	Verified document
2013-12-18	1	Stine Lund Davanger	Submitted document

## ***CENBIO: COLLECTION OF JOURNAL PAPER ABSTRACTS***

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***SP1: BIOMASS SUPPLY AND RESIDUE UTILIZATION***

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- 2014 -

***Applying simulated annealing using different methods for the neighborhood search in forest planning problems***

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*European Journal of Operational Research*

*Volume 233, Issue 3, 16 March 2014, pp. 700–710*

DOI: [10.1016/j.ejor.2013.08.039](https://doi.org/10.1016/j.ejor.2013.08.039)

D1.1.14 ([Link to eRoom](#))

***Abstract***

Adjacency constraints along with even flow harvest constraints are important in long term forest planning. Simulated annealing (SA) is previously successfully applied when addressing such constraints. The objective of this paper was to assess the performance of SA under three new methods of introducing biased probabilities in the management unit (MU) selection and compare them to the conventional method that assumes uniform probabilities. The new methods were implemented as a search vector approach based on the number of treatment schedules describing sequences of silvicultural treatments over time and standard deviation of net present value within MUs (Methods 2 and 3, respectively), and by combining the two approaches (Method 4). We constructed three hundred hypothetical forests (datasets) for three different landscapes characterized by different initial age class distributions (young, normal and old). Each dataset encompassed 1600 management units. The evaluation of the methods was done by means of objective function values, first feasible iteration and time consumption. Introducing a bias in the MU selection improves solutions compared to the conventional method (Method 1). However, an increase of computational time is in general needed for the new methods. Method 4 is the best alternative because, for large parts of the datasets, produced the best average and maximum objective function values and had lower time consumption than Methods 2 and 3. Although Method 4 performed very well, Methods 2 and 3 should not be neglected because for a considerable number of datasets the maximum objective function values were obtained by these methods.



## ***Deriving cooperative biomass resource transport supply strategies in meeting co-firing energy regulations: A case for peat and wood fibre in Ireland***

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*Applied Energy*

Volume 113, January 2014, pp. 1700–1709

DOI: [10.1016/j.apenergy.2013.09.019](https://doi.org/10.1016/j.apenergy.2013.09.019)

D1.2.16 ([Link to eRoom](#))

### ***Abstract***

The Irish government has undertaken to reduce national CO<sub>2</sub> emissions through a range of measures put out in their Biomass Action Plan and the National Renewable Energy Action Plan. The conversion of peat fired power plants to co-fire with renewable biomass is one of these. This paper considers how the adoption of sweeping policies impact on other actors presently supplying or utilizing woody biomass resources. The SAWMILL sector (18 sawmills), BOARD sector, 3 board plants, and ENERGY sector (3 peat fired power stations) were included in a Linear Programming (LP) based transportation study. Specific transport costs between each residue producing sawmill and each board and energy plant were modeled and used in finding the minimum delivered cost for a number of scenarios. Scenario 2015 represented the status quo, while Scenario 2030 represented a situation with 30% co-firing with woody biomass equivalents in the energy plants. For each time horizon, the problem was solved from the perspective of society at large (GLOBAL), for the benefit of the board sector (BOARD) or with emphasis on minimizing the cost to the energy sector (ENERGY). The cost of transporting alternative sources of renewable energy was varied between €100 and €500 TJ<sup>-1</sup>. Results showed how overall supply costs increase with increasing alternative energy cost, but also how the dynamics between sectors focus worked. The cost of transport to the Energy sector ranged from €306,043 to €996,842 in Scenario 2015, while the increased demand in 2030 led to a range of between €1,132,831 and €4,926,040, depending on the alternative cost selected. For the Board sector, whose absolute demand remained constant, the total transport cost ranged between €868,506 and €3,454,916 in Scenario 2015. The unchanged demand showed that the transport costs also remained the same for the 2030 Scenario, however, the optimization focusing on the Energy sector, increased the delivery cost to the Board sector by up to €693,730 per year by 2015 and €842,271 per year by 2030, indicating how intervention would be necessary if political ambitions of a 30% co-firing should happen without detriment to other important wood based industries.

- 2013 -

## ***Harvest residue potential in Norway – a bio-economic model appraisal***

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*Scandinavian Journal of Forest Research*  
Volume 28, Issue 5, 2013, pp. 470-480

DOI: [10.1080/02827581.2013.766259](https://doi.org/10.1080/02827581.2013.766259)

D1.1.4 ([Link to eRoom](#))

### ***Abstract***

Use of harvest residues for bioenergy is minimal in Norway, and the proposed increase of 14 TWh in annual bioenergy use by year 2020 may thus to a large part be based on residues from conventional timber harvesting. To judge the potential of harvest residues for bioenergy both in the short and long run, we present cost-supply curves for residue harvesting at national and regional levels. We produce different harvesting scenarios using the detailed forest model Gaya/J and a representative description of the Norwegian forest area from Norwegian national forest inventory (NFI) sample plots including environmental restrictions. Forest information is sufficiently detailed to estimate necessary biomass fractions and calculate costs of harvest residue extraction at plot level. We estimate a maximum annual energy production of 5.3 TWh from harvest residues with the present harvest level, which is far from the official target. In principle, there are two solutions for achieving this target; increase harvests and thus the corresponding residue supply, or increase the use of roundwood for energy purposes on the expense of pulpwood. Scenarios with long-run increase in timber production shows an annual energy potential from harvest residues in the range 6–9 TWh. Thus, to reach the political target roundwood must be used for energy production.

## ***The Performance of a Residential Pellets Combustor Operating on Torrefied and Raw Spruce and Spruce Derived Residues***

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*Energy & Fuels*

2013, 27 (8), pp. 4760–4769

DOI: [10.1021/ef400595f](https://doi.org/10.1021/ef400595f)

D1.3.5 ([Link to eRoom](#))

### ***Abstract***

The heterogeneous nature of solid biomass fuels makes their combustion a substantial challenge compared to the more traditional fuel types, such as fossil fuels and natural gas. Many studies found in the literature attempt at identifying enhancements in fuel properties of biomass after a thermal pretreatment step, such as torrefaction, but only few investigate specifically the combustion behavior of these fuels. In this study, pellet combustion of raw and torrefied spruce and spruce tree tops and branches (T&B) has been investigated with regard to the emissions of gaseous pollutants and particulate matter (PM). The combustion was performed in a residential pellet stove, where a total of six different feedstocks, with and without pretreatment, were tested. The wide range of the feedstock properties was shown to go beyond the design limitations of the pellet stove. This could be seen as combustion instability for the T&B torrefied at 275 °C. Technology adjustments might be needed in terms of combustion air distribution and chamber design for these fuels. Mild torrefaction, in general, reduced the emissions of CO, unburned hydrocarbons, and the organics in particles smaller than 1 µm. Combustion at a low load (low thermal input) resulted as expected in increased emissions of organic compounds, which was again reduced substantially for the mildly torrefied feedstocks. In comparison to raw spruce at low load, a reduction by a factor of 3 from the organic share of the PM<sub>1.0</sub> particles is obtained. For the same experiments, CO in the flue gas is reduced by 150%. For T&B, similar trends were obtained for organic particles; however, torrefaction resulted in an increase in the total PM<sub>1.0</sub> emissions. The decrease in the organic share was more than offset by a substantial increase in the inorganic share of the PM<sub>1.0</sub> emissions. For this reason, torrefaction might not be a viable pretreatment solution for feedstocks with high ash content for use in stoves for residential heating, without combustion technology adjustments.

- 2012 -

## ***Small area estimation of forest attributes in the Norwegian National Forest Inventory***

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*European Journal of Forest Research*  
July 2012, Volume 131, Issue 4, pp. 1255-1267

DOI: [10.1007/s10342-012-0596-7](https://doi.org/10.1007/s10342-012-0596-7)

D1.1.13 ([Link to eRoom](#))

### ***Abstract***

The Norwegian National Forest Inventory (NNFI) provides estimates of forest parameters on national and regional scales by means of a systematic network of permanent sample plots. One of the biggest challenges for the NNFI is the interest in forest attribute information for small sub-populations such as municipalities or protected areas. Frequently, too few sampled observations are available for such small areas to allow estimates with acceptable precision. However, if an auxiliary variable exists that is correlated with the variable of interest, small area estimation (SAE) techniques may provide means to improve the precision of estimates. The study aimed at estimating the mean above-ground forest biomass for small areas with high precision and accuracy, using SAE techniques. For this purpose, the simple random sampling (SRS) estimator, the generalized regression (GREG) estimator, and the unit-level empirical best linear unbiased prediction (EBLUP) estimator were compared. Mean canopy height obtained from a photogrammetric canopy height model (CHM) was the auxiliary variable available for every population element. The small areas were 14 municipalities within a 2,184 km<sup>2</sup> study area for which an estimate of the mean forest biomass was sought. The municipalities were between 31 and 527 km<sup>2</sup> and contained 1–35 NNFI sample plots located within forest. The mean canopy height obtained from the CHM was found to have a strong linear correlation with forest biomass. Both the SRS estimator and the GREG estimator result in unstable estimates if they are based on too few observations. Although this is not the case for the EBLUP estimator, the estimators were only compared for municipalities with more than five sample plots. The SRS resulted in the highest standard errors in all municipalities. Whereas the GREG and EBLUP standard errors were similar for small areas with many sample plots, the EBLUP standard error was usually smaller than the GREG standard error. The difference between the EBLUP and GREG standard error increased with a decreasing number of sample plots within the small area. The EBLUP estimates of mean forest biomass within the municipalities ranged between 95.01 and 153.76 Mg ha<sup>-1</sup>, with standard errors between 8.20 and 12.84 Mg ha<sup>-1</sup>.

## ***Combustion Properties of Norwegian Biomass: Wood Chips and Forest Residues***

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*Applied Mechanics and Materials*  
Volumes 110 – 116, pp. 4564-4568

DOI: [10.4028/www.scientific.net/AMM.110-116.4564](https://doi.org/10.4028/www.scientific.net/AMM.110-116.4564)

D1.3.4: ([Link to eRoom](#))

### ***Abstract***

Flue gas emissions and particle size distribution were investigated during combustion experiments of wood, forest residue and mixtures of these two. The combustion experiments were carried out in a grate fired multi-fuel reactor with and without air staging at stable operation conditions and constant temperature of 850 °C. The overall excess air ratio was held at 1.6, and the primary excess air ratio was 0.8 during air staged experiments. NO<sub>x</sub> emissions are reduced by air staging. Fly ash particle concentration of forest residues in the flue gas is lower than wood. Aerosols number increased in the staged experiments for fuel blends.

## ***Fertilization effects of organic waste resources and bottom wood ash: results from a pot experiment***

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*Agricultural and Food Science*  
*Vol 21, No 4 (2012), pp. 332-347*

DOI: <http://ojs.tsv.fi/index.php/AFS/article/view/5159>

D1.4.8 ([Link to eRoom](#))

### ***Abstract***

We conducted a pot experiment to study the fertilization effects of four N- and P-rich organic waste resources alone and in combination with K-rich bottom wood ash at two application rates (150 kg N ha<sup>-1</sup> + 120 kg K ha<sup>-1</sup>, 300 kg N ha<sup>-1</sup> + 240 kg K ha<sup>-1</sup>). Plant-available N was the growth-limiting factor. 48–73% of N applied with meat and bone meal (MBM) and composted fish sludge (CFS) was taken up in aboveground biomass, resulting in mineral fertilizer equivalents (MFE%) of 53–81% for N uptake and 61–104% for yield. MFE% of MBM and CFS decreased for increasing application rates. Two industrial composts had weak N fertilization effects and are to be considered soil conditioners rather than fertilizers. Possible P and K fertilization effects of waste resources were masked by the soil's ability to supply plant-available P and K, but effects on plant-available P and K contents in soil suggest that the waste resources may have positive effects under more nutrient-deficient conditions.

- 2011 -

## ***Modelling natural drying efficiency in covered and uncovered piles of whole broadleaf trees for energy use***

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*Biomass and Bioenergy*

*Volume 35, Issue 1, January 2011, pp. 454–463*

DOI: [10.1016/j.biombioe.2010.09.003](https://doi.org/10.1016/j.biombioe.2010.09.003)

D1.3.2/D1.3.6 ([Link to eRoom](#))

### ***Abstract***

Small dimensions regenerated forests are considered a useful fuel resource for small local heat plants in Norway, since it is not relevant for the timber industry. Most small heat plants built so far are constructed for moisture contents of about 35% on wet basis. Therefore, the material must be dried. Because artificial drying induces additional costs, storing the material in piles roadside as whole trees until desired moisture content is obtained is considered beneficial. Traditionally, leaf seasoning has been considered an efficient method. To increase the understanding of these processes, a study on drying whole trees in piles has been accomplished at three different locations with different climatic conditions. The study focuses on the following explanatory variables: harvesting season, location, climatic conditions, position in the pile, tree species, and relative crown length. The effect of covering the piles in order to reduce the moisture uptake during winter was also studied. Models, estimating the moisture content with time profiles, were developed.

During spring and summer the moisture content was reduced to approximately 35% also when the material was harvested in the autumn the year before. The climatic conditions were important for the drying result, but drying was effective also in the moist climate in western Norway. Covering the dry piles before the winter was important in order to maintain the requested moisture content. The effect of covering the material harvested in autumn was limited.

## ***The influence of storage and drying methods for Scots pine raw material on mechanical pellet properties and production parameters***

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*Fuel Processing Technology*

Volume 92, Issue 5, May 2011, pp. 871–878

DOI: [10.1016/j.fuproc.2010.12.001](https://doi.org/10.1016/j.fuproc.2010.12.001)

D1.3.6\_1 ([Link to eRoom](#))

### ***Abstract***

Converting solid biomass into pellets through densification greatly improves logistical handling and combustion processes. Raw material properties can affect pellet quality. This study investigated how storage and drying methods for wood (*Pinus sylvestris* L.) used as a raw material for pellet production influenced pellet durability, bulk density and energy consumption. The pelletization experiments were performed using a Sprout Matador M30 press (nominal production capacity 3.5 tonnes/h). Results showed that pelletization of 11 months stored wood compared to fresh material and high drying temperature (450 °C) compared to 75 °C resulted in higher energy consumption, probably due to increased friction in the matrix caused by the loss of extractives. However, the pellets produced were of higher density than those made from fresh material dried at a low temperature. The latter had the highest durability. Increased energy consumption showed no correlation with pellet durability.



## ***Modelling moisture content and dry matter loss during storage of logging residues for energy***

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*Scandinavian Journal of Forest Research*

*Volume 26, Issue 3, 2011*

DOI: [10.1080/02827581.2011.553199](https://doi.org/10.1080/02827581.2011.553199)

D1.3.7 ([Link to eRoom](#))

### ***Abstract***

To achieve optimal utilisation of logging residues for energy, it is important to know how different handling and storage methods affect fuel properties. The aim of this study was to model how the moisture content and dry matter losses of logging residues develop during storage. Logging residues were collected from five different stands of spruce and pine during different seasons of the year and stored in the same location. The logging residues were stored in covered piles of bundled residues and loose residues. Only minor differences were found in the moisture content profiles between piles of bundles and loose residues. Logging residues located in the centre of both types of piles had considerably lower moisture content than the outer parts. The moisture content significantly affected dry matter loss, with the highest dry matter losses being found in the samples with the least favourable drying conditions. The dry matter losses varied between 1 and 3% per month. Significantly higher dry matter losses were found in the spruce bundles than in the pine bundles. Seasoned logging residues had the lowest dry matter loss, while the logging residues harvested and piled in the autumn had the highest loss.

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**SP2/SP3: CONVERSION MECHANISMS AND TECHNOLOGIES**

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- 2013 -

***Large-Eddy Simulation of the Flow Over a Circular Cylinder at Reynolds Number  $2 \times 10^4$*** 

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*Flow, Turbulence and Combustion*  
*September 2013*

DOI: [10.1007/s10494-013-9509-1](https://doi.org/10.1007/s10494-013-9509-1)

D2.1.19 ([Link to eRoom](#))

***Abstract***

The flow over a circular cylinder at Reynolds number  $2 \times 10^4$  was predicted numerically using the technique of large-eddy simulation (LES). Both incompressible and compressible flow formulations were used. The present results obtained at a low-Mach number ( $M = 0.2$ ) revealed significant inaccuracies like spurious oscillations of the compressible flow solution. A detailed investigation of such phenomena was carried out. It was found that application of blended central-difference or linear-upwind schemes could damp artificial waves significantly. However, this type of schemes has a too dissipative nature compared to pure central-differences. The incompressible flow results were found to be consistent with the existing numerical studies as well as with the experimental data. Basic flow features and flow mechanics were found to be in good agreement with existing experimental data and consistent with previously obtained LES. Special emphasis was put on the spectral analysis. Here, the classical Fourier transform as well as the continuous wavelet transform were applied. Based on the latter, the separated shear-layer instability was precisely clarified. It was found that the Reynolds number dependency between vortex shedding and shear-layer instabilities had a power law relation with  $n = 0.5$ .

## ***Investigation of Biomass Ash Sintering Characteristics and the Effect of Additives***

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*Energy Fuels*,  
November 4, 2013

DOI: [10.1021/ef401521c](https://doi.org/10.1021/ef401521c)  
D2.1.13\_10 ([Link to eRoom](#))

### ***Abstract***

In this work, the effects of three additives (sewage sludge, marble sludge, and clay sludge) on the sintering behaviors of two types of biomass ash (wheat straw and wood waste ash) were investigated. The ability of the additives to abate sintering was evaluated by performing standard ash fusion characterization and laboratory-scale sintering tests on mixtures of biomass ash and additives. The possible mechanisms underlying the anti-sintering effects of the additives were examined using a combination of X-ray diffraction (XRD) and scanning electron microscopy–energy-dispersive X-ray spectrometry (SEM–EDX) analyses of residues from the sintering tests. The best anti-sintering effect was achieved when marble sludge was used. The diluting effect of the marble sludge on the biomass ashes is considered to be the main reason for the decreased degree of ash sintering. In addition, Ca from the marble sludge may promote the formation of high-temperature melting silicates and phosphates with low K/Ca ratios. These chemical reactions and consequent products are favorable for reducing ash melt formation and sintering tendency. Sewage sludge served as a suitable additive to mitigate the sintering of the studied biomass ashes. Upon addition of the sewage sludge, compositions of the biomass ash changed from low-temperature melting silicates to high-temperature melting silicates, phosphates, and oxides. The shift of ash chemistry had a considerable positive effect on biomass melting and sintering temperatures. Clay sludge exhibited a poor ability to reduce the sintering tendency of wheat straw ash. Moreover, the addition of clay sludge decreased melting temperatures and caused severe sintering behavior of wood waste ash. SEM–EDX and XRD analyses revealed that, as clay sludge was added, more Si-rich melts were formed in wood waste ash. This occurred because clay sludge provides thermodynamically reactive Si-containing species and promotes the formation of low-melting-temperature alkali silicates.

## ***Influence of drag force correlations on periodic fluidization behavior in Eulerian–Lagrangian simulation of a bubbling fluidized bed***

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*Chemical Engineering Science*  
Volume 95, 24 May 2013, pp. 94–106

DOI: [10.1016/j.ces.2013.03.038](https://doi.org/10.1016/j.ces.2013.03.038)

D2.1.16 ([Link to eRoom](#))

### ***Abstract***

In this paper, an Eulerian–Lagrangian approach, in which the gas flow is solved by the volume-averaged Navier–Stokes equation and the motion of individual particles is obtained by directly solving Newton's second law of motion, is developed within the OpenFOAM framework to investigate the effects of three well-known inter-phase drag force correlations ([Gidaspow, 1994](#) and [Di Felice, 1994](#) and [EHKL, 2006](#)) on the fluidization behavior in a bubbling fluidized bed reactor. The inter-particle and particle–wall collisions are modeled by a soft-sphere model which expresses the contact forces with the use of a spring, dashpot and friction slider. The simulation results are analyzed in terms of particle flow pattern, bed expansion, bed pressure drop and fluctuation frequency. Qualitatively, formation of bubbles and slugs and the process of particle mixing are observed to occur for all the drag models, although the Gidaspow model is found to be most energetic and the Di Felice and EHKL models yield minor difference. The flow behavior also shows a strong dependency on the restitution coefficient  $e$  and the friction coefficient  $\mu$  and no bubbling and slugging occur at all for the ideal-collision case ( $e=1$ ,  $\mu=0$ ). Quantitatively, the mean pressure drops predicted by the three models agree quite well with each other and the amplitudes of the fluctuations measured by the standard deviation are also comparable. However, a significant difference in fluctuation frequency is found and the Gidaspow model predicts a lowest fluctuation frequency whereas the Di Felice model gets a highest one. Finally, effects of the spring stiffness and the discontinuity in the Gidaspow model are studied. The results show that both mean bed pressure drop and fluctuation frequency slightly decrease as the spring stiffness increases for all the three drag models and no significant differences are observed in the mean bed pressure drop and fluctuation frequency between the Gidaspow model and the linear continuous model.

## ***The effect of peat ash addition to demolition wood on the formation of alkali, lead and zinc compounds at staged combustion conditions***

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*Fuel Processing Technology*

*Volume 105, January 2013, pp. 20–27*

DOI: [10.1016/j.fuproc.2011.04.035](https://doi.org/10.1016/j.fuproc.2011.04.035)

D2.1.13\_3 ([Link to eRoom](#))

### ***Abstract***

Combustion experiments were performed in a multi-fuel reactor with continuous feed of pellets by applying staged air combustion. Total characterization of the elemental composition of the fuel, the bottom ash and some particle size stages of fly ash was performed. This was done in order to follow the fate of some of the problematic compounds in demolition wood as a function of peat-ash addition and other combustion related parameters. A method was developed to estimate the composition and speciation of the salt part of aerosols based on SEM/EDX analysis. The results show that the concentrations of zinc and lead account for 40–50% of the salts produced for the small particles (0.093 µm) and up to 90% for the larger particles (1.59 µm). A considerable part of these metals are chemically bound to chlorides and sulfates together with potassium and sodium indicating extensive volatilization of zinc and lead. The experiments show that the reactions of potassium, zinc and lead are the most affected. This gives rise to higher concentrations of zinc and lead in the aerosols. The chloride content in the aerosols decreases with increased peat ash addition. This will have an inhibiting effect on corrosion, but the higher Zn and especially Pb concentrations will lead to a lower first melting point of the aerosol particles. This may promote deposition and cause corrosion.

## ***Automatic generation of kinetic skeletal mechanisms for biomass combustion***

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*Energy & Fuels*

2013, 27 (11), pp. 6979–6991

DOI: [10.1021/ef400949h](https://doi.org/10.1021/ef400949h)

D2.1.8 ([Link to eRoom](#))

### ***Abstract***

We present in this paper simplified chemical mechanisms for gas phase biomass combustion based on automatic reduction of detailed and comprehensive kinetics. The reduction method that has been employed is a combined reaction flow and sensitivity analysis well-known to combustion, resulting in a *necessity index* ranking all chemical species for automatic reduction. The objective is to obtain more compact chemical models, so-called skeletal mechanisms, for implementation into computational fluid dynamics, CFD, in order to reduce computational time. In the current work, the physical system used for the development and validation of the chemical models is that of a tubular reactor, or plug flow reactor, with operating conditions typically found in biomass reactors. The focus has been on gas phase reactions only, and the fuel composition is based on experimental values from biomass and coal gasification. Emphasis has been on the reliability of the simplified models and the correct prediction of important emission parameters such as NO<sub>x</sub> and important intermediate species. The original chemical model, consisting of several sub models for important reaction paths known in biomass combustion, contained 81 species and 1401 reactions. This was successfully reduced down to 36 species, providing a compact and reliable chemical model for implementation into CFD. The model still contains the reaction paths of C<sub>2</sub> species, allowing for more realistic fuel gas compositions. The model has been experimentally validated for a wide range of temperatures including low temperature chemistry and reducing conditions for NO<sub>x</sub>. The computational time saved using the simplified models was significant with over 80% reduction in CPU time.

## ***The smart biofuels of the future***

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*Biofuels*

*March 2013, Vol. 4, No. 2, pp. 159-161*

DOI: [10.4155/bfs.12.91](https://doi.org/10.4155/bfs.12.91)

D2.3.11 ([Link to eRoom](#))

### ***First paragraphs***

From the dawn of civilization mankind have utilized bioenergy and enjoyed the coziness of open fire. Knowledge and care about energy efficiency and emissions, not to mention sustainability, is something that has developed only very recently in the bioenergy history. Today a wide variety of biofuels exist – solid, liquid and gaseous – and it is not straightforward to select the right fuel for the right purpose. Liquid biofuels is a hot topic these days, brought forward by the future lack of fossil fuel certainty and the awareness of a fast-increasing GHG effect. In the future, we will need something other than fossil gasoline or diesel to fuel our motorized vehicles, but it is the fast-increasing GHG effect that is the main driver today.

Biomass can, in principle, be used to produce any kind of biofuel, through mechanical, thermal and/or chemical upgrading. Mechanically you can upgrade physically impractical biomass to pellets as a physically well defined, transport friendly, quite energy dense and versatile biofuel. Thermal upgrading opens up a wide variety of possibilities through thermal processes such as torrefaction (dry and wet [in hot compressed water]), pyrolysis, carbonization, gasification and liquefaction. Adding chemical upgrading into the picture, a number of transport fuels can be produced from biomass (e.g., diesel, ethanol, CH<sub>4</sub>, dimethyl ether and hydrogen). In principle, any kind of biomass can be used in these thermal and chemical processes. In practice there are, or should be, some limitations. The question arises, which biofuels will be the smart biofuels of the future?

## ***Is Elevated Pressure Required to Achieve a High Fixed-Carbon Yield of Charcoal from 2 Biomass? Part 2: The Importance of Particle Size***

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*Energy & Fuels*

2013, 27 (4), pp. 2146–2156

DOI: [10.1021/ef400041h](https://doi.org/10.1021/ef400041h)

D2.3.6 ([Link to eRoom](#))

### ***Abstract***

The prosperity of Silicon Valley is built upon a foundation of wood charcoal that is the preferred reductant for the manufacture of pure silicon from quartz. Because ordinary pyrolysis processes offer low yields of charcoal from wood, the production of silicon makes heavy demands on the forest resource. The goal of this paper is to identify process conditions that improve the yield of charcoal from wood. To realize this goal, we first calculate the theoretical fixed-carbon yield of charcoal by use of the elemental composition of the wood feedstock. Next, we examine the influence of particle size, sample size, and pressure on experimental values of the fixed-carbon yields of the charcoal products and compare these values with the calculated theoretical limiting values. The carbonization by thermogravimetric analysis of small samples of small particles of wood in open crucibles delivers the lowest fixed-carbon yields, closely followed by standard proximate analysis procedures that employ a closed crucible and realize somewhat improved yields. The fixed-carbon yields (as determined by thermogravimetry) improve as the sample size increases and as the particle size increases. Further gains are realized when pyrolysis occurs in a closed crucible that hinders the egress of volatiles. At atmospheric pressure, high fixed-carbon yields are obtained from 30 mm wood cubes heated in a closed retort under nitrogen within a muffle furnace. The highest fixed-carbon yields are realized at elevated pressure by the flash carbonization process. Even at elevated pressure, gains are realized when large particles are carbonized. These findings reveal the key role that secondary reactions, involving the interaction of vapor-phase pyrolysis species with the solid substrate, play in the formation of charcoal. Models of biomass pyrolysis, which do not account for the impacts of sample size, particle size, and pressure on the interactions of volatiles with the solid substrate, cannot predict the yield of charcoal from biomass. These findings also offer important practical guidance to industry. Size reduction of wood feedstocks is not only energy and capital intensive; size reduction also reduces the yield of charcoal and exacerbates demands made on the forest resource.



## ***Effect of different steam explosion conditions on methane potential and enzymatic saccharification of birch***

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*Bioresource Technology*  
Volume 127, January 2013, pp. 343–349

DOI: [10.1016/j.biortech.2012.09.118](https://doi.org/10.1016/j.biortech.2012.09.118)  
D2.4.9 ([Link to eRoom](#))

### ***Abstract***

Birch (*Betula pubescens*) was steam exploded at 13 different conditions with temperatures ranging from 170 to 230 °C and residence times ranging from 5 to 15 min. Increasing severity in the pretreatment led to degradation of xylan and formation of pseudo-lignin. The effect of the pretreatments was evaluated by running enzymatic saccharification and anaerobic digestion followed by analysis of sugar and methane yields, respectively. Enzymatically released glucose increased with pretreatment severity up to 220 °C for 10 min and levels of solubilized glucose reached 97% of the theoretical maximum. The highest methane yield (369 mL gVS<sup>-1</sup>) was obtained at a severity factor of 4.5 and this yield was 1.8 times higher than the yield from untreated birch. Enzymatic glucose yields and methane yields were generally correlated. The results indicate that steam-exploded birch can be effectively converted to either glucose or methane.

## ***Kinetic behavior of torrefied biomass in an oxidative environment***

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*Energy & Fuels*, 2013, 27 (2), pp. 1050–1060

DOI: [10.1021/ef3019222](https://doi.org/10.1021/ef3019222)

D2.5.1\_2 ([Link to eRoom](#))

### ***Abstract***

The combustion of four torrefied wood samples and their feedstocks (birch and spruce) was studied at slow heating programs, under well-defined conditions by thermogravimetry (TGA). Particularly low sample masses were employed to avoid the self-heating of the samples because of the huge reaction heat of the combustion. Linear, modulated, and constant reaction rate (CRR) temperature programs were employed in the TGA experiments in gas flows of 5 and 20% O<sub>2</sub>. In this way, the kinetics was based on a wide range of experimental conditions. The ratio of the highest and lowest peak maxima was around 50 in the experiments used for the kinetic evaluation. A recent kinetic model by Várhegyi et al. (Várhegyi, G.; Sebestyén, Z.; Czégény, Z.; Lezsovits, F.; Könczöl, S. *Energy Fuels* 2012, 26, 1323–1335) was employed with modifications. This model consists of two devolatilization reactions and a successive char burnoff reaction. The cellulose decomposition in the presence of oxygen has a self-accelerating (autocatalytic) kinetics. The decomposition of the non-cellulosic parts of the biomass was described by a distributed activation model. The char burnoff was approximated by power-law (*n*-order) kinetics. Each of these reactions has its own dependence upon the oxygen concentration that was expressed by power-law kinetics too. The complexity of the applied model reflects the complexity of the studied materials. The model contained 15 unknown parameters for a given biomass. Part of these parameters could be assumed common for the six samples without a substantial worsening of the fit quality. This approach increased the average experimental information for an unknown parameter by a factor of 2 and revealed the similarities in the behavior of the different samples.

## ***Thermal decomposition kinetics of woods with emphasis on torrefaction***

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*Energy & Fuels*, 2013, 27 (10), pp. 6134–6145

DOI: [10.1021/ef4016075](https://doi.org/10.1021/ef4016075)

D2.5.2 ([Link to eRoom](#))

### ***Abstract***

The pyrolysis kinetics of Norwegian spruce and birch wood was studied to obtain information on the kinetics of torrefaction. Thermogravimetry (TGA) was employed with nine different heating programs, including linear, stepwise, modulated and constant reaction rate (CRR) experiments. The 18 experiments on the 2 feedstocks were evaluated simultaneously via the method of least-squares. Part of the kinetic parameters could be assumed common for both woods without a considerable worsening of the fit quality. This process results in better defined parameters and emphasizes the similarities between the woods. Three pseudo-components were assumed. Two of them were described by distributed activation energy models (DAEMs), while the decomposition of the cellulose pseudo-component was described by a self-accelerating kinetics. In another approach, the three pseudo-components were described by  $n$ -order reactions. Both approaches resulted in nearly the same fit quality, but the physical meaning of the model, based on three  $n$ -order reactions, was found to be problematic. The reliability of the models was tested by checking how well the experiments with higher heating rates can be described by the kinetic parameters obtained from the evaluation of a narrower subset of 10 experiments with slower heating. A table of data was calculated that may provide guidance about the extent of devolatilization at various temperature–residence time values during wood torrefaction.

## ***A comparative assessment of wet torrefaction***

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*Energy & Fuels*, 2013, 27 (11), pp 6743–6753

DOI: [10.1021/ef401295w](https://doi.org/10.1021/ef401295w)

D2.5.3 ([Link to eRoom](#))

### ***Abstract***

Wet torrefaction of typical Norwegian biomass fuels was studied within the temperature window of 175–225 °C, using a benchtop autoclave reactor of 250 mL in volume from Parr Instrument. Two types of local biomass fuels were employed as feedstock, Norway spruce (softwood) and birch (hardwood). Effects of process parameters including pressure, reaction temperature, holding time, and feedstock particle size on the yield and properties of the solid products were investigated. It appears that birch wood is more reactive and produces less solid products than spruce wood in the same wet torrefaction conditions. Increasing pressure above the saturated vapor pressure of water enhances the torrefaction rate. Both reaction temperature and holding time have significant effects on solid product yield and fuel properties of wet torrefied biomass. The yield of solid products is slightly reduced with decreasing feedstock particle size. The ash content of biomass fuel is significantly reduced by wet torrefaction. In addition, a comparison between wet and dry torrefaction supported by regression analyses and numerical predictions shows that wet torrefaction can produce solid fuels with greater heating values at much lower temperatures and shorter holding times.

## ***Modeling of turbulent separated flows using OpenFOAM***

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*Computers and Fluids*

*Volume 80, 10 July 2013, pp. 408–422*

DOI: [10.1016/j.compfluid.2012.01.015](https://doi.org/10.1016/j.compfluid.2012.01.015)

D2.1.13\_11 ([Link to eRoom](#))

### ***Abstract***

Turbulent separated planar bluff-body flows were numerically analyzed using the state-of-the-art OpenFOAM and ANSYS FLUENT technologies, based on the conventional URANS approach. Several popular in fluid dynamics test problems such as laminar and turbulent flows over a circular cylinder and turbulent fully developed flows over a triangular cylinder in a channel were numerically replicated with the goal of validation of the selected numerical methods. The detailed, face-to-face comparison between OpenFOAM, FLUENT and experimental data was discussed. Parallel performance in the terms of a strong and weak scalability was assessed up to 1024 cores and compared as well. In general, the present results demonstrated minimum deviations between OpenFOAM and FLUENT and agreed fairly well with the experimental data and other numerical solutions.

- 2012 -

## ***Numerical investigation of particles turbulent dispersion in channel flow***

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*Thermal Science*

*Volume 16, Issue 5, pp. 1510-1514*

DOI: [10.2298/TSCI1205510L](https://doi.org/10.2298/TSCI1205510L)

D2.1.18 ([Link to eRoom](#))

### ***Abstract***

This paper investigates the performance of Reynolds-averaged Navier-Stokes model on dispersion of particles in wall turbulence. A direct numerical simulation of wall-bounded channel flow with particles suspensions was set as a benchmark. The standard  $k-\omega$  model coupled with two different eddy interaction models was used in Reynolds-averaged Navier-Stokes model and compared to the direct numerical simulation. Detailed comparisons between direct numerical simulation and Reynolds-averaged Navier-Stokes model on particle distribution evolving over time were carried out.

## ***Eulerian-Lagrangian simulation of a bubbling fluidized bed reactor: Assessment of drag force correlations***

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*Thermal Science*

*Year 2012, Vol. 16, No. 5, pp. 1442-1445*

DOI: [10.2298/TSCI1205442K](https://doi.org/10.2298/TSCI1205442K)

D2.1.17 ([Link to eRoom](#))

### ***Abstract***

An Eulerian-Lagrangian approach is developed within the OpenFOAM framework to investigate the effects of three well-known inter-phase drag force correlations on the fluidization behavior in a bubbling fluidized bed reactor. The results show a strong dependency on the restitution coefficient and the friction coefficient and no occurrence of bubbling and slugging for the ideal-collision case. The mean pressure drops predicted by the three models agree quite well with each other.

## ***Enhanced NO<sub>x</sub> Reduction by Combined Staged Air and Flue Gas Recirculation in Biomass Grate Combustion***

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*Energy & Fuels*  
2012, 26 (5), pp. 3003–3011

DOI: [10.1021/ef300199g](https://doi.org/10.1021/ef300199g)  
D\_KRAV: ([Link to eRoom](#))

### ***Abstract***

Flue gas recirculation (FGR) is a conventional means of reducing NO<sub>x</sub> emissions that involves lowering the peak flame temperature and reducing the oxygen concentration in the combustion region. Staged air combustion is also an effective means of NO<sub>x</sub> reduction, especially in biomass combustion. This article reports results on NO<sub>x</sub> emissions in a set of experiments combining FGR and staged air combustion in a grate-fired laboratory-scale reactor. Two different compositions of the recirculated flue gas were used: CO<sub>2</sub> and CO<sub>2</sub> + NO. The CO<sub>2</sub> concentration varied between 0–8 vol % of the total inlet flow rate and the NO concentration varied between 0 and 64 ppm. Two different FGR locations were also tested: above and below the grate. The results are compared with a reference experiment performed without FGR. The NO<sub>x</sub> reduction level from staged air combustion at the optimal primary excess air ratio is ~70%, while employing FGR can reduce the NO<sub>x</sub> emissions by an additional 5%–10%. The optimal primary excess air ratio range is 0.9–1. However, FGR more effectively reduces NO<sub>x</sub> when employed outside of the optimum primary excess air ratio range, i.e., excess air ratios higher than 1 and less than 0.9. The experiments with FGR located above the grate exhibit higher reduction potential, while FGR located below the grate produces decreased reduction. The recycled-NO conversion factor, which gives a measure of maximal FGR efficiency, at the maximum point, is nearly 100% when FGR is applied below the grate and is 85%–100% in the case of recirculation above the grate.



## ***NO<sub>x</sub> Emission Reduction by Staged Combustion in Grate Combustion of Biomass Fuels and Fuel Mixtures***

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*Fuel*

*Volume 98, August 2012, pp. 29–40*

DOI: [10.1016/j.fuel.2012.03.044](https://doi.org/10.1016/j.fuel.2012.03.044)

D\_KRAV ([Link to eRoom](#))

### ***Abstract***

NO<sub>x</sub> and N<sub>2</sub>O emissions have been investigated for different pelletized biomass fuels and fuel mixtures thereof both with and without air staging in a grate fired multi-fuel reactor. The fuels investigated are wood, demolition wood and coffee waste, and selected mixtures of these. The multi-fuel reactor was operated at close to constant operating conditions due to impactor (ELPI) measurements, with a total excess air ratio of about 1.6, and a primary excess air ratio of about 0.8 in the air staging experiments. The reactor set point temperature was held constant at 850 °C. NO<sub>x</sub> emission levels as a function of air supply mode and fuel nitrogen content are reported, showing a large NO<sub>x</sub> reduction potential, up to 91% and corresponding to less than 20 ppm NO<sub>x</sub> at 11% O<sub>2</sub> for a fuel containing about 3 wt.% fuel-N, using air staging. The effect on N<sub>2</sub>O, however, is adverse at the selected set point temperature and optimum primary excess air ratio for NO<sub>x</sub> reduction. The effect of fuel mixing and fuel nitrogen content on the conversion of fuel nitrogen to NO<sub>x</sub> is also reported and discussed. Fuel mixing has a positive influence on the NO<sub>x</sub> emission level, but a negative influence on the overall conversion factor for fuel-N to NO<sub>x</sub> and N<sub>2</sub>O.

## ***Reduced Chemical Kinetics Mechanisms for NO<sub>x</sub> Emission Prediction in Biomass Combustion***

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*International Journal of Chemical Kinetics*  
Volume 44, Issue 4, April 2012, pp. 219–231

DOI: [10.1002/kin.20716](https://doi.org/10.1002/kin.20716)

D\_KRAV ([Link to eRoom](#))

### ***Abstract***

Because of the complex composition of biomass, the chemical mechanism contains many different species and therefore a large number of reactions. Although biomass gas-phase combustion is fairly well researched and understood, the proposed mechanisms are still complex and need very long computational time and powerful hardware resources. A reduction of the mechanism for biomass volatile oxidation has therefore been performed to avoid these difficulties. The selected detailed mechanism in this study contains 81 species and 703 elementary reactions. Necessity analysis is used to determine which species and reactions are of less importance for the predictability of the final result and, hence, can be discarded. For validation, numerical results using the derived reduced mechanism are compared with the results obtained with the original detailed mechanism. The reduced mechanism contains much fewer reactions and chemical species, that is, 35 species and 198 reactions, corresponding to 72% reduction in the number of reactions and, therefore, improving the computational time considerably. Yet, the model based on the reduced mechanism predicts correctly concentrations of NO<sub>x</sub> and CO that are essentially identical to those of the complete mechanism in the range of reaction conditions of interest, especially for the medium-temperature range. The reduced mechanism failed to predict the concentrations in the high- and low-temperature range. Therefore, two more reduced mechanisms are also proposed for the high- and low-temperature range with 26 and 52 species, respectively. The modeling conditions are selected in a way to mimic values in the range of temperature 700–1400°C, excess air ratio 0.8–3.3, and four different residence times: 1, 0.1, 0.01, and 0.001 s, since these variables are the main affecting parameters on NO<sub>x</sub> emission.

## ***Experimental Investigation on NO<sub>x</sub> Reduction by Primary Measures in Biomass Combustion: Straw, Peat, Sewage Sludge, Forest Residues, and Wood Pellets***

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*Energies*

2012, 5, 270-290

DOI: [10.3390/en5020270](https://doi.org/10.3390/en5020270)

D\_KRAV ([Link to eRoom](#))

### ***Abstract***

An experimental investigation was carried out to study the NO<sub>x</sub> formation and reduction by primary measures for five types of biomass (straw, peat, sewage sludge, forest residues/Grot, and wood pellets) and their mixtures. To minimize the NO<sub>x</sub> level in biomass-fired boilers, combustion experiments were performed in a laboratory scale multifuel fixed grate reactor using staged air combustion. Flue gas was extracted to measure final levels of CO, CO<sub>2</sub>, C<sub>x</sub>H<sub>y</sub>, O<sub>2</sub>, NO, NO<sub>2</sub>, N<sub>2</sub>O, and other species. The fuel gas compositions between the first and second stage were also monitored. The experiments showed good combustion quality with very low concentrations of unburnt species in the flue gas. Under optimum conditions, a NO<sub>x</sub> reduction of 50–80% was achieved, where the highest reduction represents the case with the highest fuel-N content. The NO<sub>x</sub> emission levels were very sensitive to the primary excess air ratio and an optimum value for primary excess air ratio was seen at about 0.9. Conversion of fuel nitrogen to NO<sub>x</sub> showed great dependency on the initial fuel-N content, where the blend with the highest nitrogen content had lowest conversion rate. Between 1–25% of the fuel-N content is converted to NO<sub>x</sub> depending on the fuel blend and excess air ratio. Sewage sludge is suggested as a favorable fuel to be blended with straw. It resulted in a higher NO<sub>x</sub> reduction and low fuel-N conversion to NO<sub>x</sub>. Tops and branches did not show desirable NO<sub>x</sub> reduction and made the combustion also more unstable. N<sub>2</sub>O emissions were very low, typically below 5 ppm at 11% O<sub>2</sub> in the dry flue gas, except for mixtures with high nitrogen content, where values up to 20 ppm were observed. The presented results are part of a larger study on problematic fuels, also considering ash content and corrosive compounds which have been discussed elsewhere.

## ***Cost modeling approach and economic analysis of biomass gasification integrated solid oxide fuel cell systems***

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*Journal of Renewable and Sustainable Energy*  
Volume 4, Issue 4

DOI: [10.1063/1.4737920](https://doi.org/10.1063/1.4737920)

D\_KRAV ([Link to eRoom](#))

### ***Abstract***

This paper presents a cost modeling approach and the economic feasibility for selected plant configurations operating under three modes: air gasification, mixed air-steam gasification, and steam gasification combined cycle solid oxide fuel cell(SOFC)systems. In this study, three cases of biomass gasification integrated SOFC without combined cycle (base case 1) are compared with biomass gasification integrated SOFC-gas turbine (GT) with heat recovery steam generator (HRSG) hybrid configuration (case 2) and biomass gasification integrated SOFC-steam turbine (ST) cycle (case 3) for biomass feed stock. The plant design cases of integrated biomass gasification processes, SOFC, and combined cycles are investigated primarily employing aspen plus™ flow sheeting models. Based on the mass and energy balance results of the system simulations, the economic model calculates the size and cost estimates for the plant configuration equipments. Detailed purchase cost estimations for each piece of equipments and the corresponding total bare module cost were established based on the bare module factor, and the total direct permanent investment were established. The calculated direct permanent investment was used for economic feasibility analysis of the cogeneration plant configuration. The economic feasibility decision parameters, such as purchase cost estimations, total specific plant cost per kW, the financial net present value (FNPV), internal rate of return, and benefit to cost ratio for the system configurations were compared for three design cases. The results shows that the cost of the steam gasification system is shown to be highest compared to the mixed air steam gasification system and air gasification system due to the higher hydrogen production. Other than the SOFC and gasification costs, a significant cost towards the heat exchangers is about 15% to 20% of the total equipment purchase cost. The specific plant cost for the air gasification varied from the 16 600 US\$/kW to 19 200 US\$/kWe. For the case of biomass gasification-integrated SOFC-GT configuration, the major cost portions are shared by the SOFC, HRSG, and gasifier. The HRSG equipment shared a cost portion of 25% to 30% for all the operating modes. The cost is decreased with a similar trend as that of steam, mixed air-steam and air gasification systems. For the case of biomass gasification integrated with SOFC-ST configuration, the total equipment purchase cost decreases at a rate of 15% to 20% for both mixed air steam and air gasification system. Plant specific cost for the steam gasification mode varied from 15 200 to 17 200 US \$/kW which is significantly very high.

## ***Techno-economic evaluations of various Biomass CHP technologies and policy measures under Norwegian conditions***

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*Energy Procedia*

*Volume 20, 2012, pp. 1–10*

DOI: [10.1016/j.egypro.2012.03.002](https://doi.org/10.1016/j.egypro.2012.03.002)

D\_KRAV ([Link to eRoom](#))

### ***Abstract***

This work deals with evaluations of different possible cost-effective small-scale combined heat and power (CHP) solutions based on biomass for the Norwegian market. Many CHP technologies and systems exist and can easily be proposed as candidates for introduction and/or widespread use in the Norwegian market. However, today they may be far from cost-effective given the current energy market and framework situation. These constraints can, however, change relatively fast. Hence, it is important to evaluate the feasibility of small-scale CHP technologies and systems in this perspective. What will the most promising small-scale CHP technologies based on biomass be in the near to medium term future? What are the limiting factors? What can be done to speed up the introduction of small-scale CHP solutions based on biomass in the Norwegian market? This work evaluates techno-economics of various CHP solutions based on biomass in the Norwegian market. Traditional financial indicators such as financial internal rate of return and net present value are used to assess the solutions. The methodology includes the following sequential steps: estimation of the economic production costs of various options for biomass CHP for power and heat generation and sorting these options in ascending order of costs to present the supply curve to meet the national target. Finally, the analysis includes various incentive schemes, feed-in tariffs/green certificates, investment based tax exemptions (8 years for each technology), prolonged tax exemption (+5 years for each technology), investment subsidies (in % for each technology) and low-interest loans (decided for each technology). Based on the evaluations, MSW backpressure turbine, biogas engine and industrial backpressure turbine are profitable without any subsidy under Norwegian framework conditions. With additional subsidy from grid deduction fee and green certificates, district heat ORC, district heat backpressure turbine and gasification with micro gas turbine are feasible with profitability of internal rate of return above 11%. Other gasification technologies are feasible under prevailing market conditions. In addition, a cost supply curve is generated for 10 years framework conditions based on the planned CHP installations.

## ***Process synthesis and economics of combined biomethanol and CHP energy production derived from biomass wastes***

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*Journal of chemical technology and biotechnology*

July 2012, Volume 87, Issue 7, pp. 897–902

DOI: [10.1002/jctb.3696/abstract](https://doi.org/10.1002/jctb.3696/abstract)

D\_KRAV ([Link to eRoom](#))

### ***Abstract***

**BACKGROUND:** This paper reports on process synthesis and economics of combined methanol and CHP (combined heat and power) energy production from crude biooil, waste glycerol produced in biodiesel factories and biomass wastes using integrated reactor design for hydrogen rich syngas. This new process consists of three process steps: (a) pyrolysis of organic waste material to produce biooil, char and pyrogas; (b) steam assisted hydrogasification of the crude glycerol wastes, biooil mixed with pyrogas for hydrogen rich gas; and (c) a low temperature methanol synthesis process. The H<sub>2</sub>-rich gas remaining after methanol synthesis is recycled back to the pyrolysis reactor, the catalytic hydro-gasification process and the heat recovery steam generator (HRSG).

**RESULTS:** The breakeven price of the Hbiomethanol process yields positive net financial NPV and IRR above 600 USD per tonne. The total capital cost for a small-scale methanol plant of capacity 2 tonne h<sup>-1</sup> combined with a cogeneration plant of capacity 2 MWe power is estimated to be 170.5 million USD.

**CONCLUSION:** Recycling gas allows the methanol synthesis reactor to perform at a relatively lower pressure than conventionally while the plant still maintains a high methanol yield. The integrated hydrogasification reactor and energy recovery design process minimizes heat loss and increases the process thermal efficiency. The Hbiomethanol process can convert any condensed carbonaceous material and liquid wastes, to produce methanol and CHP. Copyright © 2012 Society of Chemical Industry

## ***Large-eddy simulation of the flow over a circular cylinder at Reynolds number 3900 using the OpenFOAM toolbox***

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Springer

December 2012, Volume 89, Issue 4, pp. 491-518

DOI: [10.1007/s10494-012-9405-0](https://doi.org/10.1007/s10494-012-9405-0)

D2.1.13\_12 ([Link to eRoom](#))

### ***Abstract***

The flow over a circular cylinder at Reynolds number 3900 and Mach number 0.2 was predicted numerically using the technique of large-eddy simulation. The computations were carried out with an O-type curvilinear grid of size of  $300 \times 300 \times 64$ . The numerical simulations were performed using a second-order finite-volume method with central-difference schemes for the approximation of convective terms. A conventional Smagorinsky and a dynamic  $k$ -equation eddy viscosity sub-grid scale models were applied. The integration time interval for data sampling was extended up to 150 vortex shedding periods for the purpose of obtaining a fully converged mean flow field. The present numerical results were found to be in good agreement with existing experimental data and previously obtained large-eddy simulation results. This gives an indication on the adequacy and accuracy of the selected large-eddy simulation technique implemented in the OpenFOAM toolbox.

## ***Sintering Characteristics of Sewage Sludge Ashes at Elevated Temperatures***

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*Fuel Processing Technology*  
Volume 96, April 2012, pp. 88–97

DOI: [10.1016/j.fuproc.2011.12.022](https://doi.org/10.1016/j.fuproc.2011.12.022)  
D2.1.13\_13 ([Link to eRoom](#))

### ***Abstract***

In this work the sintering characteristics and mineral transformation behaviors of sewage sludge ash (SSA) at elevated temperatures were investigated by using ash fusion analyzer, X-ray fluorescence (XRF), X-ray diffraction (XRD) and scanning electron microscopy equipped with energy dispersive X-ray spectrometry (SEM/EDX). High initial fusion temperatures above 1100 °C were detected from the sewage sludge ashes (SSA 1 and SSA 2) with high Al contents. Corundum, quartz and calcium aluminum silicates were dominating crystalline phases identified from SSA 1 and SSA 2 sintered at elevated temperatures. For the SSA 3 with a high Fe content, low initial melting temperature of 994 °C was detected with observation of severe fusion behavior from the ash sintering tests. SEM analysis revealed that SSA 3 melted completely into a more homogeneous and continuous phase at high sintering temperatures. A significant amount of Fe bearing mineral phases and quartz (SiO<sub>2</sub>) was identified from the sintered SSA 3. Diffraction intensities of hematite (Fe<sub>2</sub>O<sub>3</sub>), quartz (SiO<sub>2</sub>) and alkali feldspar decreased with increasing sintering temperatures, suggesting interaction and re-assembly of these mineral phases. In combining the XRD and SEM/EDX analyses, it is believed that formation of low melting temperature iron silicates is the main reason for sintering of SSA 3.



## ***Sintering Characteristics and Mineral Transformation Behaviors of Corn Cob Ashes***

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*Energy & Fuels*  
2012, 26 (9), pp. 5905–5916

DOI: [10.1021/ef300215x](https://doi.org/10.1021/ef300215x)  
D2.1.13\_14 ([Link to eRoom](#))

### ***Abstract***

The aim of this work was to investigate the sintering characteristics and mineral transformation behaviors of three corn cob ashes using a combination of inductively coupled plasma–atomic emission spectroscopy (ICP–AES), ash fusion analysis, X-ray diffraction (XRD), and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDX). The sintering degrees of the corn cob ashes at elevated temperatures were graded by performing laboratory-scale sintering tests. The WCob ash has a significantly low melting temperature of 834 °C and showed severe sintering behaviors during testing. The SEM–EDX and XRD analyses revealed that the fused WCob ash consisted of a mixture of potassium-rich silicate–phosphate melts. The WCob is dominated by potassium, silicon, and phosphorus, along with small amounts of alkali earth metals. Therefore, the formation and melting of potassium-rich silicates and phosphates are favored, causing severe sintering of the WCob ash at elevated temperatures. In contrast, a relatively higher melting temperature of 998 °C and a moderate sintering degree were observed from the PCob ash. High contents of chlorine, calcium, and magnesium in the PCob may promote potassium release from ash residues, instead of being incorporated into the silicate and phosphate structures. This process could inhibit the formation of low-temperature-melting silicates and phosphates and reduce ash sintering consequently. The abundance of calcium and magnesium in the PCob also led to the formation of high-temperature-melting silicates and phosphates, restraining ash melt formation and the extent of ash sintering. Results from the experimental work and analyses indicate that the combustion of corn cob may be challenging because of ash sintering. The transformation and melting behaviors of corn cob ashes are highly dependent upon the fuel compositions.

## ***Thermal Characterization of Uganda's Acacia Hockii, Combretum Molle, Eucalyptus Grandis and Terminalia Glaucescens for Gasification***

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*Biomass & Bioenergy*

Volume 46, November 2012, pp. 402–408

DOI: [10.1016/j.biombioe.2012.08.001](https://doi.org/10.1016/j.biombioe.2012.08.001)

D2.1.13\_15 ([Link to eRoom](#))

### ***Abstract***

In this paper, thermal characterization of four Ugandan woody biomass species was carried out in order to ascertain their suitability for gasification for small-scale biopower generation. The analyses and tests covered the aspects of proximate analysis, ultimate analysis, heating value, Thermogravimetric Analyses (TGA), ash melting and chemical composition. *Eucalyptus grandis* revealed ideal properties that make it the most promising wood specie for gasification applications. Furthermore, the low ash content in *E. grandis* significantly minimizes the possibilities of ash deposits on the gasifier and heat exchanger surfaces. The high fixed carbon in *Terminalia glaucescens*, *Acacia hockii* and *Combretum molle* makes these species ideal for charcoal making (pyrolysis). Due to high ash melting temperatures demonstrated by these samples, their pyrolysis and gasification can therefore take place with minimal worry of the ash related problems.

## ***The effect of kaolin on the combustion of demolition wood under well-controlled conditions***

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*Waste Management and Research*  
July 2012 vol. 30 no. 7, pp. 672-680

DOI: [10.1177/0734242X11427942](https://doi.org/10.1177/0734242X11427942)

D2.1.13\_2 ([Link to eRoom](#))

### ***Abstract***

In an attempt to look at means for reduction of corrosion in boilers, combustion experiments are performed on demolition wood with kaolin as additive. The experiments were performed in a multi-fuel reactor with continuous feed of pellets and by applying staged air combustion. A total characterization of the elemental composition of the fuel, the bottom ash and some particle size stages of fly ash was performed. This was done in order to follow the fate of some of the problematic compounds in demolition wood as a function of kaolin addition and other combustion-related parameters. In particular chlorine and potassium distribution between the gas phase, the bottom ash and the fly ash is reported as a function of increased kaolin addition, reactor temperature and air staging. Kaolin addition of 5 and 10% were found to give the least aerosol load in the fly ash. In addition, the chlorine concentration in aerosol particles was at its lowest levels for the same addition of kaolin, although the difference between 5 and 10% addition was minimal. The reactor temperature was found to have a minimal effect on both the fly ash and bottom ash properties.

## ***Ash related behaviour in staged and non-staged combustion of biomass fuels and fuel mixtures***

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*Biomass and Bioenergy*

*Volume 41, June 2012, pp. 86–93*

DOI: [10.1016/j.biombioe.2012.02.005](https://doi.org/10.1016/j.biombioe.2012.02.005)

D2.1.13\_5 ([Link to eRoom](#))

### ***Abstract***

The fate of selected elements (with focus on the important players in corrosion i.e. Na, K, Pb, Zn, Cl and S) are investigated for three biomasses (wood, demolition wood and coffee waste) and six mixtures of these as pellets both with and without air staging in a laboratory reactor. In order to get a complete overview of the combustion products, both online and offline analytical methods are used. Information is collected about: flue gas composition, particle (fly ash) size distribution and composition, bottom ash composition and melting properties. The main findings are: (1) complex interactions are taking place between the mixed fuels during combustion; (2) the mode of occurrence of an element as well as the overall structure of the fuel are important for speciation; (3) the pelletisation process, by bringing chemical elements into intimate contact, may affect partitioning and speciation; (4) staging and mixing might simultaneously have positive and negative effects on operation; (5) staging affects the governing mechanisms of fly ash (aerosols) formation.

## ***A Critical Review on Additives to Reduce Ash Related Operation Problems in Biomass Combustion Applications***

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*Energy Procedia*

Volume 20, 2012, pp. 20–29

DOI: [10.1016/j.egypro.2012.03.004](https://doi.org/10.1016/j.egypro.2012.03.004)

D2.1.13\_6 ([Link to eRoom](#))

### ***Abstract***

Biomass combustion has a huge potential to produce power and heat in a sustainable way. However, some biomass fuels have high potassium contents, which react with other ash forming elements (i.e. Cl, Si, P and S) and lead to different ash related operational problems. Utilization of additives to abate these problems have been studied and tested for several decades. This work reviews current knowledge and studies about properties and effects of additives reported in the literature. Various additives can mitigate ash related issues by the following possible mechanisms: 1) capturing problematic ash species via chemical adsorption and reactions, 2) physical adsorption and elutriating troublesome ash species from combustion facilities, 3) increasing the biomass ash melting temperature by enhancing inert elements/compounds in ash residues, and 4) restraining biomass ash sintering by diluting and powdering effects from the additives. Additives are grouped according to the contained reactive compounds, including Al-silicates based additives, sulphur based additives, calcium based additives, and phosphorous based additives. Additives with strong chemical adsorption and reaction capacities can minimize K related ash sintering, deposition and slagging during biomass combustion processes. The effective chemical reaction mechanisms are closely related to K-Al-Si, K-Ca-Si and K-Ca-P systems. The capacities of additives to reduce ash related problems are heavily influenced by mass/molar ratios between the reactive components in the additives and the problematic elements in the biomass ash, as well as the reaction atmosphere and combustion technology. More detailed studies on high temperature reactions between additives and ashes from biomass combustion are needed.

## ***Effects of additives on barley straw and husk ashes sintering characteristics***

<sup>a</sup>Liang Wang, <sup>a</sup>Geir Skjevraak, <sup>a</sup>Johan E. Hustad, <sup>a</sup>Morten G. Grønli, <sup>b</sup>Øyvind Skreiberg

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*Energy Procedia*

*Volume 20, 2012, pp. 30–39*

DOI: [10.1016/j.egypro.2012.03.005](https://doi.org/10.1016/j.egypro.2012.03.005)

D2.1.13\_7 ([Link to eRoom](#))

### ***Abstract***

A growing interest has been observed for producing sustainable heat and power by combustion of residues from local agricultural production. However, ash related problems are inclined to occur due to high contents of problematic ash forming matter in such residues. The aims of this work were to examine ash characteristics of barley straw and husk and to find mixtures of fuels and additives that can be used as basis for producing pellets giving minimal problems during combustion. Influence of kaolin and calcite additives on the two fuel ashes' sintering behaviors were investigated by X-ray fluorescence (XRF), ash fusion analyzer and X-ray diffraction (XRD) analysis. The results showed that, compared to barley straw ash, the barley husk ash has a higher sintering tendency, with observation of severe melting during combustion. Kaolin and calcite addition increased the melting temperatures of ashes from both barley straw and husk. Reactions between kaolin and potassium containing species in the barley straw and husk ashes were revealed by XRD analyses. With formation of high temperature melting species due to kaolin addition, the severe sintering of barley straw and husk ashes were significantly reduced. The dilution effect from calcite is supposed to be a main reason for improved barley straw and husk ash sintering behaviors. In addition, calcite addition led to formation of more calcium rich phases, which have higher melting points and contribute to low ash sintering degrees. Therefore, by using the additives, agricultural residues can be competitive for energy production in the future.

## ***Sintering behavior of agricultural residues ashes and effects of additives***

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SINTEF Energy Research, Sem Sælands vei 11, Trondheim, Norway

*Energy & Fuels*

2012, 26 (9), pp. 5917–5929

DOI: [10.1021/ef3004366](https://doi.org/10.1021/ef3004366)

D2.1.6 ([Link to eRoom](#))

### ***Abstract***

In this work the ash sintering behaviors and effects of aluminum silicates based additives (kaolin, zeolite 24A, and zeolite Y) during combustion of wheat straw and barley husk were investigated. The sintering degrees of fuel ashes and corresponding mixtures with additives were evaluated by performing standard ash fusion tests and laboratory scale sintering tests. The ash chemistry and microstructures were investigated by a combination of X-ray diffraction (XRD) and SEM-EDX analyses. It was found that the wheat straw and barley husk ashes have high sintering and melting tendencies. At elevated temperatures, formation and fusion of low temperature melting potassium salts and potassium silicates contributed to severe sintering of the two fuel ashes. Sintering of the barley husk ash is also associated with the presence of low melting points potassium phosphates with high K/Ca ratios. The experimental results from investigating the reactions between additives and KCl showed that kaolin and zeolite 24A can both bind KCl with formation of different potassium aluminum silicates. No clear reactions between zeolite Y and KCl were observed. Both kaolin and zeolite 24A were effective to increase sintering temperatures of the wheat straw and barley husk ashes. The reactions between kaolin and zeolite 24A with potassium containing species in the two reference ashes were revealed by XRD and SEM-EDX analyses. Identification of high temperature melting potassium aluminum silicates partially explains the higher sintering and melting temperatures of the ash-additives mixtures. Zeolite Y showed a poor ability to abate sintering of the studied ashes in this work.

## ***Kinetics of Corncob Pyrolysis***

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*Energy & Fuels*

2012, 26 (4), pp. 2005–2013

DOI: [10.1021/ef3002668](https://doi.org/10.1021/ef3002668)

D2.3.8 ([Link to eRoom](#))

### ***Abstract***

Two different corncob samples from different continents and climates were studied by thermogravimetry at linear and nonlinear heating programs in inert gas flow. A distributed activation energy model (DAEM) with three and four pools of reactants (pseudocomponents) was used due to the complexity of the biomass samples of agricultural origin. The resulting models described well the experimental data. When the evaluation was based on a smaller number of experiments, similar model parameters were obtained which were suitable for predicting experiments at higher heating rates. This test indicates that the available experimental information was sufficient for the determination of the model parameters. The checks on the prediction capabilities were considered to be an essential part of the model verification. In another test, the experiments of the two samples were evaluated together, assuming more or less common kinetic parameters for both cobs. This test revealed that the reactivity differences between the two samples are due to the differences in their hemicelluloses and extractives. The kinetic parameter values from a similar earlier work on other biomasses (Várhegyi, G.; Bobály, B.; Jakab, E.; Chen, H. *Energy Fuels*, **2011**, 25, 24–32) could also be used, indicating the possibilities of a common kinetic model for the pyrolysis of a wide range of agricultural byproduct.



## ***Impact of steam explosion on biogas production from rape straw in relation to changes in chemical composition***

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*Bioresource Technology*

*Volume 123, November 2012, pp. 608–615*

DOI: [10.1016/j.biortech.2012.06.088](https://doi.org/10.1016/j.biortech.2012.06.088)

D2.4.18 ([Link to eRoom](#))

### ***Abstract***

An 81 day trial compared the cumulative production of methane from rape straw pre-treated by steam explosion at 15 levels of severity. The final methane yields were similar. The temporal variation in production rate exhibited two peaks: maximum production occurred in the first peak at around 21 days with heights that increased with severity; the height of the second peak reduced with severity and peaked between 32 and 36 days. Changes in the straw composition were investigated using mid-infrared spectroscopy. These were also strongly related to the degree of severity, allowing good predictive models to be built of severity and subsequently the rate of methane production. The main spectral changes showed the degradation of cellulose and xylose-containing hemicelluloses and production of furfural-like components commonly associated with biomass pre-treatments. Only small changes to lignin were associated with increased methane generation suggesting a structural rather than chemical role in this process.

## ***Torrefaction of Norwegian birch and spruce – An experimental study using macro-TGA***

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*Energy & Fuels*

2012, 26 (8), pp. 5232–5240

DOI: [10.1021/ef300993q](https://doi.org/10.1021/ef300993q)

D2.5.1\_1 ([Link to eRoom](#))

### ***Abstract***

This work aims to analyze the torrefaction process with Norwegian birch and spruce as feedstocks. Torrefaction experiments were performed in a macro-TGA (thermogravimetric analysis) reactor with provisions for continuous volatile measurements through micro-GC (gas chromatography) and FTIR (Fourier transform infrared spectroscopy). The process temperature (225 and 275 °C), holdup time (30 and 60 min), and sample size (10 and 40 mm cubes) were included as variations in the experimental matrix. Fuel characterizations, DTG (derivative thermogravimetric) curves, product yields, hydrophobicity tests, grinding energies, and particle-size distributions are discussed. The raw fuels were used as a reference for the comparisons. It was found that the birch has a higher devolatilization rate than the spruce under all tested conditions, resulting in a larger percentage increase in its carbon content. An increase in the temperature has the strongest effect on the properties of the torrefied product among all of the studied parameters. At 275 °C, the solid yield decreased to 63% and 75% for the torrefied birch and spruce, respectively. In terms of torrefied product properties, the torrefied samples absorbed approximately one-third of the moisture compared to the raw fuels. The total grinding energy decreased up to 40–88% for the torrefied samples of both feedstocks. An increased percentage of fine particles (<180 μm) was found in the particle-size distributions of most of the torrefied samples. Overall, considerable improvements were observed in the properties of the torrefied products for both feedstocks. Results obtained from this study form the basis of a torrefaction feasibility study in Norway.

- 2011 -

## ***Experimental Investigation on Corrosion Abatement in Straw Combustion by Fuel Mixing***

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*Energy & Fuels*

2011, 25 (6), pp. 2687–2695

DOI: [10.1021/ef200232r](https://doi.org/10.1021/ef200232r)

D2.1.13\_1 ([Link to eRoom](#))

### ***Abstract***

In an attempt to minimize corrosion in biomass-fired boilers, combustion experiments were performed using binary mixtures of straw with peat, sewage sludge, or grot (branches and treetops). The mixing ratios were carefully selected using literature and thermodynamic calculations. All mixtures were pelletized. The combustion experiments were performed in a laboratory-scale multi-fuel reactor. Extensive analytical analysis of the system included the gas concentration and particle size distribution in the flue gas, the elemental composition of the fuel, and the bottom ash and specific particle size fractions of fly ash. This allowed for the determination of the fate of the main corrosive compounds, in particular, chlorine. The corrosion risk associated with the three fuel mixtures was quite different. Grot was found to be a poor corrosion-reduction additive because of its marginal influence on the chlorine share in aerosols. Grot could not serve as an alternative fuel for co-firing with straw either because no dilution effect on the particle load was measured. Peat was found to reduce the corrosive compounds only at high peat additions (50 wt %). Sewage sludge was the best alternative for corrosion reduction because 10 wt % addition almost eliminated chlorine from the fly ash.

## ***Effects of Sewage Sludge and Marble Sludge Addition on Slag Characteristics during Wood Waste Pellets Combustion***

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*Energy & Fuels*

2011, 25 (12), pp. 5775–5785

DOI: [10.1021/ef2007722](https://doi.org/10.1021/ef2007722)

D2.1.13\_16 ([Link to eRoom](#))

### ***Abstract***

The objectives of the present work were to investigate the effects of sewage sludge and marble sludge addition on slagging tendency and obtain better understandings for slag formation processes during the combustion of problematic wood waste pellets. Wood waste pellets produced with and without additives were combusted in a boiler (1.2 MW<sub>th</sub>) with continuous measurements of the combustion temperature and flue gas composition. The chemical composition, mineral phase, and microchemistry of the collected bottom ash and slag were examined by X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy coupled with energy dispersive X-ray analysis (SEM/EDX). Reference wood waste pellets showed a high slagging tendency with 34 wt % of the ingoing fuel ash formed as slag on the grate. XRF and SEM/EDX analyses revealed high contents of Si, K, and Na in the slag and a clear correlation among the three elements. It implies melted fractions of the slag consist of alkali silicates indirectly observed as glass phases by XRD analysis. The severe slagging of wood waste pellets was reduced distinctly upon addition of marble sludge. For two marble sludge added combustion tests, less than 3 wt % of the ingoing fuel ash formed as low sintering degrees slag. The mineral compositions of the resultant slag were changed from low melting point silicates to high temperature melting calcium based silicates, oxides, and hydroxides. SEM/EDX revealed enhancement of Ca and Mg in the melted slag, which were possibly originated from marble sludge and dissolved in ash melts. This may lead to release of alkali metals from the ash melts thereby reducing the formed melt amount. In addition, marble sludge addition restrained sintering and accumulation of melted ash into a continuous phase and resulted in fragile slag particles. Addition of 4 wt % sewage sludge has a minor effect on the slag formation of wood waste pellets combustion. The sizes and sintering degrees of the formed slag were considerably decreased and the mineral compositions in the slag were dominated by high temperature melting corundum and calcium silicates. The enrichment of kalsilite observed in the slag was probably caused by the reactions of aluminum silicates in the sewage sludge with potassium from the fuel. The corundum, calcium silicates, and kalsilite have higher melting temperatures and thus gave a lower ash melt fraction in the slag. However, as a result of the addition of sewage sludge, both the ash content and the Si level of ingoing fuel pellets were enhanced. Thereby the formed slag amount increased slightly for the combustion of the 8 wt % sewage sludge blended wood waste pellets.

## ***Optimal mixtures to reduce the formation of corrosive compounds during straw combustion: a thermodynamic analysis***

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*Energy & Fuels*

2011, 25 (7), pp. 3223–3234

DOI: [10.1021/ef2002475](https://doi.org/10.1021/ef2002475)

D2.1.13\_4 ([Link to eRoom](#))

### ***Abstract***

The thermodynamic analysis carried out focuses on biomass mixing to reduce the formation of corrosive (mainly alkali) chlorides during straw combustion. The calculations confirm the reduction abilities of sewage sludge and peat and provide information on the addition levels at which no corrosive compounds are expected to form. The calculations provide insight into the mechanisms responsible for the disappearance of alkali chlorides. The mechanisms that can potentially take place are known (reaction with sulfur and reaction with or adsorption on aluminosilicates or other ash compounds). However, many aspects remain unclear, and calculations cast light on several of them. The main result obtained in this study is that, in a given binary mixture, the chemical elements involved in the decomposition of corrosive alkali chlorides (or preventing them from forming) change with the mixing proportions, an important fact never mentioned to our knowledge. The practical implications are significant: in a real system, local elemental concentrations will vary; this means that several mechanisms will simultaneously fight the formation of corrosive alkali compounds. This new result may explain why the experimental results from the literature are often confusing or even contradictory even for a given mixture; the overall chemical picture is not static. The chemical elements reacting with alkalis during co-combustion of straw with sewage sludge or peat are predicted to be S, Ca–S, and aluminosilicates.

## ***Effect of Excess Air Ratio and Temperature on NO<sub>x</sub> Emission from Grate Combustion of Biomass in the Staged Air Combustion Scenario***

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*Energy & Fuels*

2011, 25 (10), pp. 4643–4654

DOI: [10.1021/ef200714d](https://doi.org/10.1021/ef200714d)

D2.1.2 ([Link to eRoom](#))

### ***Abstract***

The combustion of biomass, in this case demolition wood, has been investigated in a grate combustion multifuel reactor. In this work a temperature range of 850–1000 °C is applied both for staged air combustion and nonstaged combustion of biomass to investigate the effects of these parameters on the emission levels of NO<sub>x</sub>, N<sub>2</sub>O, CO, hydrocarbons (C<sub>x</sub>H<sub>y</sub>) and different other components. The composition of the flue gas is measured by four advanced continuous gas analyzers including gas chromatograph (GC), two Fourier transform infrared (FTIR) analyzers, and a conventional multispecies gas analyzer with fast response time. The experiments show the effects of staged air combustion, compared to nonstaged combustion, on the emission levels clearly. A NO<sub>x</sub> reduction of up to 85% is reached with staged air combustion. An optimum primary excess air ratio of 0.8–0.95 is found as a minimizing parameter for the NO<sub>x</sub> emissions for staged air combustion. Air staging has, however, a negative effect on N<sub>2</sub>O emissions. Even though the trends show a very small reduction in the NO<sub>x</sub> level as temperature increases in nonstaged combustion, the effect of temperature is not significant for NO<sub>x</sub> and C<sub>x</sub>H<sub>y</sub>, neither in staged air combustion or nonstaged combustion, while it has a great influence on the N<sub>2</sub>O and CO emissions, with decreasing levels with increasing temperature.

## ***Is Elevated Pressure Required To Achieve a High Fixed-Carbon Yield of Charcoal from Biomass? Part 1: Round-Robin Results for Three Different Corncob Materials***

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*Energy & Fuels*

2011, Volume 25, issue 7, pp. 3251–3265

DOI: [10.1021/ef200450h](https://doi.org/10.1021/ef200450h)

D2.3.5 ([Link to eRoom](#))

### ***Abstract***

Elevated pressure secures the highest fixed-carbon yields of charcoal from corncob. Operating at a pressure of 0.8 MPa, a flash-carbonization reactor realizes fixed-carbon yields that range from 70 to 85% of the theoretical thermochemical equilibrium value from Waimanalo corncob. The fixed-carbon yield is reduced to a range from 68 to 75% of the theoretical value when whole Waimanalo corncobs are carbonized under nitrogen at atmospheric pressure in an electrically heated muffle furnace. The lowest fixed-carbon yields are obtained by the standard proximate analysis procedure for biomass feedstocks; this yield falls in a range from 49 to 54% of the theoretical value. A round-robin study of corncob charcoal and fixed-carbon yields involving three different thermogravimetric analyzers (TGAs) revealed the impact of vapor-phase reactions on the formation of charcoal. Deep crucibles that limit the egress of volatiles from the pyrolyzing solid greatly enhance charcoal and fixed-carbon yields. Likewise, capped crucibles with pinholes increase the charcoal and fixed-carbon yields compared to values obtained from open crucibles. Large corncob particles offer much higher yields than small particles. These findings show that secondary reactions involving vapor-phase species (or nascent vapor-phase species) are at least as influential as primary reactions in the formation of charcoal. Our results offer considerable guidance to industry for its development of efficient biomass carbonization technologies. Size reduction handling of biomass (e.g., tub grinders and chippers), which can be a necessity in the field, significantly reduces the fixed-carbon yield of charcoal. Fluidized-bed and transport reactors, which require small particles and minimize the interaction of pyrolytic volatiles with solid charcoal, cannot realize high yields of charcoal from biomass. When a high yield of corncob charcoal is desired, whole corncobs should be carbonized at elevated pressure. Under these circumstances, carbonization is both efficient and quick.

## ***Biogas production and saccharification of Salix pretreated at different steam explosion conditions***

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*Bioresource Technology*

*Volume 102, Issue 17, September 2011, pp. 7932–7936*

DOI: [10.1016/j.biortech.2011.06.042](https://doi.org/10.1016/j.biortech.2011.06.042)

D2.4.8 ([Link to eRoom](#))

### ***Abstract***

Different steam explosion conditions were applied to *Salix* chips and the effect of this pretreatment was evaluated by running both enzymatic hydrolysis and biogas tests. Total enzymatic release of glucose and xylose increased with pretreatment harshness, with maximum values being obtained after pretreatment for 10 min at 210 °C. Harsher pretreatment conditions did not increase glucose release, led to degradation of xylose and to formation of furfurals. Samples pretreated at 220 and 230 °C initially showed low production of biogas, probably because of inhibitors produced during the pretreatment, but the microbial community was able to adapt and showed high final biogas production. Interestingly, final biogas yields correlated well with sugar yields after enzymatic hydrolysis, suggesting that at least in some cases a 24 h enzymatic assay may be developed as a quick method to predict the effects of pretreatment of lignocellulosic biomass on biogas yields.



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***SP4: SUSTAINABILITY ASSESSMENTS***

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- 2013 -

***A review of recent developments and applications of partial equilibrium models of the forest sector***

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*Journal of Forest Economics*

*Volume 19, Issue 4, December 2013, pp. 350–360*

DOI: [10.1016/j.jfe.2013.06.006](https://doi.org/10.1016/j.jfe.2013.06.006)

D4.3.22 ([Link to eRoom](#))

***Abstract***

Recent history has seen an increase in the utilization of partial equilibrium based forest sector models to identify potential impacts of various policies or timber market shocks. These models are particularly useful in that they employ economic theory to capture the interaction of supply and demand in a framework where commodity prices are endogenous to the policy or shock simulated. We present recent developments and linkages between models and review applications of these models to forest policy questions over the previous decade. We conclude with a discussion of potential future directions for such research.

## ***Wood biomass use for energy in Europe under different assumptions of coal, gas and CO<sub>2</sub> emission prices and market conditions***

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*Journal of Forest Economics*

*Volume 19, Issue 4, December 2013, pp. 432–449*

DOI: [10.1016/j.jfe.2013.10.001](https://doi.org/10.1016/j.jfe.2013.10.001)

D4.3.24 ([Link to eRoom](#))

### ***Abstract***

This study examines the effects of different coal, natural gas and carbon emission prices and market situations on the use of wood for electricity and heat production in the European Union. The analysis is carried out using the global forest sector model EFI-GTM expanded to cover electricity and heat production from wood, coal, natural gas, wind and solar energy. Analysis shows that with low coal and gas prices, use of wood for energy will be limited to low cost logging residues. With high coal, and especially natural gas prices, industrial wood also comes to be used for energy. At a carbon price of 100 €/tCO<sub>2</sub>, some 32 Mm<sup>3</sup> of industrial wood, in addition to 224 Mm<sup>3</sup> of logging residues, are projected to be used for electricity and heat in the EU region (including Norway and Switzerland) in 2030. The relatively low quantity of industrial wood used by the energy sector despite the collapse of the use of coal is explained by the fact that under high CO<sub>2</sub> prices, other energy forms like natural gas, solar and wind energy become more and more competitive. However, the amount of industrial wood used for energy may substantially increase with subsidies for using wood for electricity and heat, even with relatively low carbon prices. With a high coal and gas price and a carbon price of 100 €/t, a subsidy of 30 €/MWh to the wood based and coal with wood co-firing electricity production will have a significant impact on the European wood based sector. Depending on the development of the market demand for forest industry products, such a subsidy may cause a 10-12.5% reduction in forest products production, a 6-9% increase in harvest level, about 30-60% increase in the pulpwood prices, and a 6-9 fold increase of wood imports in the EU, compared to the respective case without a subsidy in 2030.

## ***Land use impacts on biodiversity from kiwifruit production in New Zealand assessed with global and national datasets***

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*The International Journal of Life Cycle Assessment*  
September 2013

DOI: [10.1007/s11367-013-0628-7](https://doi.org/10.1007/s11367-013-0628-7)

D4.1.40 ([Link to eRoom](#))

### ***Abstract***

#### ***Purpose***

Habitat loss is a significant cause of biodiversity loss, but while its importance is widely recognized, there is no generally accepted method on how to include impacts on biodiversity from land use and land use changes in cycle assessment (LCA), and existing methods are suffering from data gaps. This paper proposes a methodology for assessing the impact of land use on biodiversity using ecological structures as opposed to information on number of species.

#### ***Methods***

Two forms of the model (global and local scales) were used to assess environmental quality, combining ecosystem scarcity, vulnerability, and conditions for maintaining biodiversity. A case study for New Zealand kiwifruit production is presented. As part of the sensitivity analysis, model parameters (area and vulnerability) were altered and New Zealand datasets were also used.

#### ***Results and discussion***

When the biodiversity assessment was implemented using a global dataset, the importance of productivity values was shown to depend on the area the results were normalized against. While the area parameter played an important role in the results, the proposed alternative vulnerability scale had little influence on the final outcome.

#### ***Conclusions***

Overall, the paper successfully implements a model to assess biodiversity impacts in LCA using easily accessible, free-of-charge data and software. Comparing the model using global vs. national datasets showed that there is a potential loss of regional significance when using the generalized model with the global dataset. However, as a guide to assessing biodiversity impact, the model allows for consistent comparison of product systems on an international basis.

## ***Biogenic CO<sub>2</sub> fluxes from bioenergy and climate—A response***

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*Ecological Modelling*

*Volume 253, 24 March 2013, pp. 79–81*

DOI: [10.1016/j.ecolmodel.2013.01.007](https://doi.org/10.1016/j.ecolmodel.2013.01.007)

D4.1.39 ([Link to eRoom](#))

### ***Abstract***

In his short communication, [Holtmark \(2013\)](#) builds on our methodology for impulse response functions (IRF) of biogenic CO<sub>2</sub> emissions ([Cherubini et al., 2011a](#) and [Cherubini et al., 2011b](#)) and proposes some adjustments in order to include counterfactual CO<sub>2</sub> fluxes in the IRF. At the same time, concerns are expressed over the insights that can be gathered from the IRF and the following emission metrics like the global warming potential (GWP, labeled GWP<sub>bio</sub> when applied to biogenic CO<sub>2</sub>).

In this letter, we make evident that the “adjustments” proposed by Holtmark conflict with the definition of IRFs and their intended applications, and neither contradict nor invalidate our findings. IRFs and subsequent emission metrics clearly discern the atmospheric response to CO<sub>2</sub> emissions sourced from fossils/deforestation to that of CO<sub>2</sub> from regenerative biomass irrespective of any application involving forest scenarios. By embedding scenarios directly into the IRFs rather than in a separate analysis, Holtmark unnecessarily and unconventionally makes emission metrics dependent on counterfactual aspects, deviating from the main rationale behind physics-based emission metrics.

## ***Global climate impacts of forest bioenergy: what, when and how to measure?***

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*Environmental Research Letters*  
Volume 8, number 1

DOI: [10.1088/1748-9326/8/1/014049](https://doi.org/10.1088/1748-9326/8/1/014049)  
D4.1.38 ([Link to eRoom](#))

### ***Abstract***

Environmental impact studies of forest bioenergy systems usually account for CO<sub>2</sub> emissions and removals and identify the so-called carbon debt of bioenergy through comparison with a reference system. This approach is based on a simple sum of fluxes and does not consider any direct physical impact or climate system response. Other recent applications go one step further and elaborate impulse response functions (IRFs) and subsequent metrics for biogenic CO<sub>2</sub> emissions that are compatible with the life-cycle assessment (LCA) methodology. However, a thorough discussion about the role of the different metrics in the interpretation of the climate impacts of forest bioenergy systems is still missing. In this work, we assess a single LCA dataset of selected bioenergy systems using different emission metrics based on cumulative CO<sub>2</sub> emissions, radiative forcing and global surface temperature. We consider both absolute and normalized metrics for single pulses and sustained emissions. The key challenges are the choice of end point (emissions, concentration, radiative forcing, change in temperature, etc), the type of measure (instantaneous or time-integrated) and the treatment of time. Bioenergy systems usually perform better than fossil counterparts if assessed with instantaneous metrics, including global surface temperature change, and in some cases can give a net global cooling effect in the short term. The analysis of sustained, or continuous emissions, also shows that impacts from bioenergy systems are generally reversible, while those from fossil fuels are permanent.

As shown in this study, the metric choice can have a large influence on the results. The dominant role traditionally assigned to cumulative metrics in LCA studies and climate impact accounting schemes should therefore be reconsidered, because such metrics can fail to capture important time dependences unique to the biomass system under analysis (to which instantaneous metrics are well suited).

## ***Bioenergy vs. natural gas for production of district heat in district heat in Norway: Climate implications***

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*Energy Procedia*

*Volume 40, 2013, pp. 137–145*

DOI: [10.1016/j.egypro.2013.08.017](https://doi.org/10.1016/j.egypro.2013.08.017)

D4.1.37 ([Link to eRoom](#))

### ***Abstract***

Production of district heat is increasing in Norway, and this paper simulates the possibility to use its abundant national resources of forests and/or natural gas as energy carriers. In this study we analyze an idealized future energy scenario and compare the climate impacts from using forest biomass or natural gas as energy sources. Results show that bioenergy is a better energy option than natural gas, mainly thanks to the cooling contributions from the change in surface albedo that can more than offset the warming associated with biogenic CO<sub>2</sub>.

## ***Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life***

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*Journal of Industrial Ecology*

*February 2013, Volume 17, Issue 1, pp. 20–30*

DOI: [10.1111/j.1530-9290.2012.00507.x](https://doi.org/10.1111/j.1530-9290.2012.00507.x)

D4.1.23 ([Link to eRoom](#))

### ***Abstract***

There is growing interest in understanding how storage or delayed emission of carbon in products based on bioresources might mitigate climate change, and how such activities could be credited. In this research we extend the recently introduced approach that integrates biogenic carbon dioxide (CO<sub>2</sub>) fluxes with the global carbon cycle (using biogenic global warming potential [GWP<sub>bio</sub>]) to consider the storage period of harvested biomass in the anthroposphere, with subsequent oxidation. We then examine how this affects the climate impact from a bioenergy resource. This approach is compared to several recent methods designed to address the same problem. Using both a 100- and a 500-year fixed time horizon we calculate the GWP<sub>bio</sub> factor for every combination of rotational and anthropogenic storage periods between 0 and 100 years. The resulting GWP<sub>bio</sub> factors range from -0.99 (1-year rotation and 100-year storage) to +0.44 (100-year rotation and 0-year storage). The approach proposed in this study includes the interface between biomass growth and emissions and the global carbon cycle, whereas other methods do not model this. These results and the characterization factors produced can determine the climate change benefits or impacts associated with the storage of biomass in the anthroposphere, and the subsequent release of biogenic CO<sub>2</sub> with the radiative forcing integrated in a fixed time window.

## ***Bioenergy from forestry and changes in atmospheric CO<sub>2</sub>: Reconciling single stand and landscape level approaches***

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*Journal of Environmental Management*  
Volume 129, 15 November 2013, pp. 292–301

DOI: [10.1016/j.jenvman.2013.07.021](https://doi.org/10.1016/j.jenvman.2013.07.021)

D4.1.28 ([Link to eRoom](#))

### ***Abstract***

Analyses of global warming impacts from forest bioenergy systems are usually conducted either at a single stand level or at a landscape level, yielding findings that are sometimes interpreted as contrasting. In this paper, we investigate and reconcile the scales at which environmental impact analyses of forest bioenergy systems are undertaken. Focusing on the changes caused in atmospheric CO<sub>2</sub> concentration of forest bioenergy systems characterized by different initial states of the forest, we show the features of the analyses at different scales and depict the connections between them. Impacts on atmospheric CO<sub>2</sub> concentration at a single stand level are computed through impulse response functions (IRF). Results at a landscape level are elaborated through direct application of IRFs to the emission profile, so to account for the fluxes from all the stands across time and space. Impacts from fossil CO<sub>2</sub> emissions are used as a benchmark. At a landscape level, forest bioenergy causes an increase in atmospheric CO<sub>2</sub> concentration for the first decades that is similar to the impact from fossil CO<sub>2</sub>, but then the dynamics clearly diverge because while the impact from fossil CO<sub>2</sub> continues to rise that from bioenergy stabilizes at a certain level. These results perfectly align with those obtained at a single stand for which characterization factors have been developed. In the hypothetical case of a sudden cessation of emissions, the change caused in atmospheric CO<sub>2</sub> concentration from biogenic CO<sub>2</sub> emissions reverses within a couple of decades, while that caused by fossil CO<sub>2</sub> emissions remains considerably higher for centuries. When counterfactual aspects like the additional sequestration that would have occurred in the forest if not harvested and the theoretical displacement of fossil CO<sub>2</sub> are included in the analysis, results can widely differ, as the CO<sub>2</sub> debt at a landscape level ranges from a few years to several centuries (depending on the underlying assumptions considered).



## ***The role of forest residues in the accounting for the global warming potential of bioenergy***

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*Global Change Biology Bioenergy*  
July 2013, Volume 5, Issue 4, pp. 459–466

DOI: [10.1111/gcbb.12014](https://doi.org/10.1111/gcbb.12014)  
D4.1.31 ([Link to eRoom](#))

### ***Abstract***

Bioenergy makes up a significant portion of the global primary energy pie, and its production from modernized technology is foreseen to substantially increase. The climate neutrality of biogenic CO<sub>2</sub> emissions from bioenergy grown from sustainably managed biomass resource pools has recently been questioned. The temporary change caused in atmospheric CO<sub>2</sub> concentration from biogenic carbon fluxes was found to be largely dependent on the length of biomass rotation period. In this work, we also show the importance of accounting for the unutilized biomass that is left to decompose in the resource pool and how the characterization factor for the climate impact of biogenic CO<sub>2</sub> emissions changes whether residues are removed for bioenergy or not. With the case of Norwegian Spruce biomass grown in Norway, we found that significantly more biogenic CO<sub>2</sub> emissions should be accounted towards contributing to global warming potential when residues are left in the forest. For a 100-year time horizon, the global warming potential bio factors suggest that between 44 and 62% of carbon-flux, neutral biogenic CO<sub>2</sub> emissions at the energy conversion plant should be attributed to causing equivalent climate change potential as fossil-based CO<sub>2</sub> emissions. For a given forest residue extraction scenario, the same factor should be applied to the combustion of any combination of stem and forest residues. Life cycle analysis practitioners should take these impacts into account and similar region/species specific factors should be developed.

## ***Climate impact potential of utilizing forest residues for bioenergy in Norway***

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*Mitigation and Adaptation Strategies for Global Change*

*Volume 18, Issue 8, pp. 1089-1108*

DOI: [10.1007/s11027-012-9409-z](https://doi.org/10.1007/s11027-012-9409-z)

D4.1.32 ([Link to eRoom](#))

### ***Abstract***

The utilization of forest residues for bioenergy in Norway is foreseen to increase due to the government call to double bioenergy output by 2020 to thirty Tera-Watt hours. This study focuses on the climate impacts of bioenergy utilization where four forest residue extraction scenarios at clear-cut are considered: i) 75 % above ground residues (branches, (25 %) foliage, tops); ii) 75 % above and below ground residues (branches, tops, (25 %) foliage, stumps, coarse and small roots); iii) extracting 100 % of all available forest residue; and iv) leaving all residues in the forest. The Yasso07 soil-carbon model was utilized to quantify the carbon flux to the atmosphere due to the forest residues that are left in the forest in each scenario. The climate impact potential for each scenario was then calculated for the carbon-flux neutral Norway Spruce (*Picea abies*) forest system in five regions of Norway. The biogenic carbon dioxide emissions associated to decomposition upon forest floor, procurement losses and bioenergy conversion are included in these calculations. Results suggest that if such bioenergy can directly replace a fossil source of energy, the utilization of this biomass was found to be climatically beneficial in most fossil energy replacement cases and time horizons when compared to leaving the residues in the forest. Integrated global temperature change displacement factors have been developed which have been used to estimate the magnitude of this climate change mitigation over a particular time horizon.

## ***Empirical models of monthly and annual albedo in managed boreal forests of interior Norway***

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*Climatic change*

(2013) 120, pp. 183–196

DOI: [10.1007/s10584-013-0789-1](https://doi.org/10.1007/s10584-013-0789-1)

D4.1.34 ([Link to eRoom](#))

### ***Abstract***

An 11-year remotely sensed surface albedo dataset coupled with historical meteorological and stand-level forest management data for a variety of stands in Norway's most productive logging region is used to develop regression models describing temporal changes in forest albedo following clear-cut harvest disturbance events. Datasets are grouped by dominant tree species, and two alternate multiple regression models are developed and tested following a potential-modifier approach. This result in models with statistically significant parameters ( $p < 0.05$ ) that explain a large proportion of the observed variation, requiring a single canopy modifier predictor coupled with either monthly or annual mean air temperature as a predictor of a stand's potential albedo. Models based on annual mean temperature predict annual albedo with errors (RMSE) in the range of 0.025–0.027, while models based on monthly mean temperature predict monthly albedo with errors ranging between of 0.057–0.065 depending on the dominant tree species. While both models have the potential to be transferable to other boreal regions with similar forest management regimes, further validation efforts are required. As active management of boreal forests is increasingly seen as a means to mitigate climate change, the presented models can be used with routine forest inventory and meteorological data to predict albedo evolution in managed forests throughout the region, which, together with carbon cycle modeling, can lead to more holistic climate impact assessments of alternative forest harvest scenarios and forest product systems.

## ***Consistent quantification of climate impacts due to biogenic carbon storage across a range of bio-product systems***

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*Environmental Impact Assessment Review*  
Volume 43, November 2013, pp. 21–30

DOI: [10.1016/j.eiar.2013.05.002](https://doi.org/10.1016/j.eiar.2013.05.002)  
D4.1.35 ([Link to eRoom](#))

### ***Abstract***

Temporary and permanent carbon storage from biogenic sources is seen as a way to mitigate climate change. The aim of this work is to illustrate the need to harmonize the quantification of such mitigation across all possible storage pools in the bio- and anthroposphere. We investigate nine alternative storage cases and a wide array of bio-resource pools: from annual crops, short rotation woody crops, medium rotation temperate forests, and long rotation boreal forests. For each feedstock type and biogenic carbon storage pool, we quantify the carbon cycle climate impact due to the skewed time distribution between emission and sequestration fluxes in the bio- and anthroposphere. Additional consideration of the climate impact from albedo changes in forests is also illustrated for the boreal forest case. When characterizing climate impact with global warming potentials (GWP), we find a large variance in results which is attributed to different combinations of biomass storage and feedstock systems. The storage of biogenic carbon in any storage pool does not always confer climate benefits: even when biogenic carbon is stored long-term in durable product pools, the climate outcome may still be undesirable when the carbon is sourced from slow-growing biomass feedstock. For example, when biogenic carbon from Norway Spruce from Norway is stored in furniture with a mean life time of 43 years, a climate change impact of 0.08 kg CO<sub>2</sub>eq per kg CO<sub>2</sub> stored (100 year time horizon (TH)) would result. It was also found that when biogenic carbon is stored in a pool with negligible leakage to the atmosphere, the resulting GWP factor is not necessarily – 1 CO<sub>2</sub>eq per kg CO<sub>2</sub> stored. As an example, when biogenic CO<sub>2</sub> from Norway Spruce biomass is stored in geological reservoirs with no leakage, we estimate a GWP of – 0.56 kg CO<sub>2</sub>eq per kg CO<sub>2</sub> stored (100 year TH) when albedo effects are also included. The large variance in GWPs across the range of resource and carbon storage options considered indicates that more accurate accounting will require case-specific factors derived following the methodological guidelines provided in this and recent manuscripts.

## ***Climate change implications of shifting forest management strategy in a boreal forest ecosystem of Norway***

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*Global Change Biology*

DOI: [10.1111/gcb.12451](https://doi.org/10.1111/gcb.12451)

D4.1.36 ([Link to eRoom](#))

### ***Abstract***

Empirical models alongside remotely sensed and station measured meteorological observations are employed to investigate both the local and global direct climate change impacts of alternative forest management strategies within a boreal ecosystem of eastern Norway. Stand-level analysis is firstly executed to attribute differences in daily, seasonal, and annual mean surface temperatures to differences in surface intrinsic biophysical properties across conifer, deciduous, and clear-cut sites. Relative to a conifer site, a slight local cooling of  $-0.13\text{ }^{\circ}\text{C}$  at a deciduous site and  $-0.25\text{ }^{\circ}\text{C}$  at a clear-cut site were observed over a 6-year period, which were mostly attributed to a higher albedo throughout the year. When monthly mean albedo trajectories over the entire managed forest landscape were taken into consideration, we found that strategies promoting natural regeneration of coniferous sites with native deciduous species led to substantial global direct climate cooling benefits relative to those maintaining current silviculture regimes – despite predicted long-term regional warming feedbacks and a reduced albedo in spring and autumn months. The magnitude and duration of the cooling benefit depended largely on whether management strategies jointly promoted an enhanced material supply over business-as-usual levels. Expressed in terms of an equivalent  $\text{CO}_2$  emission pulse at the start of the simulation, the net climate response at the end of the 21st century spanned  $-8$  to  $-159\text{ Tg-CO}_2\text{-eq.}$ , depending on whether near-term harvest levels increased or followed current trends, respectively. This magnitude equates to approximately  $-20$  to  $-300\%$  of Norway's annual domestic (production) emission impact. Our analysis supports the assertion that a carbon-only focus in the design and implementation of forest management policy in boreal and other climatically similar regions can be counterproductive – and at best – suboptimal if boreal forests are to be used as a tool to mitigate global warming.

## ***Whole-tree thinnings in stands of Scots Pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*): Short- and long-term growth results***

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*Forest Ecology and Management*  
*Volume 298, 15 June 2013, pp. 52–61*

DOI: [10.1016/j.foreco.2013.02.029](https://doi.org/10.1016/j.foreco.2013.02.029)

D4.2.11 ([Link to eRoom](#))

### ***Abstract***

The relative volume growth effects of thinning after whole-tree harvesting (WTH) compared to a conventional stem-only harvest (CH) in young stands of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) were analyzed, using a series of four pine and four spruce field experiments. The series was established in the years 1972–1977, and thinning was performed only once.

Results are shown periodically and cumulatively. All sites were included for 20 (19) years in pine and 25 years in spruce. The total experimental period varied between 19 and 35 years for individual sites.

Four models assuming additive or multiplicative effects gave only slightly varying results. The inclusion of standing volume after thinning as a covariate was effective in spruce independent of whether the covariate was treated as multiplicative or additive. A logarithmic model with a multiplicative effect of the covariate was preferred in further presentations.

Results for pine stands after 20 years indicated a non-significant loss of 5% with confidence limits ( $p = 0.05$ ) of  $\pm 6$ –7%, while the spruce stands showed a significant growth loss of 11% with confidence limits of  $\pm 4$ –5% after 25 years. The difference between the species in relative growth effects was significant, and amounted to 8% for a cumulative 20-year period.

No indications of trends in response were found during a 20-year period in pine and a 25-year period in spruce.

An analysis of growth effects in the first years showed that basal area increment in spruce was significantly reduced already in the first growing season after thinning.

## ***Economic sustainability for wood pellets production – A comparative study between Finland, Germany, Norway, Sweden and the US***

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*Biomass & Bioenergy*

*Volume 57, October 2013, pp. 68–77*

DOI: [10.1016/j.biombioe.2013.01.030](https://doi.org/10.1016/j.biombioe.2013.01.030)

D4.3.15 ([Link to eRoom](#))

### ***Abstract***

The consumption of wood pellets grew rapidly during the last decade. In this paper we compare the development of the production factors for wood pellet markets in Finland, Germany, Sweden, Norway and the US; we analyze how domestic market prices for pellet production factors as well as domestic market prices for pellets vary among the countries. The analyses are based on two model plants. The first represents common technologies for small scale pellet production based on dry residues from sawnwood production, while the second represents large scale production based on a blend of dry and wet materials. The results show how differences in costs of feedstock, energy and labor affect the profitability of pellet production and hence the development of pellet production in the analyzed countries. Pellet producers in the US have lower feedstock costs than producers in the analyzed European countries. The economic sustainability for European pellet producers depends to a large extent on their domestic markets as internationally traded pellets are priced lower than their production costs. Future pellet production will, to a greater extent, be based on wet feedstock such as roundwood and wet sawdust. These feedstocks are also demanded by wood-based industries (pulp and paper, particle- and fiber-board) as well as for traditional fuelwood. The transition from smaller pellet plants using dry feedstock to larger plants using wet feedstock in future pellet production, can be expected to follow comparative advantages regarding feedstock and energy costs, but also with respect to economies of scale.

- 2012 -

***Impact assessment of biodiversity and carbon pools from land use and land use changes in LCA, exemplified with forestry operations in Norway***

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*Journal of Industrial Ecology*

*April 2012, Volume 16, Issue 2, pp. 231–242*

DOI: [10.1111/j.1530-9290.2011.00409.x](https://doi.org/10.1111/j.1530-9290.2011.00409.x)

D4.1.20 ([Link to eRoom](#))

***Abstract***

There is a strong need for methods within life cycle assessment (LCA) that enable the inclusion of all complex aspects related to land use and land use change (LULUC). This article presents a case study of the use of one hectare (ha) of forest managed for the production of wood for bioenergy production. Both permanent and temporary changes in above-ground biomass are assessed together with the impact on biodiversity caused by LULUC as a result of forestry activities. The impact is measured as a product of time and area requirements, as well as by changes in carbon pools and impacts on biodiversity as a consequence of different management options. To elaborate the usefulness of the method as well as its dependency on assumptions, a range of scenarios are introduced in the study. The results show that the impact on climate change from LULUC dominates the results, compared to the impact from forestry operations. This clearly demonstrates the need to include LULUC in an LCA of forestry products. For impacts both on climate change and biodiversity, the results show large variability based on what assumptions are made; and impacts can be either positive or negative. Consequently, a mere measure of land used does not provide any meaning in LCA, as it is not possible to know whether this contributes a positive or negative impact.



## ***Site-specific global warming potentials of biogenic CO<sub>2</sub> for bioenergy: contributions from carbon fluxes and albedo dynamics***

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*Environmental Research Letters*  
2012, Volume 7, Number 4

DOI: [10.1088/1748-9326/7/4/045902](https://doi.org/10.1088/1748-9326/7/4/045902)  
D4.1.29 ([Link to eRoom](#))

### ***Abstract***

Production of biomass for bioenergy can alter biogeochemical and biogeophysical mechanisms, thus affecting local and global climate. Recent scientific developments have mainly embraced impacts from land use changes resulting from area-expanded biomass production, with several extensive insights available. Comparably less attention, however, has been given to the assessment of direct land surface–atmosphere climate impacts of bioenergy systems under rotation such as in plantations and forested ecosystems, whereby land use disturbances are only temporary. Here, following IPCC climate metrics, we assess bioenergy systems in light of two important dynamic land use climate factors, namely, the perturbation in atmospheric carbon dioxide (CO<sub>2</sub>) concentration caused by the timing of biogenic CO<sub>2</sub> fluxes, and temporary perturbations to surface reflectivity (albedo). Existing radiative forcing-based metrics can be adapted to include such dynamic mechanisms, but high spatial and temporal modeling resolution is required. Results show the importance of specifically addressing the climate forcings from biogenic CO<sub>2</sub> fluxes and changes in albedo, especially when biomass is sourced from forested areas affected by seasonal snow cover. The climate performance of bioenergy systems is highly dependent on biomass species, local climate variables, time horizons, and the climate metric considered. Bioenergy climate impact studies and accounting mechanisms should rapidly adapt to cover both biogeochemical and biogeophysical impacts, so that policy makers can rely on scientifically robust analyses and promote the most effective global climate mitigation options.

## ***Application of probability distributions to the modeling of biogenic CO<sub>2</sub> fluxes in LCA***

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*Global Change Biology Bioenergy*  
November 2012, Volume 4, Issue 6, pp. 784–798

DOI: [10.1111/j.1757-1707.2011.01156.x](https://doi.org/10.1111/j.1757-1707.2011.01156.x)  
D4.1.30 ([Link to eRoom](#))

### ***Abstract***

In life cycle assessment (LCA), the same characterization factors are conventionally applied irrespective of when the emissions occur (the same importance is given to emissions in the past, present, and future). When the assessment is constrained by fixed timeframes, the appropriateness of this paradigm is questioned and the temporal distribution of emissions becomes of relevance. One typical example is the accounting for biogenic CO<sub>2</sub> emissions and removals. This article proposes a methodology for assessing the climate impact of time-distributed CO<sub>2</sub> fluxes using probability distributions. Three selected wood applications, such as fuel, nonstructural panels, and housing construction materials are assessed. In all the cases, CO<sub>2</sub> sequestration in growing trees is modeled with an appropriate forest growth function, whereas CO<sub>2</sub> emissions from wood oxidation are modeled with different probability distributions, such as the delta function, the uniform distribution, the exponential distribution, and the chi-square distribution. The combination of these CO<sub>2</sub> fluxes with the global carbon cycle provides the respective changes caused in CO<sub>2</sub> atmospheric concentration and hence in the radiative forcing. The latter is then used as basis for climate impact metrics. Results demonstrate the utility of using emission and removal functions rather than single pulses, which generally overestimate the climate impact of CO<sub>2</sub> emissions, especially in presence of short time horizons. Characterization factors for biogenic CO<sub>2</sub> are provided for selected combinations of biomass species, rotation periods, and probability distributions. The time discrepancy between biogenic CO<sub>2</sub> emissions and capture through regrowth results in a certain climate impact, even for a system that is carbon neutral over time. For the oxidation rate of wooden products, the use of a chi-square distribution appears the most reliable and appropriate option under a methodological perspective. The feasibility of its adoption in LCA and emission accounting from harvested wood products deserves further scientific considerations.

## ***Continent-wide response of mountain vegetation to climate change***

Michael Gottfried<sup>a</sup>, Harald Pauli, Andreas Futschik, Maia Akhalkatsi, Peter Barančok, José Luis Benito Alonso, Gheorghe Coldea, Jan Dick, Brigitta Erschbamer, Mari'a Rosa Fernández Calzado, George Kazakis, Ján Krajči, Per Larsson, Martin Mallaun, Ottar Michelsen<sup>b</sup>, Dmitry Moiseev, Pavel Moiseev, Ulf Molau, Abderrahmane Merzouki, Laszlo Nagy, George Nakhutsrishvili, Bård Pedersen<sup>b</sup>, Giovanni Pelino, Mihai Puscas, Graziano Rossi, Angela Stanisci, Jean-Paul Theurillat, Marcello Tomaselli, Luis Villar, Pascal Vittoz, Ioannis Vogiatzakis, & Georg Grabherr

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*Nature Climate Change*  
2012, Volume 2, pp. 111–115

DOI: [10.1038/nclimate1329](https://doi.org/10.1038/nclimate1329)  
D4.1.33\_1 ([Link to eRoom](#))

### ***Abstract***

Climate impact studies have indicated ecological fingerprints of recent global warming across a wide range of habitats. Although these studies have shown responses from various local case studies, a coherent large-scale account on temperature-driven changes of biotic communities has been lacking. Here we use 867 vegetation samples above the treeline from 60 summit sites in all major European mountain systems to show that ongoing climate change gradually transforms mountain plant communities. We provide evidence that the more cold-adapted species decline and the more warm-adapted species increase, a process described here as thermophilization. At the scale of individual mountains this general trend may not be apparent, but at the larger, continental scale we observed a significantly higher abundance of thermophilic species in 2008, compared with 2001. Thermophilization of mountain plant communities mirrors the degree of recent warming and is more pronounced in areas where the temperature increase has been higher. In view of the projected climate change the observed transformation suggests a progressive decline of cold mountain habitats and their biota.

## ***Climate impacts of bioenergy: Inclusion of carbon cycle and albedo dynamics in life cycle impact assessment***

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*Environmental Impact Assessment Review*  
Volume 37, November 2012, pp. 2–11

DOI: [10.1016/j.ear.2012.01.002](https://doi.org/10.1016/j.ear.2012.01.002)  
D4.1.33\_2 ([Link to eRoom](#))

### ***Abstract***

Life cycle assessment (LCA) can be an invaluable tool for the structured environmental impact assessment of bioenergy product systems. However, the methodology's static temporal and spatial scope combined with its restriction to emission-based metrics in life cycle impact assessment (LCIA) inhibits its effectiveness at assessing climate change impacts that stem from dynamic land surface–atmosphere interactions inherent to all biomass-based product systems. In this paper, we focus on two dynamic issues related to anthropogenic land use that can significantly influence the climate impacts of bioenergy systems: i) temporary changes to the terrestrial carbon cycle; and ii) temporary changes in land surface albedo—and illustrate how they can be integrated within the LCA framework.

In the context of active land use management for bioenergy, we discuss these dynamics and their relevancy and outline the methodological steps that would be required to derive case-specific biogenic CO<sub>2</sub> and albedo change characterization factors for inclusion in LCIA. We demonstrate our concepts and metrics with application to a case study of transportation biofuel sourced from managed boreal forest biomass in northern Europe. We derive GWP indices for three land management cases of varying site productivities to illustrate the importance and need to consider case- or region-specific characterization factors for bioenergy product systems. Uncertainties and limitations of the proposed metrics are discussed.

## ***A comment to “Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral”: Important insights beyond greenhouse gas accounting***

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*Global Change Biology Bioenergy*

November 2012, Volume 4, Issue 6, pp. 617–619

DOI: [10.1111/j.1757-1707.2012.01190.x](https://doi.org/10.1111/j.1757-1707.2012.01190.x)

D4.1.33\_3 ([Link to eRoom](#))

### ***Introduction***

In their recent editorial, Schulze and colleagues (Schulze et al., 2012) discuss the implications of a large-scale increase in the harvest of forest biomass to provide 20% of the current global primary energy supply. They present several well-founded concerns regarding the economic and ecological sustainability of such a scenario, concerns we largely share. However, the authors express particular apprehension regarding greenhouse gas (GHG) consequences of expanded forest bioenergy production that we do not entirely share. GHGs – while important – should not be the sole evaluation criterion when the objective is climate protection. The peer reviewed literature provides important insights beyond that presented which warrants additional commentary in order to give a more holistic and balanced perspective on the subject of forest bioenergy and climate.

In particular, the authors overlook two attributes fundamental to forest based bioenergy that distinguish it from fossil-fuel energy: (1) forests can affect climate in many ways extending beyond the biosphere-atmosphere cycling of carbon, and sometimes in ways that are in direct opposition to the carbon cycle, (2) CO<sub>2</sub> emissions from bioenergy sourced from a sustainably managed forest generates less warming than the same mass of CO<sub>2</sub> from fossil fuels.

These attributes can have positive implications for the inclusion of forest based bioenergy as part of an integrated climate mitigation strategy.

## ***Influences of international forest policy processes on national forest policies in Finland, Norway and Sweden***

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*Scandinavian Journal of Forest Research*  
2012, Volume 27, Issue 2, pp. 210-220

DOI: [10.1080/02827581.2011.635079](https://doi.org/10.1080/02827581.2011.635079)  
D4.3.21\_1

### ***Abstract***

Several international processes provide recommendations for sustainable forest management, including the Convention on Biological Diversity, the Ministerial Conference on the Protection of Forests in Europe and the United Nations Forum on Forests. This paper explores to what degree and how these processes have influenced national forest policies in Finland, Norway and Sweden employing methods developed for studying effectiveness of international agreements. Empirical data on changes in response to the international recommendations were collected, revealing influences on all policy elements in Finland. In Sweden, minor influences were identified on only two out of five investigated elements, while Norway is in an intermediate position. The variations in influences on selected policy elements in rather similar countries indicate different national considerations in response to the international recommendations, signalling challenges in determining effects of the international processes. The assessed influences are next used for an initial investigation of how the international forest policy recommendations influence national policies. Evidence indicates multifaceted and complex ways of influences, and signals of both calculative and normative influences, and their interactions, are found. Elements requiring further investigations are identified, emphasising the casual relationships in determining to what extent and how national policies are affected by international policy processes.

## ***Biodiversity protection and economics in long term boreal forest management — A detailed case for the valuation of protection measures***

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*Forest Policy and Economics*  
Volume 15, February 2012, pp. 12–21

DOI: [10.1016/j.forpol.2011.11.002](https://doi.org/10.1016/j.forpol.2011.11.002)

D4.3.21\_2 ([Link to eRoom](#))

### ***Abstract***

Increased protection of forest biodiversity implies reduced income from timber production both for society and forest owners, and consistent analysis of the relationships between biodiversity benefits and corresponding costs is important both for forest managers as well as policy makers. Using a complex dynamic forest optimization model, we analyse impacts on economy and biodiversity of forest management restrictions implemented to protect biodiversity. A reference scenario is compared to two preservation regimes based on 1) the current Norwegian forest certification system and 2) an expert judgement designed to put strong emphasis on biodiversity protection in boreal forests. Economic impacts are expressed as net present value and harvesting level, while impacts on forest structure are expressed by a vector of variables including old forest proportions, growing stock, number of retention trees, size of buffer zones and amount of dead wood. A rather detailed description of forest structure and biodiversity measures represents the main improvements compared to previous analyses. Different restrictions result in 10–45% decrease in economic value of the forest compared to no restrictions. The most costly measures are found to be 50% increased rotation and keeping old-growth proportions higher than 20%.

- 2011 -

***Impacts of combining partial and general equilibrium modelling in freight transport analyses - a forest sector case study from Norway***

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*Transportation planning and technology*  
*Volume 34, Issue 3, pp. 259-275, 2011*

DOI: [10.1080/03081060.2011.565182](https://doi.org/10.1080/03081060.2011.565182)  
D4.3.x

***Abstract***

The forest sector in Norway is very transport intensive, accounting for approximately 14% of total domestic freight transport traffic on Norwegian roads. This paper presents an analysis linking a general equilibrium freight transport modelling tool with a partial equilibrium model of the forest sector. The freight transport model predicts transport costs, modal split and transport patterns, and the results are treated as inputs to the forest sector model. The objective of the paper is to analyse the modelling effect of taking forest sector model effects back into the freight transport model and treated as new demand. Compared to a base scenario for the year 2020, we compare analyses with and without this new demand from the forest sector model back into the freight transport modelling tool.



## ***Optimal forest management with carbon benefits included***

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*Volume 17, issue 3, pp. 395-414*

DOI: <http://www.metla.fi/silvafennica/abs/sa45/sa453395.htm>

D4.3.x ([Link to eRoom](#))

### ***Abstract***

In this paper, we analyse how optimal forest management of even aged Norway spruce changes when economic values are placed on carbon fixation, release, and saved greenhouse gas emissions from using wood instead of more energy intensive materials or fossil fuels. The analyses are done for three different site qualities in Norway, assuming present climate and with a range of CO<sub>2</sub> prices and real rates of return. Compared to current recommended management, the optimal number of plants per ha and harvest age are considerably higher when carbon benefits are included, and increase with increasing price on CO<sub>2</sub>. Furthermore, planting becomes more favourable compared to natural regeneration. At the medium site quality, assuming 2% p.a. real rate of return and 20 euros per ton CO<sub>2</sub>, optimal planting density increases from 1500 per ha to 3000 per ha. Optimal harvest age increases from 90 to 140 years. Including saved greenhouse gas emissions when wood is used instead of more energy intensive materials or fossil fuels, i.e. substitution effects, does not affect optimal planting density much, but implies harvesting up to 20 years earlier. The value of the forest area increases with increasing price on CO<sub>2</sub>, and most of the income is from carbon. By using the current recommended management in calculations of carbon benefit, our results indicate that the forest's potential to provide this environmental good is underestimated. The study includes many uncertain factors. Highest uncertainty is related to the accuracy of the forest growth and mortality functions at high stand ages and densities, and that albedo effects and future climate changes are not considered. As such, the results should be viewed as exploratory and not normative.

## ***Impacts of agent information assumptions in forest sector modelling***

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*Journal of Forest Economics*

Volume 17, Issue 2, April 2011, pp. 169–184

DOI: [10.1016/j.jfe.2011.02.009](https://doi.org/10.1016/j.jfe.2011.02.009)

D4.3.x ([Link to eRoom](#))

### ***Abstract***

The forest sector faces changing political paradigms and volatile policy measures. Policy makers rely on economic and biological models to inform them of the impacts and risks associated with both anticipated and unforeseen policies or shocks to the system. Assumptions about agents' knowledge of future events are fundamental in all forms of models suggesting that the degree of information of future events may have large behavioral impacts. Despite the importance of this assumption, few studies have looked into what this difference in information may imply, and few studies have analyzed the importance of varying the degree of *a priori* information on the impacts of policy measures. This paper attempts to elucidate some of these impacts by comparing how an exogenous shock affects the Norwegian forest sector if the agents are assumed to have: (i) perfect information, (ii) information about the market shift only a limited time before its implementation or (iii) no *a priori* information. The shock analyzed is an import ban on all coniferous wood into Norway, which is possible if the Pinewood nematode (PWN) becomes more widespread in Europe. To examine this question, we adapt the Norwegian forest sector model NorFor to reflect perfect, limited and no prior information. The results indicate that if the agents anticipate the shock, they will begin to adjust harvest and production levels before it occurs. Due to high opportunity costs, harvest is reduced in the first periods to allow increases later. Bioenergy, with much lower profit than pulp and paper on the margin, is the hardest hit by the ban, while paper production is little affected. This may also be due to high capital costs in the paper industry and a perfectly elastic wood demand curve for bioenergy use. Substantial price increases for both raw materials and final products are suggested under either limited or perfect foresight. The analysis may provide useful insight about how agents react to sudden changes depending on their *a priori* information.

## ***Greenhouse gas emission impacts of use of Norwegian wood pellets: a sensitivity analysis***

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*Environmental Science and Policy*

*Volume 14, Issue 8, December 2011, pp. 1028–1040*

DOI: [10.1016/j.envsci.2011.07.011](https://doi.org/10.1016/j.envsci.2011.07.011)

D4.3.x ([Link to eRoom](#))

### ***Abstract***

The rapid growth in wood pellet consumption in Europe has promoted an increase in imports from other continents. In this study, we analyse: (i) the resource use and greenhouse gas (GHG) emissions over the life cycle of wood pellets produced in Western Europe, (ii) the net GHG emission effects of replacing the fossil fuels lignite, hard coal and paraffin with these pellets, (iii) the most important factors impacting on GHG emissions, and (iv) the costs of replacing these fossil fuels with the pellets compared to changes in the net GHG emissions. Over the life cycle of wood pellets, starting from wood harvesting, total emissions amount to 236 kg CO<sub>2</sub>eq/tonne pellets (43 kg CO<sub>2</sub>eq/GJ energy output), but can vary between 113 and 482 kg CO<sub>2</sub>eq/tonne pellets. Substituting lignite in power plants can reduce GHG emissions by about 298 kg CO<sub>2</sub>eq/GJ energy output (1620 kg CO<sub>2</sub>eq/tonne pellets), but only by 58 kg CO<sub>2</sub>eq/GJ energy output in the “Min. substitution effect” scenario where the emissions in the pellet production chain were high and paraffin replaced. The criteria for carbon neutrality are discussed. Including all CO<sub>2</sub> emissions from pellet combustion but not carbon sequestration in forest, GHG emissions from the use of pellets are slightly less than from the replaced lignite. The results of our sensitivity analyses indicate the importance of utilizing bioenergy efficiently. Including all or no CO<sub>2</sub> emissions from combustion are both simplifications, and, depending on the conditions, net CO<sub>2</sub> emissions from pellets lie somewhere between the two. Simple cost estimates suggest that reducing GHG emissions by replacing lignite and hard coal with pellets costs about 60–70 €/tonne CO<sub>2</sub>eq. Replacement of paraffin with pellets has however positive net returns due to the higher market prices for paraffin than for pellets.

## ***Radiative Forcing Impacts of Boreal Forest Biofuels: A Scenario Study for Norway in Light of Albedo***

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*Environmental Science & Technology*  
2011, 45 (17), pp. 7570–7580

DOI: [10.1021/es201746b](https://doi.org/10.1021/es201746b)

D4.1.x ([Link to eRoom](#))

### ***Abstract***

Radiative forcing impacts due to increased harvesting of boreal forests for use as transportation biofuel in Norway are quantified using simple climate models together with life cycle emission data, MODIS surface albedo data, and a dynamic land use model tracking carbon flux and clear-cut area changes within productive forests over a 100-year management period. We approximate the magnitude of radiative forcing due to albedo changes and compare it to the forcing due to changes in the carbon cycle for purposes of attributing the net result, along with changes in fossil fuel emissions, to the combined anthropogenic land use plus transport fuel system. Depending on albedo uncertainty and uncertainty about the geographic distribution of future logging activity, we report a range of results, thus only general conclusions about the magnitude of the carbon offset potential due to changes in surface albedo can be drawn. Nevertheless, our results have important implications for how forests might be managed for mitigating climate change in light of this additional biophysical criterion, and in particular, on future biofuel policies throughout the region. Future research efforts should be directed at understanding the relationships between the physical properties of managed forests and albedo, and how albedo changes in time as a result of specific management interventions.

## ***CO<sub>2</sub> emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming***

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*Global Change Biology Bioenergy*

October 2011, Volume 3, Issue 5, pp. 413–426

DOI: [10.1111/j.1757-1707.2011.01102.x](https://doi.org/10.1111/j.1757-1707.2011.01102.x)

D4.1.15 ([Link to eRoom](#))

### ***Abstract***

Carbon dioxide (CO<sub>2</sub>) emissions from biomass combustion are traditionally assumed climate neutral if the bioenergy system is carbon (C) flux neutral, i.e. the CO<sub>2</sub> released from biofuel combustion approximately equals the amount of CO<sub>2</sub> sequestered in biomass. This convention, widely adopted in life cycle assessment (LCA) studies of bioenergy systems, underestimates the climate impact of bioenergy. Besides CO<sub>2</sub> emissions from permanent C losses, CO<sub>2</sub> emissions from C flux neutral systems (that is from temporary C losses) also contribute to climate change: before being captured by biomass regrowth, CO<sub>2</sub> molecules spend time in the atmosphere and contribute to global warming. In this paper, a method to estimate the climate impact of CO<sub>2</sub> emissions from biomass combustion is proposed. Our method uses CO<sub>2</sub> impulse response functions (IRF) from C cycle models in the elaboration of atmospheric decay functions for biomass-derived CO<sub>2</sub> emissions. Their contributions to global warming are then quantified with a unit-based index, the GWP<sub>bio</sub>. Since this index is expressed as a function of the rotation period of the biomass, our results can be applied to CO<sub>2</sub> emissions from combustion of all the different biomass species, from annual row crops to slower growing boreal forest.

## ***Effects of boreal forest management practices on the climate impact of CO<sub>2</sub> emissions from bioenergy***

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*Ecological modelling*

*Volume 223, Issue 1, 24 December 2011, pp. 59–66*

DOI: [10.1016/j.ecolmodel.2011.06.021](https://doi.org/10.1016/j.ecolmodel.2011.06.021)

D4.1.19 ([Link to eRoom](#))

### ***Abstract***

In Life Cycle Assessment (LCA), carbon dioxide (CO<sub>2</sub>) emissions from biomass combustion are traditionally assumed climate neutral if the bioenergy system is CO<sub>2</sub> flux neutral, i.e. the quantity of CO<sub>2</sub> released approximately equals the amount of CO<sub>2</sub> sequestered in biomass. This convention is a plausible assumption for fast growing biomass species, but is inappropriate for slower growing biomass, like forests. In this case, the climate impact from biomass combustion can be potentially underestimated if CO<sub>2</sub> emissions are ignored, or overestimated, if biogenic CO<sub>2</sub> is considered equal to anthropogenic CO<sub>2</sub>. The estimation of the effective climate impact should take into account how the CO<sub>2</sub> fluxes are distributed over time: the emission of CO<sub>2</sub> from bioenergy approximately occurs at a single point in time, while the absorption by the new trees is spread over several decades. Our research target is to include this dynamic time dimension in unit-based impact analysis, using a boreal forest stand as case study. The boreal forest growth is modelled with an appropriate function, and is investigated under different forestry regimes (affecting the growth rate and the year of harvest). Specific atmospheric decay functions for biomass-derived CO<sub>2</sub> are then elaborated for selected combinations of forest management options. The contribution to global warming is finally quantified using the GWP<sub>bio</sub> index as climate metric. Results estimates the effects of these practices on the characterization factor used for the global warming potential of CO<sub>2</sub> from bioenergy, and point out the key role played by the selected time horizon.

## ***Life cycle assessment of bioenergy systems: State of the art and future challenges***

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*Bioresource Technology*

*Volume 102, Issue 2, January 2011, pp. 437–451*

DOI: [10.1016/j.biortech.2010.08.010](https://doi.org/10.1016/j.biortech.2010.08.010)

D4.1.2 ([Link to eRoom](#))

### ***Abstract***

The use of different input data, functional units, allocation methods, reference systems and other assumptions complicates comparisons of LCA bioenergy studies. In addition, uncertainties and use of specific local factors for indirect effects (like land-use change and N-based soil emissions) may give rise to wide ranges of final results. In order to investigate how these key issues have been addressed so far, this work performs a review of the recent bioenergy LCA literature. The abundance of studies dealing with the different biomass resources, conversion technologies, products and environmental impact categories is summarized and discussed. Afterwards, a qualitative interpretation of the LCA results is depicted, focusing on energy balance, GHG balance and other impact categories. With the exception of a few studies, most LCAs found a significant net reduction in GHG emissions and fossil energy consumption when bioenergy replaces fossil energy.

## ***Chemicals from lignocellulosic biomass: opportunities, perspectives, and potential of biorefinery systems***

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*Biofuels, bioproducts and biorefining*  
*September/October 2011, Volume 5, Issue 5, pp. 548–561*

DOI: [10.1002/bbb.297](https://doi.org/10.1002/bbb.297)

D4.1.21 ([Link to eRoom](#))

### ***Abstract***

Most of the chemical products used today in our society originate from fossil sources through refinery operations. The continual price increase of fossil resources, their uncertain availability, and the environmental concerns of their exploitation have led to a demand for the elaboration of alternative chemical production patterns based on renewable sources. Besides fossils, the only resource available for producing chemicals is biomass, and the establishment of biorefinery complexes is increasingly perceived as a promising alternative to oil refineries. This work is a position paper that provides an insight in the emerging biorefinery concept, with special focus on the opportunities, perspectives, and potential regarding the use of lignocellulosic biomass as raw material in the preparation of platform chemicals needed to meet the existing demand. Results show that replacing fossil resources with wood requires large amounts of biomass and has several technological barriers that are still far from being overcome. This paper identifies the key reactions where major efficiency improvements and research efforts are needed (dehydration, fermentation, hydrogenation, etc.), as well as the possibilities when it comes to enhancing biomass conversion performances through the synthesis of new platform chemicals, with higher oxygen content, so as to accommodate the original biomass composition.



## ***Material, energy and environmental performance of technological and social systems under a Life Cycle Assessment perspective***

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*Ecological modelling*

*Volume 222, Issue 1, 10 January 2011, pp. 176–189*

DOI: [10.1016/j.ecolmodel.2010.09.005](https://doi.org/10.1016/j.ecolmodel.2010.09.005)

D4.1.22 ([Link to eRoom](#))

### ***Abstract***

Selected energy and material resource conversion systems are compared in this paper under an extended LCA point of view. A multi-method multi-scale assessment procedure is applied in order to generate consistent performance indicators based on the same set of input data, to ascertain the existence of constraints or crucial steps characterized by low conversion efficiency and to provide the basis for improvement patterns. Optimizing the performance of a given process requires that many different aspects are taken into account. Some of them, mostly of technical nature, relate to the local scale at which the process occurs. Other technological, economic and environmental aspects are likely to affect the dynamics of the larger space and time scales in which the process is embedded. These spatial and time scale effects require that a careful evaluation of the relation between the process and its surroundings is performed, so that hidden consequences and possible sources of inefficiency and impact are clearly identified. In this paper we analyse and compare selected electricity conversion systems, alternative fuels and biofuels, waste management strategies and finally the time evolution of an urban system, in order to show the importance of a multiple perspective point of view for the proper evaluation of a system's environmental and resource use performance.

## ***Life Cycle Assessment of Biomass-based Combined Heat and Power Plants***

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*Journal of Industrial Ecology*

*December 2011, Volume 15, Issue 6, pp. 908–921*

DOI: [10.1111/j.1530-9290.2011.00375.x](https://doi.org/10.1111/j.1530-9290.2011.00375.x)

D4.1.6 ([Link to eRoom](#))

### ***Abstract***

Norway, like many countries, has realized the need to extensively plan its renewable energy future sooner rather than later. Combined heat and power (CHP) through gasification of forest residues is one technology that is expected to aid Norway in achieving a desired doubling of bioenergy production by 2020. To assess the environmental impacts to determine the most suitable CHP size, we performed a unit process-based attributional life cycle assessment (LCA), in which we compared three scales of CHP over ten environmental impact categories—micro (0.1 megawatts electricity [MWe]), small (1 MWe), and medium (50 MWe) scale. The functional units used were 1 megajoule (MJ) of electricity and 1 MJ of district heating delivered to the end user (two functional units), and therefore, the environmental impacts from distribution of electricity and hot water to the consumer were also considered. This study focuses on a regional perspective situated in middle-Norway's Nord- and Sør-Trøndelag counties. Overall, the unit-based environmental impacts between the scales of CHP were quite mixed and within the same magnitude. The results indicated that energy distribution from CHP plant to end user creates from less than 1% to nearly 90% of the total system impacts, depending on impact category and energy product. Also, an optimal small-scale CHP plant may be the best environmental option. The CHP systems had a global warming potential ranging from 2.4 to 2.8 grams of carbon dioxide equivalent per megajoule of thermal ( $\text{g CO}_2\text{-eq/MJ}_{\text{th}}$ ) district heating and from 8.8 to 10.5 grams carbon dioxide equivalent per megajoule of electricity ( $\text{g CO}_2\text{-eq/MJ}_{\text{el}}$ ) to the end user.

## ***Influence of allocation methods on the environmental performance of biorefinery products—A case study***

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*Resources, Conservation & Recycling*  
Volume 55, Issue 11, September 2011, pp. 1070–1077

DOI: [10.1016/j.resconrec.2011.06.001](https://doi.org/10.1016/j.resconrec.2011.06.001)

D4.1.9 ([Link to eRoom](#))

### ***Abstract***

Life Cycle Assessment (LCA) methodology is the prevailing framework for estimating the environmental performances of a product/service. The application of LCA frequently requires practitioners to address allocation issues, especially when a large number of co-products are produced. The choice of an allocation approach for multifunctional processes is among the most debated methodological aspects in the LCA community, given its potentially large influence on final outcomes. Despite numerous efforts, a uniform consensus on the best allocation practice is still lacking and no single method appears as the most suitable for all situations.

The aim of this paper is to assess how different allocation methods affect the environmental performances of a lignocellulosic biorefinery. Biorefinery systems represent a good example of a multifunctional process, since they co-produce multiple energy and material products. The following allocation procedures are applied: system expansion (also named substitution method), partitioning method according to different features of co-products (mass, energy, exergy and economic value), and hybrid approach (given by a combination of the previous ones). In order to enhance the clarity of the discussion, a mathematical notation for these allocation procedures is adopted, and analytical interrelations are investigated. Results show the influence of the allocation methods on the environmental impacts assigned to the individual products, both on a unit and annual flow basis.

## ***An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries***

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Journal of Forest Economics

April 2011, volume 17, issue 2. Pp 197-213

DOI: [10.1016/j.jfe.2011.02.010](https://doi.org/10.1016/j.jfe.2011.02.010)

D4.3.10 ([Link to eRoom](#))

### ***Abstract***

This study addresses the effects of increasing energy wood prices on the EU forest sector and on the use of wood biomass for energy. We examine different energy wood price levels under two contrasting scenarios of future global development, defined by the A1 and B2 storylines of IPCC. A1 depicts increased globalization and rapid economic growth. In B2, the economic growth is more modest, and the world is more environmentally conscious and regionally oriented. The analysis carried out using the global forest sector model EFI-GTM shows that as energy wood prices increase, the wood imports and reallocation of wood from competing industrial users such as board manufacturers or the pulp and paper industry also increase strongly. The quantity of wood directed from the forest industry to the energy sector would at most be around 20 Mte (million tons of oil equivalent) in terms of energy, given a price of 100 €/m<sup>3</sup> of energy wood. Still, this would cover only around 8% of the European Union's RES target for 2020, and an even lower share for 2030. For some forest industry sectors like production of pulp and panels that would mean an important output reduction, around 20-25%. Additional felling could be an important source of wood for bioenergy in the near future, when utilization of the forest resource potential is still not very high. However, toward 2030, forest resource utilization is projected to increase and might become a limiting factor for additional biomass potentials. Given the relatively high economic growth assumed in the scenarios and the rather strong development in the demand for forest industry products, there is a considerable chance that the supply of wood biomass for energy will be largely limited to logging residues in the long run.

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## ***Crop residues as raw materials for biorefinery systems – A LCA case study***

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*Applied Energy*

*Volume 87, Issue 1, January 2010, pp. 47–57*

DOI: [10.1016/j.apenergy.2009.08.024](https://doi.org/10.1016/j.apenergy.2009.08.024)

D4.1.x ([Link to eRoom](#))

### ***Abstract***

Our strong dependence on fossil fuels results from the intensive use and consumption of petroleum derivatives which, combined with diminishing oil resources, causes environmental and political concerns. The utilization of agricultural residues as raw materials in a biorefinery is a promising alternative to fossil resources for production of energy carriers and chemicals, thus mitigating climate change and enhancing energy security. This paper focuses on a biorefinery concept which produces bioethanol, bioenergy and biochemicals from two types of agricultural residues, corn stover and wheat straw. These biorefinery systems are investigated using a Life Cycle Assessment (LCA) approach, which takes into account all the input and output flows occurring along the production chain. This approach can be applied to almost all the other patterns that convert lignocellulosic residues into bioenergy and biochemicals. The analysis elaborates on land use change aspects, i.e. the effects of crop residue removal (like decrease in grain yields, change in soil N<sub>2</sub>O emissions and decrease of soil organic carbon). The biorefinery systems are compared with the respective fossil reference systems producing the same amount of products/services from fossils instead of biomass. Since climate change mitigation and energy security are the two most important driving forces for biorefinery development, the assessment focuses on greenhouse gas (GHG) emissions and cumulative primary energy demand, but other environmental categories are evaluated as well.

Results show that the use of crop residues in a biorefinery saves GHG emissions and reduces fossil energy demand. For instance, GHG emissions are reduced by about 50% and more than 80% of non-renewable energy is saved. Land use change effects have a strong influence in the final GHG balance (about 50%), and their uncertainty is discussed in a sensitivity analysis. Concerning the investigation of the other impact categories, biorefinery systems have higher eutrophication potential than fossil reference systems. Based on these results, a residues-based biorefinery concept is able to solve two problems at the same time, namely find a use for the abundant lignocellulosic residues and ensure a mitigation effect for most of the environmental concerns related to the utilization of non-renewable energy resources.

Therefore, when agricultural residues are used as feedstocks, best management practices and harvest rates need to be carefully established. In fact, rotation, tillage, fertilization management, soil properties and climate can play an important role in the determination of the amount of crop residue that can be removed minimizing soil carbon losses.

## ***Production of Biofuels and Biochemicals from Lignocellulosic Biomass: Estimation of Maximum Theoretical Yields and Efficiencies Using Matrix Algebra***

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*Energy & Fuels*  
24 (4), pp. 2657–2666

DOI: [10.1021/ef901379s](https://doi.org/10.1021/ef901379s)  
D4.1.14 ([Link to eRoom](#))

### ***Abstract***

The dependence on fossil fuels in developed countries is causing increasing concern. Global warming, issues related to peak oil, sustainability issues, and mounting concern for national energy security are the main drivers for a worldwide effort toward a reduction in fossil fuel consumption. The challenge is substantial, because fossil resources are such an integral part of our economy. However, there are many efforts to address this challenge. Development of conversion technologies fed by renewable resources is seen as a promising option. Many technologies for renewable energy are already well-developed and competitive in the market. Emerging technologies include biorefinery complexes, where biomass is used as a renewable carbon-based source for the production of bioenergy and biochemicals. The latter is perceived as a promising alternative to oil-based chemicals. Given the constraints on availability for renewable biomass supply, the importance of efficient use of biomass with a maximization of useful final products is well-acknowledged. Assessing the potentials for biochemicals can be achieved with an a priori estimation of the maximum theoretical yields, as well as a prediction of the conversion efficiencies (in terms of mass, carbon, and energy efficiency) of selected biorefinery production chains. This paper addresses this issue, providing a calculation procedure with which the theoretical yields and efficiencies of some biorefinery systems are estimated. Among the possible biomass sources, lignocellulosic biomass is selected as the raw material, because it is the most-widespread renewable source available in the world, it is locally available in many countries, and it does not compete with food and feed industries. The conversion of biomass to biofuels and chemicals requires conversion of the feedstock from a solid to a liquid state, but also the addition of hydrogen and rejection of excess oxygen, together with other undesired elements. The carbon contents of lignocellulosic biomass components (cellulose, hemicellulose, and lignin) and products are calculated with the help of mathematical equations, and then the chemical reactions for the conversion of feedstock to products are modeled using matrix algebra: the maximum amount of biofuels and/or biochemicals from biomass and the maximum mass, energy, and carbon conversion efficiency of the biorefinery pathway are determined. Following this calculation procedure, an application to some biorefinery systems is performed and discussed. Combining the best feedstock with the most promising final products, results show that up to 0.33 kg of bioethanol, 0.06 kg of furfural, and 0.17 kg of FT-diesel per kg of softwood can be produced and mass, carbon, and energy conversion efficiencies of 56%, 70%, and 82%, respectively, are achieved.

## ***GHG balances of bioenergy systems – Overview of key steps in the production chain and methodological concerns***

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*Renewable Energy*

*Volume 35, Issue 7, July 2010, pp. 1565–1573*

DOI: [10.1016/j.renene.2009.11.035](https://doi.org/10.1016/j.renene.2009.11.035)

D4.1.24 ([Link to eRoom](#))

### ***Abstract***

This paper deals with a methodology for calculating the greenhouse gas (GHG) balances of bioenergy systems producing electricity, heat and transportation biofuels from biomass residues or crops. Proceeding from the standard Life-Cycle Assessment (LCA) as defined by ISO 14040 norms, this work provides an overview of the application of the LCA methodology to bioenergy systems in order to estimate GHG balances. In this paper, key steps in the bioenergy chain are identified and the bioenergy systems are compared with fossil reference systems producing the same amount of final products/services. The GHG emission balances of the two systems can thus be compared. Afterwards, the most important methodological assumptions (e.g. functional unit, allocation, reference system, system boundaries) and key aspects affecting the final outcomes are discussed. These key aspects are: changes in organic carbon pools, land-use change effects (both direct and indirect), N<sub>2</sub>O and CH<sub>4</sub> emissions from agricultural soils and effects of crop residue removal for bioenergy use. This paper finally provides some guidelines concerning the compilation of GHG balances of bioenergy systems, with recommendations and indications on how to show final results, address the key methodological issues and give homogenous findings (in order to enhance the comparison across case studies).

## ***The biorefinery concept: using biomass instead of oil for producing energy and chemicals***

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*Energy Conversion and Management*  
Volume 51, Issue 7, July 2010, pp. 1412–1421

DOI: [10.1016/j.enconman.2010.01.015](https://doi.org/10.1016/j.enconman.2010.01.015)  
D4.1.25 ([Link to eRoom](#))

### ***Abstract***

A great fraction of worldwide energy carriers and material products come from fossil fuel refinery. Because of the on-going price increase of fossil resources, their uncertain availability, and their environmental concerns, the feasibility of oil exploitation is predicted to decrease in the near future. Therefore, alternative solutions able to mitigate climate change and reduce the consumption of fossil fuels should be promoted. The replacement of oil with biomass as raw material for fuel and chemical production is an interesting option and is the driving force for the development of biorefinery complexes. In biorefinery, almost all the types of biomass feedstocks can be converted to different classes of biofuels and biochemicals through jointly applied conversion technologies. This paper provides a description of the emerging biorefinery concept, in comparison with the current oil refinery. The focus is on the state of the art in biofuel and biochemical production, as well as discussion of the most important biomass feedstocks, conversion technologies and final products. Through the integration of green chemistry into biorefineries, and the use of low environmental impact technologies, future sustainable production chains of biofuels and high value chemicals from biomass can be established. The aim of this bio-industry is to be competitive in the market and lead to the progressive replacement of oil refinery products.



## ***LCA of a biorefinery concept producing bioethanol, bioenergy and chemicals from switchgrass***

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*International Journal of Life Cycle Assessment*  
Volume 15, issue 1, pp 53-66

DOI: DOI: [10.1007/s11367-009-0124-2](https://doi.org/10.1007/s11367-009-0124-2)

D4.1.26 ([Link to eRoom](#))

### ***Abstract***

**Background, aim, and scope:** The availability of fossil resources is predicted to decrease in the near future: they are a non-renewable source, they cause environmental concerns, and they are subjected to price instability. Utilization of biomass as raw material in a biorefinery is a promising alternative to fossil resources for production of energy carriers and chemicals, as well as for mitigating climate change and enhancing energy security. This paper focuses on a biorefinery concept which produces bioethanol, bioenergy, and biochemicals from switchgrass, a lignocellulosic crop. Results are compared with a fossil reference system producing the same products/services from fossil sources.

**Materials and methods:** The biorefinery system is investigated using a Life Cycle Assessment approach, which takes into account all the input and output flows occurring along the production chain. This paper elaborates on methodological key issues like land use change effects and soil N<sub>2</sub>O emissions, whose influence on final outcomes is weighted in a sensitivity analysis. Since climate change mitigation and energy security are the two most important driving forces for biorefinery development, the assessment has a focus on greenhouse gas (GHG) emissions and cumulative primary energy demand (distinguished into fossil and renewable), but other environmental impact categories (e.g., abiotic depletion, eutrophication, etc.) are assessed as well.

**Results:** The use of switchgrass in a biorefinery offsets GHG emissions and reduces fossil energy demand: GHG emissions are decreased by 79% and about 80% of non-renewable energy is saved. Soil C sequestration is responsible for a large GHG benefit (65 kt CO<sub>2</sub>-eq/a, for the first 20 years), while switchgrass production is the most important contributor to total GHG emissions of the system. If compared with the fossil reference system, the biorefinery system releases more N<sub>2</sub>O emissions, while both CO<sub>2</sub> and CH<sub>4</sub> emissions are reduced. The investigation of the other impact categories revealed that the biorefinery has higher impacts in two categories: acidification and eutrophication.

**Discussion:** Results are mainly affected by raw material (i.e., switchgrass) production and land use change effects. Steps which mainly influence the production of switchgrass are soil N<sub>2</sub>O emissions, manufacture of fertilizers (especially those nitrogen-based), processing (i.e., pelletizing and drying), and transport. Even if the biorefinery chain has higher primary energy demand than the fossil reference system, it is mainly based on renewable energy (i.e., the energy content of the

feedstock): the provision of biomass with sustainable practices is then a crucial point to ensure a renewable energy supply to biorefineries.

**Conclusions:** This biorefinery system is an effective option for mitigating climate change, reducing dependence on imported fossil fuels, and enhancing cleaner production chains based on local and renewable resources. However, this assessment evidences that determination of the real GHG and energy balance (and all other environmental impacts in general) is complex, and a certain degree of uncertainty is always present in final results. Ranges in final results can be even more widened by applying different combinations of biomass feedstocks, conversion routes, fuels, end-use applications, and methodological assumptions.

**Recommendations and perspectives:** This study demonstrated that the perennial grass switchgrass enhances carbon sequestration in soils if established on set-aside land, thus, considerably increasing the GHG savings of the system for the first 20 years after crop establishment. Given constraints in land resources and competition with food, feed, and fiber production, high biomass yields are extremely important in achieving high GHG emission savings, although use of chemical fertilizers to enhance plant growth can reduce the savings. Some strategies, aiming at simultaneously maintaining crop yield and reduce N fertilization application through alternative management, can be adopted. However, even if a reduction in GHG emissions is achieved, it should not be disregarded that additional environmental impacts (like acidification and eutrophication) may be caused. This aspect cannot be ignored by policy makers, even if they have climate change mitigation objectives as main goal.

## ***Forest sector impacts of the increased use of wood in energy production in Norway***

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*Forest Policy and Economics*  
*Volume 12, Issue 1, January 2010, pp. 39–47*

DOI: [10.1016/j.forpol.2009.09.011](https://doi.org/10.1016/j.forpol.2009.09.011)  
D4.3.3 ([Link to eRoom](#))

### ***Abstract***

The main objective of this study was to analyse the impacts of increased energy prices on the traditional forest sector (forestry and forest industries) in Norway. The study applied a regionalized partial equilibrium model covering forestry, forest industries and the bioenergy sector. In the model, an increase in the energy price from NOK 0.50/kWh (0.06 Euro/kWh) to NOK 0.70/kWh by the year 2015 reduces production by 12% for particleboard and by 4% for pulp (mainly sulphate), whereas the production of fibreboard was unaffected. The pulp and paper industries in Norway are mainly relying on spruce pulpwood, which is only partly affected by increased bioenergy prices. In the sawmill industries, the negative impact of higher energy prices (input of electricity) is compensated by higher prices received for chips, sawdust and bark. The production of pine sawnwood (accounting for about 31% of the sawnwood production in Norway) increased by 3% by 2015 when the energy price increased from NOK 0.50 to 0.70 NOK per kWh, whereas the production of spruce sawnwood (accounting for 69% of the sawnwood production) decreased by 0.4%. Future improvements of the model should include even more detailed descriptions of bioenergy technologies, the supply of wood residues and the energy market, including consumer behaviour and investment decisions.

## ***Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway***

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*Forest Policy and Economics*

*Volume 12, Issue 1, January 2010, pp. 57–66*

DOI: [10.1016/j.forpol.2009.08.011](https://doi.org/10.1016/j.forpol.2009.08.011)

D4.3.4 ([Link to eRoom](#))

### ***Abstract***

In many European countries, the use of policy measures to decrease greenhouse gas (GHG) emissions from energy consumption, including heating, is high on the political agenda. Also, increasing the absolute consumption of bioenergy seems to partly be an objective in itself. But neither the costs of replacing fossil fuels with bioenergy in heating, nor the effects on the GHG emission account are clear.

This study analyses first the avoided GHG emissions from substituting one energy unit of fossil fuel with forest based bioenergy (wood fuel) in several heating technologies. Secondly, the effects on bioenergy production of two policy measures in Norway - higher tax on domestic heating oil and paraffin and investment grants to district heating installations based on wood fuels - are investigated. Thereafter, the results are combined to display how the emissions from heating are affected. Finally, the achievements are compared to the costs. The analysis is done by using a partial, spatial equilibrium model of the Norwegian forest sector, wood fuels included.

Based on model runs we conclude that a tax of 60 €/CO<sub>2</sub>eq on competing fossil fuels could increase the bioenergy use in district heating installations with almost 4000 GWh/year. The same amount of bioenergy could be used in pellet stoves and central heating systems, but a higher tax is then necessary. 50% investment grant to district heating installations may also have a large effect on the bioenergy use, but the effect of the subsidies decreases rapidly if applied together with a tax. Around 70% of the emissions from heating in Norway may potentially be avoided, but such achievements depend on very high taxes on fossil fuels. Both taxes and subsidies may greatly influence the energy market, but should be used with caution in order to obtain the preferred goals. Few similar studies are carried out in this field, and the results might be of interest for the bioenergy industry and the energy policy authorities.

## ***Forest sector market impacts of changed roundwood export tariffs and investment climate in Russia***

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*Forest Policy and Economics*

*Volume 12, Issue 1, January 2010, pp. 17–23*

DOI: [10.1016/j.forpol.2009.09.016](https://doi.org/10.1016/j.forpol.2009.09.016)

D4.3.5 ([Link to eRoom](#))

### ***Abstract***

The Russian Federation is the world's largest net exporter of roundwood. To encourage shift in exports from roundwood to value-added industrial products, Russia has set large tariffs on its roundwood exports, and announced that even higher ones would be introduced in the future. Using a global forest sector model, the EFI-GTM, we analyse how the Russian and global forest product markets will evolve towards 2020 under alternative tariff levels and assumptions on investment climate in Russia. Our results show that the tariffs decrease harvest and roundwood prices in Russia, but improve the speed of development in the Russian sawnwood and pulp industry. The results also suggest that policies which improve the investment climate in Russia are more vital than the tariffs for the Russian forest industry to develop favourably. Among the tariff settings considered, the prevailing one of 15€ per cubic meter with non-coniferous pulpwood exempted, seems most beneficial for Russia. With a tax of 50€ per cubic meter, its forest industry would not develop much stronger than in the 15€ case, but forestry would suffer from a drastic harvest decrease caused by a nearly complete stop in the Russian roundwood exports, and negligible tax income would be generated. Outside Russia, the main importers of Russian roundwood would experience significant wood price increases and decreased forest industry production. The decline in the forest industry output would be largest in Asia, due to scarce supply there of raw material substitutes for wood imported from Russia, whereas the highest relative increase in roundwood prices would take place in the EU.