

Task 38

Greenhouse Gas
Balances of Biomass
and Bioenergy
Systems

Greenhouse Gas (GHG) and energy analysis of an ethanol-oriented biorefinery in Austria based on wood

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Summary

Worldwide, most of the energy carriers and material products come from fossil fuel refineries. This dependence on fossil fuels is causing environmental and political concerns, given climate change and energy security issues, leading to growing interest in energy from renewable biomass. A biorefinery is analogous to a petroleum refinery, converting biomass feedstocks into fuels and chemicals. Among the possible biomass raw materials, lignocellulosic feedstocks are particularly important, as they are locally available, in abundance, for many countries.

This case study deals with a Life Cycle Assessment (LCA) of a biorefinery system which produces ethanol, other energy carriers (electricity, heat, biomethane) and chemicals (phenols) from softwood forest residues. It is compared to a fossil reference system, which produces the same products. Since climate change mitigation and energy independence are the main driving forces behind biorefineries, the results focus on cumulative primary energy demand and greenhouse gas emissions (GHGs) including those caused by forest management change (i.e. use of residues as raw materials in the biorefinery, that would otherwise have remained in the forest). The impacts of different allocation methods, to share the total GHG emissions of the biorefinery system among the co-products, are investigated.

The biorefinery system uses 84% less non-renewable energy compared with the fossil fuel reference. Taking into account also the impact of the forest management change on carbon stocks in the forest, the

cumulative emissions up to 2020 are 28% higher for the biorefinery system. However, in the year 2020, the biorefinery produces 44% less GHGs annually than its fossil counterpart. By 2050, the biorefinery will have saved 40% of the cumulative GHGs, when compared with a fossil reference system. Forest management change and production of raw materials account for 79% and 15% of cumulative emissions by 2050, respectively.



Neste Oil Refinery, Pöytä, Finland (Photo D.N. Bird)

Scope

This work deals with a LCA of a conceptual biorefinery system in Austria producing:

- ethanol for transport;
- Combined Heat and Power (CHP) from the combustion of lignin and process residues;
- heat from the anaerobic digestion of wastewaters; and
- phenols extracted from lignin.

This system is a combination of several conversion technologies which are jointly applied in order to produce biofuels and material products from lignocellulosic biomass. According to the classification

system for biorefineries, this concept can be categorised as:

C5/C6 sugars, biogas, lignin/pyrolytic oil biorefinery for bioethanol, electricity and heat and chemicals from lignocellulosic residue

The biorefinery system is compared with a **fossil reference system** which produces the same quantity of equivalent products, namely:

- gasoline for transport;
- electricity from natural gas (typical source for Austrian power plants);
- heat from heavy oil and natural gas; and
- phenols from a conventional oil refinery.

Description

The concept biorefinery uses 530 kt dry biomass from Austrian forest residues, which comprise biomass not harvested or removed during forest management (e.g. harvest residues, pre-commercial thinnings, dead trees). If left in place, these residues naturally decay. They may inhibit forest regeneration and increase the risk of forest fire. On the other hand, increased residue use may negatively impact biodiversity and nutrient cycles (Janowiak and Webster, 2010, Bouget et al, 2012).

The yield of forest softwood residues is based on typical Austrian forests (Marschall, 1992) and tree component estimates (JRC, 2012). Collecting residues from forests requires fossil fuel inputs. The biomass is assumed to be transported for 40 km (round trip, 16 t truck) to a facility where it is firstly dried using heat from a natural gas boiler and then ground and pelletized using electricity supplied from the Austria grid. The pellets are transported 100 km to the biorefinery plant in 40 tonne-capacity trucks. For details of energy consumption factors please see the full report.

The pellets are processed (Figure 1) using:

- Pretreatment (uncatalyzed steam explosion) in order to depolymerize hemicellulose and separate lignin;
- Enzymatic cellulose hydrolysis to obtain glucose monomers;
- Fermentation and distillation of sugars to obtain ethanol;
- Anaerobic digestion of wastewaters to produce biogas;
- Flash pyrolysis of lignin (20%) followed by phenol separation from the resulting pyrolytic oil; and
- Combustion (for heat and power production) of process residues (i.e. lignin that is not pyrolyzed, pyrolytic char and unrecovered pyrolytic oil).

This biorefinery system requires electricity (0.83 GJ/t dry feedstock, 0.03 GJ/GJ pyrolytic oil produced and 0.54 GJ/t dry matter in wastewater) and heat (0.40 GJ/GJ bioethanol produced and 110 MJ/t dry matter in

wastewater). These energy needs are completely met by heat and power produced by combustion of lignin and residues. For details of energy consumption factors please see the full report.

Ethanol is transported 100 km to fuelling stations where it is used to fuel passenger cars. GHG emissions from combustion of the ethanol in cars (i.e. CH₄, N₂O) are also included. Biomethane is fed to the national natural gas grid, where it replaces natural gas in all its existing applications. It is assumed that the biomethane is burnt in a boiler and the resulting emissions are estimated. The CO₂ resulting from the combustion of these biofuels is included by accounting for the loss of carbon stocks in the forest. Phenols are transported for 50 km to their final application. It is assumed that no carbon storage in products occurs, i.e. all the carbon is released to the atmosphere within the time of the functional unit (one year).

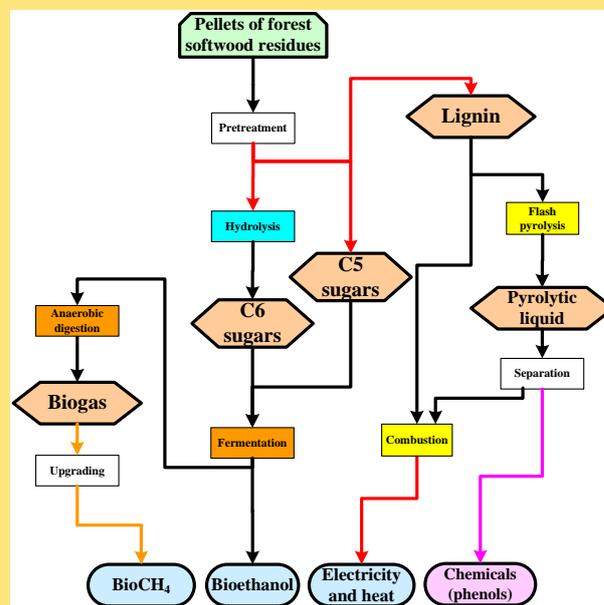


Figure 1 Main process steps of the biorefinery plant.

System boundary

Figure 2 shows the system boundaries for the biorefinery and fossil reference system. The biorefinery chain starts with the forest residue resource in the middle of the diagram. At the end, the biorefinery provides products and services. All input and output flows occurring along the full chain are accounted for using a life cycle perspective. In contrast, the fossil reference system starts with consumption of non-renewable resources (i.e. fossil oil and natural gas). The reference system also includes a **reference use** for the residues, i.e. left in the forest where a natural decomposition occurs. This forest management change from natural decay to use may cause a reduction in the carbon stocks of the forest and a consequent emission of CO₂.

Functional unit

The functional unit of the assessment is the amount of biomass treated per year, i.e. 530 kt dry of pellets from forest softwood residues.

Allocation

Allocation in LCA is carried out to attribute shares of the total environmental impact to the different products of a system. This concept is extremely important for biorefinery systems, as multiple energy and material products are produced. Allocation methods can use physical characteristics or economic value of products for sharing the total GHG emissions, or allocate a credit for avoided emissions, using the substitution method, or avoid allocation altogether by expanding the system boundary and the functional unit to encompass the co-products. Scientific publications show benefits and disadvantages of the various allocation methods (Cherubini et al 2011, Curran 2007; Ekvall and Finnveden, 2001; Frischknecht 2000; Wang et al., 2004), but which allocation procedure is most suitable is still open to discussion.

In this study, in addition to the substitution method, the following allocation procedures are used and compared:

- Energy;
- Exergy;
- Economic; and
- a method based on the shares of GHG avoided when compared with a fossil reference system.

In this assessment, the main product is assumed to be ethanol and the environmental benefits of co-products are assumed as credits. These credits (i.e. the GHG and fossil energy saved by the co-products) are then subtracted from the total GHG emissions and

energy consumption of the whole system; the resulting environmental burdens are completely assigned to the main product.

Allocation based on energy content of products can be easily carried out but its application may result in misleading conclusions if there are some products which are not energy carriers (e.g. chemicals).

Allocation based on exergy overcomes this inconsistency but can difficult to apply because the exergy content of substances needs to be estimated. In this study, exergy content of products comes from a specific database (Ayres et al., 1996).

Allocation based on economic values focuses on external characteristics of the products and has the disadvantage that it does not account for the physical properties of the products, because it is based on their “value” in human societies. In addition, market values of products may vary according to the year, production chain and geographical location (Ekvall, 2001).

The additional allocation method shares the environmental burdens among co-products according to the respective shares of the fossil counterparts in the total GHG emissions of the fossil reference system. For instance, if gasoline contributes 80% of total GHG emissions of the fossil reference system, 80% of total GHG emissions of the biorefinery system will be assigned to ethanol (which is assumed to replace conventional gasoline). The main advantages of this new allocation method are the following:

- environmental burdens are assigned according to the effective GHG savings of the products, thus gives more weight to those products which are responsible of the largest savings;
- it is not necessary to choose a main product; and
- it can be applied indifferently to energy or material products.

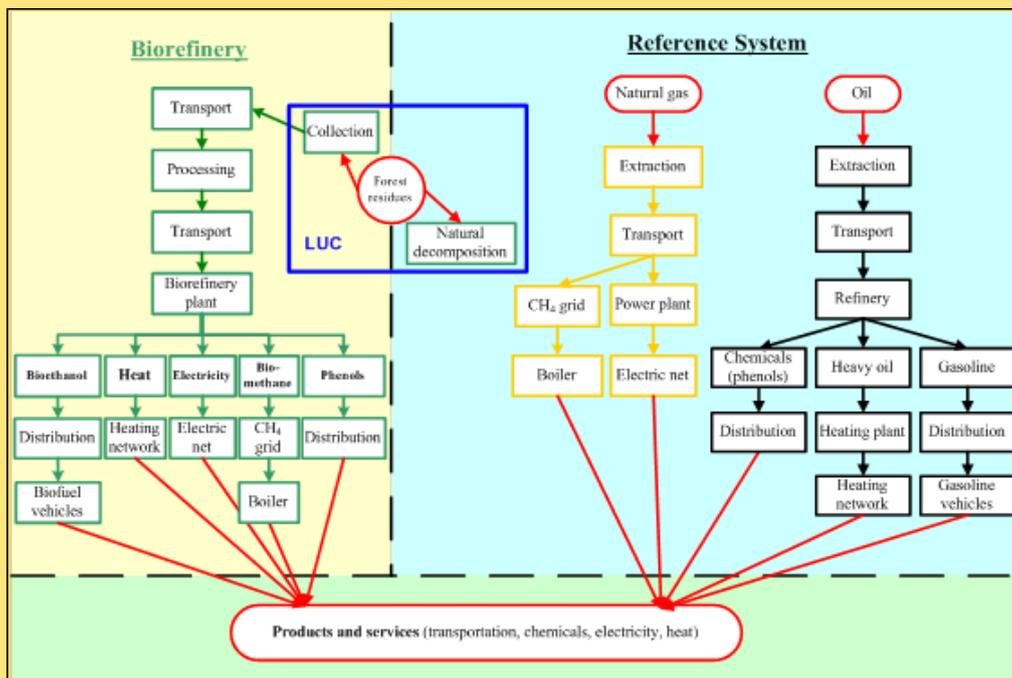


Figure 2: System boundaries of the biorefinery and fossil reference system

Leakage or indirect land use change

Leakage (or indirect land use change) is minimized since there is no competitive use for the residues.

Method

This study is modelled by means of the LCA software tool SimaPro 7 (<http://www.pre.nl/simapro/default.htm>) and selected literature references are used to estimate input flows and specific emissions (GEMIS, 2009, NREL, 2009). Forest management change effects are estimated by means of a dedicated software tool (CO2FIX, <http://www.efi.int/projects/casfor/>). Since climate change mitigation and energy independence are the main driving forces for future biorefineries, results focus on GHG emissions (CO₂, CH₄ and N₂O) and cumulative primary energy demand, divided into non-renewable (fossil and nuclear), renewable (biomass) and other renewable (mainly hydropower). Total GHG emissions are expressed in t CO₂-eq. assuming the following global warming potentials (CO₂ = 1, CH₄ = 23, N₂O = 296). Total GHG emissions of the biorefinery system are then allocated to the products using different allocation criteria and the results are finally compared.

Results and discussion

Energy balances

The energy balances of the biorefinery and fossil energy system are illustrated in Figure 3. The biorefinery system requires more cumulative primary energy (11.4 PJ/year) than the fossil reference system (6.4 PJ/year), but it is provided mostly (90%) by renewable bioenergy (the energy content of the feedstock). The biorefinery saves 5.32 PJ/year of non-renewable resources, or approximately 11.2 GJ of non-renewable energy per tonne of dry biomass.

Greenhouse gas emission balances

The emissions from the biorefinery are time dependent (Table 1). The reason for the time-dependency is that removal of residues from the land in a given year causes a loss of carbon stocks. However, over time these residues would have decayed in the reference system. It is assumed that

the carbon stocks in the reference system are in dynamic equilibrium. The use of these residues in the biorefinery causes the carbon stocks to decrease until the system reaches a new equilibrium. The biorefinery system releases more GHG emissions than the fossil reference system until 2025, but the longer the system is in operation, the more GHG emissions are saved (Figure 4). For the EU bioenergy target in 2020, the biorefinery system does not deliver any GHG emission savings. However, the average annual savings during the first 20 years (i.e. by 2032) are 125 kt CO₂-eq./a, or 33% of the fossil emissions during the same period.

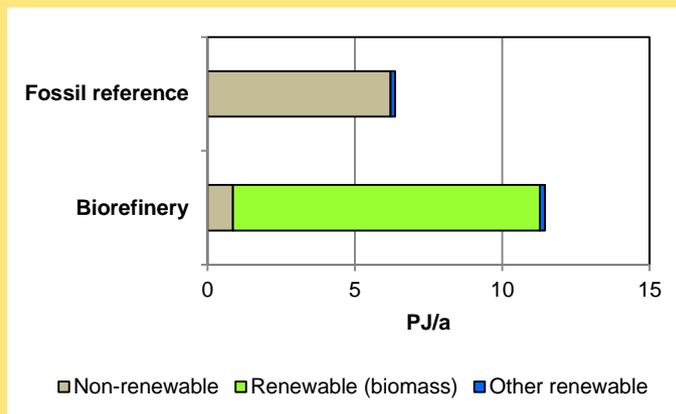


Figure 3: Cumulative primary energy demand of the biorefinery and fossil energy system.

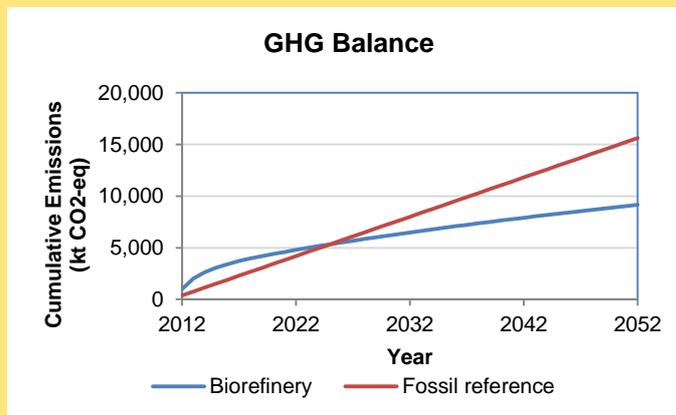


Figure 4: The cumulative emissions of the biorefinery and fossil reference systems. After 2025, the bioenergy system produces fewer emissions than the comparative fossil reference system.

Table 1: GHG balances of the biorefinery and fossil reference systems.

Unit	Biorefinery				Fossil reference system	
	2020	2032	2050	2100		
Average annual GHG emissions						
Total	kt CO ₂ -eq./year	435	256	176	104	381
CO ₂	kt CO ₂ -eq./year	430	251	171	99	357
N ₂ O	kt CO ₂ -eq./year	1.45	1.45	1.45	1.45	7.42
CH ₄	kt CO ₂ -eq./year	3.70	3.70	3.70	3.70	16.1
Average annual GHG savings						
per year	kt CO ₂ -eq./year	-	125	205	277	-
per year	%	-	33%	54%	73%	-
per input biomass	kg CO ₂ -eq./t _{dry}	-	236	387	523	-

Figure 5 shows contributions to total GHG emissions of the biorefinery system in 2032. In 2020, the emissions due to forest management change are 89% of total emissions. By 2032, this has decreased to 84%. The category “other” includes losses of CH₄ during from the handling and treatment of waste and wastewaters.

GHG emissions from pellet production have three main contributors:

- Collection of residues in the forest (35%)
- Transport of the residues from the forest to the pelletizing facility (31%)
- Energy required to produce the pellets (34%).

Concerning the fossil reference system, its total GHG emissions have the following contributions:

- 69.5% Gasoline,
- 18.6% Electricity,
- 4.30% Heat from oil,
- 5.39% heat from natural gas,
- 2.19% Phenols.

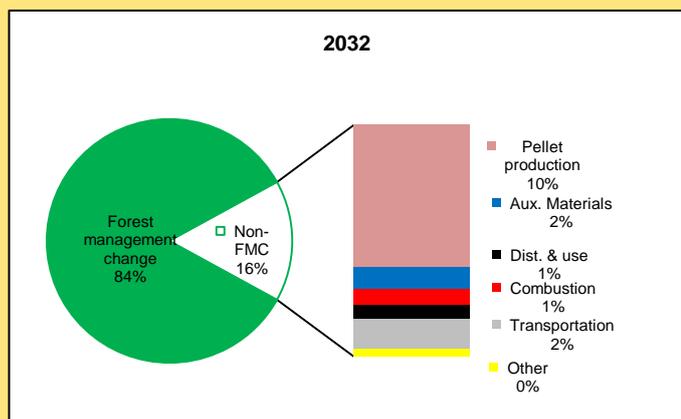


Figure 5: Contributions to total GHG emissions of the biorefinery system.

Sensitivity analysis

Allocation

The sensitivity of the results to the allocation method is shown in Table 2. Emissions from these biomass derived products and services can be compared with those derived from oil refinery. For instance, driving a car fuelled with ethanol (184 g CO₂-eq./km, energy allocation) instead of conventional gasoline (198 g CO₂-eq./km), saves approximately 7% of CO₂-eq. emissions; savings will be up to 19% if the new allocation method is used.

All the allocation methods lead to relatively similar results for ethanol and phenols, while for other products differences are larger. Allocation based on energy and exergy content of products show similar results for almost all the products. Allocation based on economic values increases the share of the transportation biofuel, while decreasing the environmental burdens assigned to electricity, heat and biomethane.

The new allocation method assigns higher emissions to electricity and heat, because these energy carriers are assumed to replace natural gas derived electricity and oil derived heat, which have a relevant contribution to the total GHG emissions of the fossil reference system. This new method is particularly important when GHG savings are the main task of the study, because it assigns more importance to those products which save more GHG emissions.

Forest management change

In this study, the parameter with the largest influence on the final results is forest management change (see Figure 5). To investigate the sensitivity of the results to the assumptions made for the assessment of forest management change we derived six different CO₂FIX scenarios (Table 3).

Table 2: GHG emissions to 2032 of the biorefinery products according to different allocation methods.

		New method	Energy	Exergy	Economic	Substitution method	Product in reference System
Ethanol	g CO ₂ -eq./km	161	184	184	207	95	198
Electricity from CHP	g CO ₂ -eq./kWh	591	271	251	229	-1,139	731
Heat from CHP	g CO ₂ -eq./kWh	345	271	151	48.7	-663	425
Heat from biomethane	g CO ₂ -eq./kWh	64.9	75.8	105	14.5	-125	289
Phenols	g CO ₂ -eq./MJ	2.82	2.40	2.31	1.17	-5.43	29.2

Table 3: Scenario descriptions for sensitivity analysis of land management change

Scenario No.	Yield class	Location	Elevation (masl)	Annual precipitation (mm)	Average annual temperature (°C)
1	8	Bruck an der Mur	482	795.2	8.1
2	10	Bruck an der Mur	482	795.2	8.1
2a	10	Afflenz	780	885.8	6.3
2b	10	Mariazell	875	1081.3	6.1
2c	10	Mürzzuschlag	700	1035.2	6.2
3	12	Bruck an der Mur	482	795.2	8.1

Yield class

The number of hectares from which the residues must be collected varies in response to the yield class (models 1, 2, and 3). However, the emissions per tonne of biomass are insensitive to yield class because the same amount of biomass is extracted in all cases and the emissions depend on the decay rate of the biomass if it had been left on site. Since the area required is sensitive to yield class but the emissions are not, the loss of biomass over a cycle on a per hectare basis is also sensitive to yield class.

Climate

The variation in results due to climate is investigated using models 2, 2a, 2b, 2c. The net emissions during a period of time from using biomass, that would otherwise have decayed, are a function of the decay rate of the biomass. In general, the faster the decay rate, the lower are the net emissions. In the extreme, if 100% of the material decays in less than one year, then there are no net annual emissions caused by combusting the material. At the other extreme, combusting biomass that would never have decayed is equivalent to combusting a fossil fuel. Using equations for decomposition rate as a function of climatic parameters (temperature and annual precipitation) from Moore et al (1999), we find for woody material that the annual decomposition is greatest for Mariazzell and lowest for Afflenz. However the variability is quite small. Across the 6 scenarios, the standard error is about 1.5% of the mean total emissions.

Rotation period

Two assumptions about forest management that were used in the models described above were tested in the sensitivity analysis:

1. Rotation period of 80 years rather than 90 years; and
2. Whether thinning residues are used for bioenergy.

If the stands had a final felling every 80 years instead of every 90 years then there is 8.5% less biomass to harvest at final felling, hence more area of forest is required. The stands with no harvesting of forest residues also have less biomass with the 80-year rather than the 90-year rotation and hence there are fewer emissions when the biomass is used for energy. However the difference is small. The emission intensity decreases by approximately 1%.

There is also variation caused by the assumption on the fate of thinning residues. When these are used fewer hectares of forest are required to produce the required amount of biomass since they are in addition to the residues from final felling. The thinning residues are 33% of the total residues removed from the forest per year. However the emission intensity does not vary if the thinning residues are used since the emissions are dependent on the amount of biomass

removed per year and not whether they come from thinning or final felling.

Conclusions

The use of softwood forest residues in a biorefinery has the potential to co-produce bioenergy and chemicals which are currently produced by oil refineries. The biorefinery system depicted in this work produces ethanol, electricity, heat and phenols from lignocellulosic biomass and is compared with a reference system producing the same amounts of equivalent products from fossil fuels.

The GHG balance reveals that the biorefinery system has lower total emissions than the fossil reference system after 13 years. Before this time, the biorefinery system produces more emissions because the land is in transition from a dynamic equilibrium with residues on site, to one with residues removed. The change in forest management causes a loss of carbon stocks in dead wood, litter and soil organic carbon and this is the major source of GHG (approximately 70-90% of total emissions depending on year). However, after 13 years, the biorefinery system produces less GHGs than the fossil reference system, and the difference between the two systems continues to increase with time so that after 50 years the biorefinery system has 55% of the emissions of the fossil reference system.

The biorefinery requires more total energy than the fossil reference system, but it is mainly from renewable energy (the energy content of the feedstock) and non-renewable energy sources are saved (90%).

In order to share the total GHG emissions of the biorefinery among the different co-products, several allocation procedures were applied. An attempt to avoid allocation through substitution method was developed. As well, allocations based on energy content, exergy content and economic value of outputs were compared with a new allocation method based on the share of the total GHG emissions of the fossil reference system contributed by each equivalent product. All allocation methods are presented for compared and the specific GHG emission factors (g CO₂-eq./unit) of each product are calculated.

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IEA Bioenergy (www.ieabioenergy.com) is an international collaborative agreement, set up in 1978 by the International Energy Agency (IEA) to improve international cooperation and information exchange between national bioenergy research, development and demonstration (RD & D) programs. IEA Bioenergy aims to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas (GHG) emissions from energy use.

IEA Bioenergy Task 38 (www.ieabioenergy-task38.org) brings together research work of national programs in all participating countries on GHG Balances for a wide range of biomass systems, bioenergy technologies and terrestrial carbon sequestration. Emphasis is placed on the development of state-of-the-art methodologies for assessing GHG balances; demonstrating the application of established methods, supporting decision-makers in implementing effective GHG mitigation strategies. As one example of work, case studies have been conducted by applying the standard methodology developed by Task 38. The case studies have assessed and compared GHG balances of different bioenergy and carbon sequestration projects in the participating countries, and this Austrian case study is one example.