



Evaluation of greenhouse gas emission risks from storage of wood residue

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Abstract

The use of renewable energy sources instead of fossil fuels is one of the most important means of limiting greenhouse gas emissions in the near future. In Finland, wood energy is considered to be a very important potential energy source in this sense. There might, however, still be some elements of uncertainty when evaluating biofuel production chains. By combining data from a stack of composting biodegradable materials and forest residue storage research there was an indication that rather great amounts of greenhouse gases may be released during storage of wood chip, especially if there is rapid decomposition. Unfortunately, there have not been many evaluations of greenhouse gas emissions of biomass handling and storage heaps. The greenhouse gas emissions are probably methane, when the temperature in the fuel stack is above the ambient temperature, and nitrous oxide, when the temperature is falling and the decaying process is slowing down. Nowadays it is still rather unusual to store logging residue as chips, because the production is small, but in Finland storage of bark and other by-products from the forest industry is a normal process. The evaluations made indicate that greenhouse gas emissions from storage can, in some cases, be much greater than emissions from the rest of the biofuel production and transportation chain.

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1. Introduction

Renewable energy sources have been identified to play an important role in future energy solutions. In Finland, wood energy is considered

to be a very important potential energy source in this sense. In the 1990s about 20% of the energy used already came from biomass.¹ Common biofuels used are by-products from the forest industry such as black liquor,² bark, and sawn wood; small-scale fuel wood is also widely used,

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¹Do not include peat fuels.

²A by-product from the paper manufacturing process.

especially in the countryside. New, increasing use of biofuel is expected to come from forest residues. The average annual growth of forest chips³ production has been about 0.3 million m³ during the late 1990s. In the year 2000, about 0.9 TWh of the forest chips used as fuel came from forest residue [1]. However, the goal is to use 5 million solid m³ (10 TWh) of fuel chips⁴ annually produced from residual forest biomass by 2010 [2].

Greenhouse gas balances of bioenergy systems have been compared with fossil energy systems in some previous works [3–8]. The production of fuel chips has usually been evaluated as energy-effective and the emissions of greenhouse gases from the production chain have been assumed to strongly correlate with the use of fossil fuels (e.g. diesel oil) in the production chain.

One of the most difficult tasks in biomass harvesting is how to manage the storage of the material [9], mainly how to avoid material losses due to degradation. It is necessary to use storage at latitudes where severe winter conditions might prevent contractors from supplying fuel during the period when the demand is biggest. On the other hand, not much fuel is needed during the warmer months but forest residues are still generated because the time of harvesting most often depends on when raw material (stem wood) is needed for industry. From a fuel properties point of view it would be optimal to cut the tree stands in early spring and let the residues dry naturally on the harvest area or on the roadside until early autumn and then use the fuel when the moisture content is lowest. Unfortunately, this is not possible because of the structure of the energy demand. In order to guarantee an uninterrupted delivery of forest chips to the users, the fuel chips have to be stored for several months [10].

The forwarding and comminution of fresh logging residue guarantee the maximum yield of dry matter, but, on the other hand, the moisture content is high, about 50–60 wt%⁵ [11]. The fuel

properties of naturally dried residues, where part of the needles have fallen off, are often more suitable for the energy production facilities [12]. Nevertheless, there are usually degradation problems during storage of fuel chips from both types of residue.

Considerable fuel chip storage research has been performed in Sweden since the 1980s [see, e.g. 13–21] and in Finland in the 1990s [e.g. 9,10, 22–25]. The results of these studies show that it is typical that the temperature in a pile of fuel chips rises very rapidly as the material starts to decay. In some extreme cases, self-ignition has even caused a fire in the fuel storage. To keep material losses moderate in long-time storage, the humidity has to be very low, usually under 20 wt%, which is not possible without artificial drying.

Combining research results from storage of wood residues with some new information coming from the waste-handling sector, a concern rises of there being a lack of knowledge concerning greenhouse gas emissions from the biofuel storage operations. The objects of the concern are self-heating biofuel piles containing such nitrogen and moisture contents that allow rapid degradation circumstances similar to those found in biowaste⁶ composting.

The objective of this study is to briefly evaluate greenhouse gas emission potentials from storage of wood residues. As the production and storage of bioenergy probably will flourish in the near future, the emission mechanisms from storage might need further research in order to learn how to avoid emissions. Currently it is not common to store logging residue as chips. In Finland, the production amounts are still small, but storage of bark and other similar by-products is a normal process for sawn mills and in the paper industry sector. In Finland, the present biofuel amounts that might be of concern for causing greenhouse gas emissions are, if stored as chips, about 6 TWh of forest chips and 15 TWh of bark.

³The general name for chips made of wood material harvested in a forest.

⁴The general term referring to chipped or crushed wood produced with various techniques for burning.

⁵Moisture content of fresh material (weight per cent).

⁶Organic waste, the part of municipal waste that is usually suitable to handle by composting. Also meaning agricultural waste or manure that usually has to be composted before used.

2. Knowledge from biofuel storage and biowaste composting research used for the evaluations

The following chapter presents some published knowledge from biofuel storage and biowaste composting that might be used for evaluating greenhouse gas emission risks in storage of wood residue. The main physical parameters of interest are the age of the stored material, rapidity of material losses, C/N⁷ rates and moisture content of the storage heap.

2.1. Material losses due to storage of fuel chip

The temperature in a pile of chipped (fresh or naturally dried) forest residue usually rises very rapidly after an initial period of approximately one week [9].⁸ This is a serious sign that the material has begun to decompose which leads to material and energy losses.

The moisture content of chips has a large influence on dry matter losses. In tests carried out in Sweden, the initial moisture content was found to be proportional to the losses—initial moisture content of 42%, 51% and 58% caused monthly dry matter losses of 1.1, 2.2 and 2.6 wt% and total losses during the 6-month storage period of 6.6, 13.2 and 15.6 wt% [14,16,17]. In another test lasting for 9 months, the initial humidity was 32 wt% and under 20 wt%. The monthly losses in these tests were 1.03 and 0.23–0.35 wt% [17].

The material losses due to storage are highest in the beginning of the storage period, right after the temperature has rapidly risen. The losses have been estimated to be 3.6 wt% per week (measured during the second week of storage) and after this 0.4–0.7 wt% per week [19,20].

There seems to be a considerable difference in temperature behaviour depending on the moisture level. If the initial moisture content is under 40 wt% the temperature rises fast but also decreases after 1–2 months. At 10–15 wt% higher moisture content, the core temperature usually

remains high during the whole storage period [10,17].

The size of the chip seems to be of importance for the temperature behaviour. Thörnqvist [17] found that in heaps with an average chip size of 8 mm, the temperature rose rapidly to over 60 °C. When the average chip size was 30 mm, the temperature rose to 40–50 °C; when the average chip size was 70 mm, the temperature did not rise above 30 °C. This has a very natural explanation: the biological activity producing heat takes place on the surface of the chips; the smaller the chip size, the larger the surface area per volume, and consequentially the higher the biological activity leading to higher temperatures. Furthermore, the natural ventilation of the heap declines as the chip size decreases [26].

Also coating, ventilating, and compressing the heaps seem to influence the temperature behaviour and the material losses [10,13,15,17,18,20,22,23], e.g. forced ventilation is discovered to decrease dry matter losses significantly [15]. Some of the reported results concerning compressing are contradictory [17,18,23].

As material losses can be significant and affect the energy content of the produced fuel directly, they must be perceived and accounted for in the emission evaluations. In some cases, the material losses can be compensated for by lower moisture content due to the drying process that occurs because of the heat produced in the decomposition process. However, since the stacks are usually kept outside with little or no cover, rain and snow are likely to keep the moisture content constant or even increase it.

2.2. C/N rates and moisture circumstances of biogenic materials allowing rapid decomposition

Source-separated biowaste has a typical nitrogen (N) content of about 2 wt% in dry matter (DM). The carbon content varies between 25 and 50 wt% (DM). Typical values for the C/N-rate are 12–20 [27]. Before the composting process, biowaste is usually mixed with a material containing a higher C/N-rate (chopped wood or straw, etc.) to obtain a more porous structure promoting aeration. The biowaste compost heaps that

⁷Ratio between carbon and nitrogen content.

⁸During severe winter conditions, the initial period with a slow rise in temperature may last longer (for several weeks) but the heating behaviour after that will still be the same.

Beck-Friis et al. [28] used for measurements contained 50–60 v%⁹ of chipped tree branches and bushes. The average moisture content was almost 60 wt%.

The nitrogen content of forest residue varies widely (0.05–1.1 wt% (DM)) depending on the freshness of the material as well as on the used tree species and parts of the tree (stemwood, bark, or needles) [24,29]. The carbon content is more constant, about 50 wt% (DM) [24,29]. The C/N rate for needles is 45...50 and for an average fuel chip about 100.

A high moisture content is favourable for the decomposition process. Practically, compost heaps have a moisture content of about 60 wt%. Higher values make it difficult to keep the process aerobic, as the weight of the material will compress the heaps. The moisture content of wood residues varies widely depending on production and storage circumstances. Forest residues are normally delivered with a moisture content of 45–55 wt% [8]. However, temperature development and fungal growth in even pellet piles have been observed at some plants. It has been found that, e.g. bark pellets with a moisture content of 19 wt% allow microbial growth [21].

As a summary, the moisture and nitrogen contents in wood-originated biofuel are normally such that rapid decomposition is known to occur. An exception to this, due to the low content of nitrogen, is sawdust from stem wood.

2.3. Emission mechanisms and rates known from biowaste degradation

Emission of climate-relevant gases such as N₂O and CH₄ is known to occur during composting of household wastes and storage of manure [28,30–32]. During the degradation process, it is typical that the temperature rapidly rises and later, after a period of time, slowly reaches the ambient temperature. To keep the degradation process intensive, compost heaps are usually turned a few times, usually when the temperature begins to fall.

Organic material is decomposed mainly to CO₂. The emitted N₂O is found to either be the end

product of incomplete ammonium oxidation (aerobic conditions) or the end product of incomplete denitrification (anaerobic conditions). As nitrifying bacteria are sensitive to high temperatures (>40 °C), no high emissions of N₂O can be expected during the most intensive composting stage. Nitrous oxide is formed either initially, before a temperature increase, or after the thermophilic phase, when the temperature is low again [32,33–35]. CH₄ is produced only during anaerobic conditions. Such conditions typically occur when the biological activity is high, or in other words, when the temperature and the CO₂ production are high. The formation of CH₄ usually takes place in the centre of the compost heap and the compost gas inside the heap can contain up to 45 vol% CH₄. Sommer and Møller [34] found that emissions of CH₄ did not occur until the CH₄ concentration at the centre of the heap reached about 500 ppm,¹⁰ which can be explained by efficient oxidation of CH₄ in the surface area of the compost heap. In other words, the emissions are likely to be smaller than the amounts of CH₄ found inside the heaps. This phenomenon is not valid for N₂O.

The behaviour described above is only valid for ideal, homogenous compost. Practically, humidity, temperature levels, aeration, etc. vary in different parts of the heap, which can e.g. make it possible that nitrous oxide can be formed although the mean temperature of the heap is over 40 °C.

2.3.1. Emission rates of N₂O from compost

Compost gas may contain N₂O concentrations over 100 times greater than the background concentration of 0.3 ppm. Estimates made by Petersen et al. [32] and Hellebrand [36] indicate that the emissions of N₂O–N¹¹ can be about 0.5 wt% of the total initial nitrogen present.

In laboratory tests, total emissions of N₂O–N accounted for less than 2 wt% of the gaseous emissions (98 wt% of the N was lost in the form of NH₃ gas), which amounted to 24–33 wt% of the

⁹Volume per cent.

¹⁰100 ppm–0.01%

¹¹Amount of nitrous oxide calculated as nitrogen.

initial N present in the composts [37]. In other words, this would mean that 0.5–0.7%¹² of the initial nitrogen was emitted as nitrous oxide. No total emission rates were calculated based on emissions from large compost heaps [28], but the reported high emission rates indicate that the amount of nitrogen released as N₂O could have been even 1–2 wt% of the initial N. In another study [38], the gaseous losses during composting were evaluated to be 26–51 wt% of the total original nitrogen. Martins and Dewes [39] evaluated gaseous nitrogen losses from manure to consist of over 95% of NH₃ but most of the remaining 5% to consist of N₂O. This means that 1.0–2.6% would have been emitted as nitrous oxide.

Beck-Friis et al. [28] found that the emission of N₂O from the large heaps increased with compost age, being less than 0.02 g N₂O–N m⁻² d⁻¹ during the first 3 months and reaching 1.5 g N₂O–N m⁻² d⁻¹ after 6 months. “Hot spots” with very high N₂O concentrations inside the heap were found in compost heaps aged 6 months or older and the levels of NO₃⁻–N were higher than 0.1 µg N per gram dry matter [28]. Beck-Friis et al. suspected the small N₂O emissions that appear at the start of composting to originate from NO₃ already present in the raw substance [37].

2.3.2. Emission rates of CH₄ from compost

Total emissions of CH₄ during composting were calculated to be less than 1% of the initial C present in the compost material [34]. Beck-Friis et al. [28] measured mean CH₄ emissions for a whole 6-month period from large composts of 35 g CH₄ m⁻² day⁻¹ (max value measured 119 g CH₄ m⁻² day⁻¹). A rough estimation for the whole 40 weeks test period would, based on the reported data, be that 4–5% of the C left the compost heap as CH₄.

3. Evaluation of greenhouse gas emissions from storage of forest residues

The calculations of emitted CH₄ and N₂O from outdoor decaying piles are rather imprecise, since the material itself, the circumstances inside the heap, the gas flows, the density¹³ of the different components and the composition of the emitted gas vary very much. Therefore, it is not too easy to define an accurate emission coefficient and to specify the quantity of material the gas has been emitted from. It is also not well-known how the initial N content, assuming that it is high enough to increase microbial activity that generates heat, affects the emitted amount of CH₄ and N₂O. On the other hand, it is also difficult to verify the quality of any theoretical calculations without knowing the possible relations between the fuel properties, decaying parameters and emissions. This means that proper evaluations of the emissions will need both further theoretical studies parallel with systematic emission measurements.

The working steps used for this theoretical evaluation are shown in Fig. 1. Based on the background described in Section 2, such typical forest residue properties are chosen that can be expected to go together with the simplified degradation behaviour shown in Fig. 2. Emission factors from degradation of organic materials are specified based on results from composting research and factors of material losses are specified based on results from biofuel storage research. Then evaluations of emission rates per energy unit (MWh) of the final biofuel are made and the magnitude of the results is verified by calculating the total conversion rates of C to CH₄ and N to N₂O.

Calculations are made for one type of forest residue with two different moisture contents, 40 and 60 wt%, shown in Table 1. It is assumed that the moisture content does not influence the amount of dry matter per loose volume, since the

¹²This test, however, lasted only for 30 days and the reference does not give any information about the temperature at which the tests were performed.

¹³If a gas component is heavier than air it is not obvious that it will flow only in the vertical direction. Therefore the measured concentrations should be compared against the concentration of carbon dioxide in the same sample.

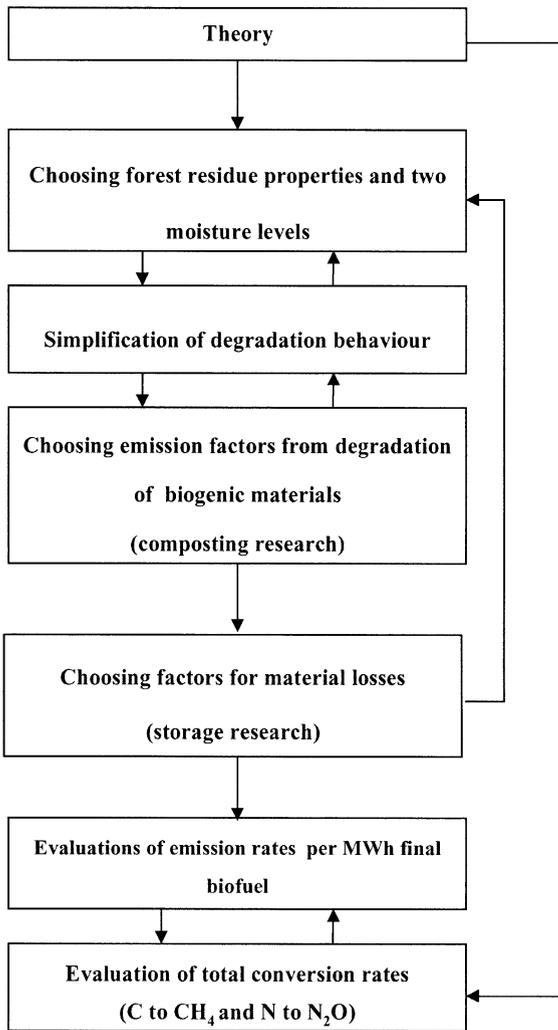


Fig. 1. Working scheme used for the evaluation.

compost heaps where the emissions originate from are only 2–2.5 m high. In order to simplify the calculations, it is also assumed that the compost contained the same amount of dry matter per loose m³ as the forest residue.

According to the different behaviour of the storage heaps (see Section 2.2), the dryer heap is expected to mainly emit methane for 2 months and then N₂O for 4 months. The fresh heap is expected to emit methane during the whole 6-month period but no N₂O emissions are either suspected or

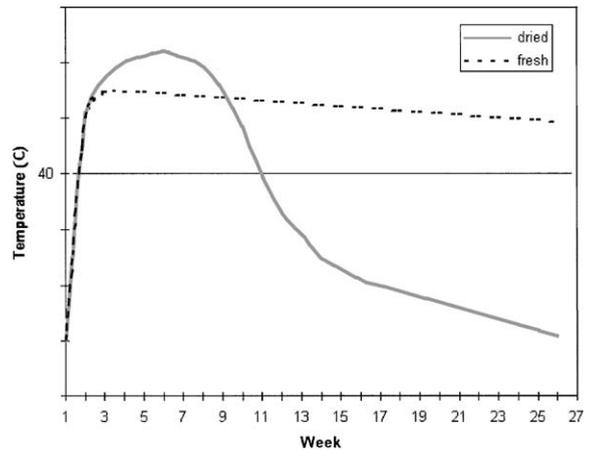


Fig. 2. Simplified principle of degradation behaviour.

calculated, because the mean temperature is expected to remain over 40 °C.

The emission coefficients needed for the calculations in this article are taken from Beck-Friis et al. [31]. To further simplify the calculations, only two temperature levels are accounted for: the time when fast degradation takes place (over 40 °C) and the phase when the heap cools down (under 40 °C). The first emission factor, 60 g CH₄ m⁻² day⁻¹, is an average value for emissions from 3-, 14-, and 18-week-old compost (the measured emissions were between 35 and 119 g CH₄ m⁻² day⁻¹). The second one, 1.2 g N₂O m⁻² day⁻¹, is an average value for 26-week and 40-week-old compost (the measured emissions were between 0.6 and 2.3 g N₂O m⁻² day⁻¹).

Using a mean methane emission of 60 g CH₄ m⁻² day⁻¹ from the large compost (see Section 2) and assuming that the biofuel storage heap has the same amount of material as the compost heap,¹⁴ a daily emission rate of 24 g CH₄ (loose m_{fuel}³)⁻¹ can be expected. Taking into account the energy content of the material and the material losses, the monthly emission rate of the naturally dried forest residue would be 840 g CH₄ month⁻¹ MWh⁻¹ and 1044 g CH₄ month⁻¹ MWh⁻¹ for the fresh material.

¹⁴2.5 loose m_{fuel}³ m⁻².

Table 1
Fuel properties and storage data on which the emission evaluations are made

Material	Naturally dried forest residue	Fresh forest residue
Moisture content	40 wt%	60 wt%
Effective energy content in DM	19.8 MJ kg ⁻¹	19.8 MJ kg ⁻¹
Dry matter in loose volume	180 kg (loose m ³) ⁻¹	180 kg (loose m ³) ⁻¹
Carbon in DM	50 wt%	50 wt%
Nitrogen in DM	0.5 wt%	0.5 wt%
Energy content in loose volume	0.9 MWh (loose m ³) ⁻¹	0.8 MWh (loose m ³) ⁻¹
Expected behaviour	2 months >40 °C 4 months <40 °C	6 months >40 °C
Expected dry material losses (6 month)	6.6%	15.6%

Calculated as kg CO₂ eq¹⁵ this would mean 19 and 24 kg.

Using a mean of nitrous emissions of 1.2 g N₂O m⁻² day⁻¹ gives a daily emission rate of 0.5 g N₂O (loose m³_{fuel})⁻¹. Accounting for the energy content of the material and the material losses, the monthly emission rate for the naturally dried forest residue will then be 17 g N₂O month⁻¹ MWh⁻¹ and 21 g N₂O month⁻¹ MWh⁻¹ for the fresh material. Calculated as kg CO₂ eq, this would mean 5 and 6 kg.

After a 6-month storage, the naturally dried forest residue (moisture 40 wt%) is evaluated to have emitted totally 58 kg CO₂ eq and the fresh forest residue (moisture 60 wt%) 144 kg CO₂ eq (see Fig. 3). The main emission source would have been CH₄ in both cases—66% of the total emissions of greenhouse gases for the dry fuel and 100% for the fresh one.

Comparing the emitted amounts of C and N as CH₄ and N₂O with the assumed initial amounts gives us the result that 1.3 and 4.4 wt% of the initial carbon were emitted as CH₄. This is well in line with figures from the literature (1–5 wt%, see

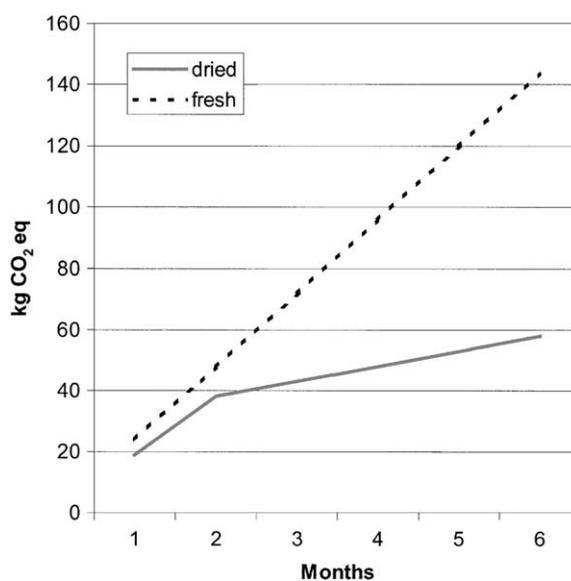


Fig. 3. Evaluated cumulative greenhouse gas emissions for a 6-month storage of two kinds of fuel chips: one chopped from fresh residue and the other from naturally dried residue.

Section 2.3.2). The same calculation for nitrogen gives the result that 4.4 wt% of the initial nitrogen would have been emitted as N₂O, which is larger than the figures found in the literature (1.0–2.6 wt%, see Section 2.3.1). This means that if the formed N₂O correlates with the initial nitrogen content, the emission evaluations for N₂O made earlier could possibly be about 2–4 times too large. This is, however, difficult to estimate because the research periods in the consulted literature have possibly been too short to account for all N₂O emissions.

¹⁵The total greenhouse gas emissions are expressed in carbon dioxide equivalents calculated from global warming potential (GWP) values. The GWP values give a measure of the relative effects of the various greenhouse gases on global warming. GWP is defined as the cumulative radiative forcing between the present and some chosen time horizon caused by a unit of mass of gas emitted now, expressed relative to the reference gas CO₂. The time horizon of 100 years has been used in the calculations and the corresponding GWP values are 23 for CH₄ and 296 for N₂O [40].

4. Conclusions and discussion

Based on these rough evaluations, the following conclusions can be drawn:

(i) A biofuel chip storage can probably cause remarkable greenhouse gas emissions. The potential amounts of CH₄ emissions seem to be of larger concern than the N₂O emissions.

(ii) It is to recommend that comminuted forest residue is used without delay, if possible within 1 week.

(iii) Storage heaps should not be mixed or moved during the storage period, as this would probably make the decomposition process more intensive, which causes increasing emissions rates.

During the period of fast decomposition, there are remarkable risks of emissions and energy losses, which can easily be detected through temperature measurements. Biofuel storage could be monitored with heat detectors, and the decisions of dismantling a storage could be made depending on the follow-up data. Due to emissions, it seems to be more important to first use a warm fuel stack than a stack that has already cooled down.

As methane emissions are only produced during anaerobic conditions, it might be a risk factor to compress piles, because then the airflow through the pile will probably decrease. This might also increase the potential risk of spontaneous ignition [10]. On the other hand, if the temperature can be kept lower by compressing the material (this result is presented in [9] but is contrary to earlier information), losses will remain smaller. Therefore, it could be advantageous to investigate how compacting of biofuel storage affects the emission rates. As the produced methane is known to oxidise in upper, aerobic layers of the biodegrading heap, the coating method of the stacks could be useful to develop as well. May be the fuel heap could be covered with a peat layer¹⁶ enriched with methane-oxidising microflora [42].

From composting, it is well known that biological activity is stimulated if the surface area

of the material is increased. The choice of comminution technique could therefore be of importance when trying to avoid emissions. Other methods used to stabilise biodegradable materials could be worth investigating.

The reliability of these calculations is not easy to evaluate as there are many, still not too well-known, factors affecting the decomposition process and subsequently the emissions. Nevertheless, the results are probably more valid for rather long-term storage (here 6 months) than for shorter periods, because the emission factors can temporarily vary widely, from being about half of the mean value (used for the evaluation) to double. Also, the dry matter losses are known to vary significantly during shorter periods but can be better predicted for long-term storage. Furthermore, 66–100% of the emitted greenhouse gases from a 6-month storage was calculated to originate from C emitted as CH₄. This makes the results more reliable than if N₂O would have had a bigger role, as the calculated emitted amounts of CH₄ and initial carbon levels seem to match quite well.

In a recent study [8] of greenhouse gas emissions from final harvest fuel chips production chains, the emissions from collecting, chipping, and transporting the residues was calculated to be 4–7 kg CO₂ eq MWh_{fuel}⁻¹, and nutrient loss compensation with fertilisation and recirculation of ash was estimated to cause emissions in the range of 7 kg CO₂ eq MWh_{fuel}⁻¹. Compared with these emission rates, the calculated greenhouse gas emissions of 58–144 kg CO₂ eq MWh_{fuel}⁻¹ from a 6-month wood chips storage that should be added to these earlier, supposedly low emission rates from the wood chips production chain, should be of very large concern and worth further investigation.

Assuming a price of biofuel of 10 euro MWh⁻¹, the losses of 6.6 and 15.6 wt% would cost the storage-keeper from 0.7 to 1.6 euro MWh⁻¹ sold fuel. Comparing the income losses with the emissions gives us an estimate that at a cost level of 12 euro t⁻¹ emitted CO₂ or more, the values of the emissions are higher than the value of material losses. As the estimated costs for CO₂ abatement probably will be much higher than this during the next decades e.g. in Finland [41], minimisation of

¹⁶The peat cover could later on be mixed with the wood fuel and co-combusted.

emissions from biofuel storage should be taken very seriously also in this respect.

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