Reassessment of the calculation procedure for the volatile solids excretion rates of cattle and pigs in the Austrian, Danish and German agricultural emission inventories

Ulrich Dämmgen*[1], Barbara Amon**[2], Steen Gyldenkærne***, Nicholas J. Hutchings****[2], Heinrich Kleine Klausing*****, Hans-Dieter Haenel* and Claus Rösemann*

Abstract

The equations provided in the IPCC Guidelines quantifying the fluxes of volatile solids were examined and corrected. National data were collated that allow the calculations of these fluxes. The combination of modified equations and national data instead of default values results in a reduction of calculated VS excretion rates for cattle and pigs and hence to reduced methane emission from manure storage facilities.

Keywords: Emissions, emission reporting, volatile solids, digestibility, energy contents, ash, cattle, pigs

Zusammenfassung

Überarbeitung des Verfahrens zur Berechnung von Ausscheidungsraten von „volatile solids“ bei Rindern und Schweinen in den österreichischen, dänischen und deutschen landwirtschaftlichen Emissionsinventaren

Die im IPCC-Regelwerk angegebenen Gleichungen zur Berechnung der Flüsse von „volatile solids“ wurden überprüft und korrigiert. Für die zur Berechnung solcher Flüsse benötigten Größen wurden nationale Daten zusammengestellt. Die Benutzung der veränderten Gleichungen und nationaler Daten anstelle von sog. default-Werten führt bei Rindern und Schweinen zu einer Verringerung der berechneten VS-Ausscheidungen und damit zu verringerten Methan-Emissionen aus dem Wirtschaftsdünger-Lager.

Schlüsselwörter: Emissionen, Emissionsberichterstattung, volatile solids, Verdaulichkeit, Energie-Gehalte, Asche, Rinder, Schweine

* Johann Heinrich von Thünen Institute (vTI), Federal Research Institute for Rural Areas, Forestry and Fisheries, Institute for Agricultural Climate Research, Bundesallee 50, D-38116 Braunschweig, Germany

[1] former co-chair of UNECE Agriculture and Nature Panel

** University of Natural Resources and Life Sciences, Department of Sustainable Agricultural Systems, Division of Agricultural Engineering, Peter-Jordan-Strasse 82, 1190 Wien, Austria

[2] co-chair of UNECE Agriculture and Nature Panel

*** University of Aarhus, National Environmental Research Institute, Dept. of Policy Analysis, Frederiksborgvej 399, 4000 Roskilde, Denmark, UNFCCC ERT member

**** University of Aarhus, National Environmental Research Institute, PO Box 50, Research Centre Foulum, 8830 Tjele, Denmark

***** Deutsche Tiernahrung Cremer GmbH, Weizenmühlenstr. 20, 40221 Düsseldorf, Germany

1 Introduction

Methane (CH_4) emissions in animal husbandry originate from enteric fermentation and from the storage of animal excreta under anaerobic conditions. These emissions have to be quantified according to the IPCC[A] Guidelines provided by the United Nations Framework Convention on Climate Change (UNFCCC) and reported to the UNFCCC secretariat. These IPCC Guidelines for National Greenhouse Inventories distinguish between simpler (Tier 1 Methods) and detailed methodologies (Tier 2 Methods). The latter include country specific parameters such as animal performance, feed composition and storage type.

In the IPCC Tier 2 methodologies for the assessment of CH_4 emissions from storage (IPCC, 1996, 2006), volatile solids (VS)[B] are considered to be the source of CH_4 from manure management. In this methodology the CH_4 emission rates are directly related to the excretion rates of VS, the maximum methane producing capacity B_o (reflecting typical composition of the excreta) and a methane conversion factor *MCF* (reflecting typical storage effects). Unless default values are used, the assessment of VS excretion rates presupposes the knowledge of the energy requirements and feed properties (including digestibility and ash contents), or representative diets, obtained by survey.

This work aims at a clarification of the IPCC (1996) and (2006) methodologies to assess VS excretion rates with respect to ash contents and digestibilities and at an improvement of the respective data base in dairy cattle husbandry and pig production, in particular with

(1) the calculation procedure to assess VS input rates into storage systems in general;
(2) the assessment of the parameters used to model VS input rates such as
   - the energy contents of feeds;
   - the digestibilities of feeds;
   - the ash contents of feeds.

1.1 IPCC calculation procedures for the derivation of volatile solids excretion rates – information provided in the guidelines

The IPCC methodologies (IPCC, 1996, 2006) relate the emission rates of CH_4 to the excretion rates of VS. They provide two different equations to quantify VS excretion rates.

In IPCC (1996), equation (15) reads:

$$VS_{1996}\ \text{(kg dm/day)} = \text{Intake (MJ/day) x (1 kg/18.45 MJ) x} \\ (1 - DE\%/100) \text{ x } (1 - ASH\%/100) \quad (1)$$

where

VS_{1996}	*VS* excretion per day on a dry weight basis
dm	dry matter
Intake	the estimated average feed intake in MJ/day
DE%	the digestibility of the feed in per cent (e.g. 60 %)
ASH%	the ash content **of the manure** in per cent (e.g. 8 %)

In addition, footnote 13 explains: The energy density of feed is about 18.45 MJ per kg dry matter. This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

IPCC (2006) equation (10.24), describes the VS excretion rate.

$$VS_{2006} = \left[GE \cdot \left(\frac{1 - DE\%}{100}\right) + (UE \cdot GE)\right] \cdot \left[\left(\frac{(1 - ASH)}{18.45}\right)\right] \quad (2)$$

where

VS_{2006}	*VS* excretion per day on a dry-organic matter basis, kg *VS* day^{-1}
GE	gross energy intake, MJ day^{-1}
DE%	the digestibility of the feed in per cent (e.g. 60 %)
(UE·GE)	urinary energy expressed as a fraction of GE. Typically 0.04 GE can be considered urinary energy excretion by most ruminants.
ASH%	the ash content **of manure** calculated as a fraction of the dry matter feed intake (e.g. 0.08 for cattle).
18.45	conversion factor of dietary GE per kg of dry matter (MJ kg^{-1}). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

Hence, the difference between the 1996 and 2006 Guidelines is the introduction of urine as an additional bearer of energy.

In the explanations to the equations, both IPCC (1996) and IPCC (2006) provide a default ash content of "around 8 %" (IPCC, 1996) for cattle and buffalo and of 0.08 MJ MJ^{-1} (IPCC, 2006) for cattle only in **manure**.

The descriptions of ash contents in pig manure in IPCC (1996), pg. 4.23, and in the appendix, Table B-2, pg. 4.42, are ambiguous. The text refers to 2 % as ash content **in manure**, whereas the appendix states that the VS default emission factor was derived for ash contents of 2 % in pig

A IPCC: Intergovernmental Panel on Climate Change

B Volatile solids are defined as "degradable organic material in livestock manure". (IPCC, 1996, pg. 4.22)

feed (developed countries). IPCC (2006) does not provide information about ash contents in pig manure.

However, at a first glance, measured ash contents of manure or excreta are far larger than the default values provided in the guidelines. Hence both the equations and the ash contents need to be checked.

1.2 Treatment of crop residues in the IPCC Guidelines

Crop residues may be used as bedding material and may contribute to CH_4 formation during storage. However, neither IPCC guidelines take this source into account.

IPCC (1996), pg. 4.90 f, recommends assessment of N in crop residues with respect to the direct formation of N_2O. Equation (1), pg. 4.92, explicitly names F_{CR} as a source of N to be taken into account. Any material removed from the field as bedding or feed is to be subtracted from the biomass grown.

IPCC (2006) refers to N inputs into managed soils with bedding material (see equation (10.3), pg 10.65). However, C transfers with bedding material and CH_4 formation from bedding material are not accounted for explicitly.

As this proposal aims at a comprehensive assessment of VS input rates into manure storage systems this is felt to be inadequate.

2 Assessment of amounts of VS entering storage

CH_4 emissions from manure storage are related to the amounts of VS discharged into the storage system. The IPCC guidelines equate these with the amounts excreted.

2.1 Standardized IPCC equations

In order to avoid confusion, the above equations are "translated" into standard symbols that allow for a better explanation of relations. Equation (15) in IPCC (1996) then reads:

$$VS_{1996} = GE \cdot \frac{1}{c} \cdot (1 - x_{DE}) \cdot (1 - x_{ash,\,fu}) \qquad (1a)$$

where
- VS_{1996} VS excretion rate according to IPCC (1996) (in kg place^{-1} d^{-1} DM[C])
- GE gross energy intake rate (in MJ place^{-1} d^{-1})
- c constant (energy content of DM for domestic animals, c = 18.45 MJ kg^{-1}; IPCC (1996), pg. 23)
- x_{DE} digestibility of energy (in MJ MJ^{-1})
- $x_{ash,\,fu}$ ash content of faeces and urine[D] (in kg kg^{-1}), DM

The 2006 equation reads:

$$VS_{2006} = GE \cdot \frac{1}{c} \cdot (1 - x_{DE} + x_{UE}) \cdot (1 - x_{ash,\,fu}) \qquad (2a)$$

where
- VS_{2006} excretion rate according to IPCC (2006) (in kg place^{-1} d^{-1} DM)
- GE gross energy intake rate (in MJ place^{-1} d^{-1})
- c constant (energy content of DM for domestic animals, c = 18.45 MJ kg^{-1}; IPCC (2006), pg. 10.42)
- x_{DE} digestibility of energy (in MJ MJ^{-1})
- x_{UE} urinary energy expressed as fraction of gross energy (cattle: x_{UE} = 0.04 MJ MJ^{-1}; pigs: x_{UE} = 0.02 MJ MJ^{-1}; IPCC (2006), pg. 10.42)
- $x_{ash,\,fu}$ ash content of faeces and urine (in kg kg^{-1}), DM

2.2 Tentative deduction of the IPCC (1996) and (2006) equations

The pathways of organic matter and ash from feed to excreta are illustrated in Figure 1.

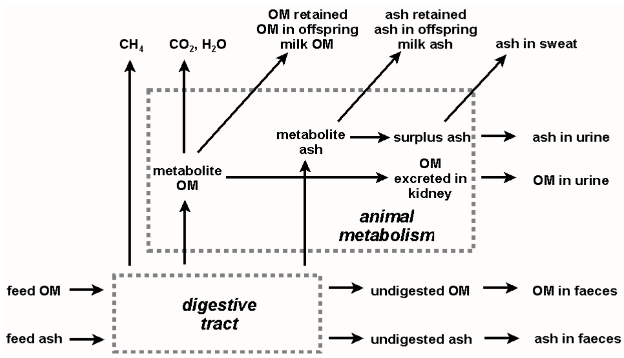

Figure 1:

Elements of the mass flow balances of organic matter and ash from animal feed to excreta

All equations and statements in this work refer to dry matter.

VS is the degradable organic matter (OM) **excreted** with faeces and urine, i.e. the sum of undigested OM, the digested OM **excreted** with urine, and the OM imported with bedding material:

[C] DM: dry matter

[D] The term "manure" used by IPCC may be restricted to faeces only (see Pain and Menzi, 2003). The term "excreta" describes any waste matter expelled from the body, such as faeces, urine, sweat, waste products of the metabolism or other non-useful materials. Hence we use the terms "faeces" and "urine".

$$VS = VS_{\text{faeces}} + VS_{\text{urine}} + VS_{\text{bedding}} \quad (3)$$

where
VS VS input rate into storage (in kg place^{-1} d^{-1})
VS_{faeces} VS excretion rate with faeces (in kg place^{-1} d^{-1})
VS_{urine} VS excretion rate with urine (in kg place^{-1} d^{-1})
VS_{bedding} VS input rate with bedding (in kg place^{-1} d^{-1})

VS in faeces

VS_{faeces} equals the amount of undigested OM and can be calculated by subtracting the proportion of digestible organic matter (DOM) from the total OM:

$$VS_{\text{faeces}} = OM_{\text{feed}} \cdot (1 - X_{\text{DOM}}) \quad (4)$$

where
VS_{faeces} VS excretion rate with faeces (in kg place^{-1} d^{-1})
OM_{feed} rate of OM intake with feed (in kg place^{-1} d^{-1})
X_{DOM} apparent digestibility[E] of organic matter (in kg kg^{-1})

IPCC (1996) and IPCC (2006) assume

$$X_{\text{DOM}} \approx X_{\text{DE}} \quad (5)$$

where
X_{DOM} apparent digestibility of organic matter (in kg kg^{-1})
X_{DE} digestibility of energy (in MJ MJ^{-1})

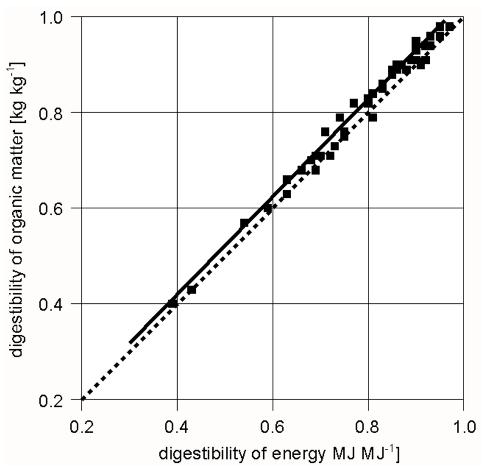

Figure 2:
Digestibility of energy and organic matter in pig feed constituents (data from Beyer et al., 2004)

However, the apparent digestibility of OM slightly exceeds X_{DE} (by a few %; see Figure 2). This is particularly true for those constituents that form the most part of the diet (wheat, barley, soy bean extraction meal).

The organic matter intake (OM_{feed}) is the difference of total dry matter and the amount of ash in feed.

$$OM_{\text{feed}} = M_{\text{feed}} - M_{\text{ash, feed}} \quad (6)$$

where
OM_{feed} intake rate of organic matter with feed (in kg place^{-1} d^{-1})
M_{feed} overall feed intake rate (in kg place^{-1} d^{-1})
$M_{\text{ash, feed}}$ rate of ash taken in with feed (in kg place^{-1} d^{-1})

For M_{feed} see Chapter 2.3. M_{ash} is the intake rate of combustion residues with feed and can be rewritten as follows:

$$M_{\text{ash, feed}} = M_{\text{feed}} \cdot X_{\text{ash, feed}} \quad (7)$$

where
$M_{\text{ash, feed}}$ rate of ash (combustion residues) taken in with feed (in kg place^{-1} d^{-1})
M_{feed} overall feed intake rate (in kg place^{-1} d^{-1})
$X_{\text{ash, feed}}$ ash content of feed (in kg kg^{-1})

VS in urine

IPCC (2006) relates VS_{urine} to GE intake:

$$VS_{\text{urine}} = \frac{GE}{\eta_{\text{GE, feed}}} \cdot x_{\text{GE, urine}} \quad (8)$$

where
VS_{urine} VS excretion rate with urine (in kg place^{-1} d^{-1})
GE gross energy intake rate with feed (in MJ place^{-1} d^{-1})
$\eta_{\text{GE, feed}}$ gross energy content of feed dry matter (in MJ kg^{-1})
$x_{\text{GE, urine}}$ share of GE excreted with urine (in MJ MJ^{-1})

The share of $x_{\text{GE, urine}}$ amounts to 0.02 to 0.04 MJ MJ^{-1} for cattle and 0.02 MJ MJ^{-1} for pigs[F].

The gross energy content of urine, $\eta_{\text{GE, urine}}$, is definitely different from c in equations (1a) and (2a) ($\eta_{\text{GE, urea}}$ of the major constituent urea is 13.74 MJ kg^{-1}).

However, the energy excreted with urine is contained in organic matter whose composition differs from that of feed. Examples of analyses of cows' urine are presented in Kool et al. (2006):

[E] Definition of digestibility: fraction (input – faecal losses)/input. For energy this is the fraction (GE – faecal losses)/GE, for OM it is the fraction DOM/OM.

[F] German data for energy losses with urine related to GE intake: dry cows: 0.036 MJ MJ^{-1}, lactating cows: 0.033 (Müller et al., 1980); cows: 0.035 MJ MJ^{-1} (Kreuzer et al., 1985)

Table 1:

Examples of composition of cows' urine (in % of N excreted with urine) (Kool et al., 2006)

constituent	feed maize based	feed grass based
urea	85.2	76.7
allanthoin	8.3	14.3
hippuric acid	4.1	5.1
uric acid	0.5	0.8
creatinine	2.0	3.2

Carbon to nitrogen ratios in urine lead to similar conclusions: the C to N ratio of urine is close to that of urea (Table 2).

Table 2:

Carbon to nitrogen ratio in urine (in kg kg^{-1}) (Hoffmann and Klein, 1980)

animal	C to N ratio
cows dry	1.64
cows lactating	1.58
bulls (beef)	1.38
pigs growing	1.15
pigs for slaughter	0.97
for comparison	
urea	1.71
allanthoin	0.86
hippuric acid	7.71

Hence, 90 to 95 % of the OM in urine is urea and allanthoin. Both are hydrolyzed within hours after excretion to CO_2 and NH_3. They do not form degradable organic matter as defined and do not account for any CH_4 formation (Monteny and Erisman, 1999). The difference between IPCC (1996) (equation 1) and IPCC (2006) (equation 2) is irrelevant, independent of the amount of the energy excreted with urine.

VS in bedding

IPCC (1996) and IPCC (2006) do not explicitly include bedding material as source of CH_4 emissions from manure management. However, the properties of customary bedding materials are similar to the undigested feed constituents. A complete inventory should include VS from decomposing bedding material.

VS_{bedding} is treated like VS_{faeces}:

$$VS_{\text{bedding}} = OM_{\text{bedding}} \quad (9)$$

where

VS_{bedding} volatile solids input with bedding (in kg place^{-1} d^{-1})

OM_{bedding} rate of OM input with bedding (in kg place^{-1} d^{-1})

The organic matter input with bedding (OM_{bedding}) is the difference of total dry matter and the amount of ash in bedding.

$$OM_{\text{bedding}} = M_{\text{bedding}} - M_{\text{ash, bedding}} \quad (10)$$

where

OM_{bedding} input rate of organic matter with bedding (in kg place^{-1} d^{-1})

M_{bedding} overall organic matter input rate with bedding (in kg place^{-1} d^{-1})

$M_{\text{ash, feed}}$ rate of ash imported with bedding (in kg place^{-1} d^{-1})

with

$$M_{\text{ash, bedding}} = M_{\text{bedding}} \cdot X_{\text{ash, bedding}} \quad (11)$$

where

$M_{\text{ash, bedding}}$ rate of ash (combustion residues) imported with bedding (in kg place^{-1} d^{-1})

M_{bedding} overall import rate of bedding (in kg place^{-1} d^{-1})

$X_{\text{ash, bedding}}$ mean ash content of bedding (in kg kg^{-1})

Synthesis

The combination of the above considerations yields the amounts of VS entering the storage system:

$$VS_{\text{faeces, sto}} = VS_{\text{faeces}} = M_{\text{feed}} \cdot (1 - X_{\text{ash, feed}}) \cdot (1 - X_{\text{DOM}}) \quad (12a)$$

$$VS_{\text{urine, sto}} \neq \frac{GE}{\eta_{\text{GE, feed}}} \cdot x_{\text{GE, urine}}; \quad VS_{\text{urine, sto}} \approx 0 \quad (12b)$$

$$VS_{\text{bedding, sto}} = VS_{\text{bedding}} = M_{\text{bedding}} \cdot (1 - X_{\text{ash, bedding}}) \quad (12c)$$

where

$VS_{\text{faeces, sto}}$ VS in faeces entering storage (in kg place^{-1} d^{-1})

VS_{faeces} VS excretion rate with faeces (in kg place^{-1} d^{-1})

M_{feed} feed intake rate (dry matter) (in kg place^{-1} d^{-1})

$X_{\text{ash, feed}}$ ash content of feed (in kg kg-1)
$VS_{\text{urine, sto}}$ VS in urine entering storage (in kg place-1 d-1)
VS_{urine} VS excretion rate with urine (in kg place-1 d-1)
X_{DOM} apparent digestibility of organic matter (in kg kg-1)
GE gross energy intake rate (in MJ place-1 d-1)
$\eta_{\text{GE, feed}}$ gross energy content of feed (in MJ kg-1)
$x_{\text{GE, urine}}$ share of GE excreted with urine (in MJ MJ -1)
$VS_{\text{bedding,sto}}$ VS entering storage with bedding (in kg place-1 d-1)
VS_{bedding} VS input with bedding (in kg place-1 d-1)
M_{bedding} overall import rate of bedding (in kg place-1 d-1)
$X_{\text{ash, bedding}}$ ash content of bedding (in kg kg-1)

Equation (15) in IPCC (1996) reflects equation (12a) in this work (albeit with a wrong ash content). Equation (10.24) in IPCC (2006) appears to be an unnecessary extension of equation (15) in IPCC (1996). The subsequent application in the Guidelines presupposes the same maximum methane producing capacity B_o for both faeces and urine. This is definitely not the case.

Both guidance documents identify the respective ash contents as "ash content of the manure" (IPCC, 1996, 2006). This is felt to be inadequate.

In principle, bedding material can be taken into account according to equation (12c).

2.3 The assessment of feed intake rates

Countries can find themselves in one of two situations:

- They have measured animal diets, in which case, they know the dry matter intake and their starting point is equation (3). They do not need to consider energy at all.
- They have to estimate the dry matter intake from the energy demand (i.e. the size of the animal and its productivity) as follows.

M_{feed} can be obtained from the respective energy requirements and energy contents, as

$$M_{\text{feed}} = \frac{GE}{\eta_{\text{GE, feed}}} = \frac{ME}{\eta_{\text{ME}}} = \frac{NEL}{\eta_{\text{NEL}}} \qquad (13)$$

where
M_{feed} feed intake rate (in kg place-1 d-1)
GE gross energy intake rate (in MJ place-1 d-1)
$\eta_{\text{GE, feed}}$ gross energy content of feed (in MJ kg-1)
ME intake rate of metabolizable energy (in MJ place-1 d-1)
η_{ME} metabolizable energy content of feed (in MJ kg-1)
NEL intake rate of net energy for lactation (in MJ place-1 d-1)
η_{NEL} NEL content of feed (in MJ kg-1)

The construction of the inventory might begin with the assessment of energy requirements. In Central Europe, ME and NEL are used for this purpose. The subsequent step would then be the derivation of the GE needed for the assessment of emissions from enteric fermentation.

If the energy requirement of an animal category is E (measured in ME, NEL or whatever energy units one's country chooses to use), then:

$$E = OM_{\text{feed}} \cdot X_{\text{DOM}} \cdot \eta_{\text{E, OM}} \qquad (14)$$

or

$$E = M_{\text{feed}} \cdot (1 - X_{\text{ash, feed}}) \cdot X_{\text{DOM}} \cdot \eta_{\text{E, OM}} \qquad (14a)$$

where
E energy intake rate (in MJ place-1 d-1)
M_{feed} feed dry matter intake rate (in kg place-1 d-1)
$X_{\text{ash, feed}}$ ash content of feed (in kg kg-1)
X_{DOM} apparent digestibility of organic matter (in kg kg-1)
$\eta_{\text{E, OM}}$ energy concentration in feed OM (in energy units per kg OM)
OM_{feed} organic matter intake rate (in kg place-1 d-1)

Hence, a simplified calculation procedure combines equations (14a) and (12a):

$$VS_{\text{faeces, sto}} = \frac{E}{\eta_{\text{E, OM}} \cdot X_{\text{DOM}}} \cdot (1 - X_{\text{DOM}}) = \frac{E}{\eta_{\text{E, OM}}} \cdot \left(\frac{1}{X_{\text{DOM}}} - 1 \right) \qquad (15)$$

where
$VS_{\text{faeces, sto}}$ VS in faeces entering storage (in kg place-1 d-1)
E energy intake rate (in MJ place-1 d-1)
$\eta_{\text{E, OM}}$ energy content of feed OM. (energy units per kg OM).
X_{DOM} apparent digestibility of organic matter (in kg kg-1)

2.4 The "constant" and the default values

Both IPCC (1996) and (2006) use the GE calculated for the assessment of CH_4 emission rates from enteric fermentation. For this procedure they provide a "constant" of 18.45 MJ kg-1, explaining that "this value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock". They also provide default values for digestibilities of energy and ash contents.

2.4.1 Gross energy content of feeds

In the IPCC methodology, GE input rates are needed to assess CH_4 emissions from enteric fermentation (see equations (14) in IPCC (1996), pg. 4.22, and (10.21) in IPCC (2006), pg. 10.31). The input rates are assessed from the feed intake rates and the GE contents of feed. Such mean GE contents of feeds can be obtained from measurements or from calculations as the weighted mean of the GE contents of the respective feed components:

$$\eta_{GE,\,feed} = x_{feed,1} \cdot \eta_{GE,1} + x_{feed,2} \cdot \eta_{GE,2} + x_{feed,3} \cdot \eta_{GE,3} + ... \quad (16)$$

where

$\eta_{GE,\,feed}$ mean GE content of feed (in MJ kg^{-1})
$x_{feed,\,1}$ fraction of feed constituent 1 (in kg kg^{-1})
$\eta_{GE,\,1}$ GE content of feed constituent 1 (in MJ kg^{-1})
$x_{feed,\,1}$ fraction of feed constituent 2 (in kg kg^{-1})
$\eta_{GE,\,1}$ GE content of feed constituent 2 (in MJ kg^{-1})
etc.

and

$$x_{feed,1} + x_{feed,2} + x_{feed,3} + ... = 1 \quad (16a)$$

In Germany, the tables provided in Beyer et al. (2004) contain gross energy contents of feeds.

Gross energy contents of dairy cattle feed

Typical dairy cattle feeds were used to derive a mean GE content of feeds, $\eta_{GE,\,feed}$, and compare it to the default value of 18.45 MJ kg^{-1}. Table 3 illustrates that both the German and the Austrian GE contents are likely to fall below the default value, but that the default value is within the range to be found in both parties to the convention. However, the treatment of concentrates whose composition is unknown, leads to additional uncertainties.[G]

Table 3:

Gross energy contents $\eta_{GE,\,feed}$ of exemplary Austrian and German dairy cow feeds (related to dry matter)

	Kryovoruchko et al. (2004)	DLG (2005)	unit
number of feeds	6	16	
mean GE content	18.32	18.34	MJ kg^{-1}
standard deviation	0.26	0.05	MJ kg^{-1}

Danish data are available for cattle (Table 4):

Table 4:

Gross energy contents $\eta_{GE,\,feed}$ of exemplary Danish cattle feeds (related to dry matter)

	lactating cows	dry cows	before delivery	pregnant heifers	unit
number of feeds	38	10	8	10	
mean GE content	18.75	18.32	18.39	18.51	MJ kg^{-1}
standard deviation	0.19	0.30	0.15	0.30	MJ kg^{-1}

German data suggest that the GE content of feed is significantly related to animal performance (Figure 3).

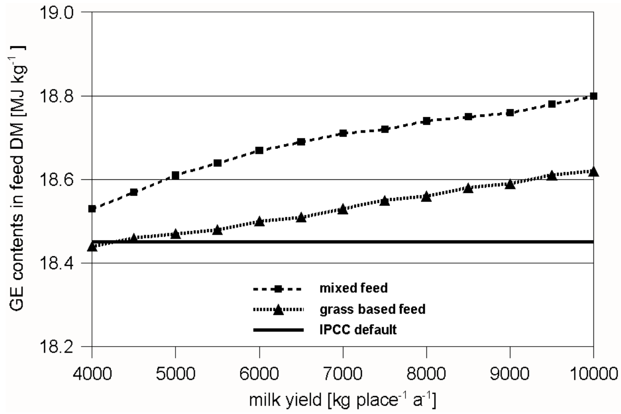

Figure 3:

Gross energy contents of German dairy cow feeds as a function of milk yield and feed type (preliminary data).
Mixed feed: diet based on grass and maize silage, pasture, standard concentrate MLF 18/3 and rape seed expeller with variable shares; grass based feed: diet based on grass silage, pasture, standard concentrate MLF 18/3 and wheat with variable shares. For details see Dämmgen et al. (2010). IPCC default: conversion factor for dietary GE provided in IPCC (1996), pg. 4.23, and IPCC (2006), pg. 10.42.

Gross energy contents of fattening pig feeds

Mean pig feed composition was available for various German districts. The analysis of the data collated in Dämmgen et al. (2011a, b) resulted in the GE contents illustrated in Table 5 and Figure 4. Again, the weighted mean GE contents for the whole pig population are likely to fall below the default value.

Table 5:

Gross energy contents of representative German pig feeds (related to dry matter) (data set generated for Dämmgen et al., 2011a, b)

	sows	weaners	fatteners	unit
number of samples	37	36	67	
mean GE content	18.31	18.65	18.32	MJ kg^{-1}
standard deviation	0.38	0.32	0.31	MJ kg^{-1}

[G] The energy content of dairy cattle feed is reported in MJ kg^{-1} NEL. The NEL content of 6.6 MJ kg^{-1} NEL is approximately equivalent to a GE content of 19.2 MJ kg^{-1} (calculated within GAS-EM)

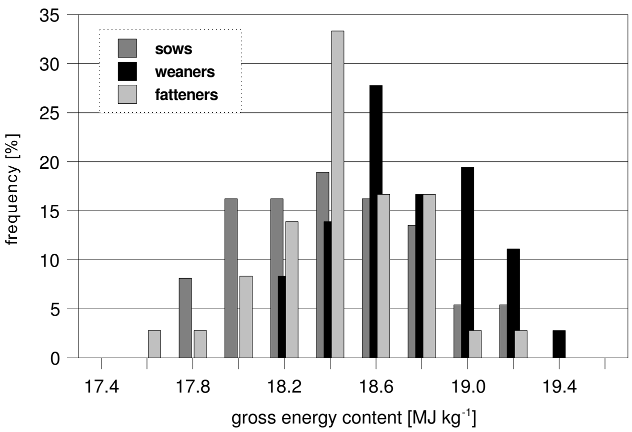

Figure 4:
Gross energy contents in representative German pig feeds

Synthesis

The gross energy content of feed, η_{GE}, is not a constant. The value provided in the IPCC guidelines should be treated as a default value. National information should be used where available. The difference between IPCC default and national values also affects the CH_4 formation from enteric fermentation, however to a lesser extent.

If the IPCC equation is used to derive VS from GE and η_{GE}, then η_{GE} exceeding the default value will result in reduced feed intake rates, and *vice versa*, and hence in modified CH_4 emission rates. The examples given above indicate the deviations from the default value will be of minor importance.

2.4.2 Digestibilities of feeds

Both IPCC (1996) and (2006) use the apparent digestibility for energy[H] to assess VS excretion rates. In fact, the digestibility of energy in feed is used. However, the three digestibilities for energy, organic matter and nitrogen in feed differ.

The mean digestibility for energy is either obtained from its constituents according to

$$X_{\text{DE, feed}} = x_{\text{feed},1} \cdot x_{\text{DE},1} + x_{\text{feed},2} \cdot x_{\text{DE},2} + x_{\text{feed},3} \cdot x_{\text{DE},3} + \ldots \quad (17)$$

where

$X_{\text{DE, feed}}$ mean apparent digestibility of energy in feed (in MJ MJ^{-1})

$x_{\text{feed, 1}}$ fraction of feed constituent 1 (in kg kg^{-1})

$x_{\text{DE, 1}}$ digestibility of energy in feed constituent 1 (in MJ MJ^{-1})

$x_{\text{feed, 1}}$ fraction of feed constituent 2 (in kg kg^{-1})

$x_{\text{DE, 1}}$ digestibility of energy in feed constituent 2 (in MJ MJ^{-1})

etc.

and

$$x_{\text{feed},1} + x_{\text{feed},2} + x_{\text{feed},3} + \ldots = 1 \quad (17a)$$

or as the fraction of known DOM and OM or DE and GE

$$X_{\text{DOM, feed}} = \frac{DOM_{\text{feed}}}{OM_{\text{feed}}} \quad (18)$$

or

$$X_{\text{DE, feed}} = \frac{DE_{\text{feed}}}{GE_{\text{feed}}} \quad (18a)$$

Digestibility of dairy cattle feed

IPCC (1996) and (2006) provide default feed digestibilities for energy in Western Europe (1996: Tables B1 and B2, pg. 4.39 to 4.42; 2006: Tables 10.A1, pg. 10.72 to 10.A2, pg. 10.73 and Table 10.2, pg. 10.14; IPCC default data in MJ MJ^{-1}: dairy cows, 1996: 0.60; 2006: 0.70; other cattle, 1996: 0.61; 2006: 0.60 to 0.65; pigs, 1996: 0.75; 2006: 0.70 to 0.90). The values provided differ considerably. The 2006 default values are in the range observed in Central Europe. The values mentioned in IPCC (1996) are not acceptable.

As the productivity of dairy cattle increases, the demand for energy also increases. The amount of energy that a cow can extract from the diet depends on the amount and quality of feed consumed. In practice, farmers respond to the increased demand by increasing both the amount of feed and its digestibility (i.e. the proportion of the total energy that can be accessed by the micro-organisms in the rumen of the cow). This is illustrated in Figure 5.

However, the digestibility of a feed is normally assessed *in vitro*, using analytical methods that measure the amount of feed dry matter that is degraded after incubation in rumen fluid for an extended period of time. As a result, the method estimates the maximum digestibility. However, the space available for feed in the rumen is limited, so as the intake rate increases, the time the feed remains in the rumen decreases. Consequently, the actual digestibility achieved will be increasingly lowered, relative to the standard value, as animal productivity increases. This means that the actual increase in digestibility of the feed with increasing milk yield will be lower than indicated in Figure 5.

[H] The apparent digestibility for energy, X_{DE}, is defined as fraction of digestible energy *DE* to gross energy *GE*. The term "digestibility" is in practice synonymous with "apparent digestibility".

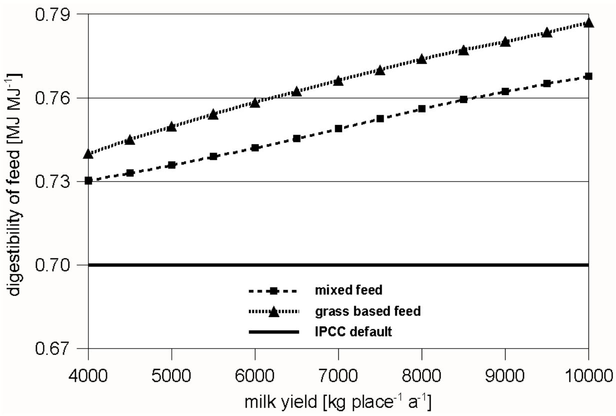

Figure 5:

Apparent digestibilities X_{DE} of German dairy cow feeds as a function of milk yield and feed type as used in the German agricultural emission inventory model GAS-EM.
For "mixed feed" and "grass based feed" see caption to Figure 3. IPCC default: digestibility for dairy cattle provided in IPCC (2006), pg. 10.72. (IPCC, 1996, pg. 4.31 proposes 0.60 MJ MJ^{-1}.)

Digestibility of pig feed

Exemplary apparent digestibilities X_{DOM} for German pig feeds (Dämmgen et al., 2011b) are:

sows gestating	0.81 kg kg^{-1}
sows lactating	0.86 kg kg^{-1}
weaners	0.87 kg kg^{-1}
fatteners	0.86 kg kg^{-1}

Danish X_{DOM} for fattener feeds are identical with German ones.

Synthesis

The use of IPCC (1996) default values for digestibilities X_{DE} leads to an overestimation of CH_4 from manure management.
The use of X_{DE} rather than X_{DOM} leads to an overestimation of CH_4 from manure management.
For pigs, application of IPCC (2006) default or national values is likely to result in half the emissions obtained from the application of IPCC (1996) default digestibilities.

2.4.3 Ash content of feeds

Both IPCC (1996) and (2006) provide default values for ash contents of cattle manure (0.08 kg kg^{-1}). IPCC (1996) also gives a default ash content for pig manure (0.02 kg kg^{-1}). As mentioned above, these data are in the range of feed ash contents.

Ash in dairy cattle feed

For dairy cattle, exemplary feed compositions provided by DLG (2005) and Kryvoruchko et al. (2004) describing various diets and animal performances were combined with fitting ash contents (Beyer et al., 2004).

$$X_{\text{ash, feed}} = x_{\text{feed},1} \cdot x_{\text{ash},1} + x_{\text{feed},2} \cdot x_{\text{ash},2} + x_{\text{feed},3} \cdot x_{\text{ash},3} + \ldots \quad (19)$$

where

$X_{\text{ash, feed}}$ mean ash content of feed (in kg kg^{-1})
$x_{\text{feed, 1}}$ fraction of feed constituent 1 (in kg kg^{-1})
$x_{\text{ash, 1}}$ ash content of feed constituent 1 (in kg kg^{-1})
$x_{\text{feed, 1}}$ fraction of feed constituent 2 (in kg kg^{-1})
$x_{\text{ash, 1}}$ ash content of feed constituent 2 (in kg kg^{-1})
etc.

with

$$x_{\text{feed},1} + x_{\text{feed},2} + x_{\text{feed},3} + \ldots = 1 \quad (19a)$$

Exemplary results are shown in Table 6.

Table 6:

Ash contents of exemplary Austrian and German dairy cow feeds (related to dry matter)

	Kryovoruchko et al. (2004)	DLG (2005)	unit
number of feeds	6	12	
mean ash content	0.088	0.087	kg kg^{-1}
standard deviation	0.008	0.002	kg kg^{-1}

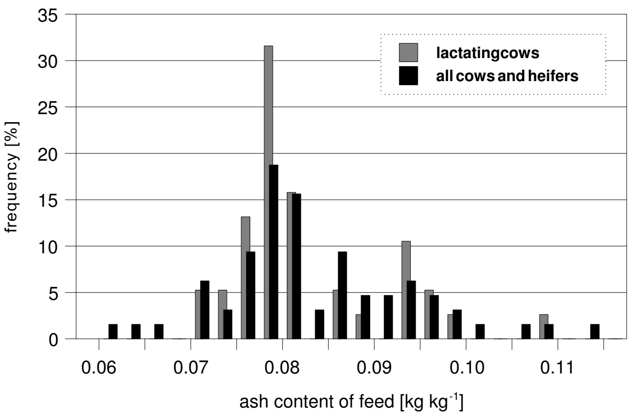

Figure 6:

Ash contents of Danish dairy cow feeds (dairy cow feeds: n = 38; all cows and heifers: n = 66). Mean ash contents of lactating dairy cow feeds: 0.082 kg kg^{-1}, all cows and heifers: 0.083 kg kg^{-1}.

Ash contents are related to animal performance. Figure 7 gives exemplary German results.

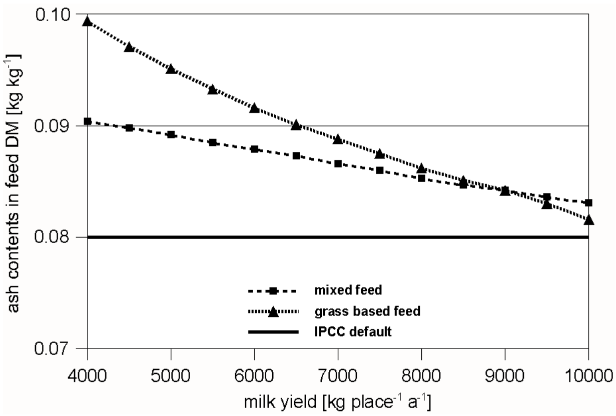

Figure 7:

Ash contents of German dairy cow feeds as a function of milk yield and feed type.
For "mixed feed" and "grass based feed" see caption to Figure 3. IPCC default: ash content of dairy cattle feed provided in IPCC (1996), pg. 4.23, and IPCC (2006), pg. 10.42.

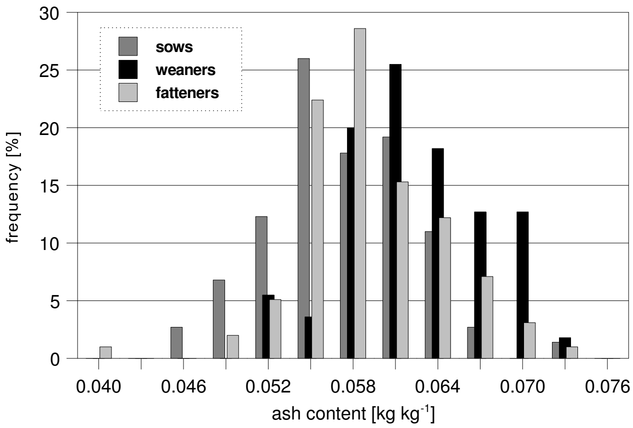

Figure 8:

Ash contents in German pig feeds

Ash in pig feed

Ash contents in feed have to be declared in the European Union (EC, 2002). Hence they may be obtained for any feed bought by a farmer. The analysis of about 230 single German feeds resulted in mean ash contents of about 0.06 kg kg^{-1}. Details are shown in Table 7 and Figure 8. Austrian feeds have the same ash contents.

Table 7:

Ash contents of representative **German** pig feeds (related to dry matter) (data set generated for Dämmgen et al., 2011a, b)

	sows	weaners	fatteners	unit
number of samples	73	56	98	
mean ash content	0.064	0.061	0.057	kg kg^{-1}
standard deviation	0.006	0.006	0.006	kg kg^{-1}

Table 8:

Ash contents of exemplary **Austrian** pig feeds (related to dry matter) (data from Solan, undated, and Gsellmann, undated)

	sows	weaners	fatteners	unit
number of samples	5	7	2	
mean ash content	0.060	0.058	0.059	kg kg^{-1}
standard deviation	0.011	0.006	0.001	kg kg^{-1}

Data compilations on feed properties (such as Beyer et al., 2004) indicate that ash contents in pig feed of about 0.02 kg kg^{-1} as proposed in IPCC (1996) are appropriate if the animals are fed maize grain or maize grain silage or wheat only. These feeds are not representative of the situation in Germany and Austria.

Synthesis

Ash contents in cattle and pig feeds in Central Europe exceed those provided as IPCC default values. For pigs, they are more than twice the values given in IPCC (1996). The application of the IPCC default values results in an overestimation of CH_4 emissions from manure management.

3 Effects of variations of input parameters on VS excretion rates

Example calculations were performed to identify the effect of modified input parameters on VS excretion rates. Tables 9 and 10 illustrate to what extent variations of the input parameters GE content (η_{GE}), digestibilities of energy (X_{DE}) and organic matter (X_{DOM}) as well as ash content result in changes of VS excretion rates. During these calculations the parameters used in IPCC (1996) are modified stepwise towards the situation observed in Austria, Germany and Denmark. Obviously the decisive entity is the digestibility of feed, and here the introduction of the digestibility of organic matter still makes a difference. Ash and GE contents of feed are of minor importance. Even the increased ash content of feeds in pig production does not have a serious effect.

Table 9:
Effect of modified parameters on VS excretion of exemplary dairy cows

	modification	GE	$\eta_{GE, feed}$	digestibility	x_{ash}	VS
unit		MJ place^{-1} a^{-1}	MJ kg^{-1}	MJ MJ^{-1} kg kg^{-1}	kg kg^{-1}	kg place^{-1} a^{-1}
IPCC 1996		125000	18.45	0.60	0.080	2493
IPCC 2006	X_{DE}	125000	18.45	0.65	0.080	2182
modified	X_{DE}	125000	18.45	0.75	0.080	1558
modified	X_{DOM}	125000	18.45	0.77	0.080	1434
modified	X_{ash}	125000	18.45	0.77	0.085	1426
modified	$\eta_{GE, feed}$	125000	18.35	0.77	0.085	1434

Table 10:
Effect of modified parameters on VS excretion of exemplary fattening pigs

	modification	GE	$\eta_{GE, feed}$	digestibility	x_{ash}	VS
unit		MJ place^{-1} a^{-1}	MJ kg^{-1}	MJ MJ^{-1} kg kg^{-1}	kg kg^{-1}	kg place^{-1} a^{-1}
IPCC 1996		12000	18.45	0.75	0.020	159
IPCC 2006	X_{DE}	12000	18.45	0.80	0.020	127
modified	X_{DE}	12000	18.45	0.85	0.020	96
modified	X_{DOM}	12000	18.45	0.87	0.020	83
modified	X_{ash}	12000	18.45	0.87	0.055	80
modified	$\eta_{GE, feed}$	12000	18.30	0.87	0.055	81

4 Summary of findings

CH_4 emissions from storage are related to the amount of VS entering the storage system. This may differ significantly from the amounts excreted. VS excreted with urine is not effective as a source of CH_4.

Feed intake rates should be calculated using the national procedure. This avoids the use of a default GE content of feeds. Any national inventory that is able to derive feed intakes will also be able to provide national values for η_{GE}.

The ambiguity connected with default ash contents in pig manure and feed, respectively, is to be clarified in the IPCC guidelines: The ash content in feed is the necessary parameter. For dairy cattle, the default ash contents provided in the guidelines are obviously meant to be ash contents of feed. For pigs the ash contents provided as default values are inadequate.

The authors suggest using the feed digestibility for organic matter rather than energy to calculate VS excretion rates. The default values for pig production given in IPCC (1996) are inadequate and should not be used.

The slight increase in ash contents of cattle (see Table 6) has a marginal effect on the VS excretion rates and subsequently on CH_4 emission rates. However, the increased ash contents in pig feeds will reduce the amounts of VS excretion rates to some extent.

It is considered inconsistent not to include bedding material in the calculation procedures to assess VS inputs to storage systems.

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