GHG mitigation in the agricultural sector

Comparing the GAINS and Danish methodology and data

Andrade de Sá, Saraly; Thomsen, Maria Nygård; Schou, Jesper Sølver

Publication date:
2018

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Andrade de Sá, S., Thomsen, M. N., & Schou, J. S. (2018). *GHG mitigation in the agricultural sector: Comparing the GAINS and Danish methodology and data*. Department of Food and Resource Economics, University of Copenhagen. IFRO Documentation, No. 2017/8

DEPARTMENT OF FOOD AND RESOURCE ECONOMICS
UNIVERSITY OF COPENHAGEN

IFRO Documentation

GHG mitigation in the agricultural sector

Comparing the GAINS and Danish methodology and data

Saraly Andrade de Sá
Maria Nygård Thomsen
Jesper Sølver Schou

2017 / 8

IFRO Documentation 2017 / 8

GHG mitigation in the agricultural sector: Comparing the GAINS and Danish methodology and data

Authors: Saraly Andrade de Sá, Maria Nygård Thomsen, Jesper Sølver Schou

This documentation is produced in connection with a project supported by the Danish Ministry of Food and Environment.

Published February 2018

Find more IFRO Documentation here (most are in Danish):
http://www.ifro.ku.dk/publikationer/ifro_serier/dokumentation/

Department of Food and Resource Economics
University of Copenhagen
Rolighedsvej 25
DK-1958 Frederiksberg
www.ifro.ku.dk/english

GHG mitigation in the agricultural sector: Comparing the GAINS and Danish methodology and data

by
Saraly Andrade de Sá, Maria Nygård Thomsen and Jesper Sølver Schou

I. Introduction

Emissions of greenhouse gases from the agricultural sector mostly include the emission of methane (CH4) and nitrous oxide (N2O). These emissions are mainly related to the livestock production and includes CH4 emission from enteric fermentation and manure management and N2O emission from manure management and agricultural soils. In what concerns Denmark, the agricultural sector was responsible for 19.6% of GHG emissions in 2014, according to Eurostat.[1]

The aim of this document is to describe and compare two methodologies for calculating marginal abatement costs for the Danish agricultural sector: the GAINS model and data, used by the European Commission and methods and data used by the Danish administration. Information on the methodology beyond the GAINS model and its baseline scenario for agriculture is based on Höglund-Isaksson et al. (2016).

In the following, we first compare the general approach used in the two methods (Section 1), before turning to the baseline scenarios (Section 2). The analysis of mitigation costs' estimation is the object of Section 3. Finally, we compare the different mitigation measures suggested for methane (CH4) and nitrous oxide (N2O) in Section 4.

II. General approach

IIASA and Danish authorities approach the computation of mitigation costs very differently. At the core of GAINS is an optimization procedure finding optimal cost-efficient solutions for emission reductions. For each pollutant, cost curves are constructed that rank emission reduction technologies to implement by increasing marginal costs. Then, in principle, the model chooses the most cost efficient technologies first and ads up until the desired emission levels have been reached. The most important point is that GAINS adopts a private (i.e., industry) perspective. Mitigation costs obtained are therefore those who would be incurred by the agricultural sector agents.

Danish authorities use a different approach: The Catalog of Danish Climate Change Mitigation Measures (Inter-ministerial working group, 2013), is based on a welfare eco-

---

[1] Data avaliable at `http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do`: 2014 Danish GHG emissions for all sectors – including indirect CO2 and international aviation – but excluding LULUCF emissions were 53,876.33 thousand tons of CO2 equivalent; emissions from the agricultural sector were of 10,569.88 thousand tons of CO2 equivalent.

nomic method which is in line with the guidelines on welfare economic analysis from the Danish Ministry of Finance. In particular, it focuses on computing a Social Shadow Cost of Carbon. It is therefore a “social” perspective that is adopted (rather than a private one as in GAINS). The report states: “The shadow price for a given mitigation measure expresses the welfare economic costs and benefits of reducing greenhouse gas emissions by one ton of CO2 equivalent. This makes it possible, by comparing the shadow prices for the measures, to obtain an overall assessment of the most cost-effective mitigation measure from a welfare economic perspective.”.

Another main difference – stemming from these different perspectives – is that while GAINS describes different measures for GHG mitigation, it does not consider which specific policy would allow those measures to be implemented in the agricultural sector. On the contrary, Danish authorities always associate a given mitigation measure to one or two policies that would have to be implemented for the measure to be adopted. Hence, the (social) mitigation cost obtained is also dependent on policy implementation costs.

III. Projected agricultural emissions – Baseline scenarios

It must be noted that CO2 removals/emissions from agricultural soils are not included in the agricultural sector. According to the IPCC guidelines, this removal/emission should be included in the LULUCF sector (Land Use, Land-Use Change and Forestry). The same applies to emissions related to agricultural machinery (tractors, harvesters and other non-road machinery), which are included in the energy sector.

According to a Scientific Report from DCE – Danish Centre for Environment and Energy – the Danish emissions from the agricultural sector are estimated to be of 10.3 million tons of CO2 equivalent in 2030, a figure that is very close to the level of emissions in 2013 (10.15 million tons of CO2 equivalent). A slight decrease of the emission from agricultural soils is estimated, but this is outweighed by an increase of CH4 emission from enteric fermentation processes. These baseline emissions for 2030 are calculated while assuming that the Agreement on Green Growth (which is meant to expand biogas production) is implemented, an uptake of ammonia reducing technologies (such as the acidification of slurry in animal housing) and taking livestock and milk production projections from the DCA – Danish Centre for Food and Agriculture (2015).

In comparison, the IIASA reference scenario 2016 predicts Danish emissions from the agricultural sector to be 10.4 million tons of CO2 equivalent by 2030. The reference scenario assumes current policies to be continued. In what concerns agriculture, it included the 2013 CAP reforms, the removal of milk and sugar quotas, the application of the Nitrates and Water Directives, and uses data for livestock development from the CAPRI model.

Table 1 summarizes the two projections for 2030.

GHG gas	GAINS	Danish data
CH4	5,626,748 tCO2 equivalent	5,862,500 tCO2 equivalent
NO2	4,732,186 tCO2 equivalent	4,240,540 tCO2 equivalent
Total emissions	10,358,934 tCO2 equivalent	10,103,040 tCO2 equivalent

Table 1: Baseline projections

IV. Emission estimation methodology

A. Emissions estimation

For the GAINS model, emissions from a given source are calculated according to the methodology described in Amann et al. (2011). In particular, emissions level depends on the level of activity (e.g., number of animals) and the activity emissions' factor (which itself depends on the technology employed). Detailed equations can be found in the Appendix.

On the other hand, computations by Danish authorities closely follow the methodology used in the annual emission inventories, which is described in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Thus, the same database setup is used, same estimation approach and the same emission factors. In particular it recommends "to identify the appropriate method for estimating emissions for each source category, and then base the characterization on the most detailed requirements identified for each livestock species.".

B. Activity data

In GAINS, activity drivers for emission projections enter calculations externally using projections from different internationally recognized sources. Agricultural data and scenarios are taken from the CAPRI model (Bonn University/EuroCare).

Activity data in the DCE projections are based on data from the DCA– Danish Centre for Food and Agriculture (DCA/DCE, 2015).

C. Emission factor

The choice of emission factors for estimation of non-CO2 greenhouse gas emissions in GAINS follows the methodology recommended in IPCC 2006 guidelines (IPCC, 2006) as closely as available data allows. This includes conversion to CO2 equivalents using Global Warming Potentials (GWP) of 25 times that of CO2 for methane, 298 times that of CO2 for nitrous oxide.

The same methodology is used for Danish projections (DCE, 2016).

D. Mitigation costs estimation

The mitigation potential assessed in the GAINS model refers to feasible reductions in emissions through adoption of mitigation technologies defined as installations or applications of physical equipment or material or modifications in physical parameters affecting emissions. Non-technical mitigation options that involve changes in human behavior and preferences, e.g., changes in human diets towards consumption of less meat and milk products, are excluded from the analysis. Also, the technical mitigation potential may differ from the politically feasible mitigation potential as the latter also takes into account costs and political barriers for implementation. Non-CO2 GHGs mitigation costs per unit of activity are calculated in GAINS as the sum of investment costs, labour costs, non-labour operation and maintenance costs, cost-savings due to recovery or saving of electricity, heat or gas, and non-energy cost savings. Detailed equations are provided in the Appendix. Costs are expressed in constant Euros of 2013 and a discount rate of 10% is used.

For the Danish data, as mentioned in the introduction, the calculation of social mitigation costs is based on welfare economic principles. Welfare economic costs express the changes in consumption possibilities for the Danish society which the implementation of a given mitigation measure would result in. Consumers' optimization of their consumption bundles is based on market prices including commodity taxes. Therefore, costs and benefits measured at factor prices are converted to the market/consumer price level using a standard conversion factor. The standard conversion factor specified by the Danish Ministry of Finance is 1.325 implying that factor prices are increased by 32.5%.

The social mitigation cost for each measure is calculated as the sum of discounted implementation costs minus ancillary benefits[2] divided by the sum of discounted annual GHG reductions measured in ton CO2 equivalent Costs are expressed in constant Danish Krone (DKK) of 2012 and discounted using a 4% rate. The social value of ancillary benefits is included in the calculations as negative costs and therefore deducted from the implementation costs. The time horizon for the calculations is 2013 to 2042.

Note that for several of the investigated policy measures, the Danish social mitigation costs are negative. This means that implementation of the measure represents a win-win or no-regret solution to society and that the value of ancillary benefits exceeds the implementation costs. In the GAINS model, at most, mitigation measures have a zero marginal cost.

Table 2 below summarizes the main differences in the assumptions made with the two methodologies, which may explain the differences observed in the final marginal mitigation costs obtained.

V. Mitigation measures in GAINS

CH4 emission sources from agriculture mainly include anthropogenic CH4 emissions from livestock, rice cultivation and burning of agricultural waste. Since there is no rice cultivation in Denmark, we focus here on emissions from livestock.

---

[2] The ancillary benefits included in the calculations are reduced nitrate and ammonia emissions incidental to GHG mitigation. Reduced nitrate and ammonia emissions are evaluated at the marginal social costs of abatement – estimated (by the Danish Environmental Protection Agency and IFRO) at DKK40 per kg N and DKK41 per kg NH3-N respectively.

Assumptions	GAINS	Danish data
Discount rate	10%	4%
Base currency	Constant EUR 2013	Constant DKK 2012
Time horizon	2030	2020
Mitigation costs estimation	Sum of investment, labour, operation and maintenance costs, cost-savings due to recovery or saving of electricity, heat or gas, and non-energy cost savings	Social mitigation cost taking into account total costs and benefits for the Danish society

Table 2: Main assumptions

CH4 emissions from livestock emerge from enteric fermentation during the digestive process in the stomachs of ruminants. When the organic content in livestock manure decomposes, emissions of CH4 and N2O are released. CH4 release occurs when manure is handled under anaerobic conditions, while the formation of N2O requires aerobic conditions with access to oxygen.

GAINS estimates CH4 emissions separately for the animal types dairy cows, non-dairy cattle, pigs, poultry, sheep and goats, buffaloes, and horses. For dairy cows, non-dairy cattle and pigs, animal numbers are further split by whether animals are subject to liquid or solid manure management. The split in the number of animals by liquid or solid manure management is stored in the GAINS model and was recently reviewed by member state experts during IIASA consultations for the proposal of the EU Thematic Strategy for Air Pollution (TSAP) in 2014. Activity data is the number of animals by type. The source for historical animal numbers for years 2005 and 2010 is EUROSTAT (2015), except for horses and buffaloes, where FAOSTAT (2013) is the source. Projections are based on future trends in animal numbers as estimated by the CAPRI model (2016). Detailed calculation of emissions is provided in the Appendix.

Recently the GAINS model started to split animal categories of dairy cows, non-dairy cattle, pigs, poultry, sheep and goats by five farm size classes, i.e., less than 15 livestock units (LSU), 15 to 50 LSU, 50 to 100 LSU, 100 to 500 LSU, and above 500 LSU. The source for data on historical farm-size distributions is EUROSTAT (2015). Projections for the future development of farm-size classes have been made applying a multinominal logistic function weighing in the development observed in historical years from 1990 onwards. The development of farm-size classes has implications for the development of the fractions of animals on liquid and solid manure management and on the future applicability of control technology options. Typically, over time more animals tend to move into the larger farm-size classes with liquid manure management and away from smaller farm-size classes with solid manure management.

A. *CH4 mitigation measures*

The GAINS model considers three main options to mitigate CH4 emissions:

- Farm-scale anaerobic digestion
- Breeding through selection to enhance feed efficiency
- Feed additives or changed feed practices.

It is assumed in GAINS that the combined mitigation effect of breeding in 2030 is 10% of enteric methane emissions from dairy cows, non-dairy cattle and sheep. The model further also assumed that measure is cost-effective (i.e., available at zero costs) in order to take into account also the costs of establishing a reference database on genetic information to enable successful breeding.

Feed management options include mechanical ways to treat the feed to facilitate digestion, ways to combine different types of feed to minimize enteric methane formation, as well as precision feeding, which means very closely monitoring the timing and the feed mix supplied to the animals in order to optimize feeding against both economic and environmental parameters. The model is based on the assumption that it is likely that at least one or a few of the above options will be able to deliver some effect on methane emissions in the future. Hence, in addition to the effects of breeding mentioned above, GAINS supposes that the combined mitigation effect in 2030 from different feed management changes and feed additives is 10% of enteric fermentation emissions in dairy cows and 5% of enteric fermentation emissions in non-dairy cattle and sheep during the time that animals are housed indoors. Regarding costs, it is considered feasible by 2030 to expect that new feed additives will become available on the market, and which are both effective in terms of reducing emissions and come at a financially feasible cost to farmers. Hence, the annual cost level is estimated to be about EUR10 per head. This cost level corresponds to a marginal cost range of about EUR30 to EUR60/t CO2 equivalent when implemented for dairy cows and with higher marginal cost levels for non-dairy cattle and sheep.

Treatment of animal manure in anaerobic digesters (ADs) that generate biogas can be an efficient way to reduce methane emissions from manure handling at a low cost. The process has the advantage of not only reducing emissions, but also generating energy to be used on the farm or sold to external users, and at the same time produces an odor-free organic fertilizer, which can substitute the use of mineral fertilizers. In the GAINS model, farm-scale anaerobic digestion is assumed applicable to manure from dairy cows, non-dairy cattle and pigs kept in systems with liquid manure management on farms with at least 100 livestock units (LSU). It is further assumed that manure is only available for anaerobic digestion during the periods that animals are kept indoors.[3]

---

[3] Information on the average number of days per year that animals spend indoors has been collected by animal category in the GAINS database during consultations with member state experts, most recently during IIASA-member state consultations for the proposal of the EU Thematic Strategy for Air Pollution (TSAP) in 2014. No potential for farm-scale anaerobic digestion is assumed for animals kept on farms smaller than 100 LSU, nor for animals in solid manure management systems, and nor for periods when animals are grazing outdoors.

B. N2O mitigation measures

Agricultural production results in both direct and indirect emissions of nitrous oxide (N2O). Direct emissions come from fertilized agricultural soils and livestock manure, while indirect emissions come from runoff and leaching of fertilizers.

Mitigation measures regarding N2O include:

- Lowering the use of mineral fertilizers
- Precision farming
- Nitrification inhibitors to reduce emission rates
- Abandonment of agricultural activities on organic soils

VI. Mitigation measures – Danish data

In their catalog of mitigation measures, Danish authorities list a number of mitigation measures. These are separated into two categories according to their mitigation potential, i.e., more than 50,000 tons of CO2 equivalent *versus* less than 50,000 tons of CO2 equivalent Also, the Danish data does not differentiate measures by farm size classes, and uses projections from the AGMEMOD model for activity data. The levels of the implementation potential for the individual measures have been stipulated at a scale assumed to allow implementation at approximately constant marginal costs when using existing technologies. For some measures the specified implementation potential is limited by the assumptions of the overall government appraisal of GHG reduction measures for the non-ETS sectors:

- Biogas production from livestock manure (coupled with a tax on unused manure)
- Mandatory acidification of slurry
- Feed with fat for dairy cows
- Tax on artificial fertilizers without nitrification inhibitors
- Reduction of nitrogen quota
- Subsidy for the establishment of 100,000 hectares of biofuel production.

The Danish estimations do not consider breeding as an abatement strategy for CH4 emissions from enteric fermentation. Regarding feed management, the main measure is the increase in fat content of the diet of dairy cows and additional concentrated feed in the diet of other cattle.

As for manure management, the Danish data considers an increase in 10% of the amount of manure used for biogas production (bringing the total share to 60% by 2020). The calculations assume that the biogas produced is used as a substitute for natural gas in combined heat and power plants (CHP).

REFERENCES

Amann, M., I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj, R. Sandler, W. Schpp, F. Wagner and W. Winiwarter (2011), "Cost-effective control of air quality and greenhouse gases in Europe: Modelling and policy applications", *Environmental Modeling and Software* 26:1489-1501.

DCE – Danish Centre for Environment and Energy (2016), "Projection of GreenHouse Gases 2014-2025", Aarhus University, Department of Environmental Science.

Höglund-Isaksson, L., W. Winiwarter, P. Purohit and A. Gomez-Sanabria (2016), "Non-CO2 greenhouse gas emissions in the EU-28 from 2005 to 2050: Final GAINS Reference scenario 2016", International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Inter-ministerial Working Group (2013) "Catalogue of Danish Climate Change Mitigation Measures",
Available at: $https://ens.dk/sites/ens.dk/files/Analyser/dk_climate_change_mitigation_uk.pdf.$

IPCC (2006), "IPCC Guidelines for National Greenhouse Gas Inventories"
Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/

APPENDIX

This appendix describes the main equations used to compute data used in the GAINS model. Equations are based on Amann et al. (2011).

A Emissions estimation

In the GAINS model, emissions from source s in region i and year t are calculated as follows:

$$E_{its} = \sum_m [A_{its} * ef_{ism} * Appl_{itsm}], \tag{1}$$

where

$$ef_{ism} = ef_{is}^{NOC} * (1 - remeff_{sm)} \text{ and } \sum_m Appl_{its} = 1, \tag{2}$$

and where A_{its} is the activity (e.g., number of animals, amounts of fuel or waste), ef_{ism} is the emission factor for the fraction of the activity subject to control by technology m, $Appl_{itsm}$ is the application rate of technology m to activity s, ef_{is}^{NOC} is the no control emission factor for activity s, and $remeff_{sm}$ is the removal efficiency of technology m when applied to activity s.

B Mitigation costs estimation

In GAINS, the unit cost of technology m in country i and year t is defined as

$$C_{itm} = I_{im}\left[\frac{(1+r)^{T_m} * r}{(1+r)^{T_m} - 1}\right] + M_{im} + (L_{im} * W_{im} * w_{is}) - S_{im} - 0.75\left(E_{im} * p_{it}^{electr}\right) - (G_{im} * p_{it}^{gas}) \tag{3}$$

where I_{im} is the upfront investment cost of technology m in country i,

$\left[\frac{(1+r)^{T_m} * r}{(1+r)^{T_m} - 1}\right]$ is the annualization factor for the investment cost with interest rate r and technology lifetime of T_m years,

M_{im} is the annual operation and maintenance cost for technology m,

L_{im} is the fraction of annual work hours for operating technology m,

W_{it} is the annual average wage in country i in year t,

w_{is} is a country-specific wage adjustment factor for type of sector s (agriculture or manufacturing industry),

S_{im} is the sum of non-energy annual cost-savings,

E_{im} is the amount of energy recovered and utilized as electricity or heat,

p_{it}^{electr} is the electricity price in country i in year t,

G_{im} is the amount of gas recovered,

and p_{it}^{gas} is the gas price in country i in year t.

Similar to how the country and year specific emission level E_{its} is estimated for each sector in equation (1), the total mitigation cost in sector s in country i and year t is defined for sets of application combinations of the possible technologies applicable in the sector. For a given country, year, and sector, a technology setting is defined such that the sum of all application rates $Appl_{itsm}$ of possible technologies m (including the no control option) is always unity. The total cost of each technology setting is defined as:

$$TC_{its} = \sum_m [A_{its} * C_{itm} * Appl_{itsm}], \tag{4}$$

where A_{its} is the activity level, C_{itm} is the cost per unit of activity and $\sum_m Appl_{itsm} = 1$.

The marginal cost per unit of reduced emissions is first defined for each technology available to a sector as the unit cost divided by the difference between the technology emission factor and the no control emission factor, such that

$$MC_{itm}^{Tech} = \frac{C_{itm}}{ef_{it}^{No-control} - ef_{itm}}. \tag{5}$$

The above defined cost is called the "technology marginal cost". Within a sector, the technologies available are first sorted by their respective technology marginal cost. The technology with the lowest marginal cost is ranked the first-best technology and assumed adopted to its full extent in a given sector. The second-best technology is the technology with the second lowest technology marginal cost and is assumed available for adoption provided it can achieve an emission factor that is lower than the first-best technology. The marginal cost of the second-best technology when implemented in the cost curve is defined as

$$MC_{it2} = \frac{C_{it2} - C_{it1}}{ef_{it1} - ef_{it2}}. \tag{6}$$

C CH4 emissions calculation

In the GAINS model, emissions from livestock are estimated as the sum of the emission types n (enteric fermentation and/or manure management) for a certain animal type s in country i and year t:

$$E_{its} = \sum_{lmns} \left[A_{itls} * ef_{ilns}^{NOC} * (1 - remeff_{mns} * h_{itsm}) + Appl_{itslm}\right], \tag{7}$$

where A_{itls} is the number of animals of type s in country i and year t, with manure management l (solid or liquid),

ef_{ilns}^{NOC} is the no control emission factor for emission type n, animal type s, in country i and subject to manure management l,

$remeff_{mns}$ is the removal efficiency of technology m when applied to emissions of type n and animal type s,

h_{itsm} is a factor correcting for application limitations of technology m, e.g., indoor housing rates for feed options or large farm rate for farm-scale anaerobic digestion,

$Appl_{itslm}$ is the application rate of technology m to animal type s with manure management l, in country i and year t.

Country-specific emission factors corresponding to the implied emission factors reported to UNFCCC-CRF (2015) for year 2010 were adopted for enteric fermentation and manure management emissions, respectively. For dairy cows, both enteric fermentation emissions and manure management emissions per animal are affected by the milk productivity of the cow. This effect is particularly accentuated for highly productive milk cows. To capture this, the no control emission factor for dairy cows is specified as the sum of a fixed emission factor per animal for cows producing up to 3,000 kg per head per year and an additional term describing the emission factor per milk yield for milk production exceeding the productivity level 3,000 kg per animal per year, i.e.,

$$ef_{it;cow}^{NOC} = ef_i^{animal} + ef_i^{milk} * (x_{it} - 3000), \tag{8}$$

where ef_i^{animal} is the default emission factor for cows in country i producing 3,000 kg milk per year,

ef_i^{milk} is the emission factor per kt of milk produced above the threshold level 3,000 kg milk per animal per year, and

x_{it} is the average milk yield per animal in country i and year t.

Note that a linear relationship between CH4 emissions per cow and the milk yield per cow is assumed. Hence, as milk yield per cow increases, CH4 emissions per cow increase while emissions per kg milk produced decline when fewer animals are needed to produce the same amount of milk. Whether the overall effect on methane emissions is positive or negative will depend on the importance of the effect of increased methane emissions per animal relative the effect of declining animal numbers.

D GAINS estimations related to manure management and anaerobic digestion

The amount of manure available for anaerobic digestion (AD) is derived from the average volatile solid excretion rate per animal per day reported by countries to the UNFCCC-CRF (2014) for year 2010. The amount of manure generated per head per year (m) in country i is calculated as

$$m_i = 0.001 \frac{(365 * VS_i/0.8)}{1 - 0.85}, \tag{9}$$

where VS_i is the country-specific average daily excretion rate for the analyzed animal type.

Methane reduction potential and costs are estimated separately for “large farms” defined as farms with 100 to 500 LSU and “extra large farms” with more than 500 LSU. The total amount of manure available for farm-scale AD in country i in a future year t is the sum of manure excreted by animals on large farms and extra large farms during times when animals are kept indoor, i.e.,

$$M_{it} = \sum_{s} A_{it}^{liquid} * VS_i * \gamma_{its} * M_{it} = \sum_{s} A_{it}^{liquid} * m_i * \gamma_{its} * h_i, \qquad (10)$$

where A_{it}^{liquid} is the number of animals on liquid manure management, γ_{its} is the fraction of animals found on farms of size s in country i and year t, and h_i is the fraction of a year that animals are housed indoor.

The cost of farm-scale AD is derived as the sum of the annualized investment cost and the operation costs (including costs for labour and additional organic substrate), less the revenues and cost-savings of utilizing the generated electricity and fertilizers. Hence, the unit cost per head of installing a farm AD plant for treatment of cattle and pig manure is defined in GAINS for country i in year t and for farm scale s in the following way:

$$C_{its} = I_{its} * \frac{r(1+r)^T}{(1+r)^T - 1} + R_{its}p_R + L_{its}w_{it} - 0.6p_{it}^{ind}E_{its} - F_{its}p_f, \qquad (11)$$

where I_{its} is the fixed initial investment cost,

T is the expected lifetime of the equipment,

r is the interest rate,

R_{its} is the amount of organic substrate added to the co-digestion,

p_R is the unit price of organic substrate,

L_{its} is the fraction of annual work hours spent on operation of AD plant,

w_{it} is the average annual wage for the agricultural sector,

p_{it}^{ind} is the average electricity price for the industry sector,

E_{its} is the amount of energy generated from the AD process,

F_{its} is the amount of pure fertilizer nutrients (N-P_2O_5-K_2O) generated from the AD process, and

p_f is the unit price of fertilizer nutrients.

Since the performance of farm AD plants can be substantially improved if manure is co-digested with other organic material rich in micronutrients,[4] GAINS assumes that the feedstock contains 20% organic substrate and 80% manure and that both these substrates have a water content of 85%, respectively. Because of the wide variety of sources for organic substrate and fluctuations in its availability over time and space, it is hard to make general assumptions about the unit price of organic substrate. It may vary from zero cost for organic waste, which suppliers would otherwise have had to pay to get rid of in an appropriate way, to EUR150 per ton if feed crops (e.g., maize) are used. In the Reference scenario, the price of organic substrate is EUR100/ton.

Regarding the amount of energy generated, it is assumed in GAINS that it is possible to generate on average 380 kWh/ton substrate loaded. Further, half of the 380 kWh/ton substrate generated is converted to electricity, which is sold to local industry at the country-specific industry sector price of electricity (based on the PRIMES reference projection of 2016), 40% is used on farms as heat, and 10% is heat used up by the

---

[4] E.g., other crop residuals like maize stems, food residuals from restaurants and municipalities, food industry waste (e.g., residuals from slaughterhouses or waste from beverage or fat production), and sewage sludge from waste water treatment.

pasteurization process or lost without any economic value. The value of the heat utilized on the farms is set to half the industry price of electricity.

During digestion, the organic nutrients present in the manure are transformed to inorganic compounds, e.g., organic nitrogen is converted to ammonia. The inorganic compounds can be more readily taken up by the plants than the organic nutrients present in undigested manure (Sommer et al., 2013). The digestate is therefore well suited as organic fertilizer. As a conservative assumption, GAINS assumes that cattle and pig slurry contains 0.6% of nutrients N- P2O5- K2O in the proportions 50-17-33 and that added organic waste contains 2.7% of nutrients N- P2O5- K2O in the proportions 55-30-15. The assumptions give a basis for estimating the amount of nutrients present in the digestate and therefore available for use as organic fertilizer. The value of pure nutrients in the proportions above is set to EUR1,000/ton N- P2O5- K2O, which would correspond to a price of EUR500/ton for an organic fertilizer containing 50% pure nutrients.

In GAINS the adopted investment cost for AD plants on farms of the size 100-500 LSU is EUR200/ton wet substrate loaded, while for farms of the size larger than 500 LSU it is EUR100/ton wet substrate loaded. Because the amount of wet substrate per animal is derived from country-specific volatile excretion rates, the derived investment cost per head is country-specific. The investment cost is the product of the investment cost per ton wet substrate for farm size s and the country-specific amount of wet substrate loaded per animal head, i.e.,

$$I_{its} = i_s * m_i * 1.25. \tag{12}$$

Note that the total amount of wet substrate loaded per head is 1.25 times the manure generated per head as the total substrate contains 80% manure and 20% other organic substrate.

Finally, to identify the extent of current adoption of farm AD in different member states, GAINS first derives the maximum technically feasible output of energy from farm AD plants by animal category and farm-size in the respective member states. Then, it derives the total energy output produced in 2015 from manure-based anaerobic digesters in consistency with the farm-based biogas production as estimated by the PRIMES model for the same year. The conversion efficiency to electricity is assumed 0.375 and to heat 0.7 (and 50% of the energy output generated is in the form of electricity and 50% in the form of heat). The source of information for farm-based biogas production in historical years in the PRIMES model is Eur'Observer (2014). By relating the total energy output from manure-based anaerobic digestion in 2015 to the maximum technically feasible output of energy from manure-based systems, we obtain the percentage of the maximum potential currently exhausted. The model exhausts the current potential using the same assumed adoption order for all member states, i.e., starting adoption on pig farms greater than 500 LSU. Once the potential in this category is exhausted, we move on to dairy farms greater than 500 LSU, then non-dairy cattle farms greater than 500 LSU, then pig farms 100 to 500 LSU, then dairy farms 100 to 500 LSU, and finally non-dairy cattle farms 100 to 500 LSU. The control strategy for 2015 has been developed in consistency with the PRIMES model and Eur'Observer (2014). The development in implied emission factors for manure management reported by member states to the UNFCCC (2015) for the years

2005 to 2013, was used as an indicator of the development in the uptake of farm AD technology between 2005 and 2015. E.g., if the reported implied emission factor for pigs in 2005 and 2010 is the same as in 2013, then the control in these two years is assumed to be at the same level as in 2015. For future years, the control strategy was developed so as to be in consistent with the growth in farm-based biogas production projected by the PRIMES model (2015).