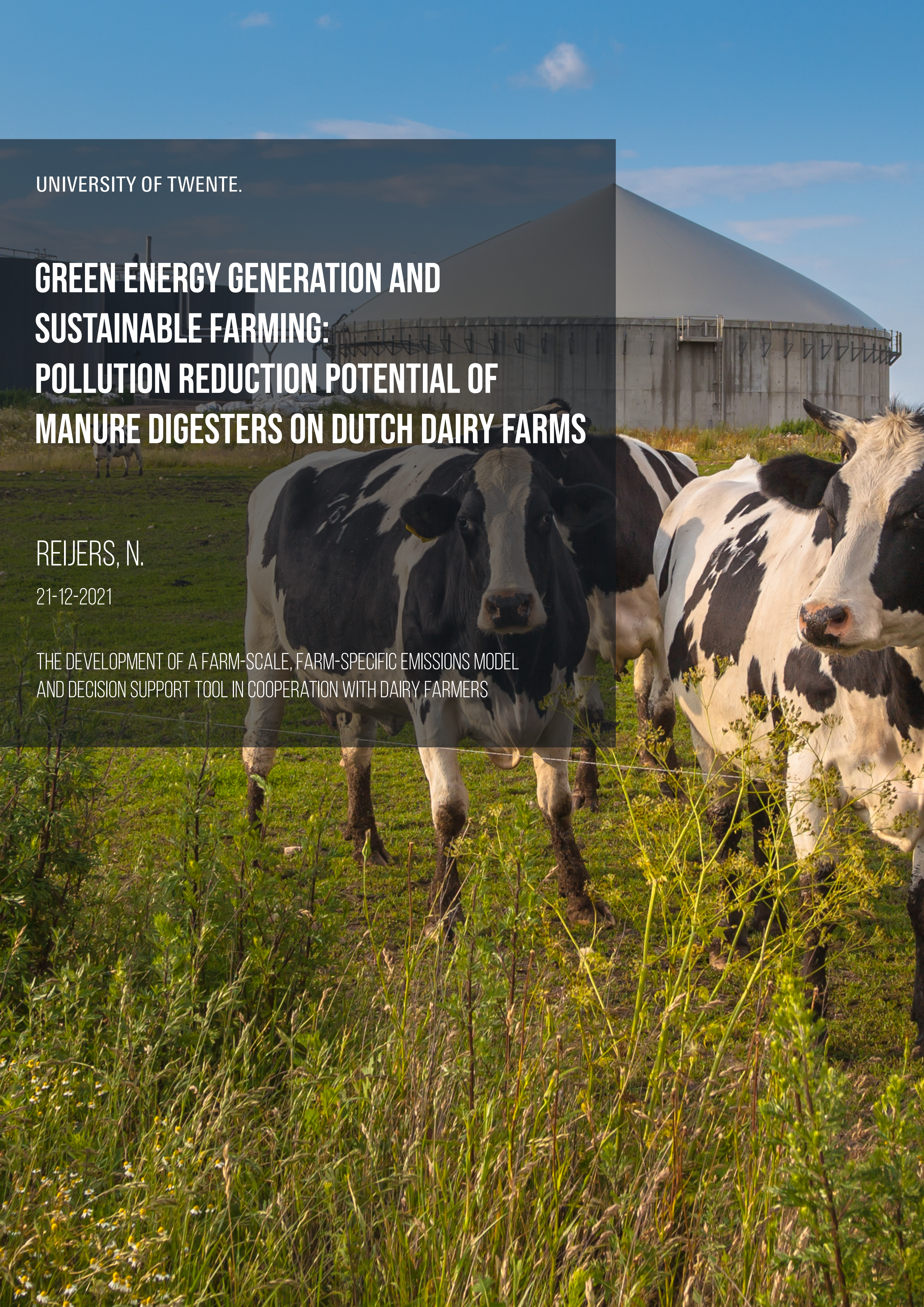

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GREEN ENERGY GENERATION AND SUSTAINABLE FARMING: POLLUTION REDUCTION POTENTIAL OF MANURE DIGESTERS ON DUTCH DAIRY FARMS

REIJERS, N.

21-12-2021

THE DEVELOPMENT OF A FARM-SCALE, FARM-SPECIFIC EMISSIONS MODEL AND DECISION SUPPORT TOOL IN COOPERATION WITH DAIRY FARMERS

University of Twente

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Green energy generation and sustainable farming: pollution reduction potential of manure digesters on Dutch dairy farms

The development of a farm-scale, farm-specific emissions model and decision support tool in cooperation with dairy farmers

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Preface

The current thesis titled ”Green energy generation and sustainable farming: pollution reduction potential of manure digesters on Dutch dairy farms”, is based on a farm-scale, farm-specific emissions model and decision support tool that was developed in cooperation with dairy farmers. This work concludes my Master in Civil Engineering and Management at the University of Twente.

This thesis would not have been possible without the help and support of numerous people. First, I would like to thank the farmers who hosted me on their farms and shared their insights, knowledge and data. Your contributions helped make this work into what it is today. I would not have been able to contact these farmers without the help of Eric Kleissen from Mineral Valley Twente. Eric, your insights in the world of dairy farming were invaluable as well as your efforts in helping me understand and translate the industry-specific jargon.

From the start of my thesis, I had the privilege of being guided by four supervisors from the University of Twente. Even though aligning their different opinions was at times challenging, it was one I thoroughly enjoyed since it pushed me to critically assess the choices I was making throughout my research. I want to thank you all for your time, feedback and support. Alexey, for his insights in systems modelling and perceptive questions which helped me develop a better model. Joanne, for helping me find this interesting thesis and guiding me through the research process. Bunyod, for our weekly meetings that kept me focused and all your advice. Maarten, for helping to link my work to practice and for providing me with new viewpoints and insights.

I also wish to thank all my friends and housemates for their support over all these years. Finally, I want to thank my father for his support during my master studies for without him this would not have been possible.

My aspiration for this thesis is that it will add to the discussion on addressing climate change and the nitrogen problem. I hope you enjoy your reading.

Niek Reijers,

Enschede, December 2021

Abstract

Due to human activities, global warming is seriously increasing the earth's temperature. Keeping the temperature rise within the limits of 1.5 degrees Celsius is currently the global ambition (IPCC, 2018; IEA, 2020). The achieve this ambition significant reductions of greenhouse gas (GHG) emissions caused by human activities are required. According to the Intergovernmental Panel of Climate Change (IPCC) the reduction of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) are specifically required (IPCC, 2018). The production and conversion of fossil energy resources are considered to be among the major causes of the global temperature rise. In the Netherlands, next to the production, conversion and consumption of fossil energy resources, the intensity of dairy production is considered a major contributor to methane and nitrogen dioxide emissions (European Commission, 2020; Ritchie and Roser, 2020). According to official Dutch statistics, the Dutch dairy sector is causing about 46% of the nitrogen (N) emissions in the Netherlands (Adviescollege Stikstofproblematiek, 2020; Environmental Data Compendium, 2019). These emissions are the downside of the high global production standards and economic relevance of Dutch dairy farming. Against this background, our research focused on the question; if and to what extent digestion of manure reduces emissions in Dutch dairy farming. Manure digestion addresses several current societal challenges. It contributes to the availability of green energy, it is assumed to reduce GHG and N emissions and provides perspectives for sustaining intensive livestock farming in the Netherlands. To date researching this combination of societal challenges is rarely done. It is the major theme of our research, which was guided by the following research question: what is the scale of GHG and nitrogen pollutants emissions reduction and net renewable energy generation when implementing manure digesters on Dutch dairy farms?

By tradition, manure is used as natural fertiliser on farmland. Currently, manure digestion is practised only on a small number of the 16,000 Dutch dairy farms despite the production of 47 million tons of manure annually. Thus, there is a huge potential for manure mono-digestion.

To analyse the biogas generation and emission reduction potential of farm-based manure digestion, we developed a new farm-scale model to assess the benefits of manure digestion in terms of biogas yield and GHG and N-pollutant emission reduction. The model is based on a farm-based manure life-cycle with two management options: traditional manure storage and manure digestion for biogas production. The model has been developed and designed in close cooperation with farmers in the province of Overijssel and realistically integrated all variables relevant in the farm-based manure life-cycle. Moreover, the model used real-life data for analysing the differences in both manure management scenarios in terms of GHG emissions (N_2O, CH_4, CO_2) and the N-pollutants (NH_3 and NO_X). Data of four different farms has been used in the analysis. This data has been obtained from the KringloopWijzer, which is a common data format used by all dairy farms in the Netherlands (van Dijk et al., 2020). The model has integrated several well-established emissions methodologies which have been adapted to work at a farm scale. Among others we used the air pollutant emission inventory guidebook 2019 by EMEP/EEA (Amon et al., 2019; Garcia et al., 2019), the Guidelines for National Greenhouse Gas inventories by IPPC (Dong et al., 2006) and the Dutch National Emissions Model for Agriculture (Lagerwerf et al., 2019; van Bruggen et al., 2020). By running the model we compared the emissions between the traditional manure storage scenario and the scenario with farm-scale manure digestion.

The results of the four different dairy farms show that at least 29% of the total-N emissions can be reduced by introducing manure digestion on a dairy farm in the Netherlands. If the barn is of the lowest emission housing type, the emission reduction can increase to about 44%. Compared to the traditional manure storage scenario, manure digestion reduces the methane (CH_4) emissions by 80%. Due to the sustainable energy generation capabilities of manure digester, the net carbon dioxide (CO_2) emissions of dairy farms also significantly reduce and in some cases more than completely offset. The total GHG emission reduction of these four farms expressed in CO_2-eq. is 1.24 million kg CO_2. These results indicate the diverse benefits of manure digestion in terms of GHG and N-pollutant emissions reduction and green energy production.

Our analysis also indicates that a nationwide introduction of farm-based manure digestion could significantly reduce emissions by removing 19.3 million kg N as well as 62.8 million kg of CH_4 and at the same time generating 1.51 TWh of sustainable energy, avoiding 562.1 million kg CO_2. The combined reduction of GHG, expressed in CO_2-eq., through the introduction of manure digesters in the Netherlands is 3,268.23 million kg CO_2.

Our model is easily accessible as an Excel tool to facilitate farmers and policy makers as a decision support tool for estimating emission reduction potential at the farm. Future research could add a financial module to the tool for assessing the financial feasibility of investments in manure digestion technology at the farm.

Samenvatting

De opwarming van de aarde door menselijke activiteiten zorgt voor een aanzielijke temperatuurstijging. Het is momenteel een mondiable ambitie om deze temperatuurstijging binnen de 1.5 graden Celcius the houden (IPCC, 2018; IEA, 2020). Om deze ambitie te realiseren is een forse reductie nodig van de uitstoot van broeikasgassen (GHG) door menselijke activiteiten. Volgens het Intergovernmental Panel of Climate Change (IPCC) zijn specifiek de reductie van koolstofdioxide (CO_2), distikstofmonoxide (lachgas, N_2O) en methaan (CH_4) vereist (IPCC, 2018). De productie en omzetting van fossiele energiebronnen wordt beschouwd als een van de belangrijkste oorzaken van de wereldwijde temperatuurstijging. In Nederland wordt de intensiteit van de zuivelproductie beschouwd als een van de belangrijkste bijdragers aan de uitstoot van methaan en stikstofdioxide, naast de productie, conversie en consumptie van fossiele energiebronnen (European Commission, 2020; Ritchie and Roser, 2020). Volgens officiële Nederlandse statistieken veroorzaakt de Nederlandse zuivelsector ongeveer 46% van de totale stikstofuitstoot (N) in Nederland (Adviescollege Stikstofproblematiek, 2020; Environmental Data Compendium, 2019). Deze emissies zijn de keerzijde van de hoge mondiale productienormen en economische relevantie van de Nederlandse melkveehouderij. Tegen deze achtergrond richtte ons onderzoek zich op de vraag; of en in hoeverre vergisting van mest de uitstoot van emissies in de Nederlandse melkveehouderij kan verminderen. Mestvergisting draagt bij aan het oplossen van een aantal actuele maatschappelijke uitdagingen. Het zorgt voor de beschikbaarheid van groene energie, biedt mogelijk mogelijkheden voor mestbeheer, wordt verondersteld de uitstoot van broeikasgassen (GHG) en stikstof (N) te verminderen en biedt perspectieven voor het verduurzamen van de intensieve veehouderij in Nederland. Onderzoek naar deze combinatie van maatschappelijke uitdagingen wordt tot op heden zelden gedaan. Het is het hoofdthema van ons onderzoek, dat werd geleid door de volgende onderzoeksvraag: Wat is de omvang van de uitstoot van broeikasgassen en stikstofgassen en de netto opwekking van hernieuwbare energie bij het implementeren van mestvergisters op Nederlandse melkveebedrijven?

Van oudsher wordt mest gebruikt als natuurlijke meststof op landbouwgrond. Op dit moment wordt mestvergisting slechts op een klein aantal van de 16.000 Nederlandse melkveebedrijven toegepast, ondanks de jaarlijkse productie van 47 miljoen ton mest. Er is dus een enorm potentieel voor monovergisting van mest.

Om het biogasproductie- en emissiereductie potentieel van mestvergisting op boerderijen te analyseren, hebben we een nieuw model op bedrijfsschaal ontwikkeld om de voordelen van mestvergisting te bepalen in termen van biogasopbrengst en vermindering van broeikasgas- en stikstof emissies. Het model is gebaseerd op een mestcyclus op bedrijfsschaal met twee beheeropties: traditionele mestopslag en mestvergisting voor biogasproductie. Het model is ontwikkeld en ontworpen in nauwe samenwerking met boeren in de provincie Overijssel en integreert op realistische wijze alle variabelen die relevant zijn tijdens mestcyclus op een melkveehouderij. Bovendien gebruikt het model data van echte melkveehouderijen om de verschillen in beide mestbeheerscenario's te analyseren in termen van broeikasgas emissies (N_2O, CH_4 en CO_2) en N-emissies (NH_3 en NO_X). Bij de analyse zijn gegevens van vier verschillende melkveehouderijeb gebruikt. Deze data was afkomstig uit de KringloopWijzer, een gangbaar dataformaat dat door alle melkveehouderijen in Nederland wordt gebruikt (van Dijk et al., 2020). Het model heeft verschillende gevestigde emissiemethodologieën geïntegreerd die zijn aangepast om op de boerderijschaal te werken. We hebben onder meer gebruik gemaakt van het air pollutant emission inventory guidebook van EMEP/EEA (Amon et al., 2019; Garcia et al., 2019), de Guidelines for National Greenhouse Gas inventories door IPPC (Dong et al., 2006) en het Dutch National Emissions Model for Agriculture (Lagerwerf et al., 2019; van Bruggen et al., 2020). Met het model vergeleken we de emissies tussen de traditionele mestopslag en het scenario waarin alle geproduceerde mest op de boederij wordt vergist.

Uit de resultaten van de vier verschillende melkveebedrijven blijkt dat minimaal 29% van de totale stikstof uitstoot kan worden verminderd door mestvergisting op een melkveehouderij in Nederland. Indien de stalconstructie van het emissiearmste type is, kan de emissiereductie oplopen tot circa 44%. Vergeleken met het traditionele mestopslagscenario vermindert mestvergisting de methaanuitstoot (CH_4) met 80%. Door het duurzame energieopwekkingsvermogen van de mestvergister wordt ook de netto CO_2-uitstoot van

de melkveehouderij aanzienlijk verminderd en in sommige gevallen meer dan volledig gecompenseerd. De totale broeikasgas emissie reductie van deze vier bedrijven uitgedrukt in CO_2-eqv. is 1.24 miljoen kg CO_2. Deze resultaten geven de gediversifieerde voordelen aan van mestvergisting in termen van broeikasgas- en N-emissiereductie en productie van groene energie.

Onze analyse geeft ook aan dat een landelijke introductie van mestvergisting op boerderijschaal de uitstoot aanzienlijk kan verminderen door 19.3 miljoen kg N en 62.8 miljoen kg CH_4 te verwijderen en tegelijkertijd 1,51 TWh duurzame energie op te wekken, waardoor 562.1 miljoen kg CO_2 vermeden wordt. De totale broeikasgas reductie uitgedrukt in CO_2-eqv. door de introductie van mestvergisters in Nederland is 3,268.23 miljoen kg CO_2.

Ons model is gemakkelijk toegankelijk als een Excel-tool om boeren en beleidsmakers te helpen als een beslissingsondersteunend instrument voor het bepalen van het emissiereductie potentieel op een boerderij. Toekomstig onderzoek zou een financiële module aan de tool kunnen toevoegen om de financiële haalbaarheid van investeringen in mestvergistingstechnologie op het bedrijf te beoordelen.

Contents

Glossary

anthropogenic

caused by human activity.

culling

Sending an farm animal to be slaughtered.

denitrification

The process of converting oxidised nitrogen (N) compounds into reduced forms.

EF

The emission factor (EF) is a representative value which links the release of a pollutant to the environment to the activity associated with the release of that pollutant.

GVE

GVE (Dutch: Groot Vee Eenheid) is a method of expressing young stock in terms of dairy cows, see section 2.2.2

GWP

The Global Warming Potential (GWP) is method to compare the relative impact of greenhouse gasses such as CO_2, CH_4 and N_2O by expressing non CO_2 GHG in CO_2 equivalents.

hydrolysis

The chemical process in which a water molecule is added to a substance. This can cause both the target molecule and water molecule to split into two parts, where one part of the target molecule receives an H^+ ion and the other a OH^-. This causes the target molecule to break into smaller molecules.

immobilisation

The conversion of mineral N into organic N in solid manure, which decreases the TAN of the solid fraction

KringloopWijzer

An analysis required by Dutch Law for every dairy farm in the Netherlands. It contains information on both the characteristics of the farm as well as the emission information.

manure management

The steps in the manure life cycle from the excretion of manure until it is either applied to soil or removed from the system.

mineralisation

The conversion of organic N into mineral N in slurry manure, which increases the TAN of the slurry fraction

NEMA

The Dutch National Emission Model for Agriculture

nitrification

The process of converting reduced nitrogen (N) compounds into oxidised forms.

nutrient budget

"The summary table of the book-keeping of nutrients inputs and outputs of a system. A nutrient surplus or deficit is calculated as the physical difference between nutrient inputs and outputs ha^{-1} of agricultural land" (Oenema et al., 2003, p.4).

particulate matter

Particulate Matter (PM) is a mixture of solid particles and liquid droplets found in the air that can consist of many different chemicals. Particle matter has a negative effects on human health and ecosystems.

pH

pH is a logarithmic scale of acidity from 0 to 14, it tells how acidic ($pH < 7$) or alkaline ($pH > 7$) a solution is. Neutral solutions have a pH of 7. Acidic and alkaline solutions have higher and lower concentrations of H^+ ions, respectively.

TAN

Total amount of NH_3 and NH_4^+ present in manure.

List of symbols

CH_4 methane

CO_2 carbon dioxide

H hydrogen

N nitrogen

N_2 di-nitrogen

N_2O nitrous oxide

NH_4^+ ammonium

NH_3 ammonia

NO nitric oxide

NO_2 nitrogen dioxide

NO_X nitrogen oxides

1 Introduction

To halt global warming and its effects on the environment, major changes need to be made to our way of living. Climate changes causes droughts, storms, increasing temperatures and other effects that impact our everyday lives. When the global average temperature is allowed to rise further, the severity of these extreme weather conditions will increase and be accompanied by further sea-level rise, loss of biodiversity and even complete loss of ecosystems (IPCC, 2018). The consequence of all this will be a changing climate which will not only impact the environment we live in but also reduce food production, negatively effect human-health and cause economic downturn (IPCC, 2018; IEA, 2020). To limit these consequences of climate change it is crucial to reduce the emissions of greenhouse gasses (GHG), such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (IPCC, 2018). Each of these three gasses plays a specific role in catalysing climate change and together they are responsible for more than half of the total greenhouse gas effect (Liu et al., 2019). The IPCC (2018) stresses that reducing the level of these gasses in the atmosphere is crucial in halting the increase of the global average temperature.

To reduce the different GHG emissions, it is crucial to understand how much of each GHG is emitted by different sectors and how each GHG contributes to global warming. The annual carbon dioxide emissions per sector show that the majority of carbon dioxide is emitted in the electricity and heat sector as well as the transportation sector (Ritchie and Roser, 2020). The agricultural sector, specifically the livestock sector, is one of the major contributors to methane emissions (European Commission, 2020). A large majority of nitrous oxide emissions is emitted by the agricultural sector through the use of synthetic and organic fertilisers such as animal manure (Ritchie and Roser, 2020). In the last years, targets and limits have been set all over the world to reduce the different GHG emissions based upon international agreements, such as the Paris climate accords (UNFCCC, 2016). The Netherlands is an especially interesting case regarding these emissions due to its intensive agricultural practices whilst dealing with the ongoing nitrogen problems (Adviescollege Stikstofproblematiek, 2020). These nitrogen problems occur due to the release of ammonia (NH_3) and nitrogen oxides (NO_X) as pollutants to the environment which impact soil and water quality as well as biodiversity (Post et al., 2020; Kok et al., 2020).

Different kinds of biomass can be used to generate sustainable energy, from specially grown energy crops to waste streams. One of these biomass sources in the agricultural sector in the Netherlands is the manure of dairy cows. The more than 1.5 million dairy cows on approximately 16,000 dairy farm in the Netherlands produce yearly an estimated 47 million tons of manure (ZuivelNL, 2020; CBS, 2020a). With each ton of manure a significant amount of N_2O and CH_4 emissions are released as well as NH_3 and NO_X. Currently, manure digesters are used to generate sustainable energy from dairy cow manure, but are less recognised as an instrument to reduce dairy farm emissions. The large scale use of manure digesters could provide green gas, a sustainable alternative to natural gas which can be used in the Dutch national gas grid. This work determines to what extent manure digester reduce emissions on Dutch dairy farms and to what extent manure digesters can contribute to the green energy generation and emission reduction goals in the Netherlands. The large scale implementation of manure digesters on livestock farms could thus mitigate climate change and the nitrogen problem by reducing GHG and N-pollutants emissions whilst generating sustainable energy.

1.1 Current State

Currently, the main function of manure digesters is to convert manure into biogas with digestate as a by-product. However, it is unclear to what extent this system reduces the different GHG emissions of the farms by capturing and converting fresh manure. Next to GHG emissions, nitrogen (N) emissions are currently a major problem hampering Dutch society (NOS, 2020; Adviescollege Stikstofproblematiek, 2020). The livestock sector plays an integral role in Dutch nitrogen problems and using manure digesters could provide a highly anticipated solution to reduce emissions. Next to these benefits, manure digesters can also contribute to the energy transition goals in the Netherlands by generating biogas.

To determine the extent to which manure digesters contribute to these fields it is important to know all the GHG emissions that take place on a dairy farm. Assessment studies have been conducted on many different types of manure GHG emissions abatement options (Hou et al., 2015; Sajeev et al., 2018). The work by Sajeev et al. (2018), which compares many different studies, shows that manure digesters are one of the most effective emission reduction options. However, there are many different types of manure digesters. They are both used at the farm scale and at a larger scale where the digester functions as a central hub. Furthermore, research focuses on improving the energy generation of digesters, through the use of co-digestion for example (Hamelin et al., 2014; Piñas et al., 2018). Studies are often conducted to evaluate manure digesters sustainability depending on certain criteria, such as the feedstock, or process variables, such as temperature and retention time (Blengini et al., 2011). However, the biggest variables influencing the release of GHG emissions are the farm characteristics such as its size (Aguirre-Villegas and Larson, 2017). Due to all these variables, it is difficult to accurately estimate the farm-scale emissions even with widely used methods and equations, such as the ones from the Intergovernmental Panel on Climate Change (IPCC) (Baldini et al., 2018). Previous research has been done on methane (CH_4) emissions based on theoretical farms in the Netherlands and on case studies abroad (K. Groenestein et al., 2020; Marañón et al., 2011). However, a combined effort to classify the different GHG emissions and N pollutants at a farm-scale has yet to be undertaken.

1.2 Research Aim

The problem described above leads to the following objective: determine the GHG and N-pollutant emissions reduction and net renewable energy generation of a manure digester on dairy farms in the Netherlands by comparing the situation with and without a manure digester.

This research focuses on the emissions stemming from the manure life-cycle on dairy farms with and without a manure digester. The main GHG emissions that impact the dairy sector are CH_4 and N_2O. Where CH_4 is released by ruminant animals and emitted from manure, particularly in long term storage and N_2O is released in the different stages of manure management, from excretion by dairy cows until its application as fertiliser. There will also be a reduction of CO_2 emissions, since the biogas produced by the manure digester does not have to be produced through the use of fossil fuels. The included N-pollutants (NH_3 and NO_X) are used to determine the impact a manure digester has on nitrogen (N) emissions that cause the nitrogen problem in the Netherlands.

This study focuses specifically on the mono-digestion of dairy cow manure on Dutch dairy farms. However, dairy manure can be combined in a manure digester with other types of feedstocks. This moves the process from mono-digestion to co-digestion, which improves biogas production (Adekunle and Okolie, 2015). However, during this research, the focus remains on mono-digestion for three reasons. The first is that there are a large number of co-products that can be added from different sources which are not per definition sustainable, for example, through competition with food products (Hoekstra, 2020). Secondly, each different co-product will have its distinctive properties and will therefore impact the system in a different manner which is outside the scope of this work (Piñas et al., 2018). Finally, the addition of co-products will generate more digestate which will only increase the total amount of fertiliser material present in the Netherlands which currently already has a large manure surplus.

The objective of this research will be achieved through the development of a model based upon real-world data and literature which, in turn, allows for the assessment of the emissions in the two different scenarios, with and without a manure digester. This model also serves as a decision support tool since it can determine the effects of a manure digester on the emissions of each individual dairy farm in the Netherlands. To enhance the accuracy the model, it will be based upon farm-specific inputs and be developed in cooperation with Dutch dairy farmers. This model can then be used to evaluate the emissions reduction and net renewable energy generation capacity of a dairy farm considering the implementation of a manure digester.

1.3 Research Questions

To achieve the objective set out above the following research question is formulated: What is the scale of GHG and nitrogen pollutants emissions reduction and net renewable energy generation when implementing manure digesters on Dutch dairy farms?

To answer this main question several issues need to be addressed within this research. To address these issues a number of sub-questions have been formulated and these are presented below.

1. What are the different steps of manure life cycle on a dairy farm with and without a manure digester?
2. What GHG and N pollutants emissions occur during each step of the manure life cycle on a dairy farm with and without a manure digester?
3. What is the scale of GHG and N-pollutants emissions reduction and the quantity of net renewable energy generation when implementing a digester on the dairy farms studied?
4. To what extent can manure digester on dairy farms contribute to the climate mitigation and energy transition goals in the Netherlands?

The first question is focused on developing an understanding of the whole system from both a practical and scientific perspective as well as the links the system has to the environment. This leads to the development of a systems description which allows for the creation of a emissions model. The second question uses the system description and assigns the emissions per step which then can be developed into a model which determines the emissions reduction and net energy generation for a dairy farm. This is done based upon certain farm-specific inputs such as; the number of cows, hectares of land, type of feed and amount of time the animals spend grazing and housed. The results of this model answer the third research question. The farm-scale model is adapted to answer the fourth research question and allows for the conclusions and recommendations to be made.

1.4 Report Outline

An overview of Dutch dairy farming and the dairy sector are given in section 2. This serves as a backdrop during model development and serves as a basis on which design decisions are made. Furthermore, it contains the data which serves as the input for the model at the provincial scale in section 5. The model is developed in section 3 which first focuses on data acquisition and existing emissions methodologies. After this, the model development is described for each of the emission types N, CH_4 and CO_2. The results are split into two sections, where the farm-scale results are presented in section 4 and the provincial-scale results in section 5. Finally, the discussion and conclusion of these results can be found in section 6 and 7 respectively.

2 Dutch Dairy Farming

To determine the role of manure digesters in reducing emissions on dairy farms in the Netherlands, it is crucial to develop a proper understanding of the dairy sector as a whole and to explore the specific characteristics of a farm. These characteristics will influence the emissions from a farm as well the impact of the manure digester. This information forms the backdrop on which, in section 3, the methodology of this work will be developed. First, an introduction into the Dutch dairy sector and the accompanying emissions is given. After that, the production of the Dutch dairy sector throughout the country is presented. Next, the farm specifics are discussed on the basis of literature research. Finally, the manure digester, its technology and implementation implications are discussed.

2.1 The Dutch Dairy Sector

The agricultural sector is economically important for the Netherlands, due to the high volume of products that are produced and exported all over the world. The annual value of these exported goods was 95.6 billion euros in 2020 (Jukema et al., 2021). This is achieved through intensive agricultural practices, which allow for large harvests and large animal herds per hectare (Viviano, 2017; van Grinsven et al., 2019). However, research has shown that these intensive agricultural practices impact soil and water quality as well as biodiversity (Post et al., 2020; Kok et al., 2020). This has resulted in a intensively regulated agricultural sector, which in recent years has been linked to a significant share of nitrogen (N) emissions (van Grinsven et al., 2019; Adviescollege Stikstofproblematiek, 2020). To address these issues, the Dutch dairy sector needs to adapt and evolve. One way to adapt is to install manure digesters on dairy farms to reduce emissions whilst generating sustainable energy.

2.1.1 The Dutch Nitrogen Problem

The agricultural sector produces about 46% of the Dutch national nitrogen (N) emissions (Environmental Data Compendium, 2019). To combat the nitrogen problems in the Netherlands, the advisory committee Remkes was formed to analyse the issue and to formulate recommendations on how to address the nitrogen problem. The advisory committee Remkes published their report, Adviescollege Stikstofproblematiek (2020), on how to address the nitrogen issues in the Netherlands. In this report the focus lies on reducing the ammonia (NH_3) and nitrogen oxides (NO_X) emissions. The majority of the agricultural emissions stem from NH_3 of which 86% comes from the agricultural sector (CBS, 2020c). This is a different focus than reducing the GHG emissions discussed previously, but release of these different nitrogen (N) pollutants go hand in hand. By adopting a holistic approach and accounting for all these pollutants, the risk of emissions trade-offs are avoided. These trade-offs occur when the emissions of certain pollutants are reduced whilst other are increased (Adviescollege Stikstofproblematiek, 2020; (Hou et al., 2015). The majority of the emissions can be contributed to the sub-sector of dairy farming, which is also the sub-sector that contributes the most to the economy, both financially and in terms of job creation (Adviescollege Stikstofproblematiek, 2020).

A large part of the nitrogen that is introduced into the agricultural sector is lost to the environment. This loss, in terms of pollution and emissions, negatively affects ecosystems significantly and contributes to climate change. The agricultural sector emits 107 million kg N per year of which 94 million kg N is emitted as NH_3 and the rest as NO_X (Adviescollege Stikstofproblematiek, 2020). The large majority of the ammonia (NH_3) emissions comes from animal manure (87%), 9% is related to other fertilisers and the remaining 4% to crops and their residues. The manure emissions come from soiled stables, the storage of liquid manure in manure cellars and the use of liquid manure as fertiliser on pastures and arable lands. Of the agricultural sub-sectors, it is the dairy sector that contributes the most both economically and in terms of emissions. The dairy sector emits for 53.8 million kg N per year of which 6.1 million kg N is NO_X and the rest is NH_3 (Adviescollege Stikstofproblematiek, 2020; van Bruggen et al., 2020). According to the committee Remkes it is crucial to approach this nitrogen problem from a holistic viewpoint due to the complex links between the different agricultural processes, GHG emissions and the environment. Furthermore, the chemical reactions that form ammonia (NH_3) occur under similar conditions as the formation of methane (CH_4), which is another GHG that plays an important role in the agricultural sector. Thus, when developing solutions, it is key to focus on integrative plans that address a multitude of related issues.

2.1.2 Climate Impact of Methane

When ruminant animals, such as cows, digest their feed, they engage in a process called enteric fermentation. During this process, in which the feed is decomposed and fermented, methane (CH_4) is produced as a by-product and emitted to the atmosphere (Etcheverry, 2014). Agriculture is with 53% the largest source of anthropogenic methane emissions in the EU, and at the same time, there are no EU policies focused on reducing anthropogenic methane emissions (European Commission, 2020). The majority of this 53% comes from enteric fermentation by animals (80.7%) and 17.4% from manure management and the remaining 1.2% from rice cultivation (European Commission, 2020). Even though the impact of methane on the environment is known, it is 28 times more potent than CO_2, the regulations are lacking behind those of carbon dioxide. The developing EU strategy on methane reduction set out by the European Commission (2020) acknowledges the power of methane as a GHG and ranks it as the second-highest contributor to climate change, behind carbon dioxide. One of the focus points of this developing strategy is the generation of biogas from manure, not only to reduce emissions and generate sustainable energy but also as a way to support farmers and invest in rural areas (European Commission, 2020).

2.1.3 Energy from Manure

Land-based livestock farming in the Netherlands is linked to many challenges: from manure surplus, methane and ammonia emissions to soil quality and climate change. A push for action to address these challenges come from different sources, due to the ongoing nitrogen crisis in the Netherlands which halted many infrastructure and construction projects (Estrada and Voogt, 2020). One way of addressing these challenges and reducing GHG emissions is to convert manure into useful energy (European Commission, 2020; IEA, 2020). This entails that a livestock farm captures its manure and feeds it into a manure digester. This allows a farm to create revenue from other products besides the traditional dairy and meat products, which can be a good economic stimulus and help with the energy transition goals (European Commission, 2020). The residual product of this process, digestate, can be converted into fertiliser or applied directly to farmland to reduce the purchasing cost of synthetic fertilisers (RVO, 2021b). This plan is in line with the vision of the Dutch government, which sees circular agriculture as the answer to the issues facing the Dutch farming industry (Ministry of Agriculture Nature and Food Quality, n.d.). Circular agriculture aims to close supply chains and to reduce pressure on the environment. Manure digesters can contribute to both of these aspects as well as aid in the energy transition.

2.1.4 Dairy Sector in Numbers

The Dutch dairy sector has been evolving over the last decades into a more centralised sector with less but larger farms (CBS, 2020b). The trend in table 1 clearly shows an increase in all farm sizes with more than a 100 cows and a decrease in all farm sizes with less than 100 cows. Furthermore, the overall population of dairy cows in the Netherlands is decreasing. However, this is partly compensated by an increase in milk production per cow (ZuivelNL, 2020; CBS, 2020a). However, the dairy sector is not spread evenly over the

Netherlands, as can be seen in figure 1, where the number of farms (indicated with a B) varies from 200 in Zeeland to more than 2500 in the provinces of Gelderland, Overijssel and Friesland.

Table 1: The number of farms ranked on size based on the number of cows presented on a farm. The trend over the last decades is that small farms disappear and larger farms are formed (CBS, 2020b).

# of cows	2000	2005	2010	2015	2019	Difference 2000 - 2019
$1 \leq 30$	6,854	4,031	2,348	1,760	1,302	- 81 %
$30 \leq 70$	16,231	11,603	7,870	5,699	4,642	- 71 %
$70 \leq 100$	4,549	5,238	5,327	4,789	4,116	- 10 %
$100 \leq 150$	1,508	2,114	3,210	4,093	3,992	165 %
$150 \leq 200$	217	369	698	1,179	1,244	473 %
$200 \geq$	107	172	352	745	964	801 %
Total	29,466	23,527	19,805	18,265	16,260	- 45 %

2.2 The Dutch Dairy Farm

Each dairy farm has its own specific characteristics that will make it stand out from other farm's. However, commonalities can be found, especially when all farms have to adhere to the same regulations. Based on these commonalities it is possible to develop a framework that represents a Dutch dairy farm that can be used for emission and energy generation calculations. This section aims to explore the important parameters for this framework. In this research two versions of this representative farm exist: one with and one without a manure digester. The difference between the two scenarios, with and without a manure digester, is the focus of this work but not the only variable considered. Other farm variables include the number of dairy cattle, harvesting methods, housing type, energy generation capabilities, etc. The most obvious commonality between all dairy farms is cattle, including young stock, which produces the farm's products, milk and meat, and also create a waste stream in the form of manure.

2.2.1 Young Stock

When evaluating a single farm during this research, dairy cattle and young stock are not accounted for separately but converted into GVE (Dutch: Groot Vee Eenheid). This is a measure used in the Dutch agricultural sector to express young stock in terms of mature dairy cows (CBS, 2017). This conversion is required since the feed consumption and manure production of young stock is significantly lower than that of dairy cows and the information collected yearly from dairy farms in the KringloopWijzer does not distinguish between the amount of feed consumed and manure excreted between the different animals. The conversion rates for this method are shown in table 2. The transition from young stock to dairy cow occurs when a cow is able to be milked for the first time. This occurs after the birth of the first calf when a cow is around two years old. The GVE can be used to more accurately estimate farms emissions, since not all dairy farms raise young stock while their manure is included in the total manure produced per farm in the KringloopWijzer.

Table 2: Conversion values for converting young stock into GVE, 1 GVE is equal to 1 mature dairy cow (CBS, 2017).

	Dairy Cow	Young Stock ($\geq$ 1 year)	Young Stock (<1 year)
GVE	1	0.53	0.23

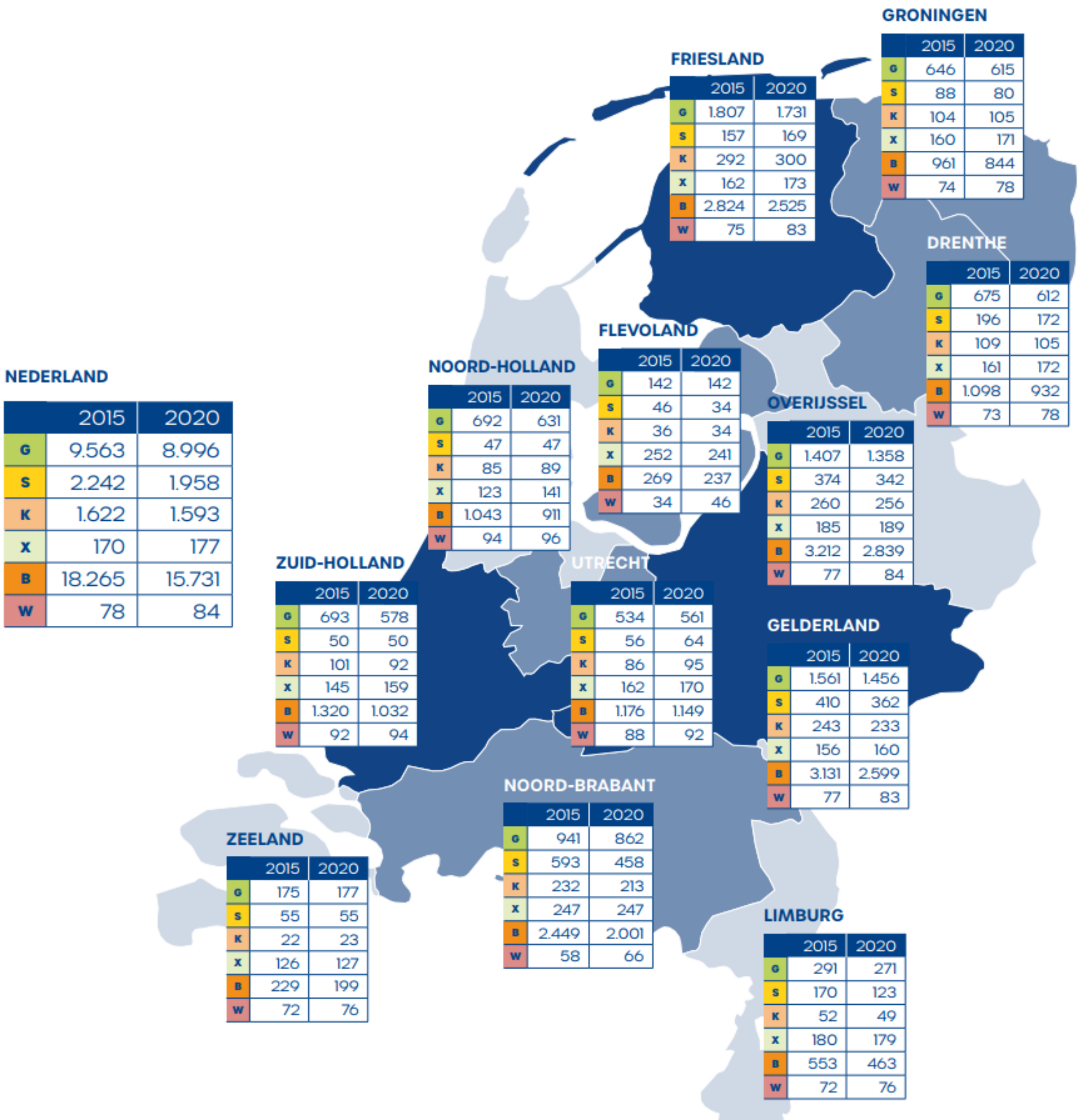


Figure 1: An overview of the Dutch diary sector in 2020, the different values indicated key sector figures per province. G and S noted the surface area in km^2 of grassland and maize, respectively. K gives the number of dairy cows (x1000) and X the number of dairy cows per km^2 of grassland. The B indicates the amount of dairy farms in a province and W the percentage of farms that have some form of grazing. Copied and adjusted from ZuivelNL (2020).

2.2.2 Regional Feed & Excretion

Each dairy farm consists of a number of dairy cows and they represent a consistent factor between the two scenario's, with and without a manure digester. The composition of the manure excreted by these cows will change with a changing diet but can be assumed constant based on the average feed intake. The average feed intake is determined by CBS (2020a) and is divided into two groups based upon soil type. This division is made because the feed composition varies between the North-West region of the Netherlands with peat and clay soil types, and the South-East region with sand and loess soil types as shown in figure 2. The North-West region consists of the provinces Groningen, Friesland, Utrecht, Noord-Holland and Zuid-Holland. The South-East region consists of the provinces Drenthe, Overijssel, Flevoland, Gelderland, Zeeland, Noord-Brabant and Limburg. The feed composition does not only vary per province, but is farm-specific and impacts both the CH_4 emissions levels as well as energy generation (Lagerwerf et al., 2019; Dong et al., 2006).

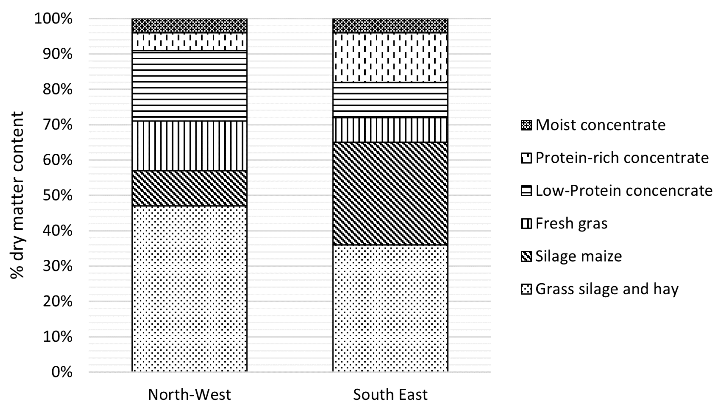


Figure 2: Dairy cow feed composition for North-West and South-East regions of the Netherlands, copied and translated from CBS (2020a).

The average yearly values for feed intake, expressed in kg dry matter, and manure excretion per region are displayed in table 3. The amount of excreted nitrogen (N) is a crucial component for the calculation of the different N pollutants, such as N_2O and NH_3. The total amount of manure excreted per animal also includes feed residues, cleaning water and spilled drinking water. This value in kilograms is thus much higher than the feed intake in dry matter. When evaluating on a farm scale, farm specific information from the KringloopWijzer will be used. However, these average values, displayed below in 3, are used on a province level to determine the possible emissions reductions in the Netherlands with the implementation of manure digesters.

Table 3: Regional feed and excretion data. Feed intake can be converted from MJ into DM by dividing the amount in MJ by 18.45 (van Bruggen et al., 2020). Note: for young stock only regional nitrogen excretion data is available, the rest are national averages. (CBS, 2020a; van Bruggen et al., 2020)

Regional Animal Data	Feed intake (MJ/animal.day)	Manure excreted (kg/animal.year)	Excreted N (kg/animal.year)
Young Stock $< 1\,year$	70.7	5000	36.9/31.8 (NW/SE)
Young Stock $\geq 1\,year$	138.2	12500	74.1/70.6 (NW/SE)
Dairy Cow NW	355.1	29000	154.4
Dairy Cow SE	360.8	30000	139.2

2.2.3 Excretion Location

One of the main influencing factors of manure emissions is its excretion location. During housing manure is collected and stored to be used later as fertiliser or feedstock for a manure digester. However, the manure excreted by cattle during grazing is inadvertently directly used as fertiliser on grasslands. This causes a major difference in released emissions and is therefore an important process variable (van Bruggen et al., 2020; Lagerwerf et al., 2019). However, it is hard to average this variable over a large population of farms due to the difference between the individual farmers. Where some would choose to house cows all year round, others either choose limited or day and night grazing. The national average data from CBS (2020a) is shown in table 4. Due to this division, the manure output of a cow is split into two different outputs: manure grazing and manure housing which are determined based upon time spent per year in either location, as well as the length of the grazing period, which also varies widely per farm. Outside the grazing period, in the housing period, all manure is captured and stored in barns.

There are three different grazing regimes considered, as shown in table 4. The hours spend outside per 24 hours are 18, 7 and 0 for day and night, limited and no grazing, respectively. The length of the grazing period also differs per region, where the Dutch average is noted at 160 days in 2019 (CBS, 2020a). The grazing period in the North-West region is 170 days on average and in the South-East region 150 days.

Table 4: Regional grazing averages percentages for the total number of dairy cows, adapted from CBS, 2020a.

Region	Day and night grazing (%)	Limited grazing (%)	No Grazing (%)
NW	17	63	21
SE	7	62	31
NL	11	62	27

2.2.4 Manure Collection & Storage

Manure in the Netherlands is traditionally stored below barns in manure cellars. The manure can only be used as fertiliser on farmland between February and August (RVO, 2021d). This means that manure can only be stored during the five month winter period. The problem with storing manure for a long time is that bacteria in manure start to ferment the manure and release CH_4. It takes a few weeks for the bacteria to develop to such levels that there is any significant release of CH_4 (K. Groenestein et al., 2020). Thus, reducing the storage time and fermenting the manure with a digester whilst capturing this CH_4 emissions stream can significantly reduce GHG emissions. For more information about the processes that take place in the manure digester, see section 2.3).

Next to the manure storage below the barn, the manure collection within the barn itself also plays an important role. There are many different housing types used in the Netherlands and NH_3 emissions are documented in Dutch law by the Wet Ammoniak en veehouderij (2002) (Regulation Ammonia and Livestock farming). There is a large difference between different housing types, the variation of NH_3 emissions can be as large as 60%. Since all nitrogen emissions occur from the same source, namely manure, the type of barn will significantly impact the nitrogen emissions of a farm and with it the GHG emissions through N_2O emissions. More information about the RAV and the housing types can be found in appendix B and the links between all the emissions are further explained in section 3.3.1.

2.2.5 Farmlands

Manure is not only produced and stored on dairy farms but also used as fertiliser on farmlands. On dairy farms in the Netherlands, farmland consists of grasslands and croplands (ZuivelNL, 2020). The croplands are full of maize which is used as cow feed, as shown in section 2.2.2. The grasslands are used for grazing and grass is harvested for use as cow feed. The fertilisation of both types of farmland in the Netherlands is heavy regulated (RVO, 2021d, RVO, 2020). Normally, a maximum limit of 170 kg animal manure per ha of farmland is set. However, farmers can apply for a derogation permit which allows an increase of 170 kg to either 230 or 250 kg based upon the province in which the farm is located and the soil type. The farms in the provinces of Overijssel, Gelderland, Utrecht, Noord-Brabant and Limburg which have sand and loess soils are capped at 230 kg nitrogen (N) per ha, whereas all the other farms can apply 250 kg N per ha (RVO, 2021a). The maximum amount of N per hectare of land includes both the manure applied as fertiliser and the manure excreted during grazing (Adviescollege Stikstofproblematiek, 2019).

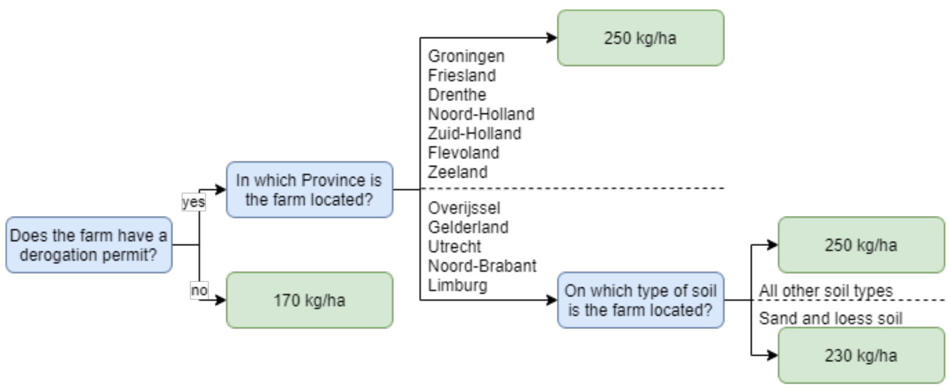


Figure 3: The impact of a derogation permit on the amount of nitrogen used during fertilisation on dairy farms in the Netherlands. The question posed in the decision tree are displayed in blue and the amounts of N per hectare in green.

2.3 Manure Digester

A manure digester is required to convert manure into biogas. This process is called anaerobic digestion (AD) and converts fresh manure into biogas in the absence of oxygen and produces digestate as a by-product. The digestate is a useful by-product since it can be used as an organic fertiliser to replace the converted manure. The process is quite slow, it usually takes at least a few weeks to convert the material in a single reactor or holding tank (Adekunle and Okolie, 2015). Currently, the quality of the biogas is not up to the standards of natural gas and needs to be upgraded and compressed first before it can be used in a similar matter. However, it can be easily used to generate electricity or combined heat and power (CHP) (K. Groenestein et al., 2020).

2.3.1 Anaerobic Digestion Processes

Anaerobic digestion (AD) is a complex biological process in which the organic molecules present in biomass are reduced and oxidised through microbial activities (Achinas et al., 2020). Due to a lack of understanding of the relationship between microbial dynamics and process functions it is difficult to consistently operate the process at stable conditions. The performance of the manure digester depends on different aspects such as pre-treatment options, the type of feedstock and process conditions. The important process conditions are temperature, hydraulic retention time and pH (Achinas et al., 2020; Adekunle and Okolie, 2015).

The AD process can be divided into multiple stages as can be seen in figure 4. These stages are the hydrolysis and fermentation stage, the acidogenesis and acetogenesis stage and the methanogenesis stage. The first stage cuts the large complex organic molecules into simpler end-products, such as sugars, amino acids and fatty acids. This is crucial since these molecules are otherwise too large to be used by the microorganisms in the next steps. The second step converts the soluble matter from the first phase into smaller volatile fatty acids (VFA), such as acetic acid, as well as ketones and alcohols. Together with some smaller compounds that were already created in the first phase, these are now converted into acetic and propionic acid, ethanol, H_2 and CO_2. The third stage of methanogenesis transforms the products of the second stage into biogas, which consists of methane (CH_4) and carbon dioxide (CO_2). Furthermore, CO_2 is reduced with H_2 into CH_4. Of the total methane production, 70% comes from the reduction of acetate and 30% from the reduction of CO_2 (Achinas et al., 2020).

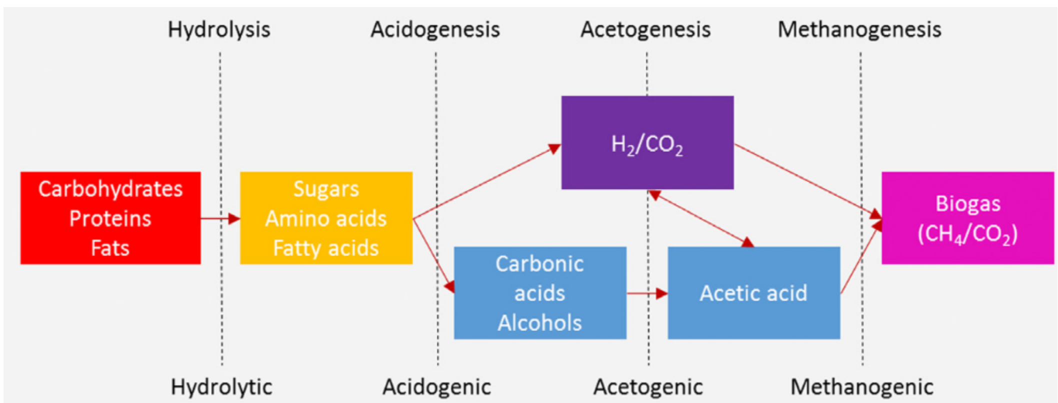


Figure 4: Overview of the different AD stages to produce biogas, copied from Achinas et al., 2020

3 Methods

This section focuses on the development of the model used for the calculating the emissions reduction when applying a manure digester on dairy farms in the Netherlands. The aim of this model is to calculate the farm-specific emissions of dairy farms in the Netherlands. To achieve this, data of dairy farmers in Netherlands were used as input for the model, this is discussed first. The model was developed in Excel so that it can be easily used as a decision support tool. This is followed by a description of the modelled system, which discusses the steps taken into account, their important parameters and interdependencies. The following three sections provide an in depth description of the model for nitrogen pollutants, CH_4 and CO_2, respectively. Each of these sections is accompanied by appendices which describe the model calculations step by step. To determine the impact manure digester can have when applied to all dairy farms in the Netherlands, certain adaptations the model and its inputs need to be made. These model alterations to the farm-scale model are discussed next. Finally, a summary of the developed model is presented.

3.1 Data & Scope

The data collected during this research came from literature, secondary sources and from dairy farmers themselves. This cooperation with dairy farmers was sought to better understand the system and to increase the trustworthiness of this work (Voinov and Bousquet, 2010; Voinov et al., 2016). The implementation of real world data from multiple dairy farms contributes to both the reliability and validity of this work. Testing the model with this real world data from different sources ensures reliable results, especially since all farms are obliged to yearly compile their data in the same format, called a KringloopWijzer. The KringloopWijzer is used as the information source for the farm-specific data. This common data format, with prescribed data collection methods, enhances reliability in terms of data collection (van Dijk et al., 2020). Furthermore, the use of established emissions methodologies as a basis for this work ensures the work adheres the worldwide accepted emissions calculation standards.

3.1.1 Farm Specific Data

To ensure that the results are not only on a farm-scale but also farm-specific, data is collected from dairy farms to be used as model inputs. The KringloopWijzer provides the ideal basis for the model, since it is both consists over all 16,000 dairy farms in the Netherlands and it is directly available for use. Another practical benefit is that it requires very little effort for dairy farmers themselves and thus also makes the model easy to use as a decision support tool. The KringloopWijzer itself contains large amounts of farm-specific data and parameters. The data collected in this work is from four dairy farms in the province of Overijssel. These farmers were approached through the network of Mineral Valley Twente and the names of all farms are known by the author. These farmers generously provided their KringloopWijzer and the one farmer, who recently installed a manure digester, was involved in the process from the beginning and his practical information and insights were vital in understanding the intricacies of farming practices and their translation into the model.

Farm-specific data already make comparisons between farms difficult. Differences in grazing regimes, fertilisation methods, number of cattle and amount of hectares are just a few of the parameters that impact the results. Some of these key parameters are displayed in table 5. The total overview of all input criteria can be found in appendix G. When looking at the GVE, which is the weighted sum of young stock and cattle (see section 2.2.1), a clear difference between the four farms is visible. Farm C is significantly smaller then the other three, but it is more in line with the national average of 101 diary cows per farm (ZuivelNL, 2020). Since many factors on a farm are dependent on the amount of GVE, it is a useful parameter that makes farms more easily comparable. For example, the feed intake per GVE on farm A is relatively high compared

Table 5: Key farm-specific parameters, a complete overview can be found in appendix G.

Farm Parameters	Farm A	Farm B	Farm C	Farm D
Number of cattle [-]	174	175	106	194
Number of young stock $_{\geq 1\,year}$ [-]	3	27	2	10
Number of Young stock $_{\leq 1\,year}$ [-]	47	72	18	50
Number of GVE [-]	186.4	205.9	111.2	210.8
manure excreted [ton]	4977	5608	2712	6803
manure excreted [ton/GVE]	26.7	27.2	24.4	32.3
Current Housing Type [-]	A 1.26	A 1.100	A 1.100	A 1.100
Feed [kg dm]	1405027	1461737	779598	1526772
Feed [kg dm/GVE]	7538.67	7099.26	7010.77	7242.75
grassland [ha]	53.01	73.77	30.94	63.96
cropland (planted with maize) [ha]	3.57	15.68	4.32	15.62
farmland total [ha]	56.68	89.45	35.26	79.58
Farming intensity [GVE/ha]	3.29	2.30	3.15	2.65

to the other. For comparison, the average feed intake in dry matter in the South-East region per dairy cow is 7137.8 kg dm (CBS, 2020a). Similarly, the manure excretion per GVE on farm D is larger than that of the other farms and the regional average of 30,000 kg per dairy cow per year (CBS, 2020a). This large difference between consumption in kg dry matter and excretion in kg manure, is due to the lack of water in dry matter and the addition of other compounds, such as feed residues, cleaning water and spilled drinking water to excreted manure.

The intensity of these farms can be compared by the intensities calculated per province in table 6. From these values it becomes clear that the average intensity of the individual farms much higher is than that of any province. It is not clear what the origins are for these differences in intensity. At a farm-scale these differences could be attributed to changing amount of land over the years. This trend was observed in the KringloopWijzers of all four farms. At a provincial scale the intensity is a an average over many different type of farms, thus it could be that the farm sample size used in this research is to small to give an accurate assessment of this value. However, this intensity values provides an indication of the amount of excess manure present on each farm. Since, manure is only used in the model as fertiliser on farmland or exported off-site.

3.1.2 Emissions Methodologies

Not only the farm data from the KringloopWijzers are used, but its accompanying documentation as well to derive useful farm scale emissions calculation methods (van Dijk et al., 2020). This is done because most methodologies are based on sector scale and thus provide not enough granularity to accurately estimate emissions on a farm level. At the basis of the model are a number of well established emissions methodologies which are adapted to work on a farm-scale, which are discussed in section 3.1.2. These works consist of the air pollutant emission inventory guidebook 2019 by EMEP/EEA (Amon et al. (2019) and Garcia et al. (2019)), the Guidelines for National Greenhouse Gas inventories by IPPC (Dong et al. (2006)) and the Dutch National Emissions Model for Agriculture (Lagerwerf et al. (2019) and van Bruggen et al. (2020)). Even though the IPCC values are used all over the world, the work of Dong et al. (2006) was not detailed enough to calculate the difference between the two scenario's for the different nitrogen (N) emissions. Work done for the Dutch diary sector by Lagerwerf et al. (2019) helped to provide updates from the IPCC values for a Dutch context wherever possible but provided similar issues as the work off Dong et al. (2006). The work by Amon et al. (2019) provided the required level of detailed but it's approach more focused on non GHG N emissions and certain steps lacked enough information to be converted into a farm scale approach. Thus a combination

Table 6: The total amount of GVE and hectares of farmland as well as the intensity expressed as the amount of GVE per hectare of farmland.

Provinces	GVE [-]	Farmland [ha]	Intensity [GVE/ha]
Zeeland (SE)	27856.86	23200	1.20
Limburg (SE)	59458.65	39400	1.51
Gelderland (SE)	287033.06	181800	1.58
Noord-Holland (NW)	107157.54	67800	1.58
Drenthe (SE)	130052.6	78400	1.66
Zuid-Holland (NW)	108449.25	62800	1.73
Utrecht (NW)	113142.85	62500	1.81
Overijssel (SE)	308805.86	170000	1.82
Groningen (NW)	126598.39	69500	1.82
Friesland (NW)	360418.09	190000	1.90
Noord-Brabant (SE)	261437.21	132000	1.98
Farm B	205.9	89.45	2.30
Flevoland (SE)	41212.47	17600	2.34
Farm D	210.8	79.58	2.65
Farm C	111.2	35.26	3.15
Farm A	186.4	56.68	3.29

between these sources was sought to develop the most accurate farm-scale model, where knowledge gaps are filled with other sources. Specific details regarding the use of each work can be found later in this section and in appendices A through F.

For each of the emissions, nitrogen (N), methane (CH_4) and carbon dioxide (CO_2), a separate model section is developed to determine the emissions on a dairy farm for two different scenarios. These two scenarios: storage (without a digester) and treatment (with a digester) vary on a crucial point which impact the emissions in the manure life-cycle. Namely, the the implementation of a manure digester on the farm. This change to the system is the origins of all differences in emissions between the two scenarios. There is, however, one other variable in the model that can be altered between the two scenario's. This variable is the housing type used during the two scenarios. The rationale behind this is that a barn could be upgraded at the same changes are made to it during the implementation of a digester to reduce more emissions on the farm. Changing the barn type will only impact the nitrogen emissions (Lagerwerf et al., 2019). If the same barn type is selected for both scenarios the model results are only impacted by the implementation of a manure digester.

3.2 System Description

Before the emissions model can be developed it is important to determine the exact system that is going to be analysed. A dairy farm is a complex system with many links to its environment. The focus of this research is on the manure life-cycle, which runs from the production and excretion of manure by dairy cows until it is applied as fertiliser or exported out of the system. There are other emissions present on a dairy farm, one example would be the application of synthetic fertiliser (Lagerwerf et al., 2019). However, these are not impacted by the introduction of a manure digester in the system and thus not taken into account. When taking a holistic look at a dairy farm and its supply chain, many more emission sources can be identified (van Dijk et al., 2020). These are also not taken into account in this work since they do not change between the two scenarios: with and without a manure digester. Furthermore, the whole supply chain of dairy farms is analysed yearly in the KringloopWijzer, which provides a detailed account of all emissions that occur in the supply chain of a dairy farm (van Dijk et al., 2020). Thus, the system analysed in this work is solely focused on the manure life-cycle on a dairy farm.

The system begins with the input of feed, which impacts emissions stemming from manure (see figure 5). Since the KringloopWijzer provides the total amount of feed consumed and manure excreted on a dairy farm, which includes young stock, this has to be converted to number of dairy cows. This can be done by expressing young stock and dairy cows in GVE, see section 2.2.1. The model does not calculate the amount of manure and its N content from the feed composition since both are given individually in the KringloopWijzer and can thus be seen as input variables. The same goes for the amount of TAN which are also noted in the KringloopWijzer. The TAN (Total Ammoniacal Nitrogen) content is used in certain N-emission calculations instead of total-N since it is deemed more accurate (Lagerwerf et al., 2019).

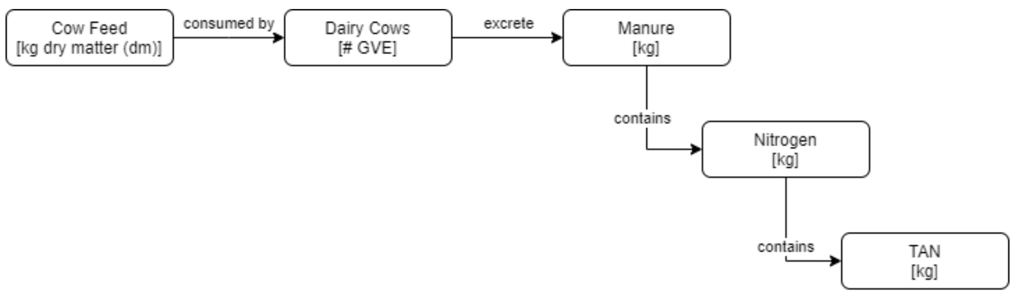


Figure 5: Overview of the first steps in the system surrounding a cow with the most important characteristics.

Manure is excreted by dairy cows at different locations on a dairy farm. In the model, two locations are used, housed in barns and grazing on grasslands (see figure 6). This division is an important farm characteristic as discussed in section 2.2.3. This division is made based upon the percentage of time spend grazing and housed. This can be calculated since the KringloopWijzer contains the length of grazing period in days and the amount of hours spend outside per day during this period. The grazing manure is directly spread onto grassland as fertiliser, where as the housing manure undergoes a number of steps, which differ between the two different scenarios, with and without a digester. Based upon the emission type, the most important characteristics of manure is not necessarily its weight but its N and TAN content.

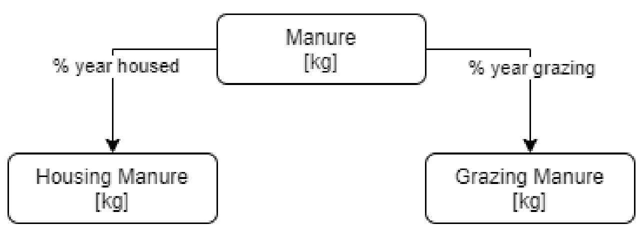


Figure 6: Overview of the manure division in the system.

The handling of the housing manure differs between the two scenario's (see figure 7). However, the total input is the same. The total input depends on the amount of cows on a farm and their grazing regime which itself is based on the days of the grazing period and the hours per day spend outside. In the first scenario, without a digester, the manure is transported from the barns to the underlying cellars where it is stored for multiple months (see section 2.2). This manure is then used as fertiliser and the remainder is exported to other farms in the Netherlands or abroad. This process changes in the second scenario, in which a digester is introduced. In this scenario the fresh manure is transported to the digester where it is converted into biogas and digestate. The digestate is then stored in a closed stored tank compared to open manure cellars. The work from Garcia et al. (2019) includes this as a one step process from an emissions perspective. This approach is adopted in this work and can be seen in figure 7.

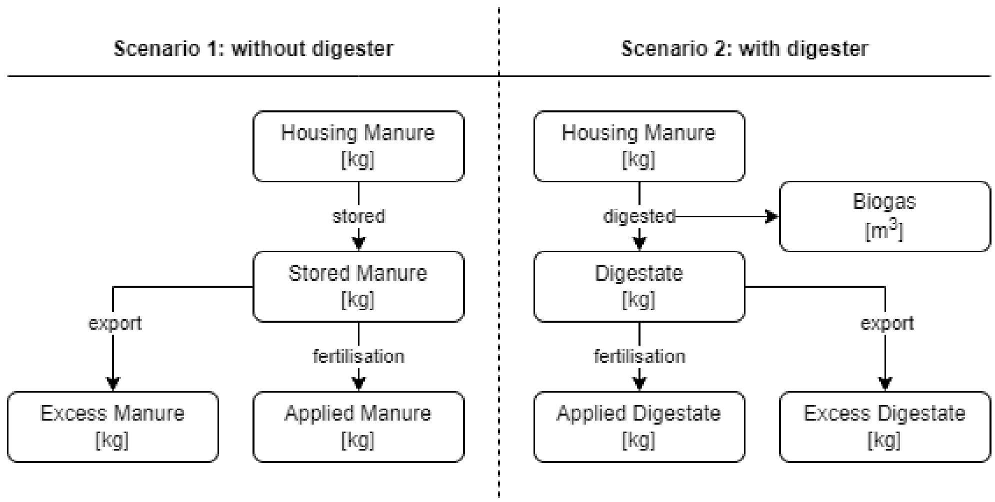


Figure 7: Overview of the two scenarios used in the model.

With the application and export of either manure or digestate, depending on the scenario, the manure life-cycle on a dairy farm comes to an end. The different steps of the manure life-cycle, shown in figures 5, 6 and 7, can be combined into a single system as shown in figure 8. Here the two scenarios, treated and stored are depicted in grey. The rest of the steps are the same for both scenarios, except biogas witch is only produced during the treatment scenario. For each of the steps in figure 8 emissions calculation are conducted for the pollutants present. The next three section discuss respectively the N, CH_4 and CO_2 emissions stemming from the different steps.

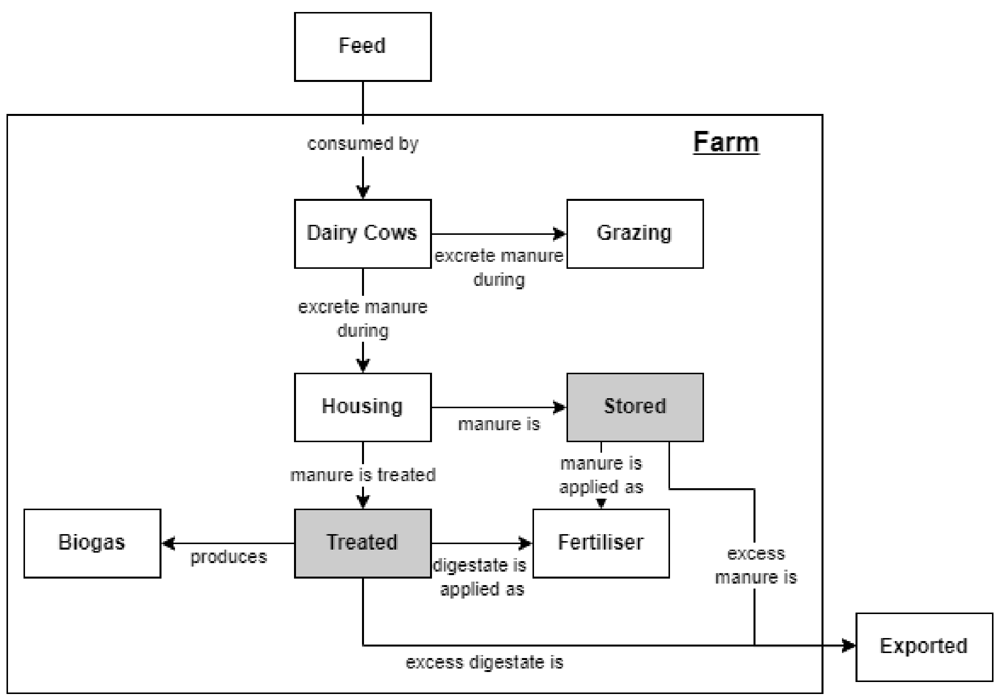


Figure 8: Overview of the different steps in the system, which shows a farm with the input: cow feed, and output: excess manure. The two different scenarios, manure treatment and storage, are depicted in grey.

3.3 Nitrogen Emissions Calculation Method

To determine the effect manure digesters have on GHG emissions, it is crucial to understand the GHG emissions released per step on a dairy farm. These steps are based on the model of a farm as presented in section 3.2. This section focuses on the nitrous oxide (N_2O) GHG emissions emitted during manure management with and without a manure digester. The term manure management is used to indicate the steps of the manure life-cycle between the excretion of manure by dairy cattle and its application to soil or its export out of the system. In these steps the different nitrogen emissions are linked together since they are all released from a common source: the excreted manure. When one pollutant is released, it contains a certain amount of N that is removed from the common source and thus cannot be emitted through other pollutants. To accurately account for all these emissions a nitrogen balance, or nutrient budget, was created to address the different stages manure moves through. First, the non GHG nitrogen pollutants will be introduced after which the nitrogen balance will be presented. After this the individual steps during the manure management are discussed while the specific calculations are shown in A. The next section describes the other nitrogen (N) emissions on a dairy farm after which two section focus on methane and carbon dioxide emissions respectively.

3.3.1 The Nitrogen Balance

The nitrogen related emissions on a farm are quite complex and cannot be computed by simply assessing the emissions in each step. This complexity stems from the different nitrogen related emissions and the relation between these emissions. Thus, for a farm it is not only important to take the greenhouse gas nitrous oxide (N_2O) into account but also the NO, NO_2 and NH_3 pollutants. To deal with all these different nitrogen related emissions nutrient budgets are used to account for all the nitrogen in the system. Nutrient budgets are used at both a farm and country scale to manage nutrients and as a policy instrument (Oenema et al., 2003). In this case, the nutrient balance is set up on a farm level and each step in the manure life cycle is addressed separately. This level of detail is crucial to model the changes between the two different situations, with and without a manure digester. However, the farm itself is not a closed system and has in- and outflows of nitrogen. These also have to be taken into account to accurately determine the effect manure digesters have on the GHG emissions of a dairy farm.

The majority of the research regarding nitrogen related emissions has been done in the manure management aspects of the manure's life cycle. These aspects run from the production of manure by cattle until it is used as fertiliser, either as manure or digestate, or sold to an external party. The basis of the current methodology is the work by Dämmgen and Hutchings (2008), which has been incorporated into the EMEP/EEA air pollutant emissions inventory guidebook by Amon et al. (2019). However, this methodology needs to be further expanded since it fails to accurately assess N_2O emissions since its focus is on other air pollutants, specifically: NO, NO_2, NH_3 and NH_4^+. This approach is preferred over, the approach of Dong et al. (2006), due to the detailed approach, the separation of the emissions in different steps and the possibility of integration of manure digesters into this work. Furthermore, the work by Amon et al. (2019) is supplemented in this research by the work of Lagerwerf et al. (2019), which uses a similar but less coherent methodology with a focus specifically on a Dutch context. The work in this research has a different aim than the works discussed above, which are focused on aggregating all emissions from a region or country. However, the basis of the work from Dämmgen and Hutchings (2008) is a manure management system of a farm with all the different nitrogen related emissions. Instead of aggregating the results from different systems parameters such as different types of housing, grazing periods, etc. these can be selected for each specific farm to create a more accurate emission estimation per farm. Certain farm level specifics have been obtained from the work of van Dijk et al. (2020), which follows a farm level approach, specifically for Dutch Dairy farms, but their methodology is based on specific farm data that is not freely available thus it is not possible to adopt the methodology in this research.

3.3.2 Non GHG Nitrogen Pollutants

The different nitrogen related pollutants such as NO, NO_2, NH_3 and NH_4^+ influence the release of each other to the atmosphere. They also influence the release of the GHG N_2O and vice versa since they all use a common source for their nitrogen components. In this section the different nitrogen (N) compounds emitted on a dairy farm are discussed, which are followed in the next section by the intricacies of the nitrogen budget based on the 3.2.

Ammonia

The release of ammonia (NH_3) to environment occurs through volatilisation when a solution containing NH_3 is exposed to the atmosphere. Such a solution is the excreted manure by dairy cattle. The extent to which this emission occurs depend on the chemical composition of the solution, its temperature, the size of the exposed surface area and the resistance to NH_3 transport in the atmosphere. The ammonia emissions lead to the acidification and eutrophication of ecosystems and are involved in the formation of particulate matter. The excreta and manure from livestock in Europe account for more than 80% of NH_3 emissions from European agriculture (Amon et al., 2019).

The volatilisation of NH_3 occurs from the equilibrium, based on Henry's law, between gaseous phase (g) NH_3 and NH_3 in solution (aq) (equation 1). The NH_3 levels in the solution are maintained through the NH_3 NH_4^+ equilibrium (equation 2). The second reaction equation is influenced by the pH of the solution: a high pH favours the right-hand side and thus causes a larger concentration of NH_3 ions in the solutions. This, in turn, will push the first reaction to the right hand side and release more ammonia to the environment (Amon et al., 2019). Thus, storing the solutions at low pHs values will decrease the potential for NH_3 volatilisation.

$$NH_3(aq) \leftrightarrow NH_3(g) \tag{1}$$

$$NH_4^+(aq) \leftrightarrow NH_3(aq) + H^+(aq) \tag{2}$$

Off the total amount of nitrogen (N) excreted by mammalian livestock, more than half is excreted in urine. Between 65% and 85% of the urine excreted N is in the form of urea. Enzymes such as urease, cause a rapid hydrolysis of urea which changes into ammonium-N ($NH_4^+ - N$) and compounds that are readily broken down to ammonium-N. This group of compounds is referred to as TAN (Total Ammoniacal Nitrogen) and is responsible for the majority of the NH_3 emissions from manure. The majority of N in mammalian livestock faces (N_{org}) in figure 9) is not readily degradable as the urine-N, thus calculating NH_3 from TAN instead of total N is a much more accurate method (Amon et al., 2019; Lagerwerf et al., 2019). It is not yet possible to distinguish between NH_3 and NH_4^+ in manure, thus TAN is commonly used to refer to the sum of NH_3 and NH_4^+ in manure.

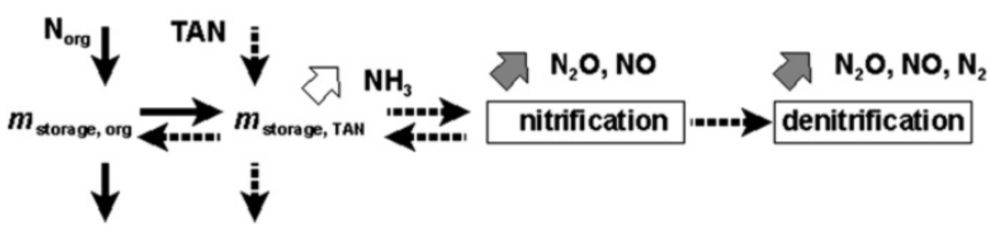


Figure 9: Processes that lead to the release of nitrogen emissions from manure. Copied from Dämmgen and Hutchings, 2008.

Nitric Oxide & Nitrous Dioxide

The emissions of nitric oxide (NO) and nitrogen dioxide (NO_2) play a role in manure management since the release of nitrogen through any source will change the N-content of the excreted manure (figure 9). The EEA methodology converts the NO emission to NO_2 and together these two are reported as nitrogen oxides (NO_X). Even though the total amount of NO_X emissions from the livestock sector only accounts for approximately 0.1% of the total NO_X emissions they need to be taken into account to create a complete nitrogen balance.

Initially, NO is formed by nitrification in the surface layers of stored manure or when manure is aerated to reduce odour or promote composting. In later stages NO is also emitted by denitrification in the surface layers of stored manure or in manure aerated to reduce odour or to promote compositing. There is not much data available regarding NO emissions form manure management, but the release of NO from soils is considered to be nitrification and this is likely to occur after the application of manure either by grazing animals or fertilisation.

Nitrogen Gas

The release of di-nitrogen (N_2) to the atmosphere is of no environmental concern, since it is not a pollutant but it is important to take into account since it is part of the nitrogen balance that is set up over manure. Thus, the release of N_2 will reduce the direct release of air pollutants but also the indirect release of nitrogen into the soil (Dämmgen and Hutchings, 2008). As shown in figure 9, the same processes of nitrification and denitrification that lead to the creation of NO_X compounds also produce N_2 (Amon et al., 2019).

3.3.3 Manure Management Nitrogen Balance

To ensure a complete nitrogen mass balance over manure during the manure management cycle the emissions per step are determine based upon the total N-content and the total ammoniacal nitrogen (TAN) of manure. These steps and their emissions are presented in figure 10. In this figure a division is made based upon the location of the manure excretion. The grazing process, on the left hand side, is a one step process in which the excreted manure emits directly from the soil of grasslands. The housing excretion, on the right hand side, is a much more complex process due to the number of different steps and the interlinks between TAN and the total nitrogen present (N_{org}). These interlinks exists due to the immobilisation and mineralisation that takes place (Dämmgen and Hutchings, 2008). The process will be discussed below and the emission calculations are shown in appendix A. The acronyms and all their units are shown in appendix 7.

3.3.4 Manure excretion

Dairy cows excrete a certain amount of manure per year, with a farm specific N and TAN content. The first steps in the manure management cycle are focused on calculating the amount of manure and nitrogen excretion and where it takes place. The two locations taken into account are grassland and housing as can been seen in figure 10. The split between these two locations is determined by the grazing regime of the respective farm. This regime consists of the number of days in the grazing period and the amount of hours spend grazing per day during this period. From this information the total organic N and TAN are calculated in both locations.

For housing the distinction is made between solid and slurry manure, because of the different properties and emissions levels. The slurry fraction consists of excreta, spilt livestock feed and drinking water, some bedding material and water added during cleaning or to assist handling. The solid fraction consists of excreta, spilt livestock feed and drinking water and bedding material (Amon et al., 2019). The average percentage of slurry on Dutch dairy farms in 2018 is 98% (van Bruggen et al., 2020). Since, the excretion of manure during grazing cannot physically be separated in slurry and solid fractions it's emissions are calculated from one value.

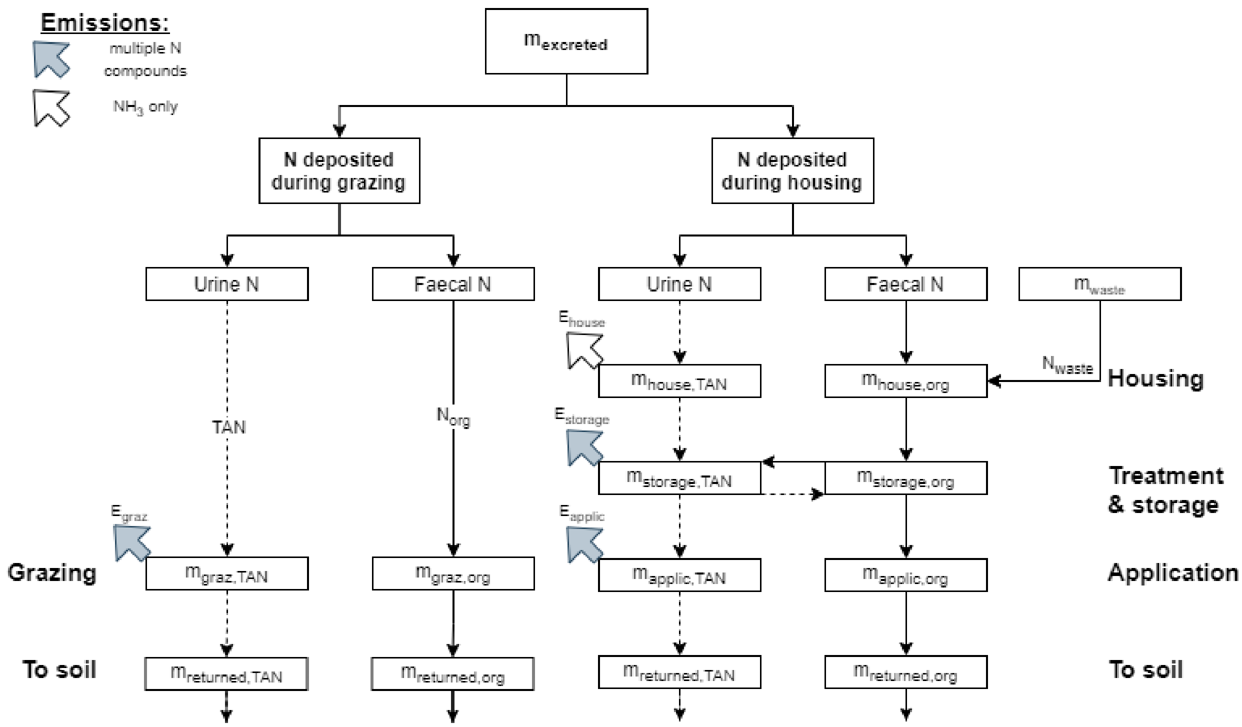


Figure 10: N flows in the manure management system. m *mass from which the emissions occur; broken arrows: TAN; solid arrows: organic N. Horizontal arrows indicate immobilisation with bedding in the house and mineralisation during storage. The broad arrows indicate emissions of all N compounds, including* N_2*, (coloured) or only* NH_3 *(white). Adapted from Dämmgen and Hutchings, 2008.*

The final step in calculating the manure output during housing the mineralisation and immobilisation of TAN needs to be taken into account. There are a number of ways to account for this, based on different methodologies. During this work the Dutch specific values from NEMA are adopted, which accounts for a mineralisation of 10% in slurry and immobilisation of 25% (Lagerwerf et al., 2019). After the accounting for these changes in the manure fraction it is possible to calculate the NH_3 emissions that are emitted during housing.

3.3.5 Grazing

The emissions from grazing are calculated from section A.3 onward. This is single step process in which specific grazing EFs are used, for NH_3, NO_X and N_2O emissions. This is based on the grazing regime, as discussed in section 3.3.4.

3.3.6 Housing Emissions

All emissions on a dairy farm are calculated with emissions factors (EF). These EFs are often determined as averages from many different studies conducted all over the world. The research done by Amon et al. (2019) and Dong et al. (2006) provide these average emission factors. However, the emission results, expressed per pollutant in kilograms for a activity on a farm, can be made more specific with the adaption of country specific EFs. Unfortunately, country specific emissions factors are not readily available for all activities on a dairy farm. An overview of all emissions factors used for N emission calculations and their sources are presented in appendix C.

The housing EF is a special case in the Netherlands, since it is decreed by law what the EF per type of barn is. The RAV (Regulation on Ammonia & Livestock farming) contains all these EFs and they are expressed in in kg NH_3 per housing type per animal place per year (Wet Ammoniak en veehouderij, 2002). However, this data is not implemented directly since research by van Dijk et al. (2020) has shown that not all values are completely accurate. This adaption of the RAV is taken as a basis for the emissions calculations during housing, the data is shown in appendix B together together with the alterations made by van Dijk et al. (2020) and this research. Furthermore, the EF for housing does not differentiate between slurry and solid fractions, thus the same value is applied to both manure fractions. To determine the actual NH_3 emissions during housing the EF values are multiplied with the mass of the TAN of both fractions to determine the emissions per manure (see section A.6).

3.3.7 Treatment & Storage

The manure excreted during housing is either treated with a manure digester or directly stored as manure. During both the treatment and storage steps nitrogen related emissions are released through the environment. The difference between these two scenario's forms the backbone of this research, to determine what the contribution of manure digesters could be to climate mitigation through emission reduction. This section will discuss the emission calculations for both steps and is succeeded by the application in the nitrogen balance in figure 10.

In a nitrogen balance, the emissions from the previous step have to be subtracted from the total amount of N and TAN present in manure. This is done because this amount of N is no longer part of the system but emitted to the atmosphere. Otherwise, all the emission in this and subsequent steps of the nitrogen balance would be overestimated since the total amount would remain constant. This goes for both the manure storage and manure treatment scenario's.

Manure Storage
Where the nitrogen emissions from housing only consist of NH_3, the emissions during storage consist of multiple N related emissions as noted in figure 10. These emissions all release concurrently and their emissions are determined with individual EFs that are presented in appendix C. Another difference compared to the housing emissions is that here there is a difference in emission levels between the slurry and solid manure fractions. Thus, these are calculated separately during this step according to what is shown in appendix A.7.

Manure Treatment
During the treatment of manure, it is converted into two products, biogas and digestate. For the nitrogen balance the only relevant product is digestate since this is the only product that emits N emissions in the form of NH_3. In addition to the emissions after treatment some NH_3 is also released by manure pre-treatment, this is also taken into account. However, it is assumed that no N emissions are released during treatment itself (Garcia et al., 2019). Furthermore, mineralisation occurs during treatment leading to a change in the TAN fraction which will impact future emission from digestate when it is used as fertiliser. In this model, it is assumed that with the implementation of a manure digester all manure is fed into the digester and converted into biogas and digestate.

3.3.8 Manure Application

When fertilisation of grassland or cropland is needed, manure or digestate can be applied to soils. This is the main focus of the application step in figure 10. However, due to the intensive agriculture in the Netherlands it often happens that the a dairy farm produces more manure that it is allowed to apply on this on land. Thus, part of the application process contains the removal of excess manure from the system. This also holds true for digestate, which is seen as animal manure by the Dutch Government and is subject to the same rules and regulations (RVO, 2021b). The assumption is made that the solid manure fraction is used first for fertilisation. This is done since this fraction is relatively small, since almost all dairy cattle manure is stored as slurry. Exporting it in small quantities is not a preferential method from an economic standpoint.

For this step the nitrogen emissions are also determined through the use of Emission Factors (EFs). The EF of non NH_3 emissions are derived from global averages used by Amon et al. (2019) and Lagerwerf et al. (2019). However, when looking at NH_3 emissions from slurry application, research summarised by Amon et al. (2019) shows large variance between different application techniques. This is even further specified based upon the emission differences from soil use, grassland or cropland. Theses EFs, expressed in fraction of TAN present in manure, vary from 0.02 to 0.74, where as the global average value are set at 0.55. The specific EFs for each application technique and soil type are displayed in appendix C. The calculation for the average EF for NH_3 emissions during fertilisation are discussed in appendix C. With this information the emissions from this step can be calculated after which, the amount of nitrogen returned to the soil can be calculated. This will be the fraction of the N excreted by dairy cattle during housing that is finally used as fertiliser for farmlands.

Exported Manure

Manure slurry or digestate that is exported is removed from the system boundaries and its emissions are not taken account in this model. However, both the transport of manure as well as it application as fertiliser at other farms will cause emissions. After this, the final step in the manure management cycle is to determine the total emissions per N compound by tabulating all the emissions per step and converting them to the correct units.

3.4 Methane Emissions Calculation Method

On a dairy farm there are a number of different sources that produce methane (CH_4). The largest source on dairy farms are the cows themselves due to the way they digest their feed. This process, called enteric fermentation, in which the feed is decomposed and fermented, CH_4 is produced as a by-product and emitted to the atmosphere (Etcheverry, 2014). In this section the CH_4 emissions from enteric fermentation and during manure management are discussed, the specific calculations can be found in appendix D. Manure management is divided into two categories regarding CH_4 emissions, manure storage for the scenario without a digester and manure treatment for the scenario with a digester.

3.4.1 Enteric Fermentation

Enteric fermentation emissions in the Netherlands are calculated as a IPCC tier 3 method (van Dijk et al., 2020). IPPC Tier 3 methods are the most detailed way of assessing GHG emissions and in the case of enteric fermentation in dairy cows, this not only take into account the amount of food but also the feed composition that is digested. However, this method requires large amounts of data that are variable per farm and not present in the KringloopWijzer. Furthermore, the enteric fermentation of dairy cattle of a specific farm does not change between the two scenarios, with and without a digester, thus a IPCC tier 2 method is used in this research to estimate the methane emissions from enteric fermentation on a dairy farm (Dong et al., 2006).

The calculation of CH_4 emissions from enteric fermentation is comparable to a single nitrogen emission from section 3.3. It is done based upon the amount of cattle, expressed in GVE and the EF specific for methane emissions from enteric fermentation. This EF is farm specific and depended on the dry matter (DM) intake per animal (Lagerwerf et al., 2019). This dry matter intake can be found in the KringloopWijzer. The calculations regarding the methane from enteric fermentation can be found in appendix D.1.

3.4.2 Manure Storage

After excretion during housing, manure is often stored for long times in the Netherlands due to regulations that prevent fertilisation between September and February (RVO, 2021d). The methane emissions from manure are caused by fermentation of organic matter in an anaerobic environment (Lagerwerf et al., 2019). It is possible to avoid these anaerobic conditions and thus reducing the CH_4 emissions by either aerating or mixing the manure, but this increases NH_3 and N_2O emissions (van Dijk et al., 2020). The fermentation process does not start instantly after excretion, it take approximately a 30 days for the methanogenic bacteria to develop and produce methane. Thus the CH_4 emissions will remain low if manure is only stored for short period of time. However, time is not the only parameter influencing the CH_4 emissions, it is also depended on environmental factors (e.g. temperature) and the type of manure (e.g. slurry) (Webb et al., 2012).

The types of manure considered here are slurry, solid and grazing manure. Compared to the slurry and solid fractions, the grazing manure's CH_4 emissions are relative low due to aerobic conditions. The slurry fraction of manure is often stored in pits underneath the slatted floors of the cattle housing. Solid manure, on the other hand, is either stored in animal housing or stacked outdoors. Outside storage is often roofed to avoid contact with rainwater. Anaerobic conditions occur in both slurry and solid manure storage (Lagerwerf et al., 2019). In the Netherlands solid manure only constitutes a small part of the total amount of manure, the large majority of the manure excreted during housing is stored as a slurry.

The storing of manure in a slurry pit is a type of accumulation system. This means that is has a constant inflow of manure, through cattle excretion, but only a few moment in which manure is extracted, for fertilisation or to be sold. In these types of systems the CH_4 emissions increase due to the increasing temperature, the increase in retention time and inoculation (Zeeman, 1994). Here inoculation of the fresh manure occurs, in which the bacteria already present in the manure that has previously accumulated in the slurry pit catalyses the fermentation process in the fresh manure. Finally, the emission of CH_4 is also depended on the chemical composition, specifically the organic matter content, of manure (Lagerwerf et al., 2019). The emissions from manure storage are also calculated with an IPCC tier 2 approach with EFs (Dong et al., 2006). The calculations are presented in appendix D.2 and general IPPC values are updated to country specific values wherever possible, since these provide a more accurate assessment for Dutch dairy farms.

3.4.3 Manure Digestion

The methane emissions from storage before manure digestion are calculated in the same way as the emissions from manure storage. The differences between the two calculations are the specific values used, these are discussed in appendix D.3. The difference in these values stem from the short storage time before digestion, so that the conditions that cause large amount of CH_4 emission cannot occur (van Dijk et al., 2020). During the digestion process, CH_4 leakages occurs which in total release approximately 4% of the total produced CH_4 (Hjort-Gregersen, 2014). During the storage of digestate CH_4 leakages also occur, which constitute the loss of another 3% of the total CH_4 production (K. Groenestein et al., 2020).

3.5 Carbon Dioxide Emissions Calculation Method

Where the nitrogen (N) and methane (CH_4) emissions are determined for specific step on the dairy farm, the energy needs and accompanying CO_2 emissions are estimated over the whole farm. This is done in the

KringloopWijzer by estimating the electricity, natural gas and other energy sources. These energy sources and their respective units are displayed in table 7. The total energy use per source is based on a large number of criteria, which include number of harvest, actions per harvest, etc., an overview of all criteria and the calculation methods can be found in the work from van Dijk et al. (2020). The CO_2 emissions stemming from these sources are not not directly linked to manure. However, the electricity, heat and fuel are needed to run a dairy farm and thus impact the overall emissions of the system. This section first uses the energy consumption and generation information from the KringloopWijzer to determine the CO_2 emissions on the dairy farm without a digester. Then the energy consumption and generation of the manure digester itself are calculated. This allows for a final determination of the net CO_2 reduction when implementing a manure digester on dairy farm through sustainable power generation.

Table 7: The different energy sources and their respective units as used in the KringloopWijzer (van Dijk et al., 2020).

Energy Sources	Unit
Electricity	kWh
Natural Gas	m^3
Propane	L
Fuel Oil	L
Diesel	L

3.5.1 Farm Energy Consumption

The energy consumption on a farm is depended on many factors, which means it is not scalable to a metric such as the number of cows or amount of manure produced on a farm. Furthermore, the energy sources used can differ between farms, thus making comparisons between farms based on their energy consumption difficult. However, the CO_2 of each of these fuel sources can be calculated by using EFs for each source. To do this the amount of fuel first has to be expressed into an amount of energy in Giga Joule (GJ). Only the electricity consumption is determined different, since it uses a EF, expressed in g CO_2 per kWh, which is representative for the composition of the Dutch energy sector (Ortiz et al., 2020). The calculations and values used are shown in appendix E.

3.5.2 Farm Energy Generation

Farms can also generate energy from other green sources, besides manure digesters, which will reduce the total farm emissions and provide sustainable energy. The KringloopWijzer takes into account four different types of green energy generation: solar, wind, biomass and other. Due to the way the KringloopWijzer presents its data all these categories have to be taken into account together. Thus the assumption is made that for the model any energy generation gained from biomass does not include the manure digester. Furthermore, the other category EF is determined as the weighted average based upon the use of the other three categories on the farm. With these assumption, any cases with these specific set of criteria can also be used in the model.

3.5.3 Digester Energy Consumption

A manure digester requires energy to heat, stir and pump and manure. These and other processes required for the operation of a manure digester combined consume 12.00 kWh per ton manure (van Dijk et al., 2020). The heat generation could be done with different fuel sources, for this work it is assumed that the energy requirement is fulfilled by extracting electricity from the Dutch national grid, which allows for the application of this specific EF to calculate the environmental impact of using a manure digester.

3.5.4 Digester Energy Generation

The energy generation of a digester is depended on the amount of CH_4 that is produced during digestion. This gas, combined with the other products in biogas, is fed into a combustion engine which in turn is used to generate electricity, expressed in kWh. To determine the CH_4 production the farm specific Organic Matter (OM) is used, as calculated during the manure storage step of the CH_4 emissions method (see section D.2). On average, 0.18 m^3 is present per kg OM (Miranda et al., 2015).

The next step is to convert the amount of CH_4 into electricity. This is done by feeding the biogas, which includes CO_2 as its other major component, into a combustion engine. The resulting electricity is based upon two factors, the energy content of the gas and the efficiency of the engine. The engine efficiency is estimated at 33% and the energy content of methane (HHV) is 39.8 MJ per m^3 (K. Groenestein et al., 2020; Engineering ToolBox, 2003). Finally, the amount of generate energy in MJ can be converted into kWh from which, with the EF for Dutch electricity, the CO_2 emission reduction from manure digesters can be calculated. With this the emissions for all three GHG gasses, N_2O, CH_4 and CO_2 are calculated for the two scenarios as well as the reduction of the linked nitrogen gasses such as NH_3, NO and NO_2.

3.6 Input Variables

With the development of each of the three GHG emission methodologies, a certain amount of input variables were used to model the emission on a farm scale. Some of these inputs are used in multiple GHG emission calculations and some intermediate results from one GHG are used in determining another GHG emissions. This section will discussed these input variables, most of which can be found in the KringloopWijzer. The two input variables not in the KringloopWijzer are: the province the farm is located and the farms derogation permit. The input variables will be discussed in the same order as the methodologies before: namely N, CH_4 and then CO_2. Any interdependencies will be discussed simultaneously.

3.6.1 Nitrogen Input Variables

The nitrogen input variables used are shows in table 8 and the source of most of these is a specific page in a farm's KringloopWijzer. The first three input determine the N inflow in the nitrogen budget. Two interesting inputs that could be varied within a farm are the length of the grazing period d_{graz} and hours spend grazing per day during this period h_{graz}. By altering these two input variables the location of manure excretion can be steered which will impact the GHG emissions. Whereas altering other variables, such as the of hectares or cows, will only scale the amount of emissions on a farm but not the composition and origin of them. The only two inputs which are not located in the KringloopWijzer are needed for the N methodology, to determine the amount of nitrogen that is allowed to be used during fertilisation. Since their is a large variation between the emissions levels of different slurry application methods and this relatively a high emission step in this process, this data is collected on a farm scale (see table 9). The nitrogen methodology does not contain any dependencies on the other parts of the model.

Table 8: Nitrogen input variables used in the model to calculate the GHG emissions savings on a dairy farm when implementing a digester.

Input Variable	Unit	Description	Source
N_{ex}	kg N	Amount of nitrogen excreted per year on a dairy farm	klw p.15
N_{waste}	kg N	Amount of nitrogen present in waste streams that are added to manure storage	klw p.15
TAN_{ex}	kg N	Amount of excreted nitrogen that is present as TAN	klw p.7
N_{cattle}	-	Number of dairy cows on the farm	klw p.3
$N_{young\,stock \geq 1year}$	-	Number of young stock older than 1 year	klw p.3
$N_{young\,stock \leq 1year}$	-	Number of young stock younger than 1 year	klw p.3
d_{graz}	days	Length of the grazing period	klw p.3
h_{graz}	hours	Hours spend grazing per day	klw p.3
Current Housing system	-	Select the current housing type for dairy cows	klw p.14
New Housing system	-	Select possible new housing type for dairy cows (if no changes, select the same as above)	klw p.14
$x_{slurry\,cattle}$	%	Percentage of slurry manure from dairy cows	klw p.14
$x_{slurry\,young\,stock \geq 1year}$	%	Percentage of slurry manure from young stock older than 1 year	klw p.14
$x_{slurry\,young\,stock \leq 1year}$	%	Percentage of slurry manure from young stock younger than 1 year	klw p.14
ha_{grass}	ha	Hectares of production grassland on a dairy farm	klw p. 3
ha_{maize}	ha	Hectares of cropland used for the production of maize on a dairy farm	klw p. 3
$ha - crop$	ha	Hectares of cropland used for the production of other crops on a dairy farm	klw p. 3
Derogation	yes or no	If derogation permit used type in yes, otherwise no	-
Province	-	Select Province from the list	-
grass peat soil type	%	Percentage grass peat soil type	klw p. 3
grass clay soil type	%	Percentage grass clay soil type	klw p. 3
crop peat soil type	%	Percentage crop peat soil type	klw p. 3
crop clay soil type	%	Percentage crop clay soil type	klw p. 3

Table 9: Slurry application method input variables used to calculate the GHG emissions.

Method of Application Slurry	Grassland (%)	Cropland (%)	Method of Application Slurry	Source
Shallow-injection	-	-	Incorporation (direct)	klw p. 7
Narrow-band (trailing-shoe)	-	-	Narrow-band (trailing-shoe)	klw p. 7
Slit-Coulter	-	-	Full coverage	klw p. 7
Surface Spreading	-	-	Surface Spreading	klw p. 7

3.6.2 Methane Input Variables

The extra input variables that are required for the methane (CH_4) methodology are shown in table 10. These are combined with some of the inputs from table 8, such as the number of cattle and the grazing regime to calculate the CH_4 emissions. Appendix D showcases all the variables used during each of the CH_4 emission calculations. The feed data, expressed in kg dry matter, is used to calculate the enteric fermentation that occurs within dairy cows.

Table 10: CH_4 input variables used in the model to calculate the GHG emissions savings on a dairy farm when implementing a digester.

Input Variable	Unit	Description	Source
Net excretion	ton	Amount of manure excreted per year on a dairy farm	klw p. 15
Feed	kg DM	Total kg DM consumed on the farm by dairy cows (GVE) per year	klw p. 12

3.6.3 Carbon Dioxide Input Variables

Whereas the models for N and CH_4 are focuses on specific steps within the system defined as a dairy farm, the CO_2 method focuses on the farms energy generation and consumption as a whole before determining the impact of the manure digester. The inputs used for the calculations are presented in table 11. However, there are no direct inputs from the KringloopWijzer for the manure digester since this is not yet present in the current situation and is thus not incorporated in the KringloopWijzer. To achieve this, some of the input from the previous methods are used here as well, such as the amount of manure excreted, time spend grazing and the amount of organic matter present.

Table 11: CH_4 input variables used in the model to calculate the GHG emissions on a dairy farm from energy consumption and generation.

Input Variable	Unit	Description	Source
Yearly energy production	kWh	Yearly energy production on a dairy farm	klw p. 11
Returned to the grid	kWh	Yearly amount of energy returned to the Dutch national energy grid	klw p. 11
Solar	%	Percentage of energy generation taking place through solar power generation	klw p. 11
Wind	%	Percentage of energy generation taking place through wind power generation	klw p. 11
Biomass	%	Percentage of energy generation taking place through biomass power generation	klw p. 11
Other	%	Percentage of energy generation taking place through other types of power generation	klw p. 11
Electricity	kWh	Yearly electricity consumption on a dairy farm	klw p. 11
Natural gas	m^3	Yearly natural gas consumption on a dairy farm	klw p. 11
Propane	L	Yearly propane consumption on a dairy farm	klw p. 11
Fuel oil	L	Yearly fuel oil consumption on a dairy farm	klw p. 11
Diesel own	L	Yearly diesel consumption on a dairy farm from own use	klw p. 11
Diesel contractors	L	Yearly diesel consumption on a dairy farm from contractors	klw p. 11

3.6.4 System Variables

Besides the input variables, the methods also use so called system variables which is data that is not farm depended but required for the conducted calculations. Some of these variables, such as the EFs are presented in the method appendices where they are used. An overview of the other variables, such as material properties, conversion factors and constants, are given in appendix F. These system variables can be assumed to be constant for all Dutch dairy farms and do not have to be altered when using the model as a decision support tool. The the following section will discuss the alternations made to the model to calculate the impact manure digester have on the Dutch dairy sector.

3.7 Calculation Method for the Dutch Dairy Sector

The method developed in the previous section for each of the GHG emissions can also be used in determining the impact of manure digesters on the Dutch dairy sector as a whole. This is achieved by calculating the dairy sector emissions per province in the farm-scale model. The adopted approach is to see each Dutch province as a single farm and then calculate the differences between the two scenarios with and without a digester. By applying the farm-scale model on a provincial scale, easy aggregation of these results will provide answers to which extend manure digester on dairy farms in the Netherlands can help reduce emissions. It is a preferred method over collecting and running the data from each of the approximately 16,000 dairy farms in the Netherlands. Furthermore, the province division is used often in the diary sector, for example in work from CBS (2020a), ZuivelNL (2020) and regulations from RVO (2021a). Selecting a province scale, still allows for some granularity in the input data to acquire more accurate results compared to an aggregation of data on a national scale.

3.7.1 Farm Size

The major consideration when aggregating farms in this manner at a provincial scale, is that each farm is assumed to contain its own manure digester. Thus, these results will present the maximal theoretical achievable emissions reduction and energy generation per province. However, since there are practical and financial considerations that will hinder small farms to implement manure digesters it will be unlikely that this full potential will be achieved. It will be more likely that larger farms, with more than 200 cows, will adopt manure digesters first. Followed by medium sized farm's, between 200 and 100 cows, when digester are subsidised to a larger degree or become more financially attractive through other means. The smallest farms will either disappear if the current trends, as seen in table 1, continue or likely not install a digester soon due to financial considerations.

3.7.2 Input Variable Changes

The calculations on a provincial scale will require certain changes to the input variables of the model since not all data is available on a provincial scale. Furthermore, certain farm specific values have to be averaged over the Dutch dairy sector. The most notable change for the nitrogen is that derogation is not taken into account and set on the minimal 170 kg N/ha for each province. National averages and the input data per province is given in appendix H.

Table 12: Changes to the nitrogen input variables from table 8 when adjusting for the provincial scale

Input Variables	Unit	Provincial Scale Change	Source
N_{ex}	kg N	North-West/South-East division (see section 2.2.2)	CBS, 2020a
N_{waste}	kg N	No data, leave empty	-
TAN_{ex}	kg N	National average of 55% of N_{ex}	van Bruggen et al., 2020
N_{cattle}	-	Provincial Value	ZuivelNL, 2020
$N_{young\,stock \geq 1year}$	-	Provincial Value	CBS, 2021a
$N_{young\,stock \leq 1year}$	-	Provincial Value	CBS, 2021a
d_{graz}	days	Provincial Average	CBS, 2021b
h_{graz}	hours	Provincial Average	CBS, 2021b
Current Housing system	-	Assume standard housing type (A 1.100)	van Bruggen et al., 2020
New Housing system	-	Assume standard housing type (A 1.100)	van Bruggen et al., 2020
$x_{slurry\,cattle}$	%	National average of 98%	van Bruggen et al., 2020
$x_{slurry\,young\,stock \geq 1year}$	%	National average of 86% for female and 56% for male	van Bruggen et al., 2020
$x_{slurry\,young\,stock \leq 1year}$	%	National average of 86% for female and 56% for male	van Bruggen et al., 2020
ha_{grass}	ha	Provincial Value	ZuivelNL, 2020
ha_{maize}	ha	Provincial Value	ZuivelNL, 2020
ha_{crop}	ha	No data, leave empty	-
Derogation	yes or no	Assume no, thus all provinces at 170 kg N/ha	RVO, 2021a
Province	-	Select Province from the list	-
grass peat soil type	%	No data, leave empty	-
grass clay soil type	%	No data, leave empty	-
crop peat soil type	%	No data, leave empty	-
crop clay soil type	%	No data, leave empty	-

There are only two extra input variables for the CH_4 method, which are the net excretion and the feed consumption, which both can be calculated based on the amount of cows, young stock and data from CBS, 2020a. These inputs variables can also be found in appendix H. The CO_2 method is the most difficult to scale, since the energy generation and consumption are not scalable based on the amount of cows, manure or another metric used in scaling from a farm level to a provincial level. Thus, all the inputs from table 11 are left empty and only calculate the CO_2 difference between the situations with and without a manure digester whilst ignoring the other energy generation and consumption on a provincial level.

3.8 Model Overview

The previous sections discussed the many aspects linked to the different emissions and the calculations of these emissions have been further specified in appendices. Figure 11 shows a summary of the model and the emissions per step. For clarity, all nitrogen (N) pollutants, such as NH_3, N_2O and NO_2, have been summed and noted as N. In a number of steps N consist of multiple pollutants. Since, there are two possible scenarios, two paths can be followed, without a digester (stored) and with a digester (treated). Both the farm and the manure digester emit CO_2 through the use of electricity and other fuel types. However, it is also possible for both to generate sustainable energy, with which CO_2 emissions are offset. On all farms in this research, solar panels are present and a manure digester is introduced in the treatment scenario to generate biogas which in turn can be converted to electricity. Furthermore, the grazing step does not have to occur if the cattle is housed year round as is the case on farm C. The difference between the two scenarios in emissions determine the impact a manure digester has as an emissions reducer on dairy farms.

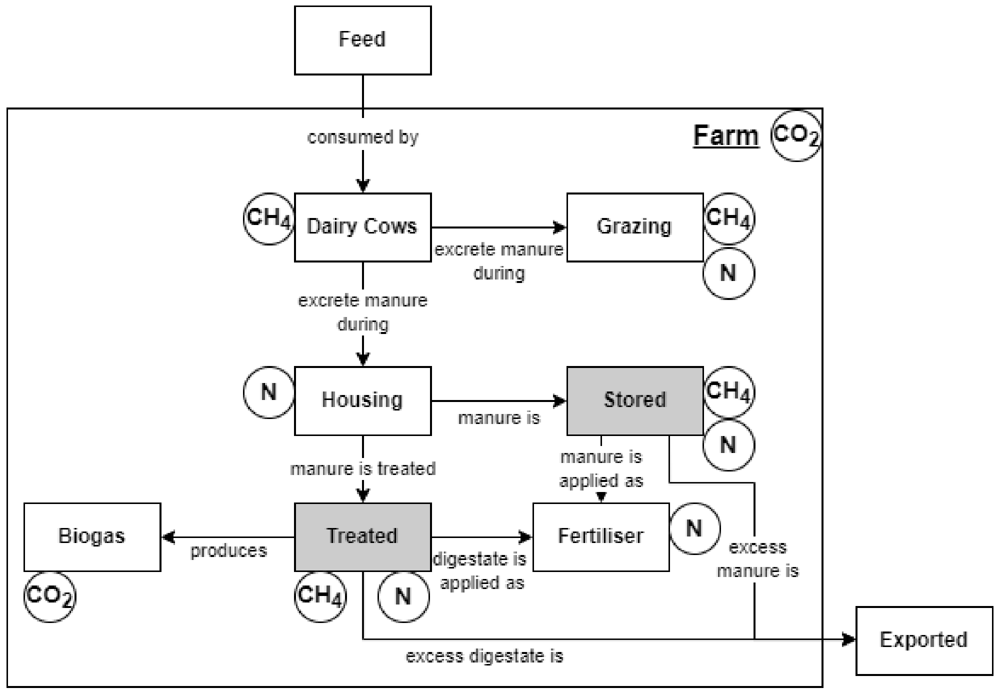


Figure 11: An overview of the different steps in the model and their emissions types.

4 Farm Results

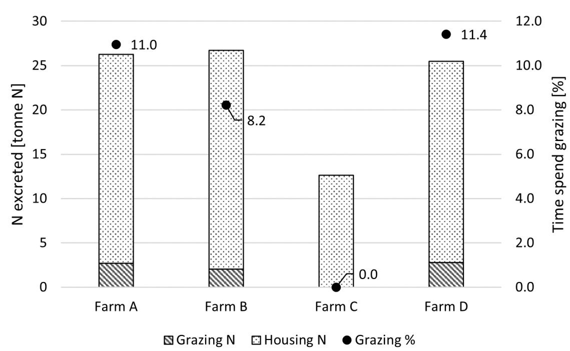
This section first discusses the different nitrogen (N) emissions steps after which the emissions reduction of the nitrogen balance over whole system is presented. Thirdly, the methane (CH_4) steps and accompanying emissions will be discussed. Followed, by the carbon dioxide (CO_2) steps and emissions which on a farm level include the energy consumption and production of the farm itself. All input variables of each farm analysed in this work are given in appendix G. Two of these variables, the housing type and the grazing regime are influence parameters early in the manure life cycle that have a big impact on the overall emissions of a farm. Thus, the farm scale results are followed by an analysis of the impact of these two variables on the emissions. Finally, a total summation of all the emission results is shown to determine the effective emissions savings on a dairy farm when implementing a digester.

4.1 Nitrogen Emissions

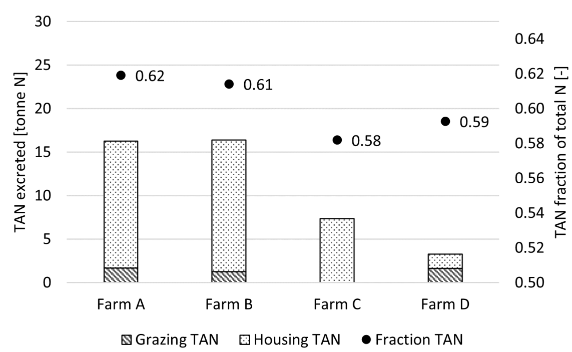
The nitrogen (N) emissions results are split in a number of sections, since a number of these steps include multiple pollutants and some vary between the two scenarios. More information supporting these results can be found in appendix I.

4.1.1 Manure Excretion

The first results show the division of manure between the housing and grazing locations. This split depends on the grazing regime of the dairy farm and the results will not differ between the two scenarios. The regional limited grazing regime, has an 12 % grazing percentage which is comparable to the results of farm A and D (CBS, 2020a). Farm C houses their cattle year round and thus has an grazing percentage of zero. The grazing regime of farm B is significantly lower than of A and D as can be seen in figure 12a in which the time spend grazing is set out for each farm.



(a) Location based total nitrogen excretion per dairy farm.



(b) Location based TAN excretion per dairy farm.

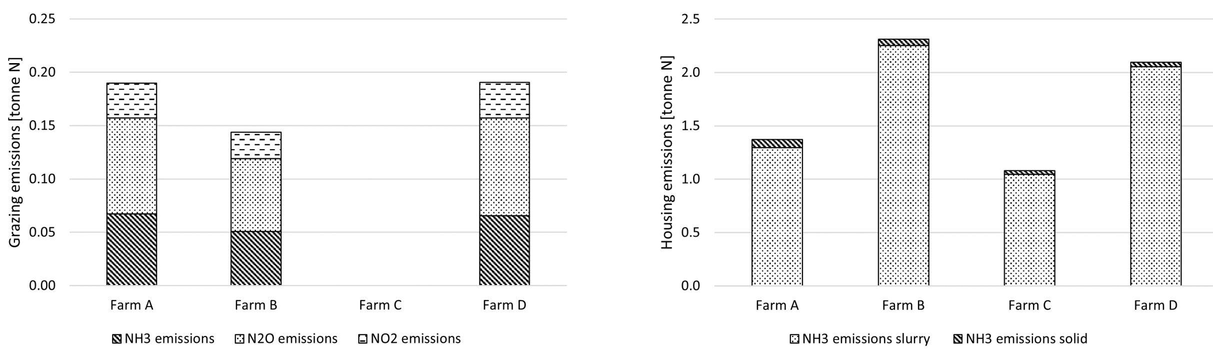
Figure 12: The location based total nitrogen and TAN excretion on the four dairy farms. The location, grazing or housing is based on the time spend grazing. The amount of TAN present as a fraction of the total-N is farm specific and influences the nitrogen emissions.

Farm C is a smaller farm, both in term of GVE and hectares of lands, than the other three farms which can clearly be seen in the lower total-N and TAN excretion in figure 12. Compared to the other farms, farm A has the highest TAN fraction but all farms score higher than the national average of 0.55 (van Bruggen et al., 2020). This result indicates that the N emissions of these farms will be higher than the national average since a higher fraction of the total amount of nitrogen (N) is easily emitted as one of the nitrogen pollutants. Thus, the individual characteristics of a farm play an important role in the N emissions levels stemming from a dairy farm. Not only the higher TAN fraction will influence the emissions of these farms, but also the total-N excreted per GVE per year, which are 141.0, 129.7, 113.7 and 120.9 kg N per GVE per year for farm A through D respectively. These excretion data are considerable higher than the national average of 73.7 kg N per cow per year indicating that the emissions per GVE of these farm will also exceed national averages due to the large amount of N available for release into the atmosphere (van Bruggen et al., 2020).

4.1.2 Grazing & Housing Emissions

Based upon the location information, presented in figure 12, the grazing and housing emissions can be determined for each farm. The grazing and housing emissions were analysed in conjunction since changes in the grazing regime impact emissions on both locations. The sum of the emissions on both locations provides a complete picture of the emissions directly after manure excretion. Both the grazing and housing emissions stayed consistent over both scenarios with and without a digester.

Since dairy cows on farm C are housed all year, these grazing emissions will be zero. The grazing regime on farm B is significantly lower than Farm A an D, thus lower grazing emissions were expected. The results from farm A and D do not differ much from each other due to the specifics of each farm. Farm D has more GVE which leads to more total emissions and farm A has an higher TAN and total-N per GVE which will both increase the overall emissions of this farm.



(a) The NH_3, NO_2 and N_2O emissions released during grazing on the different farms.

(b) The NH_3 emissions from the housing step on the different farms.

Figure 13: The grazing and housing emissions of the different farms.

The major factor influencing the housing emissions, besides the grazing regime, is the housing type which determines the housing EF. This EF is 0.09 for farm A, which means that 9 % of the TAN present slurry and solid manure is emitted as NH_3. This is lower than the national averages for slurry and solid manure which are estimated at 14.2 % and 16.9% respectively (van Bruggen et al., 2020). This difference can be explained by the type of barns, since the barns used on farm A emit approximately 62 % of the standard barn type used on 78.9 % of all dairy farms in the Netherlands (Lagerwerf et al., 2019). The results of the other three farms, which all use the standard barn type, are in line with the national averages. The model allows for different barn types to be selected for both scenarios, this option was not used for any farms, the impact of this option on farm emissions can be found in section 4.4.

The housing emissions were determined for both the slurry and solid fraction of manure. This is an important division since the emissions factors in certain stage differ between these two fractions. The slurry

Table 13: The results of the four different farms linked to the housing emissions. $x_{hous\,slurry}$ is the fraction manure excreted during housing as slurry and $EF_{house\,NH_3}$ is the emissions factor based upon the type of barn.

Housing results per Farm	Farm A	Farm B	Farm C	Farm D
$x_{hous\,slurry}$ [-]	0.92	0.96	0.95	0.97
$EF_{house\,NH_3}$ [fraction TAN]	0.09	0.15	0.14	0.15

fraction on farm A is 0.92, which means that 92% of the manure excreted by cows is in the form of slurry. The Dutch national average is 98% (van Bruggen et al., 2020). This difference occurs since this work combines the information from young stock and dairy cows together into one category (GVE). The percentage of young stock manure excreted as slurry is lower, on average 86% in the Netherlands (van Bruggen et al., 2020). Thus the slurry fraction will vary based upon the amount of young stock present on a farm. Furthermore, it will always be lower compared to the national average as long as their were young stock present on a dairy farm, as can be seen in table 13. The different types of manure collection, for young stock and dairy cattle, are responsible for the differences in slurry fractions between the farms.

The best analysis of the farms emissions can be made when combining the grazing and housing emissions. The total of these emissions constitutes the direct N emissions from manure excretion. To more easily compare farm with different size, the total amount of N is divided through the GVE per farm. This give an emissions per GVE, which is presented as well in figure 14. This clearly shows the difference in emissions between the four different farms. However, it has to be noted that these farm posses individual characteristics which makes comparison difficult. Factors such as the productivity of dairy cows or the emissions per kg of milk product are not considered as metric in this work. Farm C, has the lowest emissions per GVE but also doesn't have any grazing. Thus, other factors must play a role since grazing emissions are less polluting than housing emissions (Adviescollege Stikstofproblematiek, 2019). What is interesting to observe are the relatively lower emissions from farm A compared to B and D, since it has higher TAN and total-N values per GVE than these two farms. This is is be partly due to the housing type of farm which reduces significant emissions compared to the standard housing type of the other two farms.

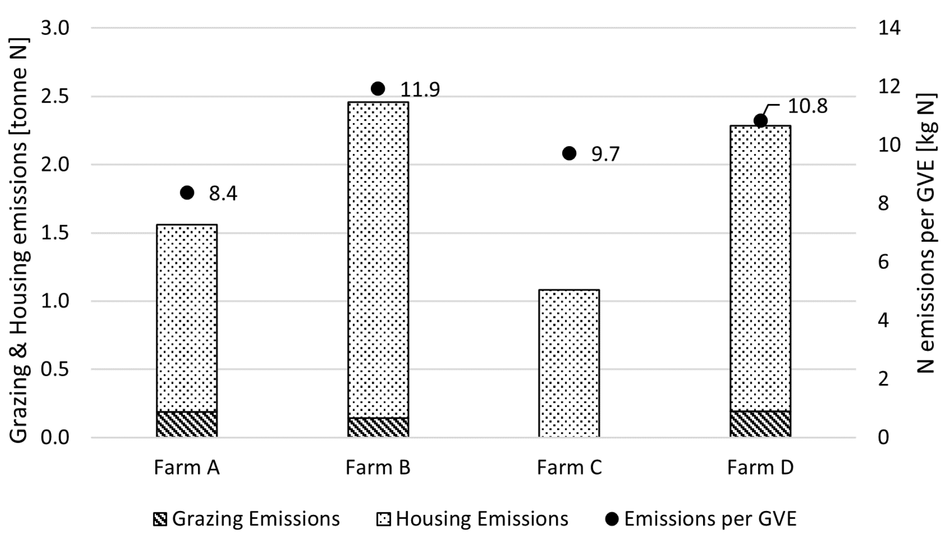


Figure 14: A combined overview of all the N emissions during housing and grazing on the different farms. The emissions per GVE indicate the emissions intensity on a farm per dairy cow during these steps.

4.1.3 Treatment & Storage

The treatment and storage step is the first step of the manure life-cycle in which differences appear between the two scenarios, without and with a manure digester. Without a digester, the long term storage caused a significant amount of emissions to be released from both the slurry and solid manure fractions. This is different from the treatment path where digestate released emissions after treatment from a manure digester. The different release in emissions between the two scenarios in this step has cascading effects on the emissions in the following steps. Of course, the previous steps also influence the emissions here, for example all the manure excreted during grazing cannot be used in the manure digester.

Traditionally, manure is stored for a long time, during which emissions are released. These emissions will reduce the total amount of N present in manure. In other words, the lower the nitrogen content of manure, the more nitrogen is emitted to the environment. A lower nitrogen amount in manure also means that it is less potent as a fertiliser. The difference between these two process will show the direct impact of the manure digester on nitrogen emissions levels on dairy farms. The model results are shown in table 14 and the N emissions per farm and per GVE are plotted in figure 15. It is clear to see that for each farm the storage step, in the scenario without a manure digester, release significant more emissions than the treatment step with a digester. Thus, the implementation of manure digesters on dairy farms has a reducing effect on nitrogen (N) emissions. When manure is stored the emissions are not limited by NH_3 as is assumed to be the case in when a manure digester is used (Garcia et al., 2019). However, the NH_3 emissions are by far still the largest pollution factor indicating the N emission reduction from manure digesters extends beyond just reducing GHG such as N_2O.

Table 14: The nitrogen (N) emissions for both the storage and treatment steps.

Nitrogen emissions	Farm A Storage	Treatment	Farm B Storage	Treatment	Farm C Storage	Treatment	Farm D Storage	Treatment
NH_3 [kg N]	3414.74	609.99	3336.18	613.96	1635.71	317.86	2968.56	567.00
N_2O [kg N]	142.00	0.00	135.89	0.00	67.02	0.00	120.43	0.00
NO_2 [kg N]	8.78	0.00	4.68	0.00	2.84	0.00	3.50	0.00
Total N [kg N]	3565.52	609.99	3476.74	613.96	1705.56	317.86	3092.48	567.00

When comparing the results between the farms, a trend appears which shows that the higher the initial storage emissions are per GVE, the higher the emissions are when using a manure digester. This is caused by the innate differences between the individual farms. However, this trend also shows that the difference between the two emissions per GVE becomes larger for a farm, if more N emissions occur during the baseline scenario. Thus, introducing a digester on farm that pollutes more during this step would help to curb emissions to a larger extent. After the treatment & storage step manure, or digestate, is either used as fertiliser or exported offsite to other farms to be used as fertiliser there.

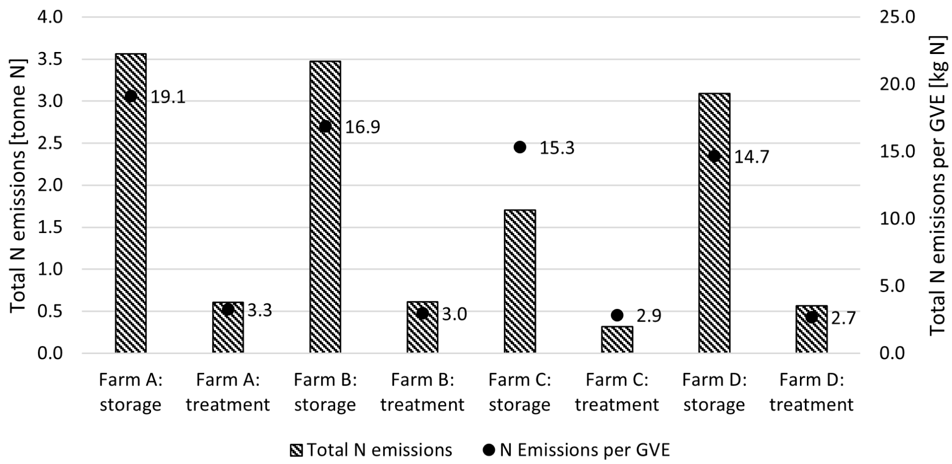


Figure 15: The total sum of the different N emissions for both the storage and treatment steps. The treatment step replaces the storage step when implementing a manure digester by converting fresh manure into biogas and digestate. The difference between these two steps per farm indicate the direct change a manure digester has on the N emissions.

4.1.4 Manure Application

Most dairy farms in the Netherlands produce too much manure so that they are left with excess manure after fertilisation. The excess manure is exported to other farms in the Netherlands or abroad to be used as fertiliser there. The maximum amount of manure scales with the amount of hectares of land available, which will vary between farms but is consistent between the two scenarios. The maximum amount of N applied on the fields is calculated and the remainder is assumed to be exported out of the system. In all cases the farms produce enough manure to allow for maximum N fertilisation. The manure application results are displayed in figure 16, where the grazing deposits are also taken into account since they take up a portion of the maximum allowed N per hectare on grasslands. The emissions for both scenarios on the farm are the same. The difference can be found in the amount of nitrogen exported, which is higher for each of the treatment scenarios. This means that digestate is a more potent fertiliser than slurry manure, since it contains more kilogram N per tonne manure, since the amount of manure flowing through both scenarios is the same. Due to this effect, more manure has to be exported since the amount is regulated based on the amount of N per hectare and not the amount of manure. Furthermore, this increase in N content between slurry manure and digestate is indicative of all the emissions saved, whose nitrogen is still present in manure instead of polluting the environment.

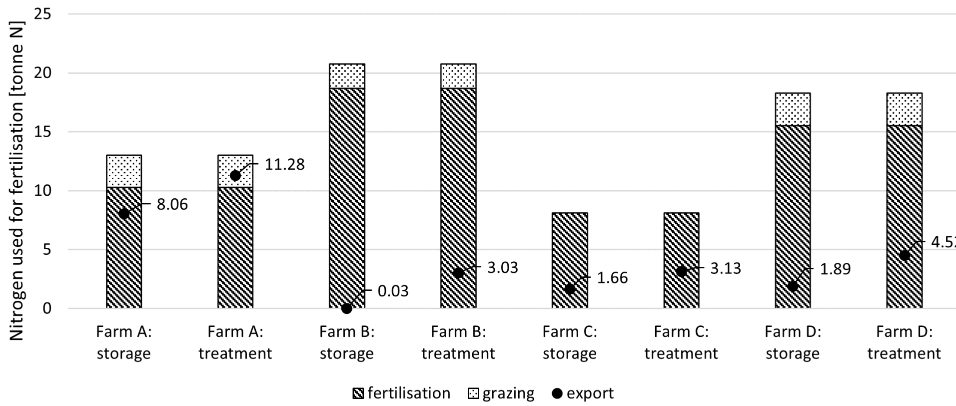


Figure 16: The amount of nitrogen (N) used on farmland during grazing and fertilisation in kilograms per farm and scenario as well as the amount of N remaining after fertilisation for export.

The application emissions, stemming from fertilisation procedure itself are, for both slurry manure and digestate, very much depended on the method used. Since these methods can vary between farms, a specific NH_3 EF is calculated for each farm which is based the methods used for both grassland and cropland. These EFs are presented in figure 17 together with the emissions in kg N that takes place during fertilisation. Due to varying amounts of, grass- and cropland, hectares between the farms, it is possible for two farms with the same application methods to have different NH_3 EFs during this step. For each of the farms the emissions during this step are higher for the treatment scenario than for the storage scenario. This all comes from the NH_3 emissions, whilst the N_2O and NO_2 emissions remain constant. This occurs, because the NH_3 EF is based upon the fraction of TAN present in manure and the other EFs are based on the total amount of N. This difference between the EFs exists because no information was available regarding TAN based EFs for N_2O and NO_2 (Lagerwerf et al., 2019; Amon et al., 2019). The actual change in emissions occurs due to a different amounts of TAN present in the total amount of nitrogen between the two scenarios.

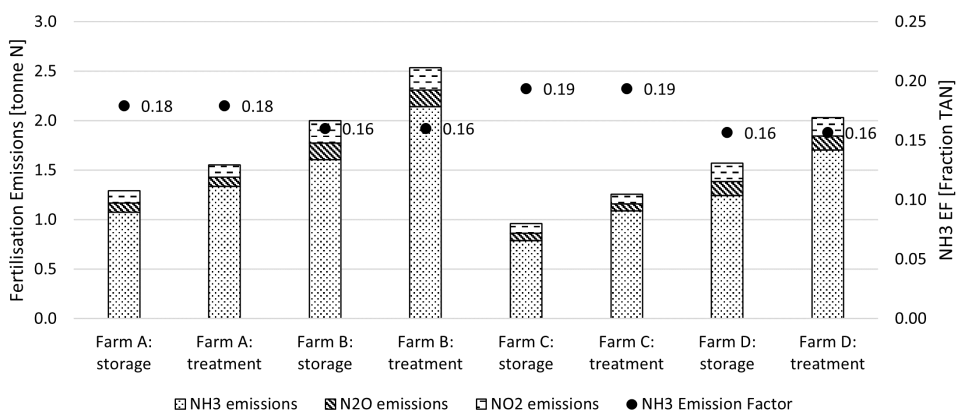


Figure 17: nitrogen (N) emissions during fertilisation on the farms for both scenarios, including the NH_3 Emission Factor, which is farm specific.

4.1.5 Nitrogen Emission Overview

With manure either being applied as fertiliser or exported out of the system, the manure life cycle on the farm comes to an end. The total changes in N emissions per pollutant were calculated for each farm and per GVE. The results of the individual pollutants per step of all four farms can be found in appendix I. The aggregated emissions of the four farms are presented in table 15 expressed in kg N for both farms in total and per GVE. The total N emissions per farm were calculated with and without N_2 emissions since N_2 is not a pollutant, but the release of N_2 does impact the nitrogen balance.

The total N emissions reduction on farm A through the implementation of a manure digester is 42%. The total N emission reduction for the other three farms is about 12% lower than that of farm A. Since each farm has its own set of characteristics it is difficult to pinpoint a single cause but low emission housing emission, high nitrogen (N) excretion and a small amount of land per GVE play a big role. Due to the low emissions housing more N remains in manure in both scenarios which changes all future emissions. The high nitrogen (N) excretion already ensure that there is a large N-budget from which to release emissions from the beginning. The relative small amount of land ensure that the application emissions are capped and can only increase a small amount from the heightened TAN. The emissions reduction percentages of farms B, C & D all are very close, which is mostly due to their similar NH_3 emissions reduction levels since these form the bulk of the total N emissions and thus dominate the total reduction percentages. Variations between the farms are due to the individual characteristics and make direct comparison between farms based on emissions levels susceptible to erroneous interpretation due to the complexity within each individual system. Overall, it can be concluded based on these results that manure digester help significantly reduce the N emissions levels during the manure life cycle on dairy farms in the Netherlands. In this case of the farms researched here these emissions reductions ranged from at least 29% to up to 42%.

Table 15: Overview of all aggregated emissions per pollutant type for all the farms and the totals and differences expressed per GVE.

Pollutants	Scenarios	Farm A		Farm B		Farm C		Farm D	
[kg N]		Total	per GVE	Total	Per GVE	Total	Per GVE	Total	Per GVE
NH3	Storage	5929	31.81	7306	35.48	3507	31.54	6375	30.24
	Treatment	3387	18.17	5119	24.86	2487	22.37	4433	21.03
	Difference	2543	13.64	2186	10.62	1020	9.17	1941	9.21
	Difference [%]	42.88		29.92		29.07		30.45	
N2O	Storage	324	1.74	372	1.81	140	1.26	352	1.67
	Treatment	182	0.98	236	1.15	73	0.66	231	1.10
	Difference	142	0.76	136	0.66	67	0.60	120	0.57
	Difference [%]	43.77		36.50		47.87		34.24	
NO2	Storage	165	0.88	254	1.23	100	0.90	223	1.06
	Treatment	156	0.84	249	1.21	97	0.88	220	1.04
	Difference	9	0.05	5	0.02	3	0.03	3	0.02
	Difference [%]	5.32		1.84		2.83		1.57	
Total (excl. N2)	Storage	6419	34.44	7932	38.52	3747	33.70	6950	32.97
	Treatment	3725	19.99	5605	27.22	2658	23.90	4884	23.17
	Difference	2693	14.45	2327	11.30	1090	9.80	2065	9.80
	Difference [%]	41.96		29.33		29.07		29.72	
N2	Storage	263	1.41	140	0.68	85	0.77	105	0.50
	Treatment	0	0.00	0	0.00	0	0.00	0	0.00
	Difference	263	1.41	140	0.68	85	0.77	105	0.50
	Difference [%]	100.00		100.00		100.00		100.00	
Total (incl. N2)	Storage	6682	35.85	8072	39.20	3832	34.46	7054	33.47
	Treatment	3725	19.99	5605	27.22	2658	23.90	4884	23.17
	Difference	2957	15.86	2467	11.98	1175	10.56	2170	10.29
	Difference [%]	44.25		30.56		30.65		30.76	

4.2 Methane Emissions

The majority of the methane (CH_4) emissions on a dairy are emitted by the dairy cows themselves through enteric fermentation. These processes occur naturally, but have a large environmental footprint. The EF per GVE per farm and the total emissions per farm are shown in table 16, the EF is farm-specific since it is depended on the amount of dry matter consumed as feed. The EF of farm A is higher than the other three farms and all farms rank above the region average of 134.0 kg CH_4 per dairy cow per year (van Bruggen et al., 2020). This in line with the N excretion results which also were above national averages for each of the farms, indication a higher production level per diary cow on the farms, since they consume more feed and produce more manure. The emissions per GVE of all the farms are in the same range and Farm C is the only one with significantly less GVE, which results in the large difference in total emissions compared to the other three farms.

Table 16: The amount of CH_4 emitted through enteric fermentation per GVE, expressed as the EF, and the total emissions for each farm.

Enteric Fermentation	Farm A	Farm B	Farm C	Farm D
EF [kg CH_4]	162.44	153.01	151.08	156.08
CH_4 emissions [tonne CH_4]	30.28	31.50	16.80	32.90

The CH_4 emissions from manure are emitted during the treatment, storage and grazing steps. The grazing step emissions are the same between both scenarios for each farm, but the treatment and storage emissions very between the two scenarios. The EFs are all determined based on the organic matter present in manure, which in turn is based on the total amount of manure excreted on a farm (see table 5). The division manure in the slurry, solid and grazing fractions was made based on time spend grazing and the slurry fraction data from the KringloopWijzer. These fractions and the organic matter content per GVE are displayed in table 17. The average organic matter content of manure in the Netherlands in 2018 was 1769 kg/year per animal (van Bruggen et al., 2020). This falls in the middle of the range of the organic matter values of the farms analysed in this research.

Table 17: The fraction and organic matter content used during the calculations for CH_4 emissions during the grazing and treatment and storage steps.

	Farm A	Farm B	Farm C	Farm D
x_{slurry} [-]	0.82	0.89	0.95	0.86
x_{solid} [-]	0.07	0.03	0.05	0.02
$x_{grazing}$ [-]	0.11	0.08	0.00	0.11
Organic Matter [kg / animal.year]	1762.24	1817.11	1609.64	2129.97

Due to the large amount of slurry compared to the grazing and solid fractions, the emissions of this fraction will be significantly larger than the other two fractions. The results of each individual fraction can be found in appendix I and the total of the treatment and storage step are given in figure 18. Here the total emissions reduction per farm is also expressed as the percentage of emissions reduced when implementing a digester. For all farms this lies around 80% indicating that the large majority of the methane emissions during this step were be reduced. However, the CH_4 emissions emitted from enteric fermentation on the dairy farms are significantly higher than the emissions emitted during the storage scenario, without a digester, see table 16. The manure digester does not impact those CH_4 emissions. The EF for slurry manure dutch dairy farms is calculated by K. Groenestein et al. (2020) as 42.8 kg/year per animal which matches well with their measurements of 41 kg/year per animal. These values are comparable with the EFs from the different farms in this research which range between 36.3 and 46.0 kg/year per animal.

The difference between the two scenarios CH_4 emissions in figure 18 occurs mostly due to different MCFs (Methane Conversion Factors) between slurry manure and digestate in the two difference scenarios. The EFs of slurry based system are very high due to their high MCF values, 17% in the Netherlands (C. M. Groenestein et al., 2016). The digester MCF value is significantly lower and can theoretically be reduced to zero (Zeeman and Gerbens, 2003). In their work, Moset et al. (2018) elaborate on the MCFs used in Germany which lie between 1 and 10 %. Furthermore, a total CH_4 emission reduction of 85% was achieved in France (Moset et al., 2018). With an digester MCF of 3%, adopted from the work of van Dijk et al. (2020), the emissions reduction here approaches those described in Moset et al. (2018) whilst assuming that some CH_4 emissions escape from the closed system. Thus, next to the N emissions reduction of at least 29%, CH_4 emissions are reduced with 80% during the storage step.

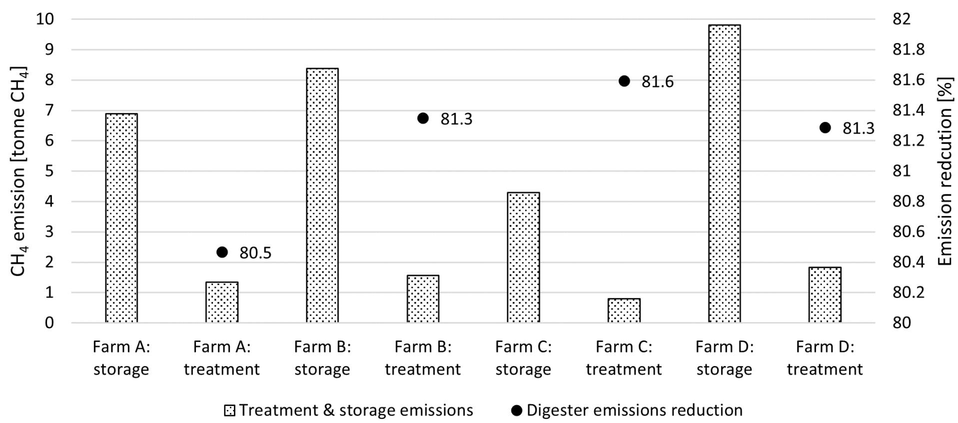
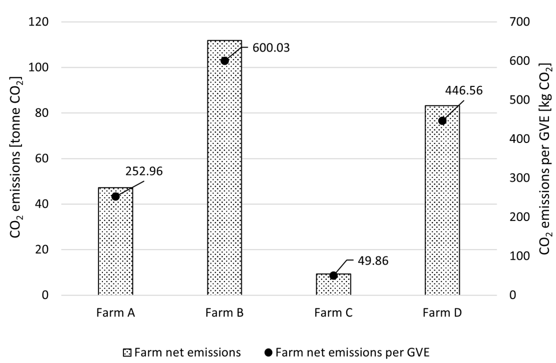


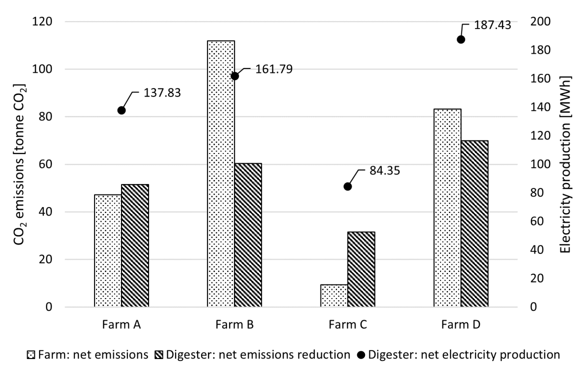
Figure 18: The total CH_4 emissions during the treatment & storage steps per dairy farm.

4.3 Carbon Dioxide Emissions

The carbon dioxide (CO_2) emissions calculations on dairy farms are split into two steps. The first steps describes the current energy consumption and generation on the different dairy farms. The second steps focuses on the manure digester and the amount of electricity this addition to farm consumes and generates. The data used in the first step was collected from the KringloopWijzer and the model calculated the CO_2 emissions associated with the different energy sources that were used. Farms do not only consume energy but also generate it for their own use, through solar panels for example. Excess energy is exported back to the grid which already helps to reduce emission footprint of a dairy farm without the use of a manure digester. The net emissions of a farm are thus the total emissions of a farm minus the emissions reduction caused by sustainable energy generation. These results can be seen in figure 19a.



(a) The net CO_2 emissions of the four different dairy farms without a manure digester.



(b) The net CO_2 emissions on the four different dairy farms with a manure digester.

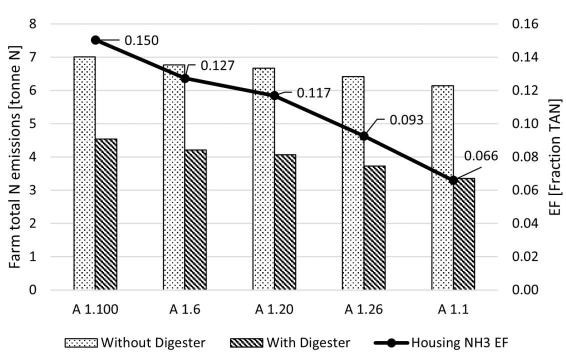
Figure 19: The CO_2 emissions on dairy farms without and with a digester.

Large differences between the farms, both in total amount of CO_2 emissions and the emissions per GVE, are observed in figure 19a. The large differences per GVE are interesting since the expression of emissions per GVE were used to normalise the results from the different sized farms. These large differences stem from a number of different sources. There is a big difference in energy consumption between the dairy farms, especially in diesel consumption which is 10,000 L for farm A and almost 30,000 L for farm B. These differences could partly be explained by the different sizes of farmland and are impact by other farm characteristics as well. Furthermore, alternative energy sources used on different farms caused different levels of CO_2 emissions. Even though all farms produce some energy through the use of solar panels, the difference here also impact the results significantly. Farm B does not deliver anything back to the grid since it consumes all the electricity it generates. Farm C, on the other hand, manages to deliver 86,000 kWh per year to the national grid. The large differences in energy consumption (e.g. type and volume) as well as the energy generation capabilities of the farms contribute to the large variations in the CO_2 emissions per farm. Each farm is still depended on fossil fuels for its operations and cannot generate enough electricity to sustain its own operations.

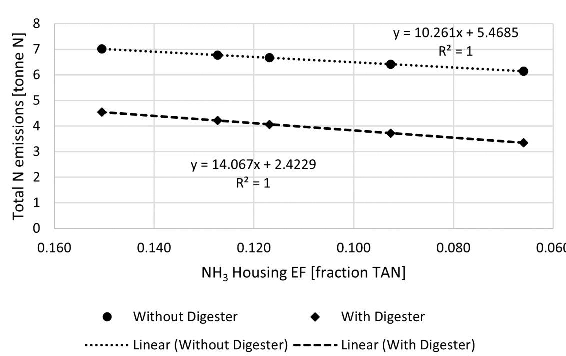
With the implementation of a manure digester on a dairy farm this changes, as can be seen in figure 19b. Farms A and C produce more then enough sustainable energy to offset their CO_2 from their own energy consumption. Furthermore, farm D almost reaches the break even point regarding their CO_2 emissions and it is only farm B that still emits much more CO_2 in this scenario than that is reduces by generating sustainable energy. When solely comparing the electricity generation from manure digester with the electricity consumption of the farms, the electricity generation is an order of magnitude higher. The total energy generation of these four farm with manure digesters is 649 MWh per year. This means that just with these four farms, of the total 16,000 dairy farms in the Netherlands, approximately 238 average Dutch households could be supplied with sustainable energy (NIBUD, 2021). This is in addition to the achieved N emissions reduction of at least 29% and CH_4 emissions reduction of 80% during the storage step.

4.4 The Impact of Housing Types

During the manure life cycle, implementing a manure digester is not the only variable that can be altered on a farm to influence the emissions. One of these variables, the housing type, is explored in this section. Since the housing step takes place early in the manure life cycle and is responsible for a large percentage of NH_3 emissions, adjusting this parameter will heavily impact all further N related emissions. An overview of all the housing types, as noted in the Regulation Ammonia and Livestock farming, can be found in appendix B (Wet Ammoniak en veehouderij, 2002). Figure 20a shows the total N emissions of the whole farm for a number of housing types, which were selected based on their reducing EFs. There is a decreasing trend for both the storage scenario, without a digester, and the treatment scenario, with a digester. Thus, upgrading to a lower emitting housing type to reduce emissions can be recommended in both cases. This linear relationship is shown in figure 20b where the total emissions of farm A were set out against the housing EF of the different housing types. This figure further shows the decrease of the total nitrogen emissions on farm A is higher when also implementing a digester than solely implementing a emission reducing housing type. Thus, combining these efforts will even further improve the emissions reduction on farm A.



(a) The total N emissions on farm A with different housing types, each with their own EF.



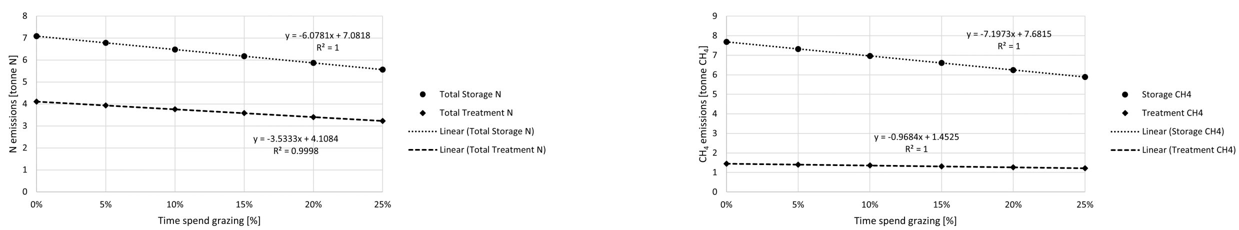
(b) The relation between the total N emissions on farm A and the NH_3 EFs from the different housing types.

Figure 20: The impact of the different housing types on farm A.

The results of the other three farms are shown in appendix J and display similar results. In each case, the linear relationship between the housing EF and the total nitrogen emissions decreases more rapidly in the treatment scenario. The previous sections have shown that implementing a manure digester on these four dairy farms would reduce at least 29% all nitrogen emissions in the manure life cycle. When implementing the least emitting housing type (A 1.1) on these farms, in conjunction with the implementation of a manure digester, the N emissions reduction increases further. For farm A, which starts with housing type A 1.26 the emission reduction increased to 47.8%. For the other three farms, which all starting with housing type A 1.100 the emissions reduction increased to 44.7%, 44.2% and 45.6% for B, C and D respectively. Combining both emission reduction measures could increase the total N emission reduction with at least another 15% for farms B, C and D. Since, farm A already starts with a low emission housing type (A 1.26), the emissions reduction here is only 5%. However, the N emissions reduction of farm A in table 15 is already 12% higher than the other three farms mostly due to the difference in housing types.

4.5 The Impact of Grazing Regimes

One of the most influential parameters on a dairy farm, from an emissions perspective, is the location where a cow spend its time. This has direct and indirect impact on both the N and CH_4 emissions as well as indirect impact on CO_2 emissions. To explore these impacts an analyse of the four dairy farms with different grazing regime was performed. The four farms in this work have grazing regimes which allow their cattle to be outside between 0% and 12% of the year. The analysis in this section analysed grazing regimes between 0% and 25%, where 25% entails that all cattle spends 6 hours outside, for 365 days a year.



(a) The relation between the total N emissions on farm A and the grazing regime.

(b) The relation between the CH_4 emissions on farm A and the grazing regime.

Figure 21: The impact of the different housing types on farm A.

The linear relationships between an increasing grazing regime and nitrogen (N) and methane (CH_4) emissions for farm A is shown in figure 21. For both emission types there was a decrease in emissions observed for both scenarios. However, the decrease in the treatment scenario, with a digester is lower than the emissions in the reference scenario. This is due the fact these two measure address emissions at the same step, namely the emissions of manure after excretion. A digester captures this manure to generate energy whilst increasing the grazing regime will reduce emissions due to a change in excretion location.

The results in figure 21 show that combing the measures, even in the scenario with a digester will have some effect in further reducing N and CH_4 emissions. However, this will come with a trade-off as shown in figure 22 which displays the CO_2 emissions and MWh generated as a function of the grazing regime. An increase in the grazing regime will reduce both the electricity production and with it the CO_2 emission reduction from the generation of sustainable energy.

The overall changes per emission type of the four farms are displayed in table 18. These changes are all the changes that occur when switching from a 0% grazing regime to a 25% grazing regime. For both the N and CH_4 the trend is that a higher level emissions reduction is achieved when increase the grazing regime without a digester which is expected since both measures interfere with each other thus the absolute emission

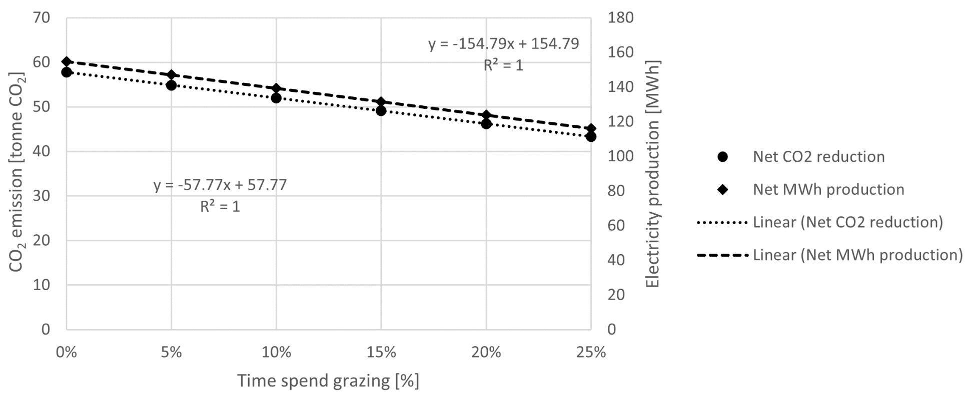


Figure 22: The relation between the CO_2 emissions and energy generation in MWh on farm A and the grazing regime.

reduction gains reduce. Furthermore, since more manure is excreted on grassland with an increasing grazing regime the energy generation from the manure digester drops. The introduction of low emission housing types is an addition next to having a manure digester on a dairy farm. However,increasing the grazing regime caused a trade-off between emission types. Increasing the grazing regime can be used as a short term measure to reduce emissions before the implementation of manure digesters is completed (Adviescollege Stikstofproblematiek, 2019).

Table 18: The emission reduction and energy generation of the four farms of both scenarios expressed as the difference between the 0% and 25% grazing regime.

Farm Results	Farm A	Farm B	Farm C	Farm D
Storage N [%]	21.5	17.9	19.6	18.8
Treatment N [%]	21.5	15.9	18.6	16.6
Storage CH4 [%]	23.4	23.5	23.5	23.5
Treatment CH4 [%]	16.7	16.7	16.7	16.7
Net electricity production [%]	-9.6	-9.6	-9.6	-9.6
Net CO2 reduction [%]	-9.6	-9.6	-9.6	-9.6

4.6 Results Synthesis

The results of the farm-scale model show emissions reduction for all pollutants on all four farms. With the introduction of a manure digester on a dairy farm, the total-N emissions can be reduced by at least 29%. Farm A performs significantly better than the other three farms with a 42% N emission reduction mostly due to its low emission housing type. When combining a manure digester with the implementation of the lowest emission housing type, nitrogen emissions reduction of 48%, 45%, 44% and 46% can be achieved for farms A, B, C and D respectively. Simultaneously, manure digestion reduces 80% of the methane (CH_4) emissions stemming from the long term storage of dairy manure. However, it does not address the CH_4 emissions stemming from enteric fermentation. Furthermore, the energy generation capabilities will significantly reduce and in some cases more than completely offset dairy farms carbon dioxide (CO_2) emissions. Together these four farms could supply 238 average Dutch households with sustainable energy with a total production of 649 MWh per year. The greenhouse gasses CH_4 and N_2O can be expressed in CO_2-eq. by multiplying them with a factor of 34 and 298 respectively (Shindell et al., 2013). This brings the total GHG emission reduction of these four farms expressed in CO_2-eq. is 1.24 million kg CO_2.

5 Provincial Results

Each dairy farm in the Netherlands can install a digester and with it reduce its emissions and generate sustainable energy, as was shown in section 4. Based on the assumption that every dairy farm in the Netherlands install a digester, the theoretical emissions reduction and energy generation numbers were determined per province. This section showcases these emissions reductions for each of the pollutants, where all N emissions are grouped together and expressed as the total N reduced.

The application of the farms scale model on a provincial level gives the emission reduction results in tonne nitrogen as shown in figure 23. This figure shows the total amount of N emissions, as a sum of NH_3, N_2O and NO_2 emissions expressed in tonne N, that can be reduced per province when installing a digester. The total emission reduction for the whole of the Netherlands based on these calculations would be 19,371 tonne N. The provinces reduce their N emissions from the manure life cycle between 31.5% and 20.0%. The provincial differences along with the detailed emissions results can be found in appendix L.

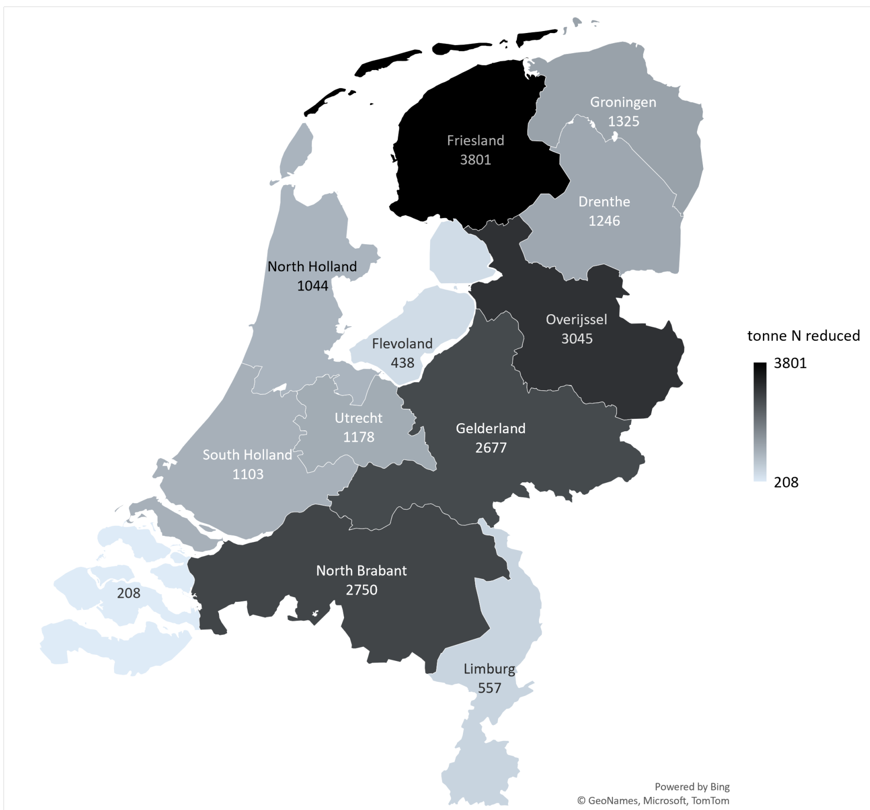


Figure 23: The emissions reduction expressed in tonne N per province when implementing a manure digester on all dairy farms in these provinces.

Differences between the provinces occur due to the different amounts of dairy cattle and hectares of farmland present in the provinces. The relationship between the amount of dairy cattle, expressed in GVE, and the total N emissions is shown in figure 24. Besides the emissions of Zeeland the provinces score relatively consistent per GVE. Overall the North-Western provinces score a bit higher than the South Eastern provinces. This is due to larger N excretion per GVE caused by a different feed composition due to soil type. The reduction of N emissions per hectare of farmland can be seen in figure 42 in appendix L. Here the differences between the provinces are larger, however the trend is similar. The provinces that score the highest per GVE also score the highest per hectare of farmland. The emission reduction in Zeeland is here also significantly lower when compared to the other provinces.

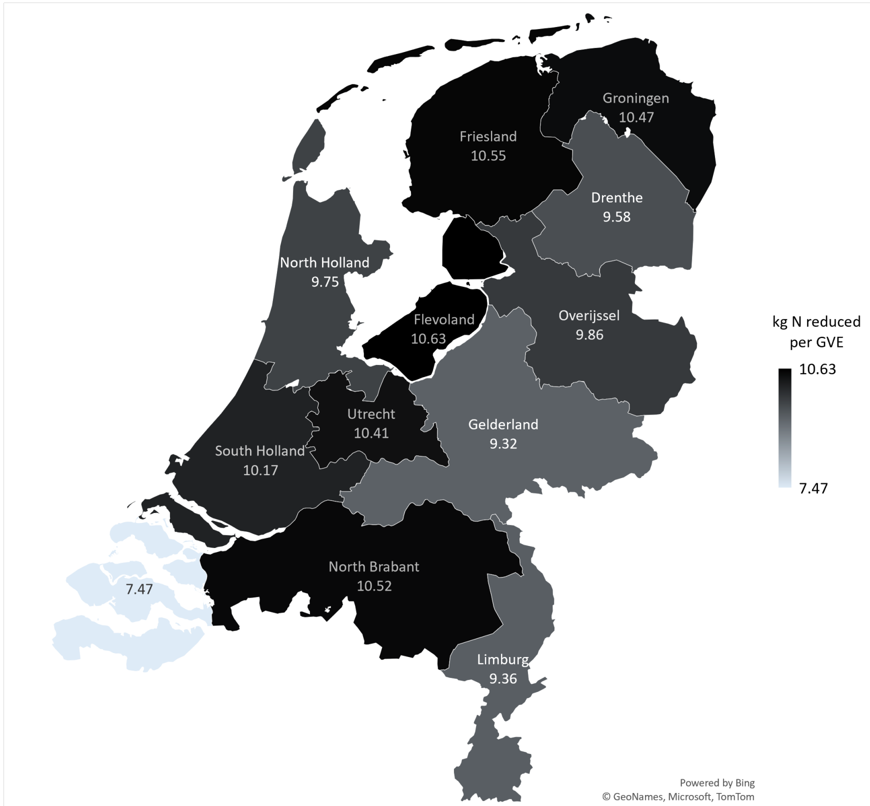


Figure 24: The emissions reduction expressed in kg N per GVE per province when implementing a manure digester on all dairy farms in these provinces.

When comparing the total NH_3 emissions of the Dutch dairy sector, 64.4 million kg NH_3, with the model results, 78.7 million kg NH_3 a significant difference is observed (van Bruggen et al., 2020). The results presented by van Bruggen et al. (2020) take different parameters into account such as housing types, farming techniques, manure storage, etc. This is not possible in this work since it is based on a farm-scale model. A big part of this difference can be attributed to some of the assumptions that were required to apply the farm-scale model over whole provinces. The only housing type considered in this work was the most polluting one, while the results in section 4.4 show that changing housing types at a farm scale reduces N emissions with more than 10%. Furthermore, changing the grazing regime also influences the total farm N emissions significantly (see section 4.5). A number of other generalisation will also play an role, such as the national average TAN and excretion N. These factors, in combination with the decision to work with GVE instead of using separate data for young stock categories and dairy cattle can explain the difference. However, these overestimations will occur in both scenarios, since the same housing, grazing and other assumption are used in both scenarios. Thus, the reduction of more than 25% of the N emissions is still useful as an theoretical benchmark when considering the impact manure digesters can have on the nitrogen emissions on the dutch dairy sector.

Similarly to the N emissions above, figure 25 shows the total emissions reduction per province expressed in tonne CH_4. The CH_4 emissions are not impacted by the same model limitations as N above. The estimated total reduction of CH_4 is 62,813 tonnes. The total storage and enteric fermentation emissions of

Netherlands calculated in this work are 77.6 and 282.5 million kg CH_4, respectively. When comparing this with the national emissions as calculated by van Bruggen et al. (2020), differences of 0.81% and 2.24% are observed. Furthermore, a report from Well and Rougoor, 2017 shows the 2016 CH_4 emissions of the diary sector in Overijssel as 45,721.3 tonnes CH_4 for enteric fermentation and 14,715.8 tonne for manure emissions from barns. This work estimates 45,450.6 and 12,832.4 tonnes CH_4 for enteric fermentation and storage emissions, respectively. These values indicate that the developed emissions model can accurately determine the CH_4 emissions. The emission reduction per GVE, which can be found in figure 43 in appendix L, show that the North-West/South-East division based upon soil types and feed composition causes the majority of the differences between the provinces.

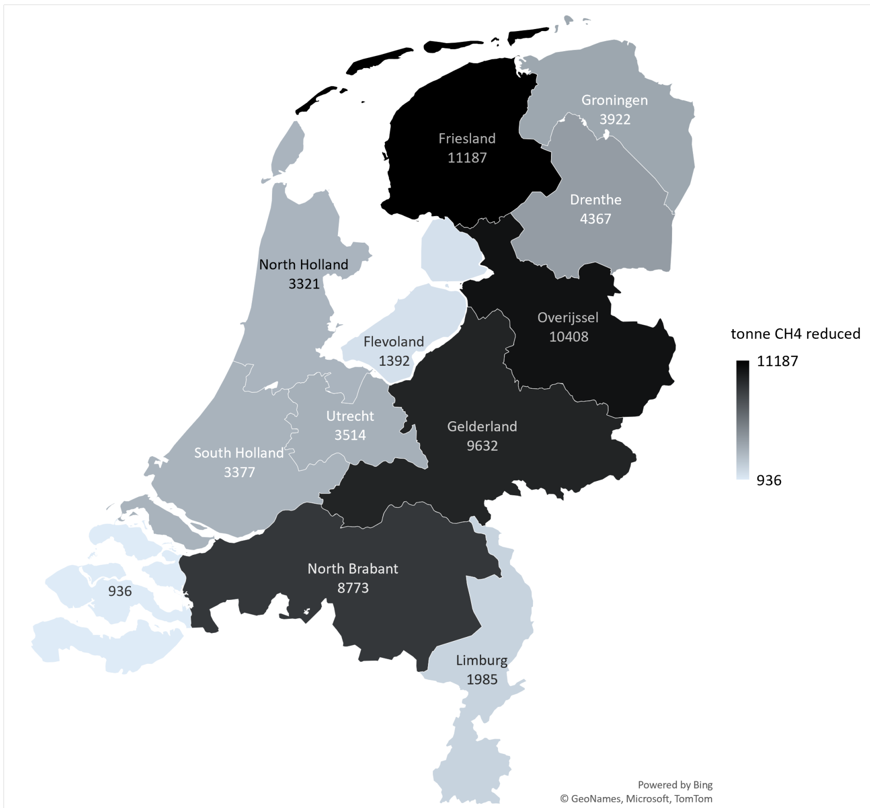


Figure 25: The emissions reduction expressed in tonne CH_4 per province when implementing a manure digester on all dairy farms in these provinces.

Due to the energy generated by manure digestion, a reduction in CO_2 emission takes places. This reduction in emissions does not take place on the farms themselves but is achieved by supplying sustainable energy to the grid. The maximum theoretical energy generation contribution of manure mono-digesters implemented on all dairy farms in the Netherlands is 1.51 TWh. This enough to electricity to power around 553,000 average Dutch households (NIBUD, 2021). The results per province, expressed in GWh are shown in figure 26. The accompanying emissions reductions are presented per province in figure 45 in appendix L and the theoretical maximum achievable CO_2 emissions reduction in the Netherlands through sustainable energy generation by implementing manure mono-digesters on all dairy farms is 562.1 million kg CO_2.

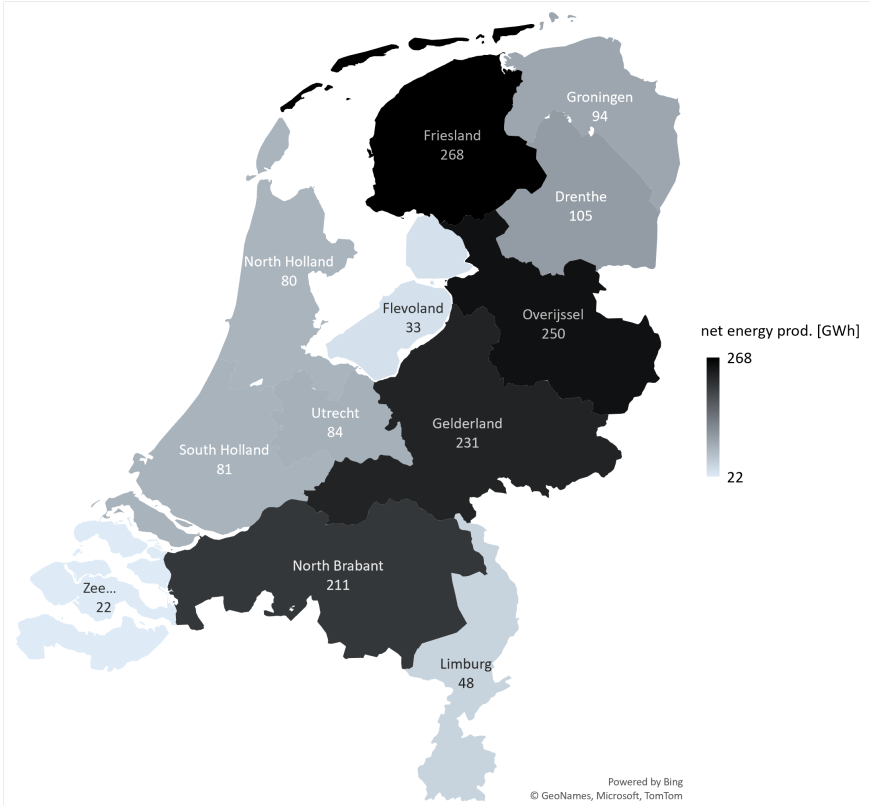


Figure 26: The net energy energy generation per province when implementing a manure digester on all dairy farms in these provinces.

5.1 Results Synthesis

With the adaptation of the farm-scale model to a provincial level it is possible to determine the impact manure digester will have when implemented throughout the dairy sector. This would lead to a removal of 19.3 million kg N across all provinces. Besides the reduction in N emissions, 62.8 million kg CH_4 is reduced when implementing manure digester on all dairy farms in the Netherlands. Furthermore, the electricity generated through sustainable biogas production will provide 1.51 TWh per year, which is enough electricity to power approximately 553,000 average Dutch households. This reduces the energy generation emissions by 562.1 million kg CO_2. The greenhouse gasses CH_4 and N_2O can be expressed in CO_2-eq. by multiplying them with a factor of 34 and 298 respectively (Shindell et al., 2013). the combined reduction of GHG, expressed in CO_2-eq., through the introduction of manure digesters in the Netherlands is 3,268.23 million kg CO_2.

6 Discussion

The aim of this work was to determine the effect manure digesters have on emissions reduction and sustainable energy generation on dairy farms in the Netherlands. This was accomplished by developing a farm-scale, farm-specific model which can also serve as a decision support tool for dairy farmers in the Netherlands wanting to assess the possible emissions reduction on their dairy farm. This section first focuses on the model development, followed by a discussion on uncertainties in the model and the impact of digestate, which contains more nitrogen than manure. Then the nationwide impact of manure digesters is discussed and finally, recommendations for future research are made.

6.1 Model Development

The nitrogen emissions are the most complex emissions to calculate on a dairy farm due to different, interconnected pollutants and subsequent emissions steps. Comparison at a farm scale with literature is difficult since not all N flows on a farm are taken into account in this work, since they are not all affected by the implementation of a manure digester. Furthermore, any emissions accounting at a larger scale is often generalised and thus not specific enough to be applied to this work (Dong et al., 2006) or focuses only on a specific type of emissions (Amon et al., 2019). National emission models, such as the Dutch National Emissions Model for Agriculture (NEMA), are also developed (Lagerwerf et al., 2019; van Bruggen et al., 2020). However, these methodologies also focus on the agricultural sector or at least a sub-sector such as the dairy sector.

Since this work is conducted at a farm scale these methodologies could not be directly implemented. Furthermore, due to this difference in scale, certain generalisations and aggregations that these methodologies apply at a sector scale do not hold necessarily hold when assessing individual farms. To this end, a farm-scale specific methodology was developed. Generalisations and aggregations are removed by translating them into farm-specific input criteria. For example, the housing types are aggregated in NEMA and serve as an input variable in this work (Lagerwerf et al., 2019). The work by Amon et al. (2019), which focuses on N-pollutants, was translated to each specific step of the farm-scale system identified in this work. This was improved by implementing Dutch specific information from van Bruggen et al. (2020) and GHG emissions from Dong et al. (2006). The integration of information from one methodology into another is possible since all methodologies work with EFs.

The application of the methodologies by EMEP/EEA, IPCC and NEMA in combination with research conducted on Dutch specific Emission Factors (EFs) increased the reliability of this work. This is further improved in this research by collecting case data directly from Dutch dairy farmers. In this work, the data of four distinct dairy farms are analysed. The data from these farms is accurate and consistent since there is a farm-scale industry standard for data collection in the Dutch dairy sector (van Dijk et al., 2020). The result of this industry standard is the KringloopWijzer, which is available for every dairy farm in the Netherlands. Thus the KringloopWijzer was used as the information basis for the farm-specific data that were required during this research. Another benefit of the KringloopWijzer is that it simplifies and promotes the use of the model as a decision support tool since data collection is removed as a barrier.

The emissions methodologies from the IPCC, EMEP/EEA and NEMA were not developed with the KringloopWijzer in mind, thus combining them posed certain challenges. The major impact the KringloopWijzer had on the methodology was that the young stock and mature dairy cows were not separated in terms of feed consumption, manure excretion and nitrogen content. Only the farm totals were available, thus it was decided to convert young stock impact into that of dairy cows based on their relative emission impact and express their sum as GVE. This decision provided additional benefits during model development. First, more research is done on mature dairy cows compared to young stock, thus more accurate and country-specific data is available (Lagerwerf et al., 2019; van Bruggen et al., 2020). Second, it simplified many modelling aspects since the whole model did not have to be developed for three different livestock categories. Third, using GVE assures that each farm is analysed based on the same merits compared to only using mature dairy cows. This is important since the amount of young stock can vary significantly between different farms. However, this aggregation of dairy cattle and young stock cause a slight overestimation of the contribution of the young stock in certain categories, such as manure excretion. This makes comparisons with other sources more difficult. Furthermore, the young stock categories have different grazing regimes, housing systems and other unique parameters. This is taken into account wherever possible by determining weighted averages, for example for slurry fractions, but this was not possible for every parameter.

6.2 Model Uncertainties

The biggest uncertainty stems from a part of the emission methodologies themselves. Each of the different emissions for all nitrogen (N) pollutants as well as for CH_4 and CO_2 are calculated with emissions factors (EFs). These factors express the number of emissions released in a specific situation based on a criterion. For the nitrogen emissions this is either the amount of TAN or the total nitrogen available in manure. For other emission types, it could also be the amount of manure, feed, energy generated, etc. These EFs are determined based on on-site measurements in earlier studies supported by the analysis of experts (van Bruggen et al., 2020). In an ideal situation, all these EFs would have been measured in a similar manner at different farms in the Netherlands to provide the most accurate data. This is, however, not the case and some values are not country-specific.

The impact of these EFs can be significant, especially in the N emissions which are all linked to the same N-balance. This can be seen in the housing emission results, where reducing the EF 20% for farm A with a manure digester will reduce the overall N emissions of the farm by 7.3%. However, the effectiveness of the low emissions stables, as noted in the Wet Ammoniak en veehouderij (2002), is reported to be overestimated (Oenema, 2020; van Well, 2021). Thus, the total emissions reduction gains for farms with low emission housing are expected to be lower in practice than calculated here based on the currently available data. Due to the complexity of the N-balance, changes in different EFs will have different impacts on the total farm emissions. Varying the NH_3 EFs will have a much larger impact on the total farm N emissions compared to the other N-pollutants since NH_3 is the dominant pollutant on dairy farms. A change of 20% in the storage NH_3 EFs will change the total N emissions of farm A by 9.7%, whereas a change of 20% in the treatment NH_3 EFs caused a difference of 3.2%. A change of 20% in the grazing NH_3 EF changes the total farm N emissions by 0.2% and 0.4% for the storage and treatment steps, respectively. Thus, the implementation of any updated EFs into the model will further increase reliability and reduce uncertainties within this research. Specifically, determining the true effect of different housing types and NH_3 emissions from the treatment and storage steps will improve the accuracy of the model in regards to the N emissions.

The CH_4 and CO_2 results are not subject to the same complexity as the N pollutants, which helps their reliability and comparison with literature. The most interesting study for comparison is the work of K. Groenestein et al. (2020) since it focuses on mono-digestion on Dutch dairy farms. In their work, the CH_4 emissions are reduced from 60% up to 75% compared to the 80% in this work. The difference is mostly due to the assumption of more CH_4 leakages in K. Groenestein et al., 2020, who also states that a reduction of these leakages from 4% to 2% will reduce emissions by 29% bringing the emissions in line with the results of this work. Their work also calculates the production of biogas gas from three theoretical farms, in which the biogas yield is estimated optimistically when compared to other sources and practical research who are more in line with this work (Gebrezgabher et al., 2012; RVO, 2021c; Gebrezgabher et al., 2010; Miranda et al., 2016).

Through the use of the KringloopWijzer, EFs and standardised emission methodologies, the impact of manure digester on dairy farms in the Netherlands can be validated. However, this validation could be improved by increasing the sample size of the cases analysed, especially with a focus on cases with varying input variables. Currently, four of the approximately 16,000 dairy farms in the Netherlands have been analysed with this model. Expanding this number with interesting cases could prove beneficial. Especially, if these new cases contain unique parameters compared to the current farms, for example, based on size or location. Since each farm contains a unique set of different parameters, it is difficult to compare different dairy farms with each other. To this end, the final product of the developed model is a farm-scale, farm-specific decision support tool. This decision support tool upon up the possibility for all these other dairy farms to be analysed with relative ease by farmers and decision makers alike.

The application of this work outside the Dutch dairy sector is possible but not straightforward. It is crucial that the system is comparable and that the corresponding EFs are available. A comparable system would require a sector that uses the same methods and practices as the Dutch dairy sector. A different agricultural sector in the Netherlands or a dairy sector abroad will require alternations to the model to be functional. More easily, the model can serve as a starting point for the development of other farm-scale models for different sectors in the Netherlands and abroad.

6.3 The Role of Digestate

The results in section 4 show that emissions can be reduced for all different N pollutants. For the farms analysed in this work at least 29% of all N emissions in the manure life-cycle can be reduced when implementing a manure digester on a dairy farm. It is, however, difficult to compare these results to other work since nitrogen emissions reduction is not often linked in literature to manure digesters. The focus is on CH_4 and CO_2 emissions. The reason therefore is that these products are formed as biogas during the digestion process, whereas seemingly nothing happens to the nitrogen present in manure. The nitrogen is retained in digestate, the other product of manure digestion. Due to this retention more nitrogen emissions could be released at later stages. This can already been seen during the fertilisation step in this research, where the emissions increase for the treatment scenario. Thus, to keep the nitrogen emission reduction gains made it is crucial to properly manage digestate.

The achieved N emissions reduction can be best described as a retention of nitrogen in manure which would otherwise be released into the atmosphere as N pollutants. This occurs due to changes in the manure life-cycle with the implementation of a manure digester. This digestate is a useful product as it can easily be applied as fertiliser as it behaves similarly to manure while being a more potent fertiliser due to extra N-content (Risberg et al., 2017; Tambone et al., 2010). However, all this extra nitrogen contained in digestate could still be released in a later stage. Furthermore, due to it being a more potent fertiliser, less digestate is allowed to be applied per hectare of farmland than traditional manure, only aggravating the excess of manure present in the Dutch agricultural sector (RVO, 2021b). Thus, to not lose all the emissions gains made in the manure life cycle, action should be undertaken to deal responsibly with digestate.

Dealing responsibly with digestate can be done in two ways, either using digestate on farms instead of other nitrogen sources such as synthetic fertilisers or treating it to reduce its environmental impacts. Research has shown that using digestate instead of synthetic fertiliser provides similar results in terms of crop yields (Doyeni et al., 2021; Sigurnjak et al., 2017). However, this has certain challenges such as nutrient variability (Sigurnjak et al., 2017). Further research has shown that replacing synthetic fertilisers with digestate increases the environmental benefits of digesters since it removes the environmental impact of the production of synthetic fertilisers (Walsh et al., 2012). Treatment of digestate can be done in multiple ways, such as evaporation, stripping and different forms of membrane treatments (Fuchs and Drosg, 2013). The downside of digestate treatment is that these processes are often economically not viable and the implementation is mostly dependent on local conditions and nutrient excesses (Barampouti et al., 2020).

Using digestate as synthetic fertiliser and treating have their own merits but expanding the direct use of digestate is arguably a more logical option at a farm scale. It requires legislation changes, which can be challenging but does not require the investment of building farm-scale digestate treatment plants. These plants then have to be operated by farmers who are not trained to do this or by specialists which add more costs, when it is already difficult to profitable operate these technologies (Herbes et al., 2020). Another option would be to develop central digestate treatment options, however, this means that all digestate from farms has to be transported to central treatments plants with all the added emissions from transportation and processing. From a financial, practical and environmental perspective allowing the use of digestate instead of synthetic fertiliser on a dairy farm is the preferred option.

6.4 The Nationwide Impact of Manure Digesters

Besides determining the emissions impact at a farm scale, the model was also used to estimate the nationwide impact of installing manure digesters on all dairy farms. However, due to the nature of the model the total N emissions are lower than what was expected. This is based on the fact that the model does not account for the import of manure on a dairy farm. It only used the available nitrogen (N) present on the farm or in the case of section 5, the province itself. Thus, if a province does not produce enough manure to fertilise all its farmland it will release fewer emissions instead of importing manure. The origins of this issue can be found in the farming intensity in the different provinces, the higher this intensity, expressed in this work as the number of GVE per hectare of farmland, the more manure there is available for each hectare. If this number becomes too low, not enough manure is present to fertilise all farmland in a province. In practice, this would be remedied by importing manure from regions that have an excess but this is not possible in the model.

This issue is not consistent for both scenarios, with and without a digester, since more N remains per tonne digestate and the end of the manure life cycle. Thus, more of the province available N space can be filled up. As a consequence, more N emissions occur during the fertilisation step, since more N is applied. This reduces the emission reduction gains between the two scenarios. The affected provinces are Zeeland and Limburg. For Zeeland, both scenario's do not produce enough manure to fertilise all the farmland. However, all the N saved by using a digester is still applied to the fields. This reduces the overall N emissions reduction to 20.0% compared to the other provinces whose nitrogen emission reduction levels are between 25.0% and 31.5 %. The situation in Limburg is different, since it has excess manure in the second scenario, with a digester. Thus, the difference is not as large as in Zeeland and the overall N reduction comes out at 25.4%, which means it still comes out at the lower end of the other ten provinces. However, it is important to note that this emissions reduction value will be higher in practice. Since there are no national goals linked to nitrogen emission reduction it is difficult to determine to which extent manure digester can contribute. The current focus is to achieve certain deposit levels in Nature 2000 areas (Paul, 2021). It is, however, clear that the significant reduction of these emissions, especially NH_3 emissions, will help alleviate the pressure on these areas.

As of this moment, manure treatment is mentioned on the Dutch national nitrogen website as an option for farmers to become more sustainable but no further information is given (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2021). When specifically looking at the province of Overijssel similar trends are observed compared to the national level. Currently, Overijssel is running a province-wide program to stimulate innovation, circular agriculture and to develop a sustainable food chain (Provincie Overijssel, 2020). The goals of this program align with the implementation of manure digesters, since they are focused on reduce the ecological footprint, the energy transition, and a cleaner and healthier environment. Thus, even though it is impossible to define the contribute manure digester can make on any environmental goals since there are non yet, their implementation nationwide is in line with the current ambitions and needs.

The total amount of CH_4 emission released in the air in the Netherlands in 2020 according to IPCC methodology is estimated at 676,800 tonnes. Thus implementing digesters on all dairy farms could reduce up to 9.3 % of all CH_4 emissions (loket emissieregistratie, 2020). Manure digesters on all dairy farms could theoretically reduce 81.0% of all manure CH_4 emissions stemming from manure storage. However, the main source of CH_4 emissions on dairy farms is enteric fermentation. When including these emissions in this calculation, manure digester can theoretically reduce 17.1% of all CH_4 emissions on Dutch Dairy farms. Thus, the implementation of manure digesters on Dutch dairy farms reduces CH_4 significantly but cannot address the main CH_4 source. To reduce CH_4 emissions from enteric fermentation other changes have to be made on a farm, such as dietary changes, which are outside the scope of this work (Haque, 2018).

In the Netherlands, the country is divided into 30 regional energy strategy (RES) regions which are each responsible for developing an energy transition strategy. The primary focus of this strategy is to generate 35 TWh of energy in 2030 to help achieve CO_2 emission reduction targets (Nationaal Programma Regionale Energie Strategieën, 2021). The maximum theoretical contribution of manure mono-digestion on all dairy farms in the Netherlands is 1.51 TWh, which represents 4.3% of this goal. Thus, the implementation of manure digesters on dairy farms in the Netherlands can not only help to reduce emissions but also contribute to the energy transition. The generation of 1.51 Twh of sustainable energy reduces CO_2 emissions by 562,100 tonnes. It has to be noted that these values would increase if co-digestion is applied since this would increase the energy generation compared to mono-digestion of dairy manure (Seppälä et al., 2013; Piñas et al., 2018). This is, however, outside the scope of this work and raises other questions about the production of co-products and their sustainability and emissions during their life cycle.

6.5 Future Research

One of the most impactful design decisions of the model was to combine young stock and mature dairy cows into a single category, classified as GVE. To expand on this research in the future, the created methodology could be split into these categories and the emissions determined per category to increase the accuracy of the model. This does require certain farm-specific input to be subdivided over these categories. New uncertainties would be introduced by this split but this allows for the fine-tuning of the ratio between young stock and mature dairy cows per category which should provide a better representation per category on the total emissions.

The emissions stemming from the manure life cycle are not the only emissions released from dairy farms or their supply chains to the environment. Thus, future research could build on this by including other farm emissions, supply chain emissions and other emission reduction strategies for the other aspects of dairy farms to further reduce the overall footprint. However, this will create added complexity, especially at a farm-scale where all variable input parameters have to be taken into account. A more impactful development of this research would be the inclusion of other decision-making criteria into the model. Emissions reduction decisions are not taken in a vacuum and the evaluated against other criteria such as financial investments, operating costs, possible subsidies and others. By including these aspects are more comprehensive decision support tool can be developed.

The modelling approach of the manure digester in this work is something which could be the subject of further research. In this work the focus was placed on emissions calculations which did not require intensive exploration of the manure digester parameters. However, there are plenty of options to further improve on this work. Firstly, the assumption is made that the yield of manure digesters is constant, which in practice it is not. A lot of research has been done on modelling digester output based on certain criteria such as retention time, temperature, biogas use and co-digestion. The implementation of co-digestion specifically could increase the biogas yield significantly (RVO, 2021c).

7 Conclusion

Our research has been guided by the following research question: *What is the scale of GHG and nitrogen pollutants emissions reduction and net renewable energy generation when implementing manure digesters on Dutch dairy farms?* We answered this question by identifying and answering four sub questions. This section summarises the answers to the four sub questions and the overall question.

The first question - *What are the different steps of manure life cycle on a dairy farm with and without a manure digester?* - was answered in close cooperation with dairy farmers located in Overijssel. With this farm as an expert reference and with academic literature, we designed a system with the different steps common to Dutch dairy farming. By means of different site visits, we calibrated the system and thus allowed for a proper understanding and design of the different steps in the manure life-cycle of dairy farming.

The second research question - *What GHG and N pollutants emissions occur during each step of the manure life cycle on a dairy farm with and without a manure digester?* – was answered by identifying the different emissions in the manure life cycle of dairy farming. The following emissions were identified: the greenhouse gasses CO_2, CH_4 and N_2O and the nitrogen (N) pollutants NH_3 and NO_X. A reduction of GHG is important for reducing climate change and a reduction of N-pollutants contribute to reducing nitrogen emissions in the Netherlands. After identifying the core emissions, we modelled the manure life cycle, to be able to quantitatively analyse the impact of manure digestion on the emission levels in the manure life cycle of dairy farming. We designed the model with the help of the emission accounting standards from EMEP/EEA (Amon et al., 2019; Garcia et al., 2019), IPCC (Dong et al., 2006) and NEMA (Lagerwerf et al., 2019; van Bruggen et al., 2020). These standards have been modified and fine-tuned to make them applicable to dairy farming in the Netherlands at the farm scale. The model was also modified to be able to use data from the KringloopWijzer as model inputs (van Dijk et al., 2020). In this way, we were able to model as realistically as possible, the emissions stemming from the manure life cycle on Dutch dairy farms for two scenarios. The first scenario focuses on common manure management at a dairy farm scale, without manure digestion, where manure is stored in manure cellars. The second scenario contains a manure digester and biogas production.

The model was used to quantify the emission reduction effect of manure digestion and biogas production compared to common manure management of dairy farming without manure digestion. This step in the analysis was guided by the third sub question: *What is the scale of GHG and N-pollutants emissions reduction and the quantity of net renewable energy generation when implementing a digester on the dairy farms studied?*

Thanks to the cooperation of four different dairy farms located in Overijssel, we were able to answer the third question with realistic data of four different dairy farm types. The core result of our analysis is displayed in table 19.

Table 19: An overview of the emission reduction and energy generation results for the four different farms studied in this work.

Results	Farm A	Farm B	Farm C	Farm D
Nitrogen reduction [tonne N] (%)	2.7 (42%)	2.3 (29%)	1.1 (29%)	2.1 (30%)
Methane reduction [tonne CH_4] (%)	5.5 (81%)	6.8 (81%)	3.5 (82%)	8.0 (81%)
Digester: net emissions reduction [tonne CO_2]	51.44	60.38	31.48	69.95
GHG reduction [tonne CO_2-eq.]	306.51	355.87	182.16	397.25
Digester: net electricity production [MWh]	137.83	161.79	84.35	187.43

The first row of the table shows that independent of farming size and circumstances, manure digestion can have a significant effect on the emission of nitrogen pollutants, ranging between a reduction of 29% and

42%. The higher effect on N-reduction at farm A compared to the other three farms, stems from the housing of the animals in low emission housing. These barn types have an extra emission reduction effect additional to manure digestion. If the barns on farms A, B, C and D would have been changed to the lowest emission housing whilst installing the manure digester, the N-emissions of these farms would reduce by 48%, 45%, 44% and 46% respectively. The table also shows the effect of manure digestion on the emission of methane (CH_4) during the manure storage/treatment step. Fresh manure flows constantly into the digester with a significant effect on the emission of methane. Independent of farm type, the reduction can be up to 80%, predominantly caused by the elimination of the long term storage of manure by manure digestion. On every farm type manure digestion also reduces carbon dioxide (CO_2) emissions due to avoiding fossil-based energy sources. With a digester, the farms can supply manure digestion based electricity to some 238 average Dutch households. Together the four farms could have a GHG emission reduction in CO_2-eq. of approximately 1.24 million kg CO_2. These data show the significant effect manure digestion can have on the reduction of greenhouse gases and nitrogen at a farm level.

To answer the fourth research question - *To what extent can manure digester on dairy farms contribute to the climate mitigation and energy transition goals in the Netherlands?* - the farms-scale model needed to be adapted and several assumptions were introduced. We aggregated the farm-based data to the provincial level to calculate the emission reduction and biogas production potential of all 16,000 dairy farms in the Netherlands. The calculations were conducted to determine the impact of the introduction of mono-manure digestion on all Dutch dairy farms. Our provisional analysis resulted in a nitrogen reduction of some 19.3 million kg, methane reduction of 62.8 million kg an avoidance of 562.1 million kg CO_2 and an energy production of 1.51 TWh. The combined reduction of GHG expressed in CO_2-eq. through the introduction of manure digesters in the Netherlands will be 3,268.23 million kg CO_2.

Within methodological limitations, our research holds strong indications that manure digestion incorporates the potential to contribute to the reduction of greenhouse gases and nitrogen (N) pollutants as well as the increase in the availability of renewable-based energy. This holds at the level of an individual dairy farm as well as the aggregated level of all dairy farms in the Netherlands.

References

Achinas, S., Achinas, V., & Euverink, G. J. W. (2020). *Microbiology and biochemistry of anaerobic digesters: An overview*. Elsevier. https://doi.org/10.1016/b978-0-12-821264-6.00002-4

Adekunle, K. F., & Okolie, J. A. (2015). A review of biochemical process of anaerobic digestion. *Advances in Bioscience and Biotechnology*, *06*, 205–212. https://doi.org/10.4236/abb.2015.63020

Adviescollege Stikstofproblematiek. (2019). *Bemesten en beweiden in 2020 [fertilizing and grazing in 2020]*.

Adviescollege Stikstofproblematiek. (2020). *Eindadvies over structurele aanpak adviescollege stikstofproblematiek [final advice on structural approach of the advisory board on nitrogen problems]*. https://www.rijksoverheid.nl/documenten/rapporten/2020/06/08/niet-alles-kan-overal

Aguirre-Villegas, H. A., & Larson, R. A. (2017). Evaluating greenhouse gas emissions from dairy manure management practices using survey data and lifecycle tools. *Journal of Cleaner Production*, *143*, 169–179. https://doi.org/10.1016/j.jclepro.2016.12.133

Amon, B., Hutchings, N., Dämmgen, U., Sommer, S., & Webb, J. (2019). Emep/eea air pollutant emission inventory guidebook 2019 - 3.b manure management.

Baldini, C., Bava, L., Zucali, M., & Guarino, M. (2018). Milk production life cycle assessment: A comparison between estimated and measured emission inventory for manure handling. *Science of The Total Environment*, *625*, 209–219. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.12.261

Barampouti, E. M., Mai, S., Malamis, D., Moustakas, K., & Loizidou, M. (2020). Exploring technological alternatives of nutrient recovery from digestate as a secondary resource. *Renewable and Sustainable Energy Reviews*, *134*, 110379. https://doi.org/10.1016/J.RSER.2020.110379

Blengini, G., Brizio, E., Cibrario, M., & Genon, G. (2011). Lca of bioenergy chains in piedmont (italy): A case study to support public decision makers towards sustainability. *Resources, Conservation and Recycling*, *57*, 36–47.

CBS. (2017). *Overschrijding fosfaatplafond daalt met 4,5 miljoen kg*. https://www.cbs.nl/nl-nl/nieuws/2017/17/overschrijding-fosfaatplafond-daalt-met-4-5-miljoen-kg

CBS. (2020a). Dierlijke mest en mineralen 2019. Retrieved February 23, 2021, from https://longreads.cbs.nl/dierlijke-mest-en-mineralen-2019/

CBS. (2020b). *Melkkoeien en melkgeiten per grootteklasse, 2000-2019*. Retrieved July 4, 2021, from https://www.cbs.nl/nl-nl/maatwerk/2020/12/melkkoeien-en-melkgeiten-per-grootteklasse-2000-2019

CBS. (2020c). *Stikstofemissies naar lucht*. Retrieved November 16, 2021, from https://www.cbs.nl/nl-nl/dossier/dossier-stikstof/stikstofemissies-naar-lucht

CBS. (2021a). *Statline - landbouw; gewassen, dieren en grondgebruik naar regio*. Retrieved October 11, 2021, from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/80780ned/table?ts=1634632481200

CBS. (2021b). *Statline - weidegang van melkvee; gve-klasse, regio*. Retrieved October 11, 2021, from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83953NED/table?ts=1634571672449

Dämmgen, U., & Hutchings, N. J. (2008). Emissions of gaseous nitrogen species from manure management: A new approach. *Environmental Pollution*, *154*, 488–497. https://doi.org/10.1016/j.envpol.2007.03.017

Dong, H., Mangino, J., McAllister, T. A., Hatfield, J. L., Johnson, D. E., Bartram, D., Gibb, D., & Martin, J. H. (2006). *2006 ipcc guidelines for national greenhouse gas inventories - chapter 10: Emissions from livestock and manure management*. IPCC.

Doyeni, M. O., Stulpinaite, U., Baksinskaite, A., Suproniene, S., & Tilvikiene, V. (2021). The effectiveness of digestate use for fertilization in an agricultural cropping system. *Plants*, *10*. https://doi.org/10.3390/plants10081734

Engineering ToolBox. (2003). *Fuels - higher and lower calorific values*. Retrieved October 10, 2021, from https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

Environmental Data Compendium. (2019). *Nitrogen deposition, 1990-2018*. Retrieved November 16, 2021, from https://www.clo.nl/en/indicators/en0189-nitrogen-deposition

Estrada, A., & Voogt, F. (2020). *Handvol agrarische bedrijven houdt nederland op slot - investico*. Retrieved February 12, 2021, from https://www.platform-investico.nl/artikel/handvol-agrarische-bedrijven-houdt-nederland-op-slot/

Etcheverry, C. (2014). *Enteric fermentation*. Retrieved February 23, 2021, from https://www.ccacoalition.org/en/activity/enteric-fermentation

European Commission. (2020). *Eu strategy to reduce methane emissions*. EU. Retrieved February 9, 2021, from https://www.eea.europa.eu/media/newsreleases/many-europeans-still-exposed-to-air-pollution-2015/premature-

Fuchs, W., & Drosg, B. (2013). Assessment of the state of the art of technologies for the processing of digestate residue from anaerobic digesters. *Water Science and Technology*, *67*, 1984–1993. https://doi.org/10.2166/WST.2013.075

Garcia, J. M. R., Barbara Amon, J. W., Broomfield, M., Haenel, H.-D., Wulf, S., & Hutchings, N. (2019). Emep/eea air pollutant emission inventory guidebook 2019 - 5.b.2 biological treatment.

Gebrezgabher, S. A., Meuwissen, M. P., & Lansink, A. G. O. (2010). Costs of producing biogas at dairy farms in the netherlands. *International Journal on Food System Dynamics*, *1*, 26–35. https://doi.org/10.22004/AG.ECON.91139

Gebrezgabher, S. A., Meuwissen, M. P., & Lansink, A. G. O. (2012). Energy-neutral dairy chain in the netherlands: An economic feasibility analysis. *Biomass and Bioenergy*, *36*, 60–68. https://doi.org/10.1016/j.biombioe.2011.10.006

Groenestein, C. M., Mosquera, J., & Meise, R. W. (2016). Methaanemissie uit mest schatters voor biochemisch methaan potentieel (bmp) en methaanconversiefactor (mcf). www.wageningenUR.nl/livestockresearch

Groenestein, K., Melse, R. W., Mosquera, J., & Timmerman, M. (2020). Effect mestvergisting op de emissies van broeikasgassen uit mest van melkvee een literatuur-en scenariostudie.

Hamelin, L., Naroznova, I., & Wenzel, H. (2014). Environmental consequences of different carbon alternatives for increased manure-based biogas. *Applied Energy*, *114*, 774–782.

Haque, M. N. (2018). Dietary manipulation: A sustainable way to mitigate methane emissions from ruminants. *Journal of Animal Science and Technology*, *60*. https://doi.org/10.1186/S40781-018-0175-7

Herbes, C., Roth, U., Wulf, S., & Dahlin, J. (2020). Economic assessment of different biogas digestate processing technologies: A scenario-based analysis. *Journal of Cleaner Production*, *255*, 120282. https://doi.org/10.1016/J.JCLEPRO.2020.120282

Hjort-Gregersen, K. (2014). Methane emission from danish biogas plants economic impact of identified methane leakages.

Hoekstra, A. Y. (2020). The energy transition: How to combine carbon and water footprint reduction? *The water footprint of modern consumer society* (pp. 96–114). Routledge, Taylor & Francis Group.

Hou, Y., Velthof, G. L., & Oenema, O. (2015). Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: A meta-analysis and integrated assessment. *Global Change Biology*, *21*, 1293–1312. https://doi.org/10.1111/gcb.12767

IEA. (2020). *Energy technology perspectives 2020*. Retrieved December 9, 2020, from https://www.iea.org/reports/energy-technology-perspectives-2020

IPCC. (2018). *Global warming of 1.5°c. an ipcc special report on the impacts of global warming of 1.5°c above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Retrieved December 9, 2020, from https://www.ipcc.ch/sr15/

Jukema, G., Ramaekers, P., & Berkhout, P. (2021). De nederlandse agrarische sector in internationaal verband - editie 2021. https://doi.org/10.18174/538688

Kok, A., Oostvogels, V. J., de Olde, E. M., & Ripoll-Bosch, R. (2020). Balancing biodiversity and agriculture: Conservation scenarios for the dutch dairy sector. *Agriculture, Ecosystems & Environment*, *302*, 107103. https://doi.org/10.1016/J.AGEE.2020.107103

Lagerwerf, L., Bannink, A., van Bruggen, C., Groenestein, C., Huijsmans, J., van der Kolk, J., Luesink, H., van der Sluis, S., Velthof, G., & Vonk, J. (2019). *Methodology for estimating emissions from agriculture in the netherlands : Calculations of ch4, nh3, n2o, nox, nmvoc, pm10, pm2.5 and co2 with the national emission model for agriculture (nema), update 2019*. https://doi.org/10.18174/472366

Liu, D., Guo, X., & Xiao, B. (2019). What causes growth of global greenhouse gas emissions? evidence from 40 countries. *Science of The Total Environment*, *661*, 750–766. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.01.197

loket emissieregistratie, R. (2020). *Emissieregistratie*. Retrieved November 10, 2021, from http://www.emissieregistratie.nl/erpubliek/erpub/weergave/grafiek.aspx

Marañón, E., Salter, A. M., Castrillón, L., Heaven, S., & Fernández-Nava, Y. (2011). Reducing the environmental impact of methane emissions from dairy farms by anaerobic digestion of cattle waste. *Waste Management*, *31*, 1745–1751. https://doi.org/10.1016/j.wasman.2011.03.015

Ministerie van Landbouw Natuur en Voedselkwaliteit. (2021). *Maatregelen landbouw — landbouw — aanpak stikstof*. Retrieved November 10, 2021, from https://www.aanpakstikstof.nl/themas/landbouw/maatregelen

Ministry of Agriculture Nature and Food Quality. (n.d.). *Vision ministry of agriculture, nature and food quality*. Retrieved February 12, 2021, from https://www.government.nl/ministries/ministry-of-agriculture-nature-and-food-quality/vision-anf

Miranda, N. D., Granell, R., Tuomisto, H. L., & McCulloch, M. D. (2016). Meta-analysis of methane yields from anaerobic digestion of dairy cattle manure. *Biomass and Bioenergy*, *86*, 65–75. https://doi.org/10.1016/J.BIOMBIOE.2016.01.012

Miranda, N. D., Tuomisto, H. L., & McCulloch, M. D. (2015). Meta-analysis of greenhouse gas emissions from anaerobic digestion processes in dairy farms. *Environmental Science and Technology*, *49*, 5211–5219. https://doi.org/10.1021/acs.est.5b00018

Moset, V., Wahid, R., Ward, A., & Møller, H. (2018). Modelling methane emission mitigation by anaerobic digestion: Effect of storage conditions and co-digestion. *https://doi.org/10.1080/09593330.2018.1447999*, *40*, 2633–2642. https://doi.org/10.1080/09593330.2018.1447999

Nationaal Programma Regionale Energie Strategieën. (2021). *Nationaal programma regionale energiestrategie - regionale energiestrategie*. Retrieved November 11, 2021, from https://regionale-energiestrategie.nl/default.aspx

NIBUD. (2021). *Energie en water - nibud - nationaal instituut voor budgetvoorlichting*. Retrieved October 28, 2021, from https://www.nibud.nl/consumenten/energie-en-water/

NOS. (2020, August 6). *Commissie kraakt nieuwe stikstofaanpak kabinet*. Retrieved January 19, 2021, from https://nos.nl/artikel/2336574-commissie-kraakt-nieuwe-stikstofaanpak-kabinet.html

Oenema, O. (2020). Cdm-advies 'stikstofverliezen uit mest in stallen en mestopslagen'.

Oenema, O., Kros, H., & Vries, W. D. (2003). Approaches and uncertainties in nutrient budgets: Implications for nutrient management and environmental policies [*In]. *European Journal of Agronomy*, *20*, 3–16. https://doi.org/10.1016/S1161-0301(03)00067-4

Ortiz, P. S., Flórez-Orrego, D., de Oliveira Junior, S., Filho, R. M., Osseweijer, P., & Posada, J. (2020). Unit exergy cost and specific co2 emissions of the electricity generation in the netherlands. *Energy*, *208*, 118279. https://doi.org/10.1016/j.energy.2020.118279

Paul, H. (2021). *Stikstofruimte voor de toekomst*.

Piñas, J. A. V., Venturini, O. J., Lora, E. E. S., & Roalcaba, O. D. C. (2018). Technical assessment of mono-digestion and co-digestion systems for the production of biogas from anaerobic digestion in brazil. *Renewable Energy*, *117*, 447–458. https://doi.org/10.1016/J.RENENE.2017.10.085

Post, P. M., Hogerwerf, L., Bokkers, E. A., Baumann, B., Fischer, P., Rutledge-Jonker, S., Hilderink, H., Hollander, A., Hoogsteen, M. J., Liebman, A., Mangen, M. J. J., Manuel, H. J., Mughini-Gras, L., van Poll, R., Posthuma, L., van Pul, A., Rutgers, M., Schmitt, H., van Steenbergen, J., . . . de Boer, I. J. (2020). Effects of dutch livestock production on human health and the environment. *Science of The Total Environment*, *737*, 139702. https://doi.org/10.1016/J.SCITOTENV.2020.139702

Provincie Overijssel. (2020). *Agro food*. Retrieved November 10, 2021, from https://www.overijssel.nl/onderwerpen/economie/innovatie/agro-food/

Risberg, K., Cederlund, H., Pell, M., Arthurson, V., & Schnürer, A. (2017). Comparative characterization of digestate versus pig slurry and cow manure – chemical composition and effects on soil microbial activity. *Waste Management*, *61*, 529–538. https://doi.org/10.1016/j.wasman.2016.12.016

Ritchie, H., & Roser, M. (2020). *Emissions by sector - our world in data*. Retrieved February 4, 2021, from https://ourworldindata.org/emissions-by-sector

RVO. (2020). *Hoeveel dierlijke mest landbouwgrond*. Retrieved July 23, 2021, from https://www.rvo.nl/onderwerpen/agrarisch-ondernemen/mest/gebruiken-en-uitrijden/hoeveel-dierlijke-mest-landbouwgrond

RVO. (2021a). *Derogatie*. Retrieved September 28, 2021, from https://www.rvo.nl/onderwerpen/agrarisch-ondernemen/mest/derogatie

RVO. (2021b). *Digestaat als mest gebruiken*. Retrieved July 23, 2021, from https://www.rvo.nl/onderwerpen/agrarisch-ondernemen/mest/mest-bewerken/digestaat-als-mest-gebruiken

RVO. (2021c). *Technieken vergisting*. Retrieved November 18, 2021, from https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/duurzame-energie-opwekken/bio-energie/vergisting-en-vergassing/technieken-vergisting

RVO. (2021d). *Wanneer mest uitrijden*. Retrieved August 10, 2021, from https://www.rvo.nl/onderwerpen/agrarisch-ondernemen/mest/gebruiken-en-uitrijden/wanneer-mest-uitrijden

Sajeev, E. P. M., Winiwarter, W., & Amon, B. (2018). Greenhouse gas and ammonia emissions from different stages of liquid manure management chains: Abatement options and emission interactions. *Journal of Environmental Quality*, *47*, 30–41. https://doi.org/10.2134/jeq2017.05.0199

Schlömer, S., Bruckner, T., Fulton, L., Austria, E. H., McKinnon, A. U., Perczyk, D., Roy, J., Schaeffer, R., Hänsel, G., de Jager, D., Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., Roy, J., Schaeffer, R., Sims, R., Smith, P., ... Minx, J. (2014). Iii annex technology-specific cost and performance parameters to the fifth assessment report of the intergovernmental panel on climate change.

Seppälä, M., Pyykkönen, V., Väisänen, A., & Rintala, J. (2013). Biomethane production from maize and liquid cow manure - effect of share of maize, post-methanation potential and digestate characteristics. *Fuel*, *107*, 209–216. https://doi.org/10.1016/j.fuel.2012.12.069

Shindell, D., Bréon, F.-m., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-f., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., Qin, D., Plattner, G.-k., Tignor, M., Allen, S., Boschung, J., ... Midgley, P. (2013). Anthropogenic and natural radiative forc-ing. in: Climate change 2013: The physical science basis. contribution of working group i.

Sigurnjak, I., Vaneeckhaute, C., Michels, E., Ryckaert, B., Ghekiere, G., Tack, F. M., & Meers, E. (2017). Fertilizer performance of liquid fraction of digestate as synthetic nitrogen substitute in silage maize cultivation for three consecutive years. *Science of The Total Environment*, *599-600*, 1885–1894. https://doi.org/10.1016/J.SCITOTENV.2017.05.120

Tambone, F., Scaglia, B., D'Imporzano, G., Schievano, A., Orzi, V., Salati, S., & Adani, F. (2010). Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost [Digestate composition information. However, not focussed on dairy]. *Chemosphere*, *81*, 577–583. https://doi.org/10.1016/j.chemosphere.2010.08.034

UNFCCC. (2016). *The paris agreement*. Retrieved February 12, 2021, from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

U.S. Environmental Protection Agency. (2021). *Inventory of u.s. greenhouse gas emissions and sinks*. Retrieved October 10, 2021, from https://www.eia.gov/environment/emissions/co2_vol_mass.php

van Bruggen, C., Bannink, A., Groenestein, C., Huijsmans, J., Lagerwerf, L., Luesink, H., Velthof, G., & Vonk, J. (2020). *Emissies naar lucht uit de landbouw,1990-2018 : Berekeningen met het model nema*. https://doi.org/10.18174/521575

van Dijk, W., de Boer, J., de Haan, M., Mostert, P., Oenema, J., & Verloop, J. (2020). *Rekenregels van de kringloopwijzer 2020*. https://doi.org/10.18174/533882

van Grinsven, H. J., van Eerdt, M. M., Westhoek, H., & Kruitwagen, S. (2019). Benchmarking eco-efficiency and footprints of dutch agriculture in european context and implications for policies for climate and environment. *Frontiers in Sustainable Food Systems*, *3*, 13. https://doi.org/10.3389/FSUFS.2019.00013/BIBTEX

van Well, E. (2021). *Mineral valley twente: Data-analyse bedrijven*. www.clm.nl

Viviano, F. (2017). *How the netherlands feeds the world*. Retrieved February 23, 2021, from https://www.nationalgeographic.com/magazine/article/holland-agriculture-sustainable-farming

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software*, *25*(11), 1268–1281. https://doi.org/https://doi.org/10.1016/j.envsoft.2010.03.007

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., & Ramu, P. (2016). Modelling with stakeholders – next generation. *Environmental Modelling & Software*, *77*, 196–220. https://doi.org/https://doi.org/10.1016/j.envsoft.2015.11.016

Walsh, J. J., Jones, D. L., Edwards-Jones, G., & Williams, A. P. (2012). Replacing inorganic fertilizer with anaerobic digestate may maintain agricultural productivity at less environmental cost. *Journal of Plant Nutrition and Soil Science*, *175*, 840–845. https://doi.org/10.1002/JPLN.201200214

Webb, J., Sommer, S. G., Kupper, T., Groenestein, K., Hutchings, N. J., Eurich-Menden, B., Rodhe, L., Misselbrook, T. H., & Amon, B. (2012). Emissions of ammonia, nitrous oxide and methane during the management of solid manures. *Agroecology and Strategies for Climate Change*, 67–107. https://doi.org/10.1007/978-94-007-1905-7_4

Well, E. V., & Rougoor, C. (2017). Landbouw en klimaat-verandering in overijssel. Retrieved November 10, 2021, from www.clm.nl

Wet Ammoniak en veehouderij. (2002). *Regeling ammoniak en veehouderij*. Retrieved June 3, 2021, from https://wetten.overheid.nl/BWBR0013629/2020-11-21

Zeeman, G. (1994). Methane production/emission in storages for animal manure. *Fertilizer Research*, *37*, 207–211.

Zeeman, G., & Gerbens, S. (2003). Ch4 emission from animal manure. *IPCC: Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Retrieved October 28, 2021, from https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_3_CH4_Animal_Manure.pdf

Zijlema, P. (2020). The netherlands: List of fuels and standard co2 emission factors. Retrieved October 10, 2021, from https://english.rvo.nl/sites/default/files/2020/03/The-Netherlands-list-of-fuels-version-January-2020.pdf

ZuivelNL. (2020). *Zuivel in cijfers*. Retrieved September 28, 2021, from https://www.zuivelnl.org/marktinformatie/zuivel-in-cijfers

Appendices

List of Symbols for Appendix A

$\%_{slurry\,cattle}$ percentage manure excreted by dairy cattle as a slurry [-]

$\%_{slurry\,young\,stock\,\leq 1}$ percentage manure excreted by young stock younger than 1 year as a slurry [-]

$\%_{slurry\,young\,stock\,>1}$ percentage manure excreted by young stock older than 1 year as a slurry [-]

d_{graz} length of the grazing period $[days]$

$E_{applic\,slurry\,N_2O}$ emissions from slurry during field application $[kgN_2O - N]$

$E_{applic\,slurry\,NH_3}$ emissions from slurry during field application $[kgNH_3 - N]$

$E_{applic\,slurry\,NO_x}$ emissions from slurry during field application $[kgNO_2 - N]$

$E_{applic\,solid\,N_2O}$ emissions from solid during field application $[kgN_2O - N]$

$E_{applic\,solid\,\,NH_3}$ emissions from solid during field application $[kgNH_3 - N]$

$E_{applic\,solid\,NO_x}$ emissions during from solid field application $[kgNO_2 - N]$

$E_{dig\,total\,NH_3}$ emissions from the digestion process $[kgNH_3 - N]$

$E_{graz\,N_2O}$ N_2O emissions during grazing $[kgN_2O - N]$

$E_{graz\,NH_3}$ NH_3 emissions during grazing $[kgNH_3 - N]$

$E_{graz\,NO_x}$ NO_X emissions during grazing $[kgNO_2 - N]$

$E_{hous\,slurry\,NH_3}$ emissions from slurry during housing $[kgNH_3 - N]$

$E_{hous\,solid\,NH_3}$ emissions from solid during housing $[kgNH_3 - N]$

$E_{storage\,slurry\,N_2}$ emissions from slurry during storage $[kgN_2]$

$E_{storage\,slurry\,N_2O}$ emissions from slurry during storage $[kgN_2O - N]$

$E_{storage\,slurry\,NH_3}$ emissions from slurry during storage $[kgNH_3 - N]$

$E_{storage\,slurry\,NO}$ emissions from slurry during storage $[kgNO - N]$

$E_{storage\,solid\,N_2}$ emissions from solid during storage $[kgN_2]$

$E_{storage\,solid\,N_2O}$ emissions from solid during storage $[kgN_2O - N]$

$E_{storage\,solid\,NH_3}$ emissions from solid during storage []

$E_{storage\,solid\,NO}$ emissions from solid during storage $[kgNO - N]$

$EF_{applic\,slurry\,N_2O}$ emission factor for slurry during field application $[N_2O - N]$

$EF_{applic\,slurry\,NH_3}$ emission factor for slurry during field application $[NH_3 - N]$

$EF_{applic\,slurry\,NO_x}$ emission factor for slurry during field application $[NO_2 - N]$

$EF_{applic\,solid\,N_2O}$ emission factor for solid during field application $[N_2O - N]$

$EF_{applic\,solid\,NH_3}$ emission factor for solid during field application $[NH_3 - N]$

$EF_{applic\,solid\,NO_x}$ emission factor for solid during field application $[NO_2 - N]$

$EF_{digestate\,storage\,NH_3}$ emission factor for digestate storage post digestion $[NH_3 - N]$

$EF_{graz\,N_2O}$ N_2O emission factor during grazing $[N_2O - N]$

$EF_{graz\,NH_3}$ NH_3 emission factor during grazing $[NH_3 - N]$

$EF_{graz\,NO_x}$ NO_X emission factor during grazing $[NO_2 - N]$

$EF_{hous\,slurry\,NH_3}$ emission factor for slurry during housing $[NH_3 - N]$

$EF_{hous\,solid\,NH_3}$ emission factor for solid during housing $[NH_3 - N]$

$EF_{pre-storage\,NH_3}$ emission factor for manure storage pre digestion $[NH_3 - N]$

$EF_{storage\,slurry\,N_2}$ emission factor for slurry during storage $[N_2]$

$EF_{storage\,slurry\,N_2O}$ emission factor for slurry during storage $[N_2O - N]$

$EF_{storage\,slurry\,NH_3}$ emission factor for slurry during storage $[NH_3 - N]$

$EF_{storage\,slurry\,NO}$ emission factor for slurry during storage $[NO - N]$

$EF_{storage\,solid\,N_2}$ emission factor for solid during storage $[N_2]$

$EF_{storage\,solid\,N_2O}$ emission factor for solid during storage $[N_2O - N]$

$EF_{storage\,solid\,NH_3}$ emission factor for solid during storage $[NH_3 - N]$

$EF_{storage\,solid\,NO}$ emission factor for solid during storage $[NO - N]$

f_{imm} fraction of TAN that immobilised to organic N $[-]$

f_{min} fraction of organic N that mineralises to TAN $[-]$

$f_{min\,biogas}$ relative share of organic N entering then digester that is mineralised to TAN in the digester $[kgN\,kg^{-1}]$

GVE_{cattle} Conversion factor for dairy cattle into GVE $[-]$

$GVE_{young\,stock\,>1}$ Conversion factor for young stock older than 1 year into GVE $[-]$

$GVE_{young\,stock\,>\leq 1}$ Conversion factor for young stock younger than 1 year into GVE $[-]$

h_{graz} hours spend grazing per day $[hours]$

$ha_{cropland}$ Hectares of cropland on the farm. $[ha]$

$ha_{grassland}$ Hectares of grassland on the farm. $[ha]$

ha_{other} the amount hectares of soil types that are not loess or sand $[ha]$

$ha_{sand\,\&\,loess}$ the amount hectares of soil types loess or sand $[ha]$

$m_{applic\,room\,N}$ room for N being able to be added as fertiliser $[kg]$

$m_{applic\,slurry\,N}$ the amount of N applied to fields $[kg]$

$m_{applic\,slurry\,TAN}$ the amount of TAN applied to fields $[kg]$

$m_{applic\,solid\,N}$ the amount of N applied to fields $[kg]$

$m_{applic\,solid\,TAN}$ the amount of TAN applied to fields $[kg]$

$m_{applic\,used\,N}$ total amount of N used as fertiliser $[kg]$

$m_{dig\,feed\,N}$ the total annual amount of N in the digester feedstock $[kg]$

$m_{dig\,feed\,TAN}$ the total annual amount of TAN in the digester feedstock $[kg]$

$m_{dig\,N}$ the amount of N in digestate after digestion $[kg]$

$m_{dig\,TAN}$ the amount of TAN in digestate after digestion $[kg]$

$m_{export\,N}$ the amount of N exported of the farm $[kg]$

$m_{export\,TAN}$ the amount of TAN exported of the farm $[kg]$

$m_{graz\,N}$ amount of N excreted during grazing $[kg]$

$m_{graz\,TAN}$ amount of TAN excreted during grazing $[kg]$

$m_{hous\,N}$ amount of N excreted during housing $[kg]$

$m_{hous\,slurry\,N}$ total amount of N excreted as slurry during housing $[kg]$

$m_{hous\,slurry\,TAN}$ amount of TAN excreted as slurry during housing $[kg]$

$m_{hous\,solid\,N}$ total amount of N excreted as solid during housing $[kg]$

$m_{hous\,solid\,TAN}$ amount of TAN excreted as solid during housing $[kg]$

$m_{hous\,TAN}$ amount of TAN excreted during housing $[kg]$

$m_{max\,allowed\,N}$ the amount of N that is maximum allowed to be applied to the fields $[kg]$

$m_{returned\,grazing\,N}$ TAN returned to soil after grazing $[kg]$

$m_{returned\,grazing\,TAN}$ N returned to soil after grazing $[kg]$

$m_{returned\,slurry\,N}$ the amount of N returned to the soil $[kg]$

$m_{returned\,slurry\,TAN}$ the amount of TAN returned to the soil $[kg]$

$m_{returned\,solid\,N}$ the amount of N returned to the soil $[kg]$

$m_{returned\,solid\,TAN}$ the amount of TAN returned to the soil $[kg]$

$m_{storage\,slurry\,N}$ total amount of N present as slurry during storage $[kg]$

$m_{storage\,slurry\,TAN}$ amount of TAN present as slurry during storage $[kg]$

$m_{storage\,solid\,N}$ total amount of N present as solid during storage $[kg]$

$m_{storage\,solid\,TAN}$ amount of TAN present as solid during storage $[kg]$

$m_{t\&s\,slurry\,N}$ total amount of N entering treatment & storage as slurry $[kg]$

$m_{t\&s\,slurry\,TAN}$ amount of TAN entering treatment & storage as slurry $[kg]$

$m_{t\&s\,solid\,N}$ total amount of N entering treatment & storage as solid $[kg]$

$m_{t\&s\,solid\,TAN}$ amount of TAN entering treatment & storage as solid $[kg]$

$mm_{hous\,slurry\,TAN}$ amount of TAN from slurry manure adjusted for the occurring mineralisation $[kg]$

$mm_{hous\,solid\,TAN}$ amount of TAN from solid manure adjusted for the occurring immobilisation $[kg]$

N_{cattle} Number of dairy cattle $[-]$

N_{ex} total N excretion per year $[kg\,N]$

$N_{ex\,TAN}$ Amount of N excreted as TAN $[kg\,N]$

N_{GVE} Number of GVE $[-]$

N_{waste} Nitrogen content of agricultural waste $[kgN]$

$N_{young\,stock\,\leq 1}$ Number of young stock younger than 1 year $[-]$

$N_{young\,stock\,>1}$ Number of young stock older than 1 year $[-]$

x_{graz} fraction of time per year spend grazing [-]

x_{slurry} fraction manure excreted as a slurry [-]

$x_{slurry\,cattle}$ fraction manure excreted by dairy cattle as a slurry [-]

$x_{slurry\,young\,stock\,\leq 1}$ fraction manure excreted by young stock younger than 1 year as a slurry [-]

$x_{slurry\,young\,stock\,>1}$ fraction manure excreted by young stock older than 1 year as a slurry [-]

x_{TAN} fraction of N excreted as TAN [-]

A Nitrogen Emission Calculations during Manure Management

This appendix describes the step by step approach for the calculation of nitrogen related emissions during the manure management portion of the manure life cycle. See section 3.3, specifically figure 10, for the description of the process and the links between the process steps. The methodology used here is specifically developed to asses emissions on Dutch dairy farms based upon the work of Amon et al. (2019). Specific changes to this method were made to tailor this methodology to the Dutch context from the works of Lagerwerf et al. (2019) and van Dijk et al. (2020) and to incorporate the manure digester (Garcia et al., 2019).

The complete methodology works on a combination of farm-specific inputs and system data. Farm-specific inputs varies per farm, such as the number of dairy cattle or hectares of farmland, and requires a manual input. The majority of the farm-specific inputs can be found in the KringloopWijzer. The system data is assumed to be constant for all dairy farms in the Netherlands or calculated based on farm specific inputs. The following sections will each discuss a step in the manure management N mass balance. These steps correspond with the steps in the model as discussed in section 3.3 and the use of farm or system specific data is indicated throughout the steps.

A.1 Manure Excretion location

The first step in the process is to determine where the excretion of manure takes place. The method by the EEA takes three locations into account: grazing, housing and yard. However, it is unknown to what extent the cattle spend time on the yard according to Amon et al. (2019) and the emission data of these steps are the most unreliable. Furthermore, both the KringloopWijzer and research conducted by Lagerwerf et al. (2019) only have grazing and housing classifications, thus the decision has been made to remove the yard category from this work.

The first step in determining the amount of nitrogen excreted during housing and grazing is to determine how much time dairy cattle spend on these two activities. This is done by gathering the first two farm specific inputs from the KringloopWijzer. These two are the d_{graz} and h_{graz}, which describe the days of the grazing period and hours per day spend grazing during the grazing period respectively. They are used to determine x_{graz}, the fraction of time per year spend by cattle grazing, with the equations below.

$$x_{graz} = (d_{graz} \cdot h_{graz})/(365 \cdot 24) \tag{A.1}$$

With this known, the manure can be divided according to the two activities assuming that the manure is excreted equally over time throughout the year. The excreted manure per year has a certain amount of kg nitrogen in it (N_{ex}). This information is extracted from the KringloopWijzer together with the amount of nitrogen (in kg) added to manure during housing as waste (N_{waste}). Thus the equations to determine the mass of nitrogen excreted during grazing ($m_{graz\,N}$) and housing ($m_{hous\,N}$) are:

$$m_{graz\,N} = x_{graz} \cdot N_{ex} \tag{A.2}$$

$$m_{house\,N} = (1 - x_{graz}) \cdot N_{ex} + N_{waste} \tag{A.3}$$

A.2 TAN Excretion

For certain nitrogen emissions from manure the TAN, not the total amount of N, is used since this is a more accurate measurement (Lagerwerf et al., 2019). Thus, the next step is to determine the TAN fraction in manure. The KringloopWijzer provides the total amount of TAN in kg ($N_{ex\,TAN}$) which can be divide by N_{ex} to get the TAN fraction (x_{TAN}).

$$x_{TAN} = N_{ex\,TAN}/N_{ex} \tag{A.4}$$

With the $m_{graz\,N}$, $m_{hous\,N}$ the TAN fraction known, the total amount of TAN in both locations can be determined. The average TAN value for dairy cows in the Netherlands is 0.55 (van Bruggen et al., 2020).

$$m_{graz\,TAN} = x_{TAN} \cdot m_{graz\,N} \tag{A.5}$$

$$m_{hous\,TAN} = x_{TAN} \cdot m_{hous\,N} \tag{A.6}$$

A.3 Emissions from Grazing

The single emission calculation step for grazing includes includes NH_3, NO_X and N_2O emissions of which the former is based on TAN and the latter two on the total-N. During grazing there is no split between fraction and the freshly excreted manure is directly used as fertiliser on grasslands.

$$E_{graz\,NH_3} = m_{graz\,TAN} * EF_{graz\,NH_3} \tag{A.7}$$

$$E_{graz\,NO_x} = m_{graz\,N} * EF_{graz\,NO_x} \tag{A.8}$$

$$E_{graz\,N_2O} = m_{graz\,N} * EF_{graz\,N_2O} \tag{A.9}$$

$$m_{graz\,returned\,TAN} = m_{graz\,TAN} - (E_{graz\,NH_3} + E_{graz\,NO_x} + E_{graz\,N_2O}) \tag{A.10}$$

$$m_{graz\,returned\,N} = m_{graz\,N} - (E_{graz\,NH_3} + E_{graz\,NO_x} + E_{graz\,N_2O}) \tag{A.11}$$

A.4 Housing Slurry & Solid Fractions

The manure excreted during housing consist of slurry and solid fractions. On average 98% of all manure produced during housing on a dairy farm is stored as slurry (van Bruggen et al., 2020). This step determines the amount of N and TAN excreted as either a solid or slurry during housing. This is done based on the fraction of manure excreted as a slurry (x_{slurry}), which is the weighted average of the slurry fractions of dairy cattle and young stock categories based on number of livestock and emission impact.

$$x_{slurry\,cattle} = (\%_{slurry\,cattle}/100 * N_{cattle} * GVE_{cattle})/N_{GVE} \tag{A.12}$$

$$x_{slurry\,slurry\,young\,stock>1} = (\%_{slurry\,slurry\,young\,stock>1}/100* \\ N_{young\,stock>1} * GVE_{young\,stock>1})/N_{GVE} \tag{A.13}$$

$$x_{slurry\,young\,stock\leq1} = (\%_{slurry\,young\,stock\leq1}/100* \\ N_{young\,stock\leq1} * GVE_{young\,stock\leq1})/N_{GVE} \tag{A.14}$$

$$x_{slurry} = x_{slurry\,cattle} + x_{slurry\,young\,stock>1} + x_{slurry\,young\,stock\leq1} \tag{A.15}$$

$$m_{hous\,slurry\,TAN} = x_{slurry} \cdot m_{hous\,TAN} \tag{A.16}$$

$$m_{hous\,solid\,TAN} = (1 - x_{slurry}) \cdot m_{hous\,TAN} \tag{A.17}$$

$$m_{hous\,slurry\,N} = x_{slurry} \cdot m_{hous\,N} \tag{A.18}$$

$$m_{hous\,solid\,N} = (1 - x_{slurry}) \cdot m_{hous\,N} \tag{A.19}$$

A.5 Mineralisation and Immobilisation of TAN

After the excretion of manure during housing both mineralisation and immobilisation occur in the slurry the solid fraction of manure respectively. This leads to an increase in the TAN in the slurry fraction and a decrease in the solid fraction. These value are shown in table 20 and are used in the equations below.

Table 20: The mineralisation and immobilisation values used during manure management.

Symbol	Value	Unit	Source
f_{min}	0.10	Fraction of organic N excretion	Lagerwerf et al., 2019
f_{imm}	0.25	Fraction of organic N excretion	Lagerwerf et al., 2019
$f_{min\,biogas}$	0.32	kg N/kg	Garcia et al., 2019

$$mm_{hous\,slurry\,TAN} = m_{hous\,slurry\,TAN} + (m_{hous\,slurry\,TAN} \cdot (1 - x_{TAN}) \cdot f_{min}) \tag{A.20}$$

$$mm_{hous\,solid\,TAN} = m_{hous\,solid\,TAN} - (m_{hous\,solid\,TAN} \cdot f_{imm}) \tag{A.21}$$

A.6 Emissions from livestock housing

The only nitrogen related pollutant is NH_3 and this emission ($E_{hous\,NH_3}$), in kg NH_3-N, can be determined for both the slurry and solid fraction with the emission factor for housing ($EF_{hous\,NH_3}$). This EF is farm specific, but does not differ between slurry and solid fraction of manure so both use the same EF. The housing EF is calculated based upon a emission standard and a the conversion factor based on the type of housing use. The exact housing EF calculation is explained in appendix B.

$$E_{hous\,slurry\,NH_3} = mm_{hous\,slurry\,TAN} \cdot EF_{hous\,NH_3} \tag{A.22}$$

$$E_{hous\,solid\,NH_3} = mm_{hous\,solid\,TAN} \cdot EF_{hous\,NH_3} \tag{A.23}$$

A.7 Manure entering Storage & Treatment

After excretion during housing, manure can be used in different ways. The traditional way, without a digester, sees the manure being stored until it is used as fertiliser. However, with the implementation of a digester on a dairy farm it is assumed that all manure is fed into the digester to generate biogas. The byproduct of this process is digestate which can also be used as fertiliser. In both cases, the manure entering the treatment & storage step has released the same amount of emissions during the housing step. The total-N and TAN going into this step are calculated as follows.

$$m_{t\&s\,slurry\,TAN} = mm_{hous\,slurry\,TAN} - E_{hous\,slurry\,NH_3} \tag{A.24}$$

$$m_{t\&s\,slurry\,N} = m_{hous\,slurry\,N} - E_{hous\,slurry\,NH_3} \tag{A.25}$$

$$m_{t\&s\,solid\,TAN} = mm_{hous\,solid\,TAN} - E_{hous\,solid\,NH_3} \tag{A.26}$$

$$m_{t\&s\,solid\,N} = mm_{hous\,solid\,N} - E_{hous\,solid\,NH_3} \tag{A.27}$$

A.8 Storage Emissions

Without a manure digester, both manure fractions are simply stored over a long time. Throughout this whole time nitrogen emissions are released. In this case it are NH_3, N_2O, NO and N_2 emissions for both fractions. This lead to eight different emission calculations with eight different EFs, which can be found in appendix C.

$$E_{storage\,slurry\,NH_3} = m_{t\&s\,slurry\,TAN} \cdot EF_{storage\,slurry\,NH_3} \tag{A.28}$$

$$E_{storage\,slurry\,N_2O} = m_{t\&s\,slurry\,TAN} \cdot EF_{storage\,slurry\,N_2O} \tag{A.29}$$

$$E_{storage\,slurry\,NO} = m_{t\&s\,slurry\,TAN} \cdot EF_{storage\,slurry\,NO} \tag{A.30}$$

$$E_{storage\,slurry\,N_2} = m_{t\&s\,slurry\,TAN} \cdot EF_{storage\,slurry\,N_2} \tag{A.31}$$

$$E_{storage\,solid\,NH_3} = m_{t\&s\,solid\,TAN} \cdot EF_{storage\,solid\,NH_3} \tag{A.32}$$

$$E_{storage\,solid\,N_2O} = m_{t\&s\,solid\,TAN} \cdot EF_{storage\,solid\,N_2O} \tag{A.33}$$

$$E_{storage\,solid\,NO} = m_{t\&s\,solid\,TAN} \cdot EF_{storage\,solid\,NO} \tag{A.34}$$

$$E_{storage\,solid\,N_2} = m_{t\&s\,solid\,TAN} \cdot EF_{storage\,solid\,N_2} \tag{A.35}$$

The resulting N amount flowing out of the storage step are shown below. The summation of the slurry and solid emissions calculated above is subtracted from the amount of N flowing in the storage step from housing.

$$m_{storage\,slurry\,TAN} = m_{t\&s\,slurry\,TAN} - \sum E_{storage\,slurry} \tag{A.36}$$

$$m_{storage\,slurry\,N} = m_{t\&s\,slurry\,N} - \sum E_{storage\,slurry} \tag{A.37}$$

$$m_{storage\,solid\,TAN} = m_{t\&s\,solid\,TAN} - \sum E_{storage\,solid} \tag{A.38}$$

$$m_{storage\,solid\,N} = m_{t\&s\,solid\,N} - \sum E_{storage\,solid} \tag{A.39}$$

A.9 The Manure Digester

This steps focuses on the nitrogen related emissions from the manure digester process. This step uses the output of step A.7 with the information from Garcia et al., 2019 to compute the nitrogen emissions and changes from manure to digestate. The first step is to determine the feed that goes into the digester, this is done for both the total-N and TAN below.

$$m_{dig\,feed\,TAN} = m_{t\&s\,slurry\,TAN} + m_{t\&s\,solid\,TAN} \tag{A.40}$$

$$m_{dig\,feed\,N} = m_{t\&s\,slurry\,N} + m_{t\&s\,solid\,N} \tag{A.41}$$

Next, the total of NH_3 emissions for the digestion process can be determined. It is assumed that the emissions from the digester itself is negligible (Garcia et al., 2019). This leaves the steps of pre-storage and digestate storage, with their respective EFs. These EFs are based on total-N and not TAN as the previous EFs and are shown in appendix C.

$$E_{dig\,total\,NH_3} = m_{dig\,feed\,N} \cdot (EF_{pre-storage\,NH_3} + EF_{digestate\,storage\,NH_3}) \tag{A.42}$$

However, the release of NH_3 is not the only nitrogen related step that occurs in the digester. During the fermentation process mineralisation occurs which increase the TAN in digestate, the conversion factor $f_{min\,biogas}$ is noted in table 20 and used in the equation below to determine the amount of TAN leaving the digester.

$$m_{dig\,TAN} = N_{dig\,feed\,TAN} + (f_{min\,biogas} \cdot (N_{dig\,feed\,N} - N_{dig\,feed\,TAN})) - E_{dig\,total\,NH_3} \tag{A.43}$$

$$m_{dig\,N} = N_{dig\,feed\,N} - E_{dig\,total\,NH_3} \tag{A.44}$$

A.10 Maximum Nitrogen Amount for Field Application

As explained in section 2.2.3, the maximum allowed nitrogen concentration from manure or digestate is depended on a number of factors such as a derogation permit, the province and the type of soil. These factors are farm specific are require input from the farmer to be accurate. A flow chart describing the options is shown in figure 3. The equation below allow for the calculation of the maximum allowed nitrogen amount that can be applied to the field of a farm in a year. The rest of the manure or digestate is exported.

$$m_{max\,allowed\,N} = derogation_{other} \cdot ha_{other} + derogation_{sand\&loess} \cdot ha_{sand\,\&\,loess} - m_{graz\,N} \tag{A.45}$$

After taking into account the different derogation values ($derogation_{other}$ and $derogation_{sand\&loess}$), derived from figure 3, the amount of N already excreted during grazing ($m_{graz\,N}$) has to be subtracted from the maximum allowed amount of N.

A.11 Nitrogen applied to Farmland

The previous step determined the maximal amount of N that might be applied on a farm during a year ($m_{max\,allowed\,N}$). However, it is possible that a dairy farm does not produce enough manure to fertilise all fields to their maximum. Therefore, first the amount N used is determined, this is done by using an if function, which is written out below.

$$m_{applic\,used\,N} = m_{max\,allowed\,N} \textbf{ except if } (m_{storage\,slurry\,N} + m_{storage\,solid\,N}) < m_{max\,allowed\,N} \tag{A.46}$$

$$\textbf{then } m_{applic\,used\,N} = (m_{storage\,slurry\,N} + m_{storage\,solid\,N}) \tag{A.47}$$

However, this can mean that there is still room for more manure to be applied ($m_{applic\,room\,N}$). Which will either be zero, if there is excess manure or provide the amount of N room.

$$m_{applic\,room\,N} = m_{max\,allowed\,N} - m_{applic\,used\,N} \tag{A.48}$$

Next, the total-N and TAN during the application of manure and digestate to fields are calculated. However, since the processes between the two scenarios, with and without a digester, are slightly different special care has to be taken to ensure proper emissions accounting. The assumption is made that for the scenario without a digester the solid manure is applied first as fertiliser since it only exist in small amounts on Dutch dairy farms. In the case of the digester these values are zero since no solid manure remains after the digestion process.

$$m_{applic\,solid\,TAN} = m_{storage\,solid\,TAN} \tag{A.49}$$

$$m_{applic\,solid\,N} = m_{storage\,solid\,N} \tag{A.50}$$

The slurry manure of digestate, can then fill up the remaining field application budget based on total-N, as calculated in the precious step. In the case of digestate $m_{applic\,solid\,N}$ is zero so the $m_{applic\,slurry\,N}$ is equal to the maximum amount of N that is allowed to be used as fertiliser.

$$m_{applic\,slurry\,N} = m_{applic\,used\,N} - m_{applic\,solid\,N} \tag{A.51}$$

The last equation determines the amount of TAN applied to the fields. Since the TAN fraction differs for both scenario's it has to be recalculated based on the amount of N applied and the TAN fraction in the previous step. For manure this is:

$$m_{applic\,slurry\,TAN} = (m_{storage\,slurry\,TAN}/m_{storage\,slurry\,N}) \cdot m_{applic\,slurry\,N} \tag{A.52}$$

For digestate this is:

$$m_{applic\,slurry\,TAN} = (m_{dig\,TAN}/m_{dig\,N}) \cdot m_{applic\,slurry\,N} \tag{A.53}$$

A.12 Manure for Export

The manure for export step is straight forward but the input differs between the two scenario's. For both scenario's there is only one export value since it is assumed that all solid manure is used first as fertiliser and no solid digestate exists. For manure:

$$m_{export\,TAN} = m_{storage\,slurry\,TAN} - m_{applic\,slurry\,TAN} - (m_{storage\,slurry\,TAN}/m_{storage\,slurry\,N}) * m_{applic\,room\,N} \tag{A.54}$$

$$m_{export\,N} = m_{storage\,slurry\,N} - m_{applic\,slurry\,N} - m_{applic\,room\,N} \tag{A.55}$$

For digestate:

$$m_{export\,TAN} = m_{dig\,TAN} - m_{applic\,slurry\,TAN} - (m_{dig\,TAN}/m_{dig\,N}) * m_{applic\,room\,N} \tag{A.56}$$

$$m_{export\,N} = m_{dig\,N} - m_{applic\,slurry\,N} - m_{applic\,room\,N} \tag{A.57}$$

By subtracting $m_{applic\,room\,N}$ from the export equations, the amount available for export can become negative. This indicates that there is a room left on the dairy farm for more manure, thus manure could be imported. In the export TAN equations the $m_{applic\,room\,N}$ is first converted to TAN by multiplying it with the current TAN fraction.

A.13 Emissions from Field Application

The emission from field application are calculated with EFs that are noted in appendix C. The NH_3 EFs are based on TAN and the NO_X and N_2O on the total amount of N. All the solid fraction emissions are of course zero from the scenario with a digester since there is no solid digestate. A special case is the EF for NH_3 for the slurry fraction. Research by Lagerwerf et al. (2019) and van Dijk et al. (2020) show that the EF values vary greatly based upon the method of field application. This method is known, since it is recorded in the KringloopWijzer. Thus a new method is implemented to determine a accurate value for this EF, which is explained with the other EFs in appendix C,

$$E_{applic\,slurry\,NH_3} = m_{applic\,slurry\,TAN} \cdot EF_{applic\,slurry\,NH_3} \tag{A.58}$$

$$E_{applic\,solid\,NH_3} = m_{applic\,solid\,TAN} \cdot EF_{applic\,solid\,NH_3} \tag{A.59}$$

$$E_{applic\,slurry\,NO_x} = m_{applic\,slurry\,N} \cdot EF_{applic\,slurry\,NO_x} \tag{A.60}$$

$$E_{applic\,solid\,NO_x} = m_{applic\,solid\,N} \cdot EF_{applic\,solid\,NH_x} \tag{A.61}$$

$$E_{applic\,slurry\,N_2O} = m_{applic\,slurry\,N} \cdot EF_{applic\,slurry\,NH_3} \tag{A.62}$$

$$E_{applic\,solid\,N_2O} = m_{applic\,solid\,N} \cdot EF_{applic\,solid\,N_2O} \tag{A.63}$$

A.14 Nitrogen returned to the Soil

The amount of N returned to soil after the nitrogen emission losses can be calculated with the four equations below. Here all the emissions calculated in the previous step are subtracted. Here there is still no solid digestate so these two equations will remain zero for that scenario.

$$m_{returned\,slurry\,TAN} = m_{applic\,slurry\,TAN} - (E_{applic\,slurry\,NH_3} + E_{applic\,slurry\,NO_x} + E_{applic\,slurry\,N_2O}) \quad (A.64)$$

$$m_{returned\,slurry\,N} = m_{applic\,slurry\,N} - (E_{applic\,slurry\,NH_3} + E_{applic\,slurry\,NO_x} + E_{applic\,slurry\,N_2O}) \quad (A.65)$$

$$m_{returned\,solid\,TAN} = m_{applic\,solid\,TAN} - (E_{applic\,solid\,NH_3} + E_{applic\,solid\,NO_x} + E_{applic\,solid\,N_2O}) \quad (A.66)$$

$$m_{returned\,solid\,N} = m_{applic\,solid\,N} - (E_{applic\,solid\,NH_3} + E_{applic\,solid\,NO_x} + E_{applic\,solid\,N_2O}) \quad (A.67)$$

A.15 Emissions Overview

The final step of this section is to create an overview per pollutant and convert all values to the mass of the relevant compound. The emissions (E) calculated per step, are so far expressed in their N atoms (e.g. $NH_3 - N$) instead of the total molecule (e.g. NH_3). Thus, to determine these exact emissions these have to be corrected based on molecule mass. See table 33 for the different conversion factor. Furthermore, Reporting guidelines state that all NO emissions have to be reported as NO_2 (Amon et al., 2019).

The overall account will be done based upon pollutant type, so all NH_3, NO_X, N_2O and N_2 will be accounted separately. Not all emissions occurs in each step of the manure management cycle so this process is slightly different for each pollutant. However, in general the emissions of each step are first converted to the correct compound with certain conversion values based upon compound masses and then summed (e.g. slurry and solid fraction during housing).

Table 21: Overview of all nitrogen related emissions that occur during the manure management cycle per pollutant.

NH_3 Emissions	N_2O Emissions	NO_X Emissions	N_2 Emissions
Slurry housing			
Solid housing			
Slurry storage	Slurry storage	Slurry storage	Slurry storage
Solid storage	Solid storage	Solid storage	Solid storage
Treatment			
Slurry application	Slurry application	Slurry application	
Solid application	Solid application	Solid application	
Grazing	Grazing	Grazing	

B Housing Emission Factor

The housing EF for dairy farms in the Netherlands is based upon Dutch law which notes all emissions in kg NH_3 per animal place per year (Wet Ammoniak en veehouderij, 2002). The different types of barns all have their specific RAV-code, which is also noted in the farm-specific KringloopWijzer that exist for all dairy farms in the Netherlands. With this readily available information it is possible to calculate a farm-specific housing EF. This information is noted in animal place per year instead of animal per year. However, research by Lagerwerf et al. (2019) shows that the housing capacity on Dutch dairy farms over the last years has been one animal per animal place. Thus, no additions have to be to apply this information to the number of diary cows, in GVE, present on a farm.

Recently, van Dijk et al. (2020) have used an effective way of translating the data from Wet Ammoniak en veehouderij (2002) into a format which can be used easily as an EF. This is done by linking the emissions of each housing types to a standard, with the RAV code A1.100, which is assume to be synonymous with the term non low-emission stable (*Dutch: niet emissiearme stal*) from the work of Lagerwerf et al. (2019). For the other housing types a correction factor is calculated to link the housing type of the farm with the standard housing types. An example calculation is given in table 22.

Table 22: Example calculation of the correction factor for RAV stable A 1.5 compared to the reference A 1.100.

RAV-code	Emission Factor (kg NH_3 per animal place per year)	Correction factor (compared to A 1.100)
A 1.100 (standard)	13	
A 1.5	11.8	11.8/13=0.91

A usable EF needs to be expressed in NH_3-N as a fraction of TAN. To convert the emission factor from kg NH_3 per animal place per year we can thus use the conversion factor calculated above on the EF of the standard housing type (RAV A 1.100) which EF is known. This is 14.3 % of TAN during the housing period but differs based on the hours spend outside grazing (h_{graz}) during the grazing period (van Dijk et al., 2020). The grazing emissions are shown in table 23. To account for this difference in emissions the following equation is used to determine EF for NH_3 housing emission on a farm.

$$EF_{hous\,NH_3} = RAV_{corr.} \cdot (((365 - d_{graz}) \cdot EF_{hous\,hous\,NH_3\,h_{graz}=0}) + (d_{graz} \cdot EF_{hous\,graz\,NH_3\,h_{graz}=i})/365 \quad (B.1)$$

In appendix A this EF can be multiple with the total amount of TAN present during housing to determine the NH_3 emissions during this step. All conversion values are shown in table 24. The only changed compared to the original data from Wet Ammoniak en veehouderij (2002) is the value for stable A 1.17. This is a stable with a air washer, which does remove the NH_3 from the manure but stores it in the cleaning water, thus not reducing the total amount of NH_3 release to the environment.

Table 23: The NH_3 emissions from the standard barn (RAV 1.100) during the grazing period depended on the mount of hours spend grazing.

Hours grazing (h_{graz})	EF NH_3-N fraction of TAN (kg)
0	0.143
1	0.145
2	0.148
3	0.150
4	0.153
5	0.157
6	0.160
7	0.165
8	0.169
9	0.175
10	0.181
11	0.188
12	0.196
13	0.206
14	0.217
15	0.232
16	0.249
17	0.272
18	0.303
19	0.355
20	0.409

Table 24: Correction factors for all different stables according to the information from the Wet Ammoniak en veehouderij (2002).

RAV-code	EF (kg NH_3/animal place/year)	Conversion factor (-)
A 1.1	5.70	0.44
A 1.2	10.20	0.78
A 1.3	10.20	0.78
A 1.4	9.20	0.71
A 1.5	11.80	0.91
A 1.6	11.00	0.85
A 1.7	11.00	0.85
A 1.8	11.80	0.91
A 1.9	6.00	0.46
A 1.10	7.00	0.54
A 1.11	11.80	0.91
A 1.12	12.20	0.94
A 1.13	6.00	0.46
A 1.14	7.00	0.54
A 1.15	10.30	0.79
A 1.16	11.70	0.90
A 1.17	5.10	1.00
A 1.18	8.00	0.62
A 1.19	11.00	0.85
A 1.20	10.10	0.78
A 1.21	7.00	0.54
A 1.22	11.00	0.85
A 1.23	6.00	0.46
A 1.24	7.00	0.54
A 1.25	10.30	0.79
A 1.26	8.00	0.62
A 1.27	8.00	0.62
A 1.28	6.00	0.46
A 1.29	9.90	0.76
A 1.30	8.00	0.62
A 1.31	8.10	0.62
A 1.32	9.10	0.70
A 1.33	7.10	0.55
A 1.34	9.00	0.69
A 1.35	8.30	0.64
A 1.100	13.00	1.00
A 1.100 bio-postal	13.00	1.00
A 1.100 bio-grupstal	13.00	1.00
A 1.100 bio-overig	13.00	1.00

C Nitrogen Emission Factors during Manure Management

Next to the housing EF that is calculated in appendix B a number of other EFs are used to determine the different nitrogen emissions. In the tables below the different EFs are presented. The only EF that is calculated in this section is the NH_3 during slurry application. This is done due to the different application methods that are possible both on grassland and cropland and the large variation between their NH_3 emissions. Information about the application method is presented in the KringloopWijzer and a method for calculation was derived and will be presented first after which all the other EFs are presented.

C.1 Slurry application ammonia EF calculation

To calculate EF of slurry during application first it is important to know the EF for the different application techniques used in the Netherlands. They differ between grassland and cropland and the same method applied on both soils will have different emissions. These EFs are presented in table 25. The direct use of narrow-band has an emissions factor of 0.31, but is not allowed in the Netherlands anymore. It is only allowed to be used in a mix with water which is assumed to have the same emissions levels as shallow-injection (van Dijk et al., 2020). The slit-coulter emission is set as the average between narrow-band and shallow-injection (van Dijk et al., 2020).

Table 25: The Emissions Factors (EF) of NH_3 emissions in fraction of TAN for the different application methods of slurry manure used in the Netherlands from van Bruggen et al. (2020) & van Dijk et al. (2020).

Application Method	EF	Landtype
Shallow-injection	0.19	Grassland
Narrow-band (trailing-shoe)	0.19	Grassland
Slit-Coulter	0.25	Grassland
Surface Spreading	0.71	Grassland
Incorporation (direct)	0.22	Cropland
Narrow-band (trailing-shoe)	0.36	Cropland
Full coverage	0.02	Cropland
Surface Spreading	0.69	Cropland

With the EFs for the different application methods known and with their use specified in the Kringloop-Wijzer in %, the following equation calculates the average slurry application EF for a farm. It uses both the hectares of grassland ($ha_{grassland}$) and the hectares of cropland ($ha_{cropland}$) to properly scale use of the application methods based on this farm characteristic.

$$EF_{applic\,slurry\,NH_3} = \sum\left(\frac{EF_{grass\,applic\,method} \cdot \%_{grass\,applic\,method}}{100}\right) \cdot \frac{ha_{grassland}}{ha_{grassland} + ha_{cropland}} + \sum\left(\frac{EF_{crop\,applic\,method} \cdot \%_{crop\,applic\,method}}{100}\right) \cdot \frac{ha_{cropland}}{ha_{grassland} + ha_{cropland}} \tag{C.1}$$

C.2 Application EFs

The remaining application EFs are presented in table 26. For NO_X, represented as both NO and NO_2 in literature but expressed in terms of NO_2-N there is not enough accurate data available to make this EF more specific. This also holds true for the N_2O EF for this section, as well as for many other EFs of which the complex underlying processes are not well understood.

Table 26: The remaining EFs for the application of manure on farmland.

Emission Factor	Value	Unit	Source
$EF_{NH_3\,manure\,applic\,solid}$	0.71	Fraction TAN	van Bruggen et al., 2020
$EF_{NO\,manure\,applic}$	0.012	kg NO2-N/kg N input	van Bruggen et al., 2020
$EF_{N_2O\,manure\,applic}$	0.009	kg N2O-N/kg N input	van Bruggen et al., 2020

C.3 Grazing EFs

Table 27: The EFs during grazing.

Emission Factor	Value	Unit	Source
$EF_{NH_3\,grazing}$	0.04	Fraction TAN	van Bruggen et al., 2020
$EF_{NO\,grazing}$	0.012	kg NO2-N/kg N input	van Bruggen et al., 2020
$EF_{N_2O\,grazing}$	0.033	kg N2O-N/kg N input	van Bruggen et al., 2020

C.4 Storage & Application EFs

Table 28: The EFs during manure storage.

Emission Factor	Value	Unit	Source
$EF_{NH_3\,storage\,slurry}$	0.25	Fraction TAN	Amon et al., 2019
$EF_{N_2O\,storage\,slurry}$	0.01	Fraction TAN	Amon et al., 2019
$EF_{NO\,storage\,slurry}$	0.0001	Fraction TAN	Amon et al., 2019
$EF_{N_2\,storage\,slurry}$	0.003	Fraction TAN	Amon et al., 2019
$EF_{NH_3\,storage\,solid}$	0.32	Fraction TAN	Amon et al., 2019
$EF_{N_2O\,storage\,solid}$	0.02	Fraction TAN	Amon et al., 2019
$EF_{NO\,storage\,solid}$	0.01	Fraction TAN	Amon et al., 2019
$EF_{N_2\,storage\,solid}$	0.3	Fraction TAN	Amon et al., 2019

Table 29: The EFs during the digestion process.

Emission Factor	Value	Unit	Source
$EF_{NH_3\,pre-storage}$	0.0009	kg NH3-N per kg N feedstock	Garcia et al., 2019
$EF_{NH_3\,digestate\,storage}$	0.0266	kg NH3-N per kg N feedstock	Garcia et al., 2019

D Methane Emissions Calculations

D.1 Enteric Fermentation

The calculation of CH_4 emissions from enteric fermentation can be done with the following equation. Here the specific EF for enteric fermentation is used, which is calculated below and the number of cattle (N_{GVE}) on a specific farm.

$$CH_4\ emissions\ enteric\ fermentation = N_{GVE} \cdot EF_{CH_4\ enteric\ fermentation} \tag{D.1}$$

The EF can be calculated with the following equation in which the EF is expressed in kg CH_4 per animal per year. The methane-conversion factor Y_m is defined as 0.065 by Dong et al. (2006) and is the fraction of the gross energy (GE) intake that is converted into CH_4. This is then divide by the standard energy content of 1 kg of CH_4 which has a value of 55.65 MJ per kg CH_4.

$$EF_{CH_4\ enteric\ fermentation} = (Y_m \cdot GE)/55.65 \tag{D.2}$$

The only unknown in the equation above is the Gross Energy (GE) intake in MJ/animal/year. This can be estimated by multiplying the dry matter (DM) consumption of a cow (kg dry matter/animal/year) through the gross energy content per kg dry matter, which has a value of 18.45, as shown in the equation below (Dong et al., 2006). This DM is farm-specific and its value can be extracted from the KringloopWijzer. However, since it is a single value describing all cattle and young stock it has to be divided by the amount of GVE.

$$GE = (DM/N_{GVE}) \cdot 18.45 \tag{D.3}$$

D.2 Manure Storage

The CH_4 emission during storage can be determined with a tier 2 method from the IPCC (Dong et al., 2006). This method is used trice to determine the emissions from slurry, solid and grazing manure. The first step is to determine the organic matter (OM) consumed by a cow per year. The second step is focused on calculating the EF and the final step is calculation of the CH_4 emissions.

The OM calculation uses the N_{GVE} calculated in section D.1 as well as the amount of manure excreted by dairy cattle and young stock (m_{ex}) expressed in kg and obtained from the KringloopWijzer. This division give the manure excretion per GVE per year in kg. This is multiplied with the fraction organic matter ($OM_{fractionDM}$) in dry matter, 0.60, and the fraction of DM in manure, 0.11, both from K. Groenestein et al. (2020) to obtain the farm specific organic matter content in kg per animal per year.

$$OM = \frac{m_{ex}}{N_{GVE}} \cdot DM_{fraction\,manure} \cdot OM_{fraction\,DM} \tag{D.4}$$

With the OM known the following equations can be used to determine the EFs for the slurry, solid and grazing manure. The grazing fraction x_{graz} has already been determined based on the grazing regime in appendix A. The fraction of manure stored during housing as a slurry (x_{slurry}) can be used to determine the actual slurry fraction based of the total amount of manure ($x_{slurry\,CH_4}$). This allows for the calculation of

$x_{solid\,CH_4}$ as is shown in the equations below. $x_{slurry\,CH_4}$ different then the x_{slurry} in appendix B since here the slurry fraction is based of all manure, including the grazing fraction, and in appendix B it is the fraction of the housing manure, excluding the grazing fraction.

$$x_{slurry\,CH_4} = (1 - x_{graz}) * x_{slurry} \tag{D.5}$$

$$x_{solid\,CH_4} = 1 - x_{graz} - x_{slurry\,CH_4} \tag{D.6}$$

The amount of organic matter (OM) is multiplied by the fraction of manure that is excreted in that form (slurry, solid or grazing). This is further multiplied by the maximum methane production potential (B_o), the density of methane (ρ_{CH_4}) and the methane-conversion factor (MCF). The values, unit and their sources are displayed in table 30. In equation D.7 the i indicates the different types of manure.

$$EF_{CH_4\,storage\,i} = OM \cdot x_i \cdot B_o \cdot MCF_i \cdot \rho_{CH_4} \tag{D.7}$$

Table 30: Data used in calculating the EFs during manure storage.

Data	Value	Unit	Source
ρ_{CH_4}	0.67	kg/m^3	Dong et al., 2006
MCF_{slurry}	0.17	-	C. M. Groenestein et al., 2016
MCF_{solid}	0.02	-	Dong et al., 2006
MCF_{graz}	0.01	-	Dong et al., 2006
B_o	0.22	$m^3CH_4/kgOM$	C. M. Groenestein et al., 2016

The B_o is depended on the degradability of the organic compounds on manure, but is assumed to be constant (C. M. Groenestein et al., 2016). The MCF indicates the fraction of B_o that is actually converted into methane. The most important influence parameters are temperature, retention time and inoculum of the methane-forming bacteria (K. Groenestein et al., 2020). Finally, the CH_4 storage emissions for the different manure types can be calculated with the following equation. The total results is the sum of the different $E_{CH_4\,emissions\,storage\,i}$.

$$E_{CH_4\,emissions\,storage\,i} = N_{GVE} \cdot EF_{CH_4\,storage\,i} \tag{D.8}$$

D.3 Manure Digestion

The calculation of CH_4 emissions for the treatment scenario, with a digester, is done in the same way. However, a different MCF value is used which in this case has a value of 0.03 (van Dijk et al., 2020). This replace the slurry and solid calculations from section D.2, however the grazing emissions calculated there are also present in the treatment scenario.

$$EF_{CH_4\,dig} = OM \cdot (x_{slurry} + x_{solid}) \cdot B_o \cdot MCF_{dig} \cdot \rho_{CH_4} \tag{D.9}$$

$$E_{CH_4\,emissions\,dig} = N_{GVE} \cdot EF_{CH_4\;dig} \tag{D.10}$$

E Carbon Dioxide Emissions Calculations

This appendix shows the calculations done to determine the CO_2 emissions on a dairy farm in the Netherlands with and without a digester. The first two section are focused on the dairy farms overall energy consumption and generation as described in the KringloopWijzer. The last two sections are specifically focused on the manure digester and the changes this brings in terms of energy generation and CO_2 emissions.

E.1 Farm Energy Consumption

As mentioned in section 3.5, the total energy consumption per energy source is obtained from the Kringloop-Wijzer. Sometimes unit conversion needs to take place before the EFs can be applied, since these are expressed in g CO_2 per GJ. The exception is electricity in which the EF is expressed in g CO_2 per kWh. The EFs for each energy sources used on Dutch dairy farms in displayed in table 31. The equations used for calculations of CO_2 emissions in kg are shown below.

Table 31: The different energy sources from van Dijk et al. (2020), EFs and their respective units and sources.

Energy Sources	Unit	EF	EF unit	EF source
Electricity	kWh	373.21	$g\ CO_2/kWh$	Ortiz et al., 2020
Natural Gas	m^3	56.4	$kg\ CO_2/GJ$	Zijlema, 2020
Propane	L	66.5	$kg\ CO_2/GJ$	U.S. Environmental Protection Agency, 2021
Fuel Oil	L	77.4	$kg\ CO_2/GJ$	Zijlema, 2020
Diesel	L	72.5	$kg\ CO_2/GJ$	Zijlema, 2020

$$E_{electricity} = (Electricity\,Consumption \cdot EF_{electricity})/1000 \tag{E.1}$$

$$E_{natural\,gas} = (Natural\,Gas\,Consumption \cdot NCV_{natural\,gas})/1000 \cdot EF_{natural\,gas}) \tag{E.2}$$

To convert natural gas to energy unit it is multiplied by the Net Calorific Value, expressed in $MJ/Nm^3a.e$, which for natural gas has a value of 31.65 (Zijlema, 2020).

$$E_{propane} = ((Propane\,Consumption/1000) \cdot density_{propane} \cdot NCV_{propane})/1000 \cdot EF_{propane}) \tag{E.3}$$

To convert propane to energy unit it is multiplied by the Net Calorific Value, expressed in MJ/kg, which for propane has a value of 46.40 (Engineering ToolBox, 2003). The density of propane is 498.00 kg/m^3 (Engineering ToolBox, 2003).

$$E_{fuel\,oil} = ((Fuel\,Oil\,Consumption/1000) \cdot density_{fuel\,oil} \cdot NCV_{fuel\,oil})/1000 \cdot EF_{fuel\,oil}) \tag{E.4}$$

To convert fuel oil to energy unit it is multiplied by the Net Calorific Value, expressed in MJ/kg, which for fuel oil has a value of 41.00 (Zijlema, 2020). The density of fuel oil is 960 kg/m^3 (Engineering ToolBox, 2003).

$$E_{diesel} = ((Diesel\,Consumption/1000) \cdot density_{diesel} \cdot NCV_{diesel})/1000 \cdot EF_{diesel}) \tag{E.5}$$

To convert diesel to energy unit it is multiplied by the Net Calorific Value, expressed in MJ/kg, which for diesel has a value of 43.20 (Zijlema, 2020). The density of diesel is 846.00 kg/m^3 (Engineering ToolBox, 2003).

E.2 Farm Energy Generation

A farm can generate energy through other means than a manure digester, such as solar panels or windmills. These options already reduce the environmental impact of a dairy farm. The energy generation and emission impact of these already existing measures are calculated in this section. A division in the KringloopWijzer is made between four different categories: solar, wind, biomass and other. As explained in section 3.5, the assumption here is made that biomass does not include a manure digester in this work. Furthermore, the EF of the other category is calculated as weighted average of the other EFs.

Table 32: The different energy generation sources on a dairy farm van Dijk et al. (2020), EFs and their respective units and sources.

Energy Sources	Unit	EF	EF unit	EF source
Wind	kWh	11	$g\ CO_2/kWh$	Schlömer et al., 2014
Solar	kWh	41	$g\ CO_2/kWh$	Schlömer et al., 2014
Biomass	kWh	230	$g\ CO_2/kWh$	Schlömer et al., 2014
Other	kWh	t.b.d.	$g\ CO_2/kWh$	-

The first step is the calculation of the EF for the other category, this is done by adopting the weighted average on the farm of the other three categories, as described by van Dijk et al. (2020).

$$EF_{other} = \frac{\%\,wind \cdot EF_{wind} + \%\,solar \cdot EF_{solar} + \%\,biomass \cdot EF_{biomass}}{\%\,wind + \%\,solar + \%\,biomass} \tag{E.6}$$

With the last EF known, the average EF over the whole farm can be calculated with the following equation, as described by van Dijk et al. (2020):

$$EF_{farm} = \frac{\%\,wind \cdot EF_{wind} + \%\,solar \cdot EF_{solar} + \%\,biomass \cdot EF_{biomass} + \%\,other \cdot EF_{other}}{\%\,wind + \%\,solar + \%\,biomass + \%\,other} \tag{E.7}$$

With the energy production and the EF of the farm known, the total CO_2 emissions in kg can be calculated for the production of energy on this farm.

$$E_{energy\,production} = Electricity\,generated \cdot EF_{farm} \tag{E.8}$$

However, part of this electricity is put back into the grid, where it reduce the electricity generation by the Dutch energy sector with an much higher EF, see table 31. Thus the savings, from the amount of kWh returned to the grid is:

$$E_{savings_{farm}} = Electricity\,returned\,to\,grid \cdot EF_{electricity}/1000 \tag{E.9}$$

E.3 Digester Energy Consumption

The energy consumption of a manure digester is in this work based on the KringloopWijzer documentation, which states that an mono manure digester consumes approximately 12 kWh per ton of manure (van Dijk et al., 2020). The total amount of manure is known as well as the time fraction spend grazing (see section 3.3.4 and appendix A). This means that the total amount of energy consumed by the digester can be calculated with the following equation.

$$digester_{energy\,consumption} = (1 - x_{graz}) \cdot N_{ex} \cdot Energy\,use\,per\,ton\,manure \tag{E.10}$$

When assuming that all energy consumed is supplied through the Dutch national grid, the operational emissions from the manure digester are.

$$E_{manure\,digester} = \cdot E_{electricity} \cdot digester_{energy\,consumption} \tag{E.11}$$

E.4 Digester Energy Generation

The traditional use of a manure digester is to generate sustainable energy in either the form of biogas, electricity or CHP (combined heat and power). In this work it is assumed that only electricity is generated from the digester. The first step is to determine the amount of CH_4 produced, this is based on the amount of Organic Matter(OM) in manure. This value is calculated in the methane (CH_4) model, see section 3.4 and appendix D.

$$production_{CH_4} = OM \cdot GVE \cdot yield_{digester} \cdot (1 - x_{graz}) \tag{E.12}$$

The digester yield is defined as 0.18 m^3 CH_4 per kg OM (Miranda et al., 2015). GVE is a term used to express young stock in units of dairy cows, for more information see section 2.2.1. With this data the yearly production of CH_4 can be calculated, which in turn has to be converted into energy in the form of electricity. This is done by converting the m^3 of CH_4 into MJ, through the use of the energy content of methane (HHV = 39.8 MJ per m^3) (Engineering ToolBox, 2003).

$$digester_{energy\,production} = production_{CH_4} \cdot HHV \cdot engine\,efficiency \tag{E.13}$$

The energy production in MJ can be easily converted into kWh, since 3.6 MJ is equal to 1 kWh. This is further multiplied by the efficiency of the combustion engine which is estimated at 33% (K. Groenestein et al., 2020).

$$digester_{electricity\,production} = \frac{digester_{energy\,production}}{3.6} \cdot engine\,efficiency \tag{E.14}$$

This value can then be multiplied with the EF for dutch electricity generation to determine emission reduction through energy generation. The following equation gives the CO_2 emission reduction in kgCO_2.

$$E_{digester\ ,reduction} = digester_{electricity\,production} \cdot EF_{electricity}/1000 \tag{E.15}$$

F System Variables

The system variables used during the are displayed in the tables below.

Table 33: The system data used during the calculation of the nitrogen related emissions. The conversion factors are based upon the molecular weights of the compounds

Description	Value
days/year	365
hours/day	24
Conversion Factor N to NH3 (=17/14)	1.21
Conversion Factor N to N2O (=44/28)	1.57
Conversion Factor kg/kt	0.000001
Conversion Factor N to NO2 (=46/14)	3.29
Conversion Factor N to N2 (=28/28)	1.00

Table 34: The system data used during the calculation of the methane emissions.

Description	Value	Unit	Source
Gross energy content	18.45	MJ/ kg DM	Dong et al., 2006
Methane conversion factor (Y_m)	0.07	-	Dong et al., 2006
Methane energy content	55.65	MJ/ kg CH4	Engineering ToolBox, 2003
Methane density	0.67	kg/ m^3	Engineering ToolBox, 2003
Methane conversion factor (MCF_{slurry})	0.17	-	C. M. Groenestein et al., 2016
Methane conversion factor (MCF_{solid})	0.02	-	Dong et al., 2006
Methane conversion factor ($MCF_{grazing}$)	0.01	-	Dong et al., 2006
Maximum methane production potential (B_o)	0.22	m^3 CH_4/ kg OM	C. M. Groenestein et al., 2016
Dry matter fraction in manure	0.11	-	K. Groenestein et al., 2020
Organic matter fraction in manure	0.60	OM	K. Groenestein et al., 2020
Methane conversion factor ($MCF_{digestion}$)	0.03	-	van Dijk et al., 2020

Table 35: The system data used during the calculation of the carbon dioxide emissions.

Description	Value	Unit	Source
Mono digester energy use	12.00	kWh/ ton manure	van Dijk et al., 2020
Diesel: Net Calorific Value	43.20	MJ/ kg	Zijlema, 2020
Diesel: Density	846.00	kg/ m^3	Engineering ToolBox, 2003
Natural gas: Net Calorific Value	31.65	MJ/ Nm^3 a.e.	Zijlema, 2020
Propane: Net Calorific Value	46.40	MJ/ kg	Engineering ToolBox, 2003
Propane: Density	498.00	kg /m^3	Engineering ToolBox, 2003
Fuel Oil: Net Calorific Value	41.00	MJ/ kg	Zijlema, 2020
Fuel Oil: Density	960.00	kg/ m^3	Engineering ToolBox, 2003
Digester yield	0.18	m^3 CH_4/ kg OM	Miranda et al., 2016
Engine Efficiency	0.33	-	K. Groenestein et al., 2020
Methane HHV	39.80	MJ/ m^3	Engineering ToolBox, 2003

G Farm Scale Input Data

Table 36: The N input variables for the four different farms

Symbol	Farm A	Farm B	Farm C	Farm D
N_{ex}	24824	25144	11899	24292
N_{waste}	1450	1561	741	1194
TAN_{ex}	15370	15442	6924	14398
N_{cattle}	174	175	106	194
$N_{young\,stock \geq 1year}$	3	27	2	10
$N_{young\,stock \leq 1year}$	47	72	18	50
d_{graz}	160	120	0	200
h_{graz}	6	6	0	5
Current Housing system	A 1.26	A 1.100	A 1.100	A 1.100
New Housing system	A 1.26	A 1.100	A 1.100	A 1.100
$x_{slurry\,cattle}$	95	99	99	100
$x_{slurry\,young\,stock \geq 1year}$	100	100	100	100
$x_{slurry\,young\,stock \leq 1year}$	50	67	0	50
ha_{grass}	53.01	73.77	30.94	63.96
ha_{maize}	3.57	15.68	4.32	15.62
ha_{crop}	0	0	0	0
Derogation	yes	yes	yes	yes
Province	Overijssel	Overijssel	Overijssel	Overijssel
grass peat soil type	0	0	0	0
grass clay soil type	0	12	0	0
crop peat soil type	0	0	0	0
crop clay soil type	0	0	0	0

Table 37: The slurry application EFs input for the different farms. All farms only use 1 method per type of farmland, thus the farm labels are noted here instead of percentages. Thus, farm A uses 100 % shallow injection on grassland and 100 % full coverage on cropland.

Method of Application Slurry	Grassland (Farm)	Cropland (Farm)	Method of Application Slurry
Shallow-injection	A, B, C, D	C	Incorporation (direct)
Narrow-band (trailing-shoe)	-	-	Narrow-band (trailing-shoe)
Slit-Coulter	-	A, B, D	Full coverage
Surface Spreading	-	-	Surface Spreading

Table 38: The CH_4 input variables for the four different farms

Symbol	Farm A	Farm B	Farm C	Farm D
Net excretion	4977	5668	2712	6803
Feed	1405027	1461737	779598	1526772

Table 39: The CO_2 input variables for the four different farms

Symbol	Farm A	Farm B	Farm C	Farm D
Yearly energy production	22000	10921	107000	31400
Returned to the grid	10770	0	86000	26110
Solar	100	100	100	100
Wind	0	0	0	0
Biomass	0	0	0	0
Other	0	0	0	0
Electricity	46491	62754	32900	76132
Natural gas	3600	5993	6800	7225
Propane	0	0	0	0
Fuel oil	0	0	0	0
Diesel own	7000	16636	4750	10670
Diesel contractors	2998	12530	0	8346

H Provincial Scale Input Data

Table 40: National averages of the slurry application methods used as input variables for every province. (van Bruggen et al., 2020)

Method of Application Slurry	Grassland (%)	Cropland (%)	Method of Application Slurry
Shallow-injection	64	5	Incorporation (direct)
Narrow-band (trailing-shoe)	13	9	Narrow-band (trailing-shoe)
Slit-Coulter	22	86	Full coverage
Surface Spreading	1	0	Surface Spreading

Table 41: Input variables for the provinces located in the North-West (NW) region.

Input Variables	Groningen	Friesland	Utrecht	Noord-Holland	Zuid-Holland
$N_{young\,stock \leq 1\,year}$ [-]	29651	81489	24189	22861	23239
$N_{young\,stock \geq 1\,year}$ [-]	29522	84454	25946	25867	23376
N_{cattle} [-]	104132	296915	93828	88190	90715
N_{ex} [kg N]	19359682.9	55108661.5	17302215.9	16376851.6	16596076.7
TAN_{ex} [kg N]	10647825.6	30309763.8	9516218.7	9007268.4	9127842.2
$x_{slurry\,young\,stock \leq 1\,year}$ [-]	0.83	0.83	0.83	0.83	0.83
$x_{slurry\,young\,stock \leq 1\,year}$ [-]	0.85	0.86	0.85	0.85	0.85
$x_{slurry\,cattle}$ [-]	0.98	0.98	0.98	0.98	0.98
d_{graz} [days]	170	170	170	170	170
h_{graz} [hours]	7.5	7.5	7.5	7.5	7.5
Current Housing system	A 1.100	A 1.100	A 1.100	A 1.100	A 1.100
New Housing system	A 1.100	A 1.100	A 1.100	A 1.100	A 1.100
ha_{grass} [ha]	61500	173100	56100	63100	57800
ha_{maize} [ha]	8000	16900	6400	4700	5000
Net excretion [ton]	3537108.0	10073655.0	3166282.0	2995152.5	3039130.0
Feed [kg dm]	853715005.1	2430708728.1	763912798.9	722232347.0	733688715.7

Table 42: Input variables for the provinces located in the South-East (SE) region.

Input Variables	Drenthe	Overijssel	Flevoland	Gelderland	Zeeland	Noord-Brabant	Limburg
$N_{young\,stock \leq 1\,year}$ [-]	31346	72099	9638	70035	7226	65389	15794
$N_{young\,stock \geq 1\,year}$ [-]	33134	73953	9641	73517	7096	68158	16051
N_{cattle} [-]	105282	253028	33886	231961	22434	210274	47319
N_{ex} [kg N]	17991317.6	42735327.6	5704074.2	39706384.4	3853577.2	36161465.8	8222254.6
TAN_{ex} [kg N]	9895224.68	23504430.18	3137240.81	21838511.42	2119467.46	19888806.19	4522240.03
$x_{slurry\,young\,stock \leq 1\,year}$ [-]	0.83	0.83	0.83	0.83	0.84	0.83	0.83
$x_{slurry\,young\,stock \leq 1\,year}$ [-]	0.85	0.85	0.86	0.85	0.86	0.86	0.85
$x_{slurry\,cattle}$ [-]	0.98	0.98	0.98	0.98	0.98	0.98	0.98
d_{graz} [days]	150	150	150	150	150	150	150
h_{graz} [hours]	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Current Housing system	A 1.100	A 1.100	A 1.100	A 1.100	A 1.100	A 1.100	A 1.100
New Housing system	A 1.100	A 1.100	A 1.100	A 1.100	A 1.100	A 1.100	A 1.100
ha_{grass} [ha]	61200	135800	14200	145600	17700	86200	27100
ha_{maize} [ha]	17200	34200	3400	36200	5500	45800	12300
Net excretion [ton]	3729365.0	8875747.5	1185282.5	8227967.5	797850.0	7487140.0	1699177.5
Feed [kg dm]	885911908.3	2109090802.1	281709999.1	1954640338.0	189636444.4	1778693411.5	403727176.6

I Farm Scale Model Results

Note that N_2 is not considered a pollutant but does play a role in the nitrogen budget, thus the total emission reduction results are displayed with and without N_2.

Table 43: The N emissions of farm A per pollutant per step in the manure life cycle.

	Farm A	Grazing	Housing	Treatment & Storage	Application	Total
NH3	Storage Scenario	67.38	1372.20	3414.74	1075.08	5929.40
	Treatment Scenario	67.38	1372.20	609.99	1337.29	3386.86
	Difference	0.00	0.00	2804.75	-262.21	2542.55
	Difference [%]	0.00	0.00	82.14	-24.39	42.88
N2O	Storage Scenario	89.77	-	142.00	92.64	324.41
	Treatment Scenario	89.77	-	0.00	92.64	182.41
	Difference	0.00	-	142.00	0.00	142.00
	Difference [%]	0.00	-	100.00	0.00	43.77
NO2	Storage Scenario	32.65	-	8.78	123.52	164.94
	Treatment Scenario	32.65	-	0.00	123.52	156.16
	Difference	0.00	-	8.78	0.00	8.78
	Difference [%]	0.00	-	100.00	0.00	5.32
Total (excl. N2)	Storage Scenario	189.80	1372.20	3565.52	1291.23	6418.75
	Treatment Scenario	189.80	1372.20	609.99	1553.44	3725.43
	Difference	0.00	0.00	2955.53	-262.21	2693.32
	Difference [%]	0.00	0.00	82.89	-20.31	41.96
N2	Storage Scenario	-	-	263.40	-	263.40
	Treatment Scenario	-	-	0.00	-	0.00
	Difference	-	-	263.40		263.40
	Difference [%]	-	-	100.00	-	100.00
Total (incl. N2)	Storage Scenario	189.80	1372.20	3828.92	1291.23	6682.15
	Treatment Scenario	189.80	1372.20	609.99	1553.44	3725.43
	Difference	0.00	0.00	3218.93	-262.21	2956.72
	Difference [%]	0.00	0.00	84.07	-20.31	44.25

Table 44: The N emissions of farm B per pollutant per step in the manure life cycle.

	Farm B	Grazing	Housing	Treatment & Storage	Application	Total
NH3	Storage Scenario	50.77	2312.39	3336.18	1606.24	7305.58
	Treatment Scenario	50.77	2312.39	613.96	2142.35	5119.47
	Difference	0.00	0.00	2722.22	-536.10	2186.11
	Difference [%]	0.00	0.00	81.60	-33.38	29.92
N2O	Storage Scenario	68.20	-	135.89	168.16	372.24
	Treatment Scenario	68.20	-	0.00	168.16	236.35
	Difference	0.00	-	135.89	0.00	135.89
	Difference [%]	0.00	-	100.00	0.00	36.50
NO2	Storage Scenario	24.80	-	4.68	224.21	253.68
	Treatment Scenario	24.80	-	0.00	224.21	249.01
	Difference	0.00	-	4.68	0.00	4.68
	Difference [%]	0.00	-	100.00	0.00	1.84
Total (excl. N2)	Storage Scenario	143.77	2312.39	3476.74	1998.60	7931.50
	Treatment Scenario	143.77	2312.39	613.96	2534.71	5604.83
	Difference	0.00	0.00	2862.78	-536.10	2326.67
	Difference [%]	0.00	0.00	82.34	-26.82	29.33
N2	Storage Scenario	-	-	140.32	-	140.32
	Treatment Scenario	-	-	0.00	-	0.00
	Difference	-	-	140.32	-	140.32
	Difference [%]	-	-	100.00	-	100.00
Total (incl. N2)	Storage Scenario	143.77	2312.39	3617.06	1998.60	8071.82
	Treatment Scenario	143.77	2312.39	613.96	2534.71	5604.83
	Difference	0.00	0.00	3003.10	-536.10	2466.99
	Difference [%]	0.00	0.00	83.03	-26.82	30.56

Table 45: The N emissions of farm C per pollutant per step in the manure life cycle.

	Farm C	Grazing	Housing	Treatment & Storage	Application	Total
NH3	Storage Scenario	0.00	1081.41	1635.71	790.03	3507.15
	Treatment Scenario	0.00	1081.41	317.86	1088.21	2487.48
	Difference	0.00	0.00	1317.85	-298.18	1019.67
	Difference [%]	0.00	0.00	80.57	-37.74	29.07
N2O	Storage Scenario	0.00	-	67.02	72.99	140.01
	Treatment Scenario	0.00	-	0.00	72.99	72.99
	Difference	0.00	-	67.02	0.00	67.02
	Difference [%]	0.00	-	100.00	0.00	47.87
NO2	Storage Scenario	0.00	-	2.84	97.32	100.15
	Treatment Scenario	0.00	-	0.00	97.32	97.32
	Difference	0.00	-	2.84	0.00	2.84
	Difference [%]	0.00	-	100.00	0.00	2.83
Total (excl. N2)	Storage Scenario	0.00	1081.41	1705.56	960.34	3747.31
	Treatment Scenario	0.00	1081.41	317.86	1258.51	2657.79
	Difference	0.00	0.00	1387.70	-298.18	1089.52
	Difference [%]	0.00	0.00	81.36	-31.05	29.07
N2	Storage Scenario	-	-	85.10	-	85.10
	Treatment Scenario	-	-	0.00	-	0.00
	Difference	-	-	85.10	-	85.10
	Difference [%]	-	-	100.00	-	100.00
Total (incl. N2)	Storage Scenario	0.00	1081.41	1790.66	960.34	3832.42
	Treatment Scenario	0.00	1081.41	317.86	1258.51	2657.79
	Difference	0.00	0.00	1472.80	-298.18	1174.63
	Difference [%]	#DIV/0!	0.00	82.25	-31.05	30.65

Table 46: The N emissions of farm D per pollutant per step in the manure life cycle.

	Farm D	Grazing	Housing	Treatment & Storage	Application	Total
NH3	Storage Scenario	65.74	2094.88	2968.56	1245.52	6374.70
	Treatment Scenario	65.74	2094.88	567.00	1705.82	4433.44
	Difference	0.00	0.00	2401.56	-460.30	1941.26
	Difference [%]	0.00	0.00	80.90	-36.96	30.45
N2O	Storage Scenario	91.51	-	120.43	139.77	351.71
	Treatment Scenario	91.51	-	0.00	139.77	231.28
	Difference	0.00	-	120.43	0.00	120.43
	Difference [%]	0.00	-	100.00	0.00	34.24
NO2	Storage Scenario	33.28	-	3.50	186.36	223.14
	Treatment Scenario	33.28	-	0.00	186.36	219.64
	Difference	0.00	-	3.50	0.00	3.50
	Difference [%]	0.00	-	100.00	0.00	1.57
Total (excl. N2)	Storage Scenario	190.53	2094.88	3092.48	1571.65	6949.55
	Treatment Scenario	190.53	2094.88	567.00	2031.96	4884.36
	Difference	0.00	0.00	2525.49	-460.30	2065.19
	Difference [%]	0.00	0.00	81.67	-29.29	29.72
N2	Storage Scenario	-	-	104.90	-	104.90
	Treatment Scenario	-	-	0.00	-	0.00
	Difference	-	-	104.90	-	104.90
	Difference [%]	-	-	100.00	-	100.00
Total (incl. N2)	Storage Scenario	190.53	2094.88	3197.38	1571.65	7054.45
	Treatment Scenario	190.53	2094.88	567.00	2031.96	4884.36
	Difference	0.00	0.00	2630.39	-460.30	2170.08
	Difference [%]	0.00	0.00	82.27	-29.29	30.76

Table 47: CH_4 emissions during manure and digestate storage as well as during grazing on dairy farms.

Emissions [kg CH4]	Farm A: storage	Farm A: treatment	Farm B: storage	Farm B: treatment	Farm C: storage	Farm C: treatment	Farm D: storage	Farm D: treatment
Slurry	6774.47	0.00	8301.93	0.00	4275.44	0.00	9694.77	0.00
Solid	65.25	0.00	35.47	0.00	24.68	0.00	31.98	0.00
Grazing	53.06	53.06	45.32	45.32	0.00	0.00	75.55	75.55
Digestate	0.00	1293.36	0.00	1518.25	0.00	791.50	0.00	1758.82
Total	6892.78	1346.43	8382.72	1563.58	4300.12	791.50	9802.31	1834.37
Difference	80.5%		81.3%		81.6%		81.3%	

Table 48: Net CO_2 emissions on dairy farms without a digester and digester emissions reduction through energy generation.

Results	Farm A	Farm B	Farm C	Farm D
Farm: net emissions [tonne CO2]	47.15	111.85	9.29	83.24
Digester: net emissions reduction [tonne CO2]	51.44	60.38	31.48	69.95
Digester: net electricity production [MWh]	137.83	161.79	84.35	187.43

J Farm Scale Housing Type Results

Table 49: The total N emissions of farm A based on different housing types. The difference per housing type indicates the total N emission reduction at a farm-scale when combining a digester with a specific housing type.

Pollutants	Parameter	A 1.100	A 1.6	A 1.20	A 1.26	A 1.1
NH3 [Fraction TAN]	Housing Emission Factor	0.150	0.127	0.117	0.093	0.066
NH3	Without Digester	6.53	6.29	6.18	5.93	5.65
[tonne N]	With Digester	4.20	3.88	3.73	3.39	3.01
N2O	Without Digester	0.32	0.32	0.32	0.32	0.33
[tonne N]	With Digester	0.18	0.18	0.18	0.18	0.18
NO2	Without Digester	0.16	0.16	0.16	0.16	0.17
[tonne N]	With Digester	0.16	0.16	0.16	0.16	0.16
	Without Digester	7.01	6.77	6.67	6.42	6.15
Total	With Digester	4.54	4.21	4.07	3.73	3.35
[tonne N]	Difference	2.47	2.56	2.60	2.69	2.79
	Difference (%)	35.27	37.80	39.00	41.96	45.48

Table 50: The total N emissions of farm B based on different housing types. The difference per housing type indicates the total N emission reduction at a farm-scale when combining a digester with a specific housing type.

Pollutants	Parameter	A 1.100	A 1.6	A 1.20	A 1.26	A 1.1
NH3 [Fraction TAN]	Housing Emission Factor	0.149	0.126	0.115	0.091	0.065
NH3	Without Digester	7.31	7.06	6.95	6.69	6.41
[tonne N]	With Digester	5.12	4.79	4.64	4.29	3.90
N2O	Without Digester	0.37	0.38	0.38	0.38	0.39
[tonne N]	With Digester	0.24	0.24	0.24	0.24	0.24
NO2	Without Digester	0.25	0.25	0.25	0.25	0.25
[tonne N]	With Digester	0.25	0.25	0.25	0.25	0.25
	Without Digester	7.93	7.69	7.58	7.33	7.05
Total	With Digester	5.60	5.27	5.12	4.77	4.39
[tonne N]	Difference	2.33	2.42	2.46	2.55	2.66
	Difference (%)	29.33	31.44	32.44	34.87	37.73

Table 51: The total N emissions of farm C based on different housing types. The difference per housing type indicates the total N emission reduction at a farm-scale when combining a digester with a specific housing type.

Pollutants	Parameter	A 1.100	A 1.6	A 1.20	A 1.26	A 1.1
NH3 [Fraction TAN]	Housing Emission Factor	0.143	0.121	0.111	0.088	0.063
NH3 [tonne N]	Without Digester	3.51	3.39	3.34	3.22	3.09
	With Digester	2.49	2.33	2.26	2.10	1.92
N2O [tonne N]	Without Digester	0.14	0.14	0.14	0.14	0.15
	With Digester	0.07	0.07	0.07	0.07	0.07
NO2 [tonne N]	Without Digester	0.10	0.10	0.10	0.10	0.10
	With Digester	0.10	0.10	0.10	0.10	0.10
Total [tonne N]	Without Digester	3.75	3.64	3.58	3.47	3.34
	With Digester	2.66	2.50	2.43	2.27	2.09
	Difference	1.09	1.13	1.15	1.20	1.25
	Difference (%)	29.07	31.15	32.13	34.53	37.34

Table 52: The total N emissions of farm D based on different housing types. The difference per housing type indicates the total N emission reduction at a farm-scale when combining a digester with a specific housing type.

Pollutants	Parameter	A 1.100	A 1.6	A 1.20	A 1.26	A 1.1
NH3 [Fraction TAN]	Housing Emission Factor	0.151	0.127	0.117	0.093	0.066
NH3 [tonne N]	Without Digester	6.37	6.15	6.05	5.81	5.56
	With Digester	4.43	4.13	4.00	3.68	3.33
N2O [tonne N]	Without Digester	0.35	0.35	0.36	0.36	0.36
	With Digester	0.23	0.23	0.23	0.23	0.23
NO2 [tonne N]	Without Digester	0.22	0.22	0.22	0.22	0.22
	With Digester	0.22	0.22	0.22	0.22	0.22
Total [tonne N]	Without Digester	6.95	6.73	6.63	6.40	6.14
	With Digester	4.88	4.58	4.45	4.13	3.78
	Difference	2.07	2.15	2.18	2.27	2.36
	Difference (%)	29.72	31.90	32.94	35.47	38.47

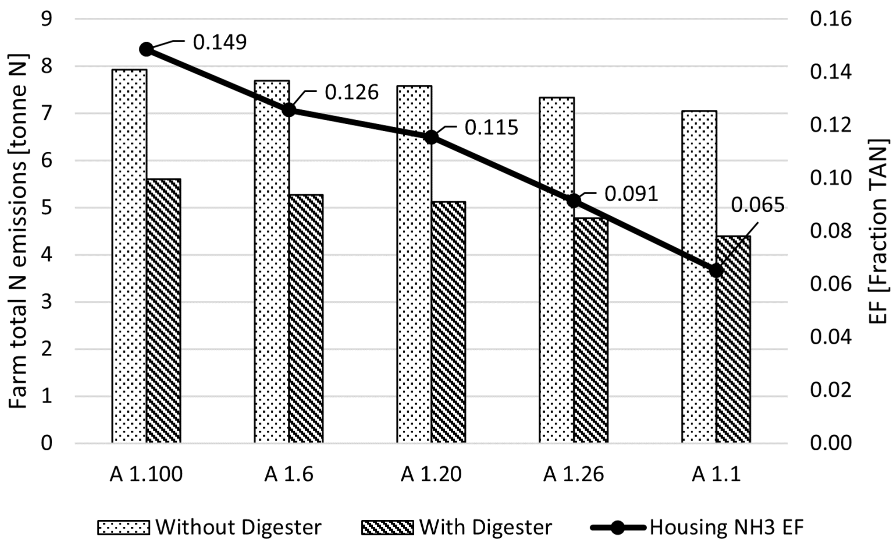


Figure 27: The total N emissions on farm B with different housing types, each with their own EF.

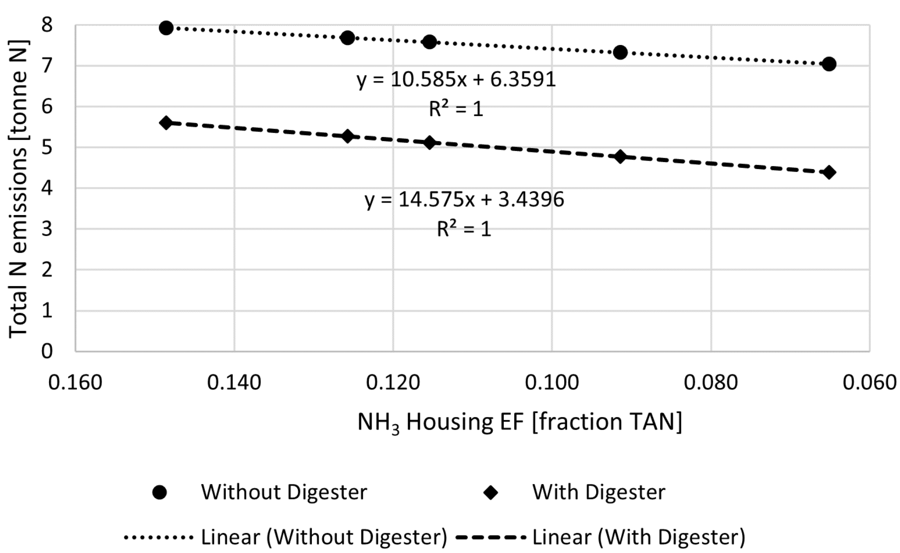


Figure 28: The relation between the total N emissions on farm B and the NH_3 EFs from the different housing types.

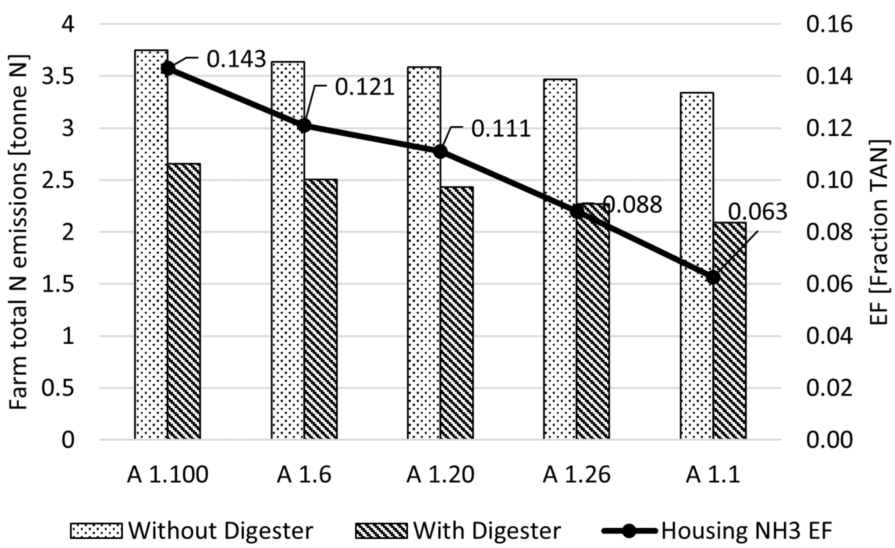


Figure 29: The total N emissions on farm C with different housing types, each with their own EF.

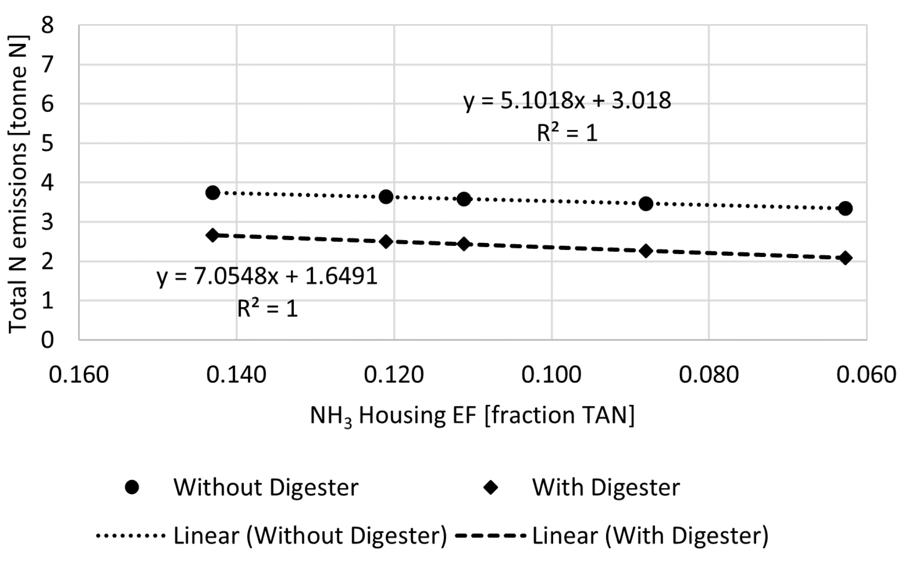


Figure 30: The relation between the total N emissions on farm C and the NH_3 EFs from the different housing types.

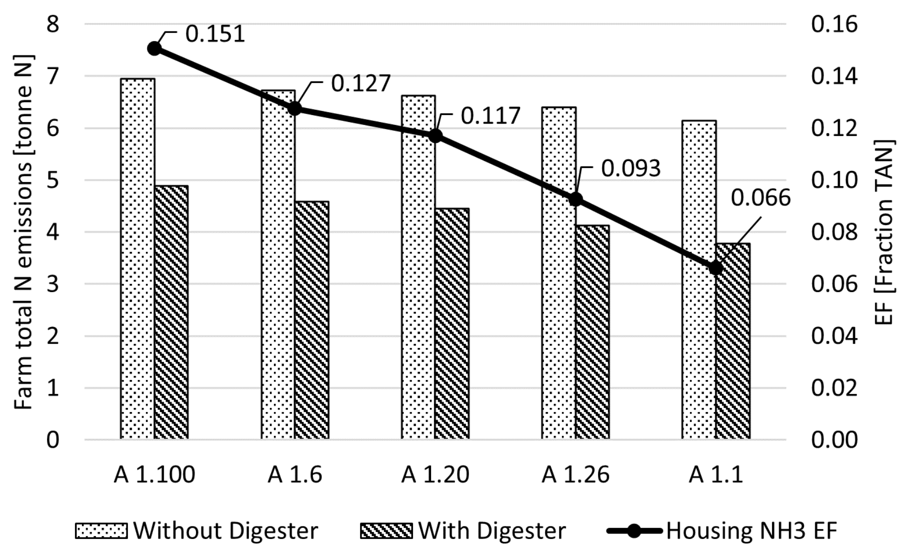


Figure 31: The total N emissions on farm D with different housing types, each with their own EF.

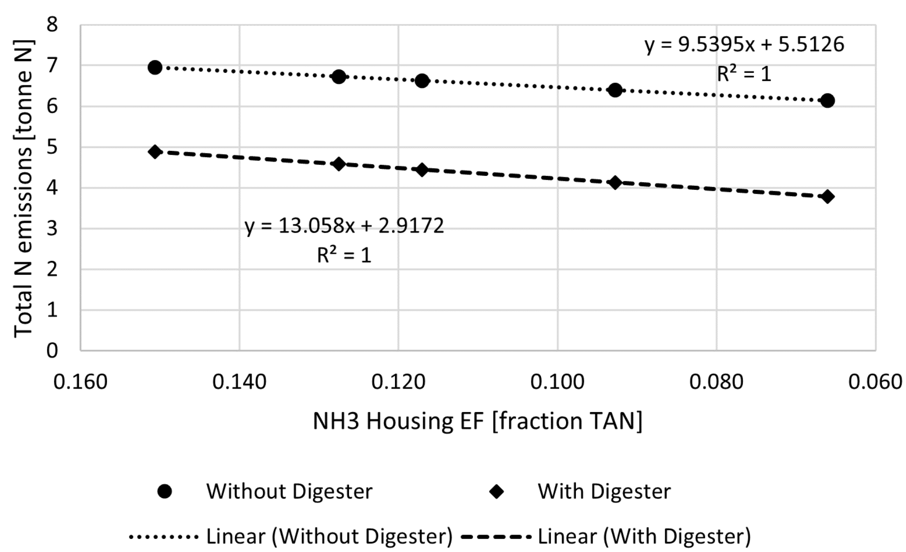


Figure 32: The relation between the total N emissions on farm D and the NH_3 EFs from the different housing types.

Table 53: The total N emissions on the four farm different farms, where the change from their current housing type (A 1.26 for farm A and A 1.100 for the other three) to the least polluting housing type A.1.1 is conducted at the same time as the implementation of A digester (between the storage and treatment scenarios). The total emissions reduction here is thus the result of the combination of both measures: adjusting the housing type and digesting manure.

	Farm A: Storage	Farm A: Treatment	Farm B: Storage	Farm B: Treatment	Farm C: Storage	Farm C: Treatment	Farm D: Storage	Farm D: Treatment
Housing NH3 EF [fraction TAN]	0.093	0.066	0.149	0.065	0.143	0.063	0.151	0.066
NH3 [tonne N]	5.93	3.01	7.31	3.90	3.51	1.92	6.37	3.33
N2O [tonne N]	0.32	0.18	0.37	0.24	0.14	0.07	0.35	0.23
NO2 [tonne N]	0.16	0.16	0.25	0.25	0.10	0.10	0.22	0.22
Farm Total N emissions [tonne N]	6.42	3.35	7.93	4.39	3.75	2.09	6.95	3.78
Difference [tonne N] (%)	3.07	(47.80%)	3.54	(44.67%)	1.66	(44.19%)	3.17	(45.61%)

K Farm Scale Grazing Regime Results

Table 54: The emission reduction and energy generation results of farm A based upon an increasing grazing regime.

Farm Results	0%	5%	10%	15%	20%	25%	Difference [0% - 25%]	Difference (%) [0% - 25%]
Storage N [tonne N]	7.1	6.8	6.5	6.2	5.9	5.6	1.5	21.5
Treatment N [tonne N]	4.1	3.9	3.8	3.6	3.4	3.2	0.9	21.5
Storage CH4 [tonne CH4]	7.7	7.3	7.0	6.6	6.2	5.9	1.8	23.4
Treatment CH4 [tonne CH4]	1.5	1.4	1.4	1.3	1.3	1.2	0.2	16.7
Net electricity production [MWh]	154.8	147.1	139.3	131.6	123.8	116.1	38.7	25.0
Net CO2 reduction [tonne CO2]	57.8	54.9	52.0	49.1	46.2	43.3	14.4	25.0

Table 55: The emission reduction and energy generation results of farm B based upon an increasing grazing regime.

Farm Results	0%	5%	10%	15%	20%	25%	Difference [0% - 25%]	Difference (%) [0% - 25%]
Storage N [tonne N]	8.4	8.1	7.8	7.5	7.2	6.9	1.5	17.9
Treatment N [tonne N]	5.9	5.7	5.5	5.4	5.2	5.0	0.9	15.9
Storage CH4 [tonne CH4]	9.1	8.7	8.2	7.8	7.4	7.0	2.1	23.5
Treatment CH4 [tonne CH4]	1.7	1.6	1.5	1.5	1.4	1.4	0.3	16.7
Net electricity production [MWh]	176.3	167.5	158.7	149.8	141.0	132.2	44.1	25.0
Net CO2 reduction [tonne CO2]	65.8	62.5	59.2	55.9	52.6	49.3	16.4	25.0

Table 56: The emission reduction and energy generation results of farm C based upon an increasing grazing regime.

Farm Results	0%	5%	10%	15%	20%	25%	Difference [0% - 25%]	Difference (%) [0% - 25%]
Storage N [tonne N]	3.7	3.6	3.5	3.3	3.2	3.0	0.7	19.6
Treatment N [tonne N]	2.7	2.6	2.5	2.4	2.3	2.2	0.5	18.6
Storage CH4 [tonne CH4]	4.3	4.1	3.9	3.7	3.5	3.3	1.0	23.5
Treatment CH4 [tonne CH4]	0.8	0.8	0.7	0.7	0.7	0.7	0.1	16.7
Net electricity production [MWh]	84.3	80.1	75.9	71.7	67.5	63.3	21.1	25.0
Net CO2 reduction [tonne CO2]	31.5	29.9	28.3	26.8	25.2	23.6	7.9	25.0

Table 57: The emission reduction and energy generation results of farm D based upon an increasing grazing regime.

Farm Results	0%	5%	10%	15%	20%	25%	Difference [0% - 25%]	Difference (%) [0% - 25%]
Storage N [tonne N]	7.6	7.3	7.0	6.7	6.5	6.2	1.4	18.8
Treatment N [tonne N]	5.3	5.1	4.9	4.8	4.6	4.4	0.9	16.6
Storage CH4 [tonne CH4]	11.0	10.5	9.9	9.4	8.9	8.4	2.6	23.5
Treatment CH4 [tonne CH4]	2.0	1.9	1.9	1.8	1.7	1.7	0.3	16.7
Net electricity production [MWh]	211.6	201.0	190.4	179.8	169.3	158.7	52.9	25.0
Net CO2 reduction [tonne CO2]	79.0	75.0	71.1	67.1	63.2	59.2	25.0	-9.6

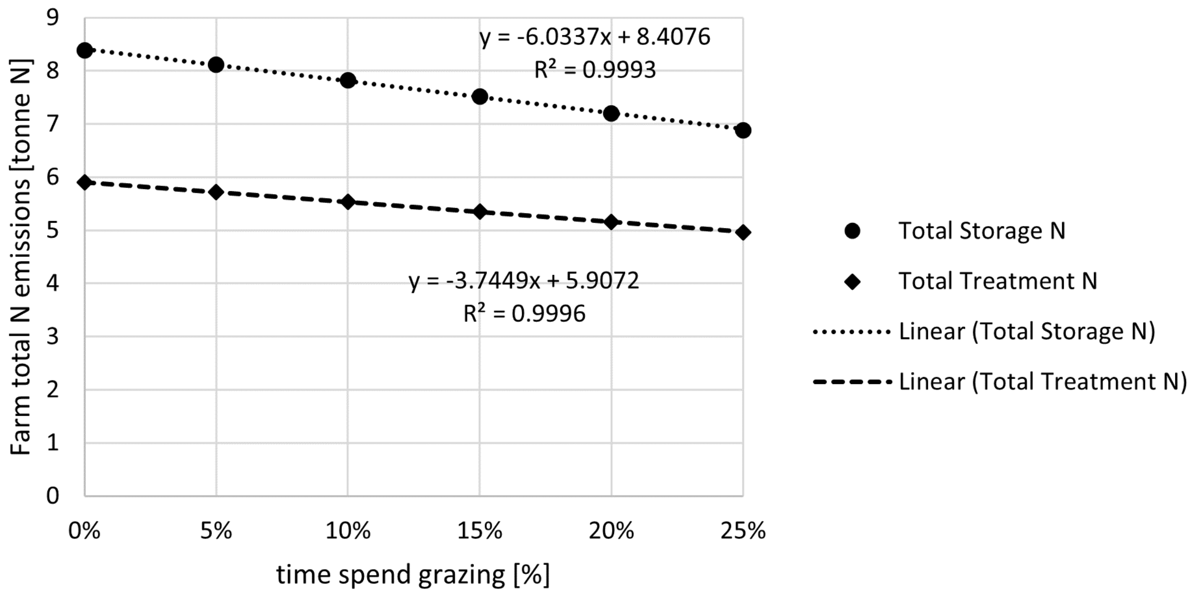


Figure 33: The relation between the total N emissions on farm B and the grazing regime.

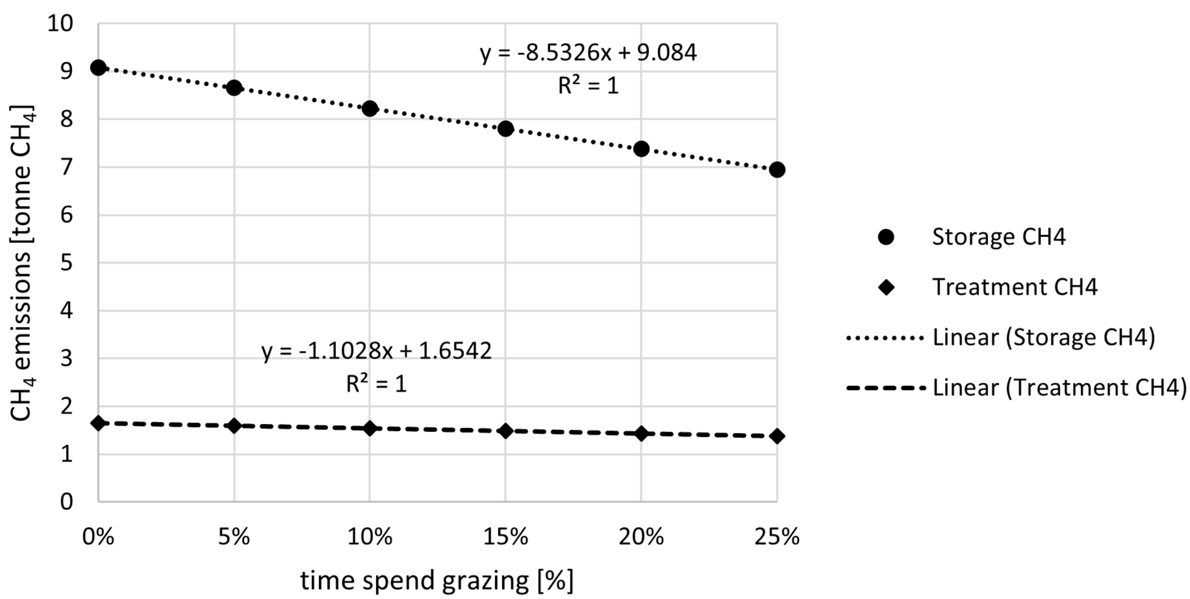


Figure 34: The relation between the CH_4 emissions on farm B and the grazing regime.

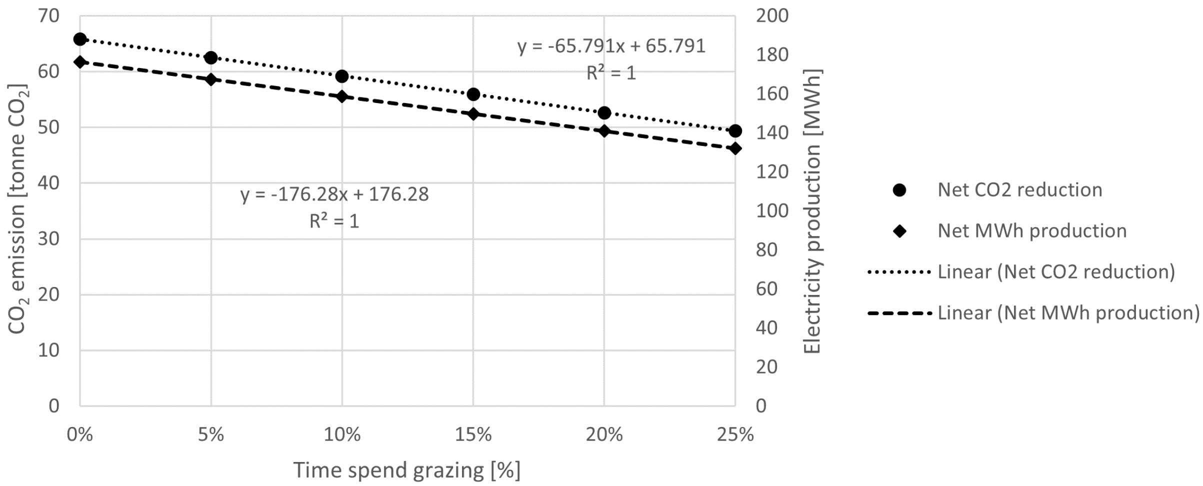


Figure 35: The relation between the CO_2 emissions and energy generation in MWh on farm B and the grazing regime.

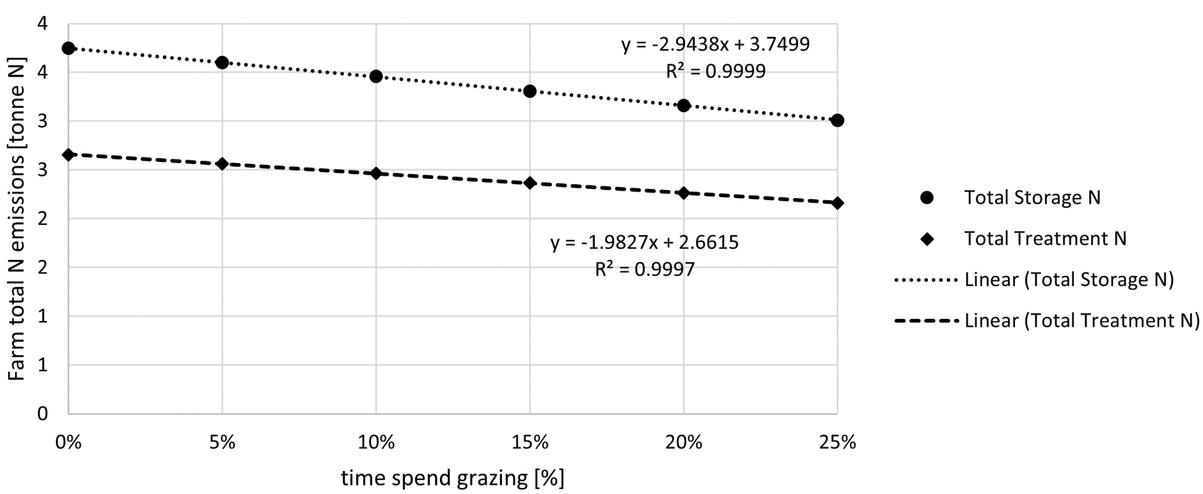


Figure 36: The relation between the total N emissions on farm C and the grazing regime.

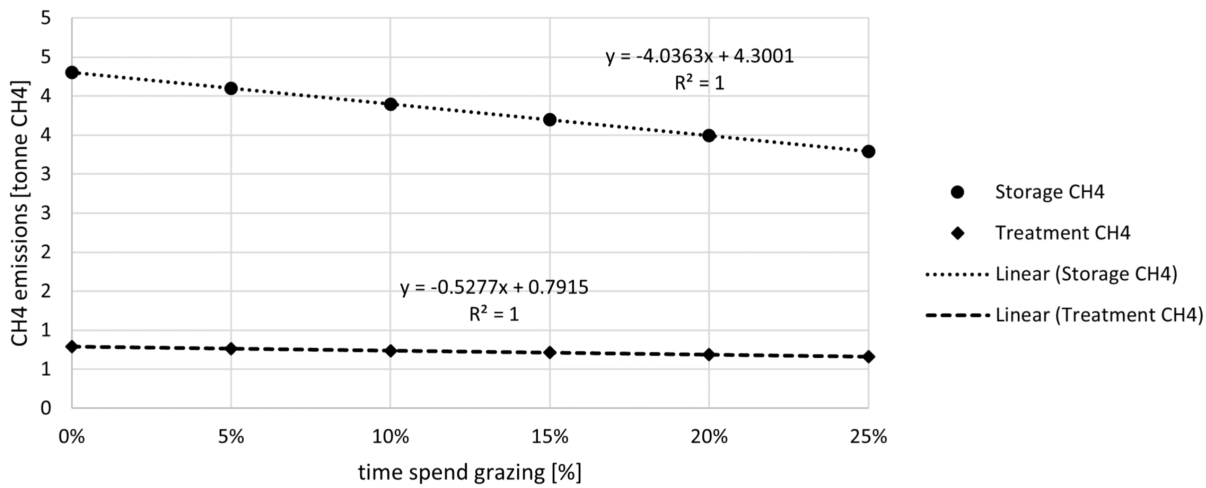


Figure 37: The relation between the CH_4 emissions on farm C and the grazing regime.

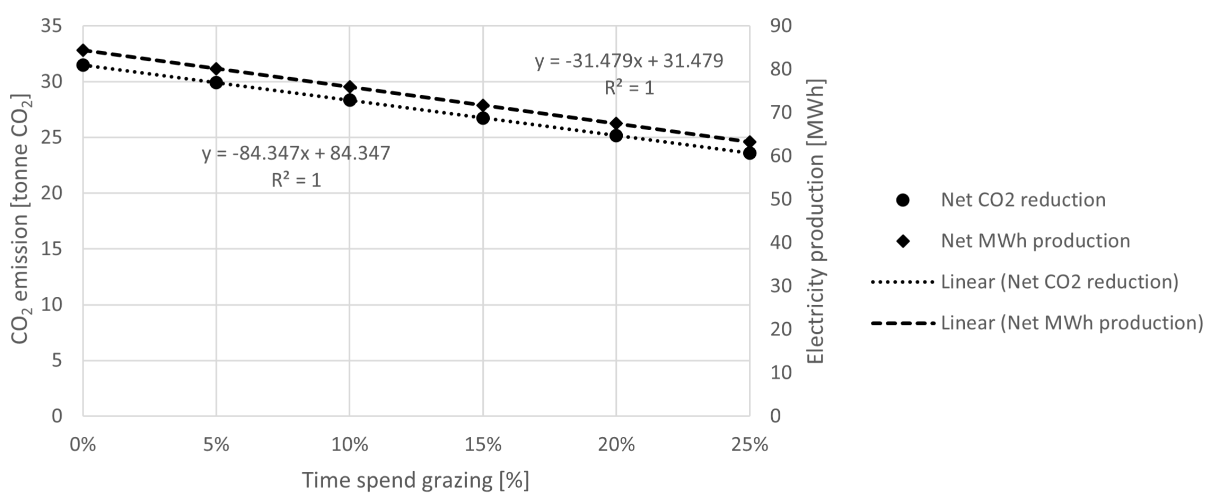


Figure 38: The relation between the CO_2 emissions and energy generation in MWh on farm C and the grazing regime.

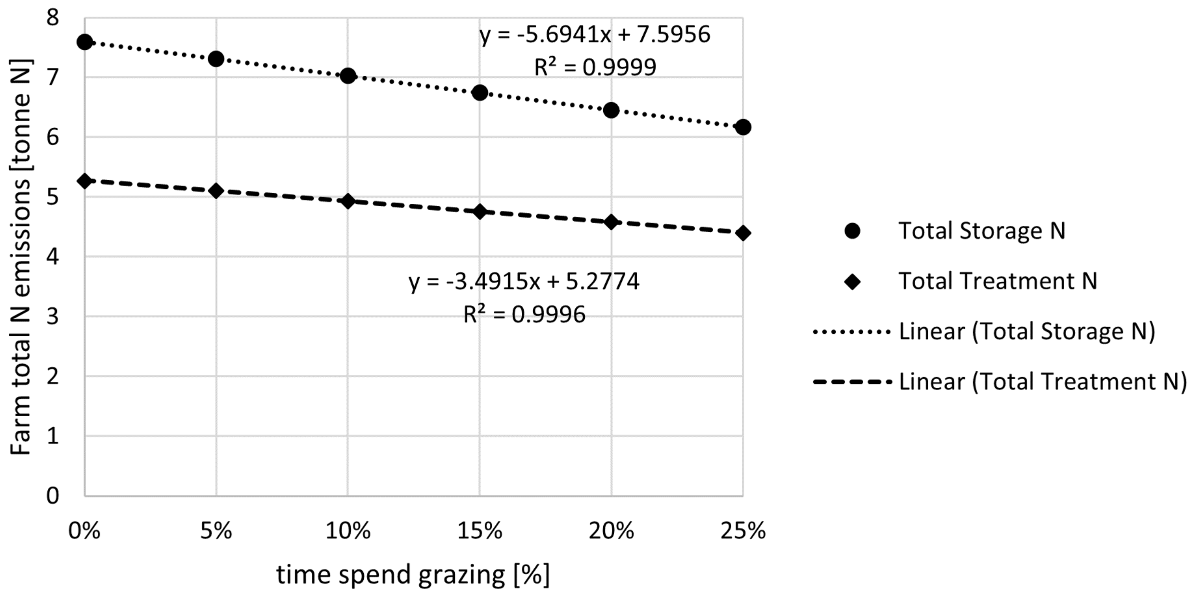


Figure 39: The relation between the total N emissions on farm D and the grazing regime.

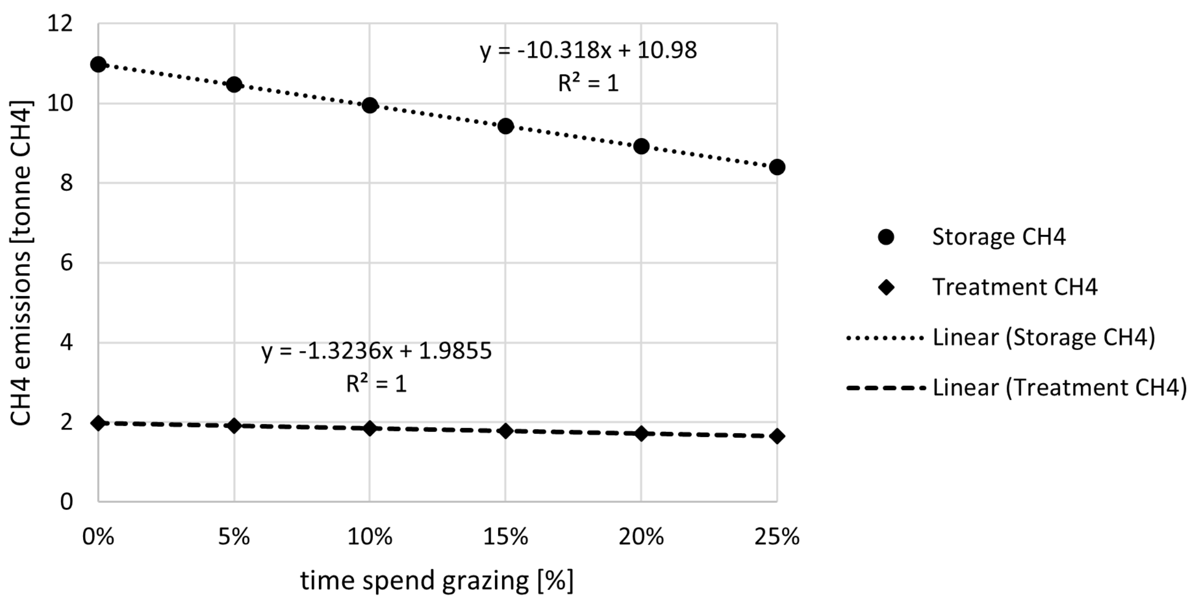


Figure 40: The relation between the CH_4 emissions on farm D and the grazing regime.

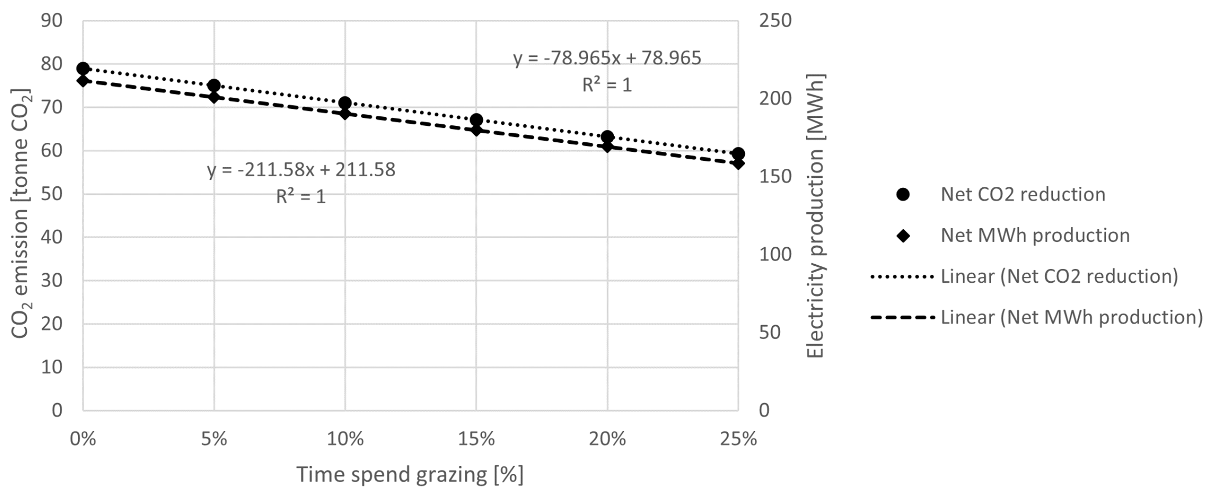


Figure 41: The relation between the CO_2 emissions and energy generation in MWh on farm D and the grazing regime.

L Provincial Scale Model Results

Table 58: The estimated N emissions per pollutant for the provinces in the North-West region of the Netherlands. (note that N_2 is not considered a pollutant but does play a role in the nitrogen budget, thus the total emission reduction results are displayed with and without N_2. The difference between both totals is on average 1.5% per province.)*

Pollutants [tonne N]		Groningen	Friesland	Utrecth	Noord-Holland	Zuid-Holland
NH_3	Storage	4324.09	12233.40	3877.00	3818.73	3773.78
	Treatment	3084.22	8674.20	2775.54	2846.38	2743.98
	Difference	1239.87	3559.19	1101.46	972.35	1029.80
	Difference (%)	28.7	29.1	28.4	25.5	27.3
N_2O	Storage	255.83	716.11	229.20	230.19	224.18
	Treatment	173.96	483.20	156.06	160.94	154.06
	Difference	81.87	232.91	73.14	69.25	70.13
	Difference (%)	32.0	32.5	31.9	30.1	31.3
NO_2	Storage	145.09	396.80	130.41	141.11	130.86
	Treatment	141.78	387.60	127.50	138.31	128.11
	Difference	3.31	9.20	2.91	2.80	2.75
	Difference (%)	2.3	2.3	2.2	2.0	2.1
N_2*	Storage	99.39	275.91	87.35	83.85	82.42
	Treatment	0.00	0.00	0.00	0.00	0.00
	Difference	99.39	275.91	87.35	83.85	82.42
	Difference (%)	100.0	100.0	100.0	100.0	100.0
Total (incl. N_2)	Storage	4824.40	13622.21	4323.97	4273.88	4211.24
	Treatment	3399.96	9545.01	3059.11	3145.63	3026.15
	Difference	1424.45	4077.20	1264.86	1128.25	1185.09
	Difference (%)	29.5	29.9	29.3	26.4	28.1
Total (excl. N_2)	Storage	4725.01	13346.30	4236.62	4190.03	4128.82
	Treatment	3399.96	9545.01	3059.11	3145.63	3026.15
	Difference	1325.06	3801.30	1177.51	1044.40	1102.67
	Difference (%)	28.0	28.5	27.8	24.9	26.7

Table 59: The estimated N emissions per pollutant for the provinces in the South-East region of the Netherlands. (note that N_2 is not considered a pollutant but does play a role in the nitrogen budget, thus the total emission reduction results are displayed with and without N_2. The difference between both totals is on average 1.5% per province.)*

Pollutants [tonne N]		Drenthe	Overijssel	Flevoland	Gelderland	Zeeland	Noord-Brabant	Limburg
NH_3	Storage	4359.62	10162.33	1286.81	9777.48	949.96	8256.91	1998.39
	Treatment	3197.87	7317.66	875.42	7287.33	752.11	5676.64	1478.16
	Difference	1161.76	2844.67	411.39	2490.14	197.85	2580.28	520.23
	Difference (%)	26.6	28.0	32.0	25.5	20.8	31.2	26.0
N_2O	Storage	242.41	550.87	65.72	548.43	54.06	448.05	115.39
	Treatment	161.36	358.45	40.06	369.53	40.09	285.18	179.20
	Difference	81.05	192.42	25.67	178.90	13.97	162.87	36.18
	Difference (%)	33.4	34.9	39.1	32.6	25.8	36.4	31.4
NO_2	Storage	163.31	354.64	36.92	378.34	37.83	275.99	80.78
	Treatment	159.94	346.80	35.90	370.87	41.63	269.28	80.38
	Difference	3.37	7.84	1.02	7.47	-3.80	6.71	0.41
	Difference (%)	2.1	2.2	2.8	2.0	-10.0	2.4	0.5
N_2*	Storage	101.23	235.19	30.53	224.14	21.21	201.23	47.72
	Treatment	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Difference	101.23	235.19	30.53	224.14	21.21	201.23	47.72
	Difference (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total (incl. N_2)	Storage	4866.58	11303.03	1419.98	10928.40	1063.07	9182.18	2242.28
	Treatment	3519.16	8022.91	951.38	8027.74	833.84	6231.10	1637.74
	Difference	1347.42	3280.13	468.60	2900.66	229.23	2951.08	604.54
	Difference (%)	27.7	29.0	33.0	26.5	21.6	32.1	27.0
Total (excl. N_2)	Storage	4765.35	11067.84	1389.45	10704.25	1041.86	8980.95	2194.56
	Treatment	3519.16	8022.91	951.38	8027.74	833.84	6231.10	1637.74
	Difference	3519.16	8022.91	438.07	2676.52	208.02	2749.85	556.82
	Difference (%)	26.2	27.5	31.5	25.0	20.0	30.6	25.4

Table 60: The amount of manure expressed in tonne N exported out of the system for both scenarios.

Provinces	Storage [tonne N]	Treatment [tonnen N]	Difference [tonne N]
Groningen	3902.81	5673.51	-1770.70
Friesland	12446.82	17480.57	-5033.75
Utrecht	3423.44	5004.55	-1581.11
Noord-Holland	1770.26	3267.92	-1497.67
Zuid-Holland	2800.07	4315.35	-1515.29
Drenthe	1114.33	2870.00	-1755.67
Overijssel	5409.11	9574.41	-4165.30
Flevoland	1588.01	2143.15	-555.14
Gelderland	967.33	4842.75	-3875.42
Zeeland	-850.24	-474.64	-375.60
Noord-Brabant	6589.83	10116.50	-3526.67
Limburg (SE)	-98.73	705.02	-803.76

Table 61: The estimated CH_4 emissions for each of the provinces in the Netherlands for both scenarios with (treatment) and without (storage) a manure digester.

Provinces	CH4 storage [tonne]	CH4 treatment [tonne]	Difference [tonne]	Difference (%)
Groningen	4853.73	932.14	3921.58	80.80
Friesland	13841.51	2654.74	11186.77	80.82
Utrecht	4348.70	834.42	3514.28	80.81
Noord-Holland	4110.62	789.32	3321.30	80.80
Zuid-Holland	4177.60	800.91	3376.69	80.83
Drenthe	5385.40	1018.84	4366.56	81.08
Overijssel	12832.44	2424.81	10407.64	81.10
Flevoland	1716.18	323.81	1392.37	81.13
Gelderland	11879.50	2247.84	9631.66	81.08
Zeeland	1153.52	217.97	935.55	81.10
Noord-Brabant	10818.35	2045.45	8772.90	81.09
Limburg	2449.46	464.21	1985.25	81.05

Table 62: Energy production and use of a manure digester per province expressed in GWh. The net energy production indicates the difference between the two and is the amount of electricity per province available for export to the national energy grid.

Provinces	Energy prod. [GWh]	Energy use [GWh]	Net energy prod. [GWh]	Difference (%)
Groningen	130.26	36.27	94.00	72.16
Friesland	370.99	103.36	267.63	72.14
Utrecht	116.61	32.47	84.14	72.16
Noord-Holland	110.31	30.71	79.60	72.16
Zuid-Holland	111.93	31.16	80.76	72.16
Drenthe	145.33	40.46	104.87	72.16
Overijssel	345.87	96.30	249.58	72.16
Flevoland	46.19	12.86	33.33	72.16
Gelderland	320.63	89.27	231.36	72.16
Zeeland	31.09	8.66	22.43	72.16
Noord-Brabant	291.76	81.23	210.53	72.16
Limburg	66.21	18.43	47.78	72.16

Table 63: The estimated CO_2 emissions for each of the provinces in the Netherlands for both scenarios wih (treatment) and without (storage) a manure digester.

Provinces	CO2 reduced [tonne]	CO2 emitted [tonne]	Difference [tonne]	Difference (%)
Groningen	48616.17	13535.38	35080.79	72.16
Friesland	138458.47	38574.93	99883.54	72.14
Utrecht	43519.31	12116.35	31402.96	72.16
Noord-Holland	41167.21	11461.49	29705.71	72.16
Zuid-Holland	41771.66	11629.78	30141.88	72.16
Drenthe	54237.63	15100.47	39137.16	72.16
Overijssel	129083.51	35938.55	93144.96	72.16
Flevoland	17238.03	4799.30	12438.74	72.16
Gelderland	119662.59	33315.64	86346.95	72.16
Zeeland	11603.45	3230.55	8372.90	72.16
Noord-Brabant	108888.44	30315.98	78572.47	72.16
Limburg	24711.81	6880.09	17831.72	72.16

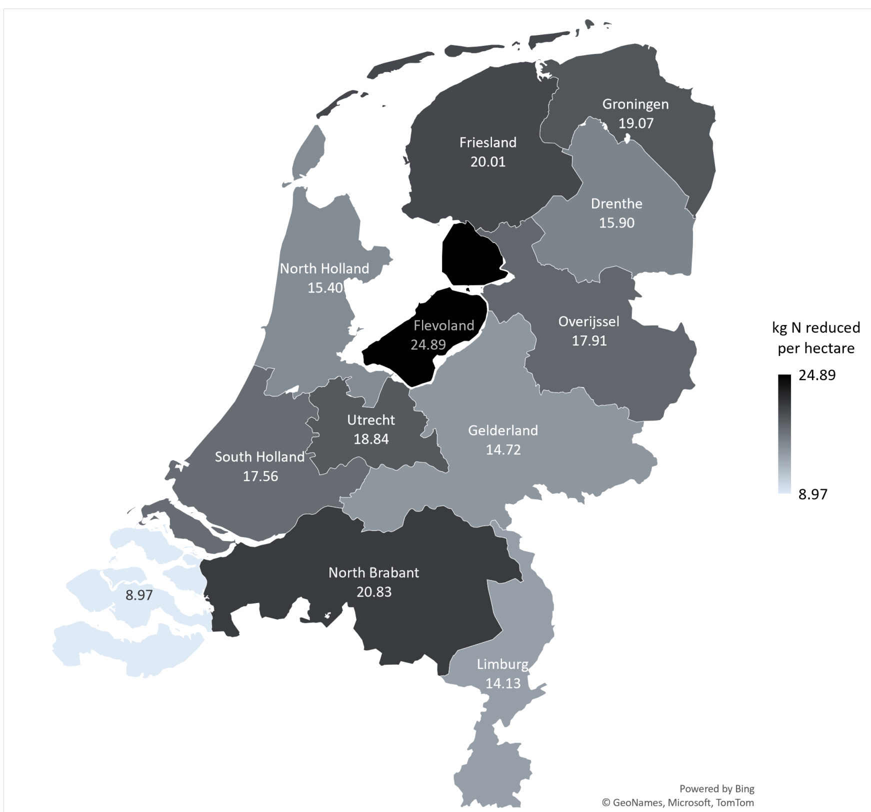


Figure 42: The emissions reduction expressed in kg N per hectare of farmland per province when implementing a manure digester on all dairy farms in these provinces.

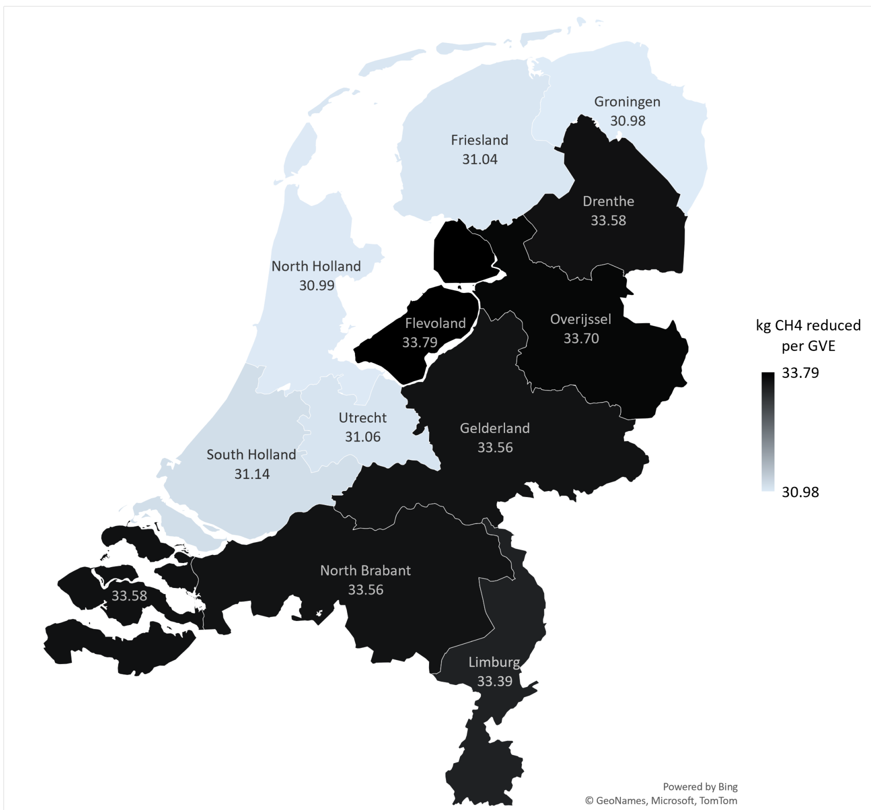


Figure 43: The emissions reduction expressed in kg CH_4 per GVE per province when implementing a manure digester on all dairy farms in these provinces.

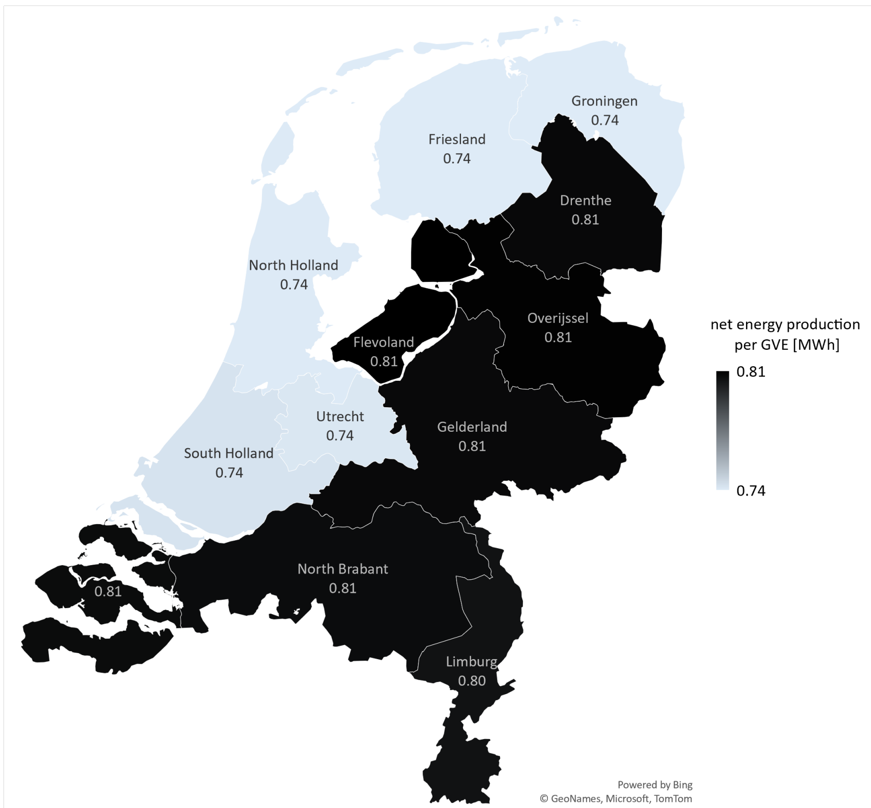


Figure 44: The emissions reduction expressed in MWh per GVE per province when implementing a manure digester on all dairy farms in these provinces.

Figure 45: The emissions reduction expressed in tonne CO_2 per province when implementing a manure digester for all dairy farms in these provinces.

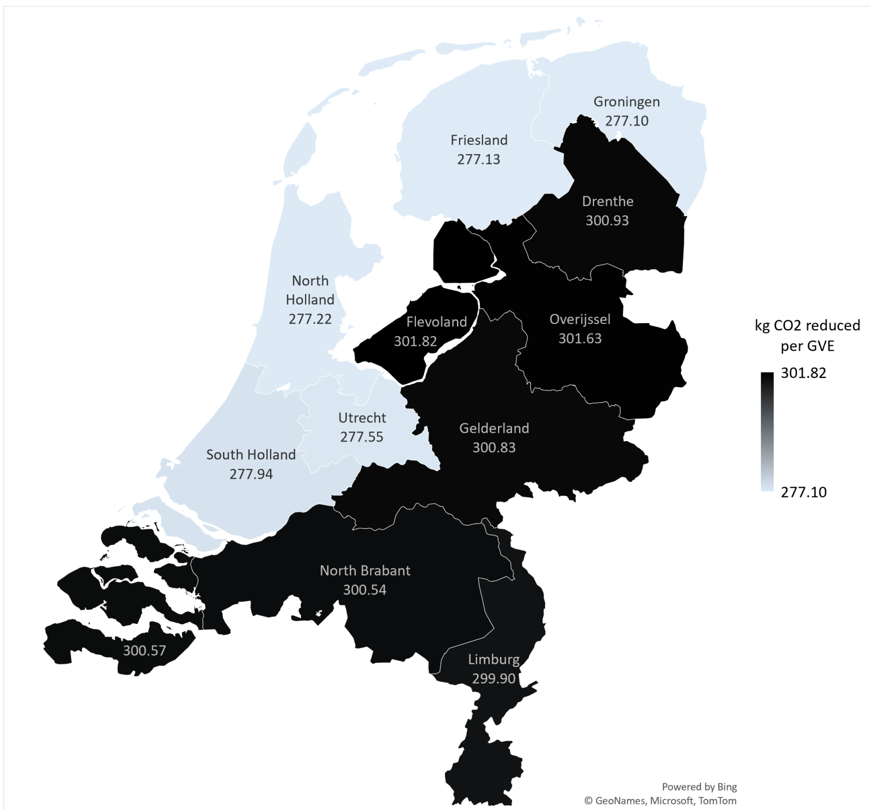


Figure 46: The emissions reduction expressed in kg CO_2 per GVE per province when implementing a manure digester on all dairy farms in these provinces.