Achieving energy self-sufficiency and circularity in the Dutch agricultural sector, using anaerobic digestion.

Focus on Dutch dairy farms

Tim Middelburg
EES-2019-359

Master Programme Energy and Environmental Sciences, University of Groningen

university of groningen / faculty of science and engineering / energy and sustainability research institute groningen

Research report of Tim Middelburg

Report: EES-2019-359

Supervised by:
Dr. F. (Frank) Pierie, Center for Energy and Environmental Sciences (IVEM)
MSc. G.A.H. (Gideon) Laugs, Center for Energy and Environmental Sciences (IVEM)

University of Groningen
Energy and Sustainability Research Institute Groningen, ESRIG
Nijenborgh 6
9747 AG Groningen
T: 050 - 363 4760
W: www.rug.nl/research/esrig

TABLE OF CONTENTS

Summary

The agricultural sector is responsible of 6.7% of the total Dutch energy consumption and 12% of the total GHG emissions. Currently, the largest share of the electricity production in the Netherlands is generated energy companies using fossil-fuels, emitting 48 million tons of CO_2 per year [97]. Since, the European Union (EU) is shifting its focus towards a more circular economy, in order to create a more sustainable economy and thereby reducing CO_2-emissions. The EU is boosting the use of renewable energy sources, even low-grade energy sources, like manure, might play a role in the transition to a more circular economy. Therefore, in this study we focus on supplying dairy farmers with energy produced from their onsite manure production, using anaerobic digestion (AD), thereby improving sustainability and self-sufficiency. In this research the level of sustainability is expressed with the use of three indicators (sustainable impact indicators); carbon footprint, environmental impact and costs.

This study focusses on matching the electricity demand of an average Dutch dairy farm with the biogas supply patterns of an AD system. Two different milking methods with very different demand patterns are used within this research. A model is developed in order to match these demand and supply patterns and several scenarios were composed and compared to the reference scenarios in order to determine the most optimal scenario for increasing sustainability. In the composed scenarios, several measures are taken to increase the sustainability. These measures are: addition of AD system, adding storage capacity, feeding energy back into the grid, making use of other energy sources and conversion of energy with the use of a CHP unit.

Results indicate, using the automated milking system (AMS) method in combination with energy storage, to be completely energy self-sufficient and an improvement in sustainability. Which indicates that the addition of the AD system results in an improvement in sustainability, in terms of decreasing anthropogenic carbon footprint and environmental impact. Furthermore, conversion of biogas into another energy carrier (e.g. electricity or green gas), which is consequently fed back into the grid, show variations in the increase of sustainability. One scenario shows to be completely self-sufficient and thereby autarkic, making this scenario an interesting option for implementation in other sectors, where there can be made use of this method and/or model. Furthermore, the outcomes indicate the importance of feeding energy back into the grid in order to increase sustainability, however, since the currently energy system is not balancing the energy production when additional energy is fed in, like a smart-grid, this assumption has a large influence on the end-results. Future potential subsidies might increase the implementation and thereby increase the sustainability of the agricultural sector.

Concluding, the addition of an AD system on a dairy farm increases the sustainability for all composed scenarios, ranging from 88 to 92% decrease of carbon footprint, 83 to 87% decrease in environmental impact and a costs reduction of up to 26%. Incentives may increase the speed of the transition to a more circular and sustainable economy and achieve the set goals.

List of Abbreviations

AD	-	Anaerobic digestion
AMS	-	Automated milking system
CAPEX	-	Capital Expenditures
CHP	-	Combined Heat and Power
CM	-	Conventional milking
DM	-	Dry Matter
EU	-	European Union
GG	-	Green gas
GHG	-	Greenhouse gas
GJ	-	Gigajoule
GWP	-	Global Warming Potential
Kg	-	Kilogram
LDC	-	Load Duration Curve
Mg	-	Megagram
MJ	-	Megajoule
NG	-	Natural gas
Nm^3	-	Normal Cubic Meter
NPV	-	Net Present Value
oDM	-	Organic Dry Matter
OPEX	-	Operational Expenditures
Pt	-	EcoPoints
RES	-	Renewable Energy Source
SI	-	Sustainable Impact

1. Introduction

The traditional economic system consumes vast amounts of fossil energy sources and has a low tendency to recycle [1], causing serious environmental harm [4]. Therefore, in line with the Paris Agreement, the focus of the European Union shifted toward a more circular economy [4,5], which is often a more sustainable economy, thereby also addressing another goal of the EU; reducing CO_2-emissions. However, the term 'sustainability' is a difficult concept and definitions are abundant. Within this research 'sustainability' is used as "meeting the needs of the present without compromising the ability of future generations to meet their needs" [93]. Currently, the foremost share of energy production is supplied by fossil energy sources (e.g. coal, oil, natural gas). A shift in the use of these fossil energy sources is required in order to become more sustainable. And looking to sheer quantity of energy use, even low-grade energy sources, like manure, might play a role in the transition to a more circular economy. Since there is a surplus of manure production in the Netherlands, this manure can be used more efficiently, thereby increasing energy circularity and reduce the load on the energy utilities [34].

In the Netherlands, the agricultural sector is responsible for 6.7% of the total Dutch energy consumption [11]. This energy is for 82% generated by fossil fuel powered powerplants, which have large CO_2 emissions [12]. Besides the large energy consumption, the agricultural sector is responsible for 12% of the total greenhouse gas (GHG) emissions in the Netherlands [13]. Within the Dutch agricultural sector, the largest share consists of the dairy sector. The GHG emissions, by dairy farms, mainly consist of methane (CH_4) and nitrous oxide (N_2O), which are emitted by manure. These gases are stronger GHGs compared to carbon dioxide (CO_2) [3].

Therefore, the dairy sector has set a goal to become completely energy neutral by 2030 [96]. This has to be achieved for the largest share by emission reduction and the use of renewable energy sources (RESs). Furthermore, changes in manure use and manure storage should decrease CO_2-eq emissions by 2030 due to reduction of methane that is released into the atmosphere [10]. Currently a lot of research is being done about electrification of dairy farms in order to reach these goals, which showed promising results in reducing GHG emissions and diesel consumption [2]. Within this context, anaerobic digestion (AD) can play a significant role, since biogas can be locally produced from manure, which is in over-abundance in the Netherlands [34]. Within this context, a report by Pedroli and Langeveld (2011) [15] shows that, within the agricultural sector in the EU, the production of energy by RESs is larger than the energy consumption [14]. Which makes becoming completely self-sufficient as a sector a realistic option. Furthermore, biogas is a very flexible energy carrier and has a far better storage ability compared to electricity [17, 18] and can be easily transformed into other energy carriers like electricity and heat [17].

Multiple studies have about optimizing the AD process and integration with farming practices have been published [16][26][52]. However, to the author's knowledge, there is no literature discussing how AD can contribute to match energy demand and supply patterns within the dairy farm itself, in order obtain energy self-sufficiency and become autarkic. Therefore, within this research, the potential to produce their own energy demands on an hourly basis is investigated. The level of sustainability is analysed using three indicators of sustainability (i.e. carbon footprint, environmental impact and costs) [16]. Exploring these combinations could improve currently used processes. Furthermore, the use of biogas, from anaerobic digestion of manure, as energy source can help shift to a more circular economy. Thereby pursuing the set goals for 2030 of reducing GHG emissions from the manure itself and becoming completely energy neutral.

1.1 Research Aim & Questions

Currently the foremost share of Dutch dairy farms is powered by electricity from the electricity grid. However, is this the most energy efficient and sustainable way of powering a dairy farm? This study provides insight if the current policies, that stimulate electrification, is a more sustainable and efficient way to power a dairy farm. In order to reach the central aim of the research, the following research question is developed.

"To what extent is self-produced biogas, obtained from manure, a more sustainable, feasible and self-sufficient energy supplier for a dairy farm compared to electricity from the grid?"

In order to answer the main research question, several sub-questions are developed.

- What includes an average dairy farm and what are the energy demand patterns?
- How do the demand patterns match the supply patterns and how can this be modeled?
- How can energy demand and supply match be optimized?

1.2 Scope

The research focus is on determining which optimization combination has the highest sustainability for powering a dairy farm. The energy suppliers that are taken into consideration are biogas, natural gas and electricity. This electricity is obtained from large centralized powerplants or generated from biogas and/or natural gas; the biogas is obtained from manure from the farm itself with AD. Besides taking a look at which energy supplier is optimal, there is taken a look at which milking method is more sustainable and financially more attractive for the farmer, therefore, costs are taken into consideration as well. The two milking methods that are taken into consideration are the conventional milking method (CM) and a method where an automatic milking system (AMS) is used.

2. Methods

In this section the methods used in order to obtain the results are described. Data with a high temporal resolution shows the daily energy demand of an (average) dairy farm, which provides insight into the energy demand. This literature shows two ways of milking methods at the dairy farm; the conventional milking (CM) method and the automatic milking system (AMS) method, which widens the scope of this research. In chapter 4 these milking methods are described in further detail. In this research there is made use of two models. The first used model is an Excel based model named 'The (Excel) Biogas Simulator', or EBS model [32][51]. Besides the EBS model there is made use of a self-made Excel model, called the Renewable Energy Sources model, or RES model, which provides insight into potential mismatches in energy demand and supply of the dairy farm. The choice for these particular models is discussed in section 2.2.

2.1 System boundary

The system boundary of this research is limited to one dairy farm consisting of 120 dairy cows. Only manure that is produced inside the barn is used to feed the anaerobic digestion (AD) system, it is assumed that the cows reside inside the barn for 8.040 hours per year [53]. Within this research two milking methods are researched, the conventional milking (CM) method and the automated milking system (AMS) method. Within the set system boundary, the AD process, including the harvesting, transport and storage of manure are taken into account. The upgrading and storage of green gas after the AD process is also taken into consideration. Furthermore, the energy needs for all processes (e.g. the digester system, upgrader system, etc) within this system boundaries are taken into consideration. The system boundaries of this research are limited to the energy flows on the farm. Energy and material requirements for the construction of the used equipment are not taken into consideration. The produced digestate from the AD system is not within the system boundary and therefore out of the scope of this research.

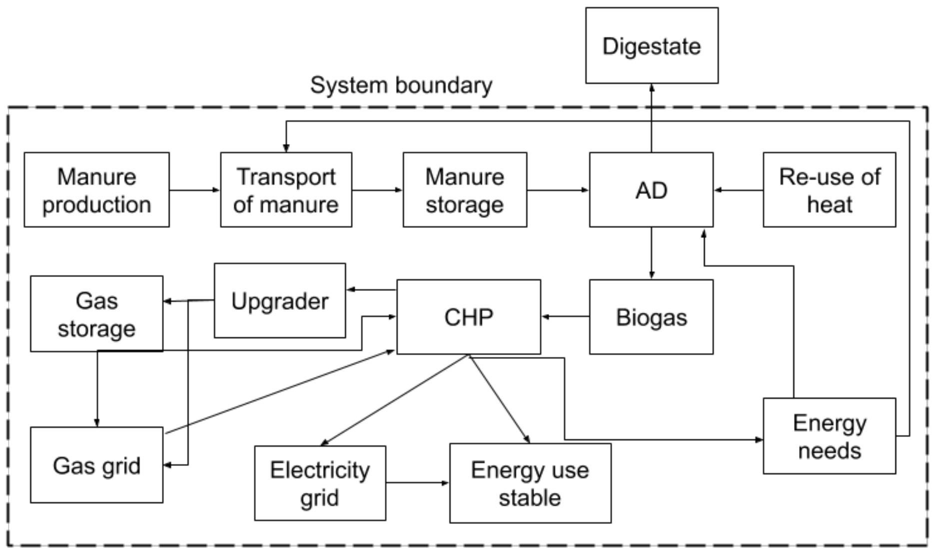

Figure 1. System boundary of energy generation and utilization on a Dutch dairy farm.

"Energy needs" are the processes that require energy for the formation of green gas from manure.

2.2 Models used

2.2.1 The Biogas Simulator (EBS)

The EBS model simulates the entire AD system and provides accurate insight into energy use, carbon footprint and environmental impacts [32]. The model starts with manure as input and ends with methane or electricity as an output. The values of the concerning impact indicators per energy unit (e.g. carbon footprint, environmental impact and financial feasibility) are adopted from this model. Chapter 3 describes these impact indicators into further detail. The main advantages of the EBS model are the clear visual display and the level of completeness. Section 2.2.3 defines to what extend there is made use of this model. Since some of the used values result from outdated articles, these values are updated to the most recently published articles (Table 11). The remaining components are assumed to be similar as the EBS model already simulates. No update of these values is required, since these values have not changed in more recent research. Appendix 13.3 shows the changed values.

2.2.2 The Renewable Energy Source (RES) model

The RES model is comparable to the validated EBS model, made by F. Pierie [16]. The outputs of the model are expressed in the used sustainable impact (SI)-indicators, which are described in detail in chapter 3. However, an additional feature is added; the RES model is able to balance the energy supply and demand. There is made use of load duration curves (LDC) in order to balance the demand and supply patterns for both milking methods (CM and AMS). The LDCs are used to determine the number of hours and the size of the mismatch in supply and demand. The RES model is described into more detail in chapter 5. With the use of the RES model several scenarios are constructed in order to find the most sustainable scenario. These scenarios are described in chapter 7.

2.2.3 Interaction between models

Figure 2 displays the interaction between the EBS and the RES model. The biogas production per cow and the SI-indicator values per energy source are adopted from the EBS model into the RES model. Subsequently, the RES model matches the, from literature obtained, energy demand patterns, with the biogas production per cow. Since the energy shortages and surpluses are now modeled by the RES model, the SI-indicator values per energy source can be simulated.

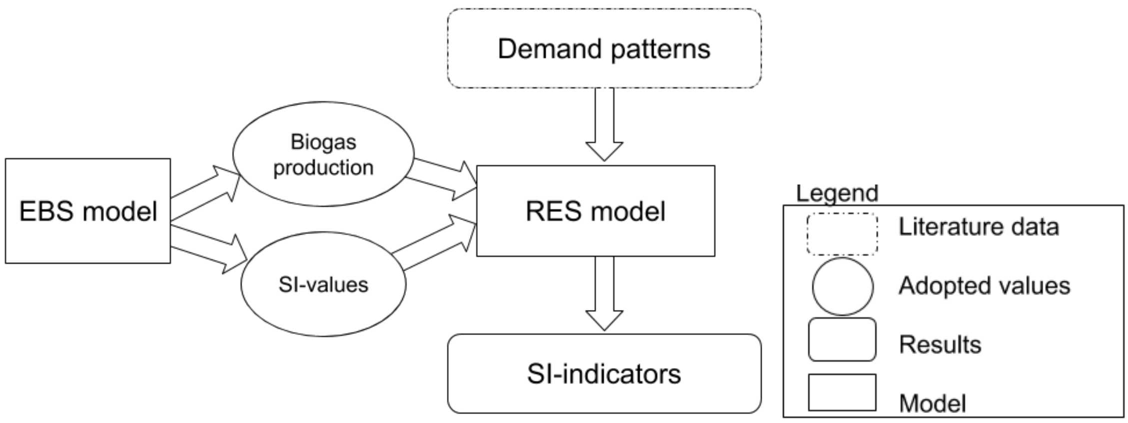

Figure 2. Model interactions.

3. Sustainable Impact (SI)-Indicators

In this research three expressions are used to indicate the carbon footprint, environmental impact and the financial feasibility. In this section these expressions are explained in further detail. As described in chapter 2, all the SI-indicators are simulated by the RES model. In this research the emphasize is on environmental quality and sustainability and economic feasibility. Environmental sustainability is correlated to the definition of “strong sustainability” [31]. “Strong sustainability” is expressed in three indicators, which are described in the sub-sections below, two of these will be used in this research [30]. Besides these two indicators an economic indicator is used, this indicator is given in Net Present Value (NPV) over a period of 25 years [82]. There is made use of an economic indicator since the probability of actual implementation of the research is strongly dependent on the costs. All used indicators are expressed per year (e.g. kgCO_2-eq emissions per year). These indicators give a transparent and clear view which scenario is most sustainable and economic feasible. The following sections briefly describes these indicators, a more extensive description is described by Pierie et al. [30].

3.1 Carbon footprint expressed in GWP (100) (kg CO_2-eq/year)

The carbon footprint is expressed in carbon dioxide equivalents (CO_2-eq) using the 100-year global warming potential scale or GWP(100) [52]. In this research the carbon footprint is valued as a net increase or decrease of GWP(100), compared to the reference scenario. The emissions from processing and harvesting are within the carbon footprint included. In this research there are two possibilities that may increase the GWP(100): first, the use of fossil fuels for the production of green gas, which results in an increase in anthropogenic CO_2 emissions and second the conversion of carbonaceous biomass to a stronger GHG (e.g. methane) [52]. The RES model is able to simulate the carbon footprint (in kgCO_2-eq/year) for each scenario. This is done by multiplying the quantity of the required energy source(s) (e.g. biogas, electricity, green gas, natural gas) with the, from the EBS model obtained, corresponding kgCO_2-eq per energy unit values. The remaining gas that is not used and the corresponding amount of kgCO_2-eq that is therefore not emitted, is subtracted from the total emissions.

3.2 Environmental impact expressed in EcoPoints (Pt/year)

The environmental impact to ecosystems, nature and human health is expressed with the Eco Indicator ReCiPe 2008, used by the SimaPro model [61][62]. The results of an LCA inventory are usually complex and hard to understand. In order to increase the comprehensibility, the ReCiPe method was designed. This method makes use of so-called Eco indicators, which is an indicator with a damage-oriented approach on the overall load on the environment [62][63]. This Eco indicator is a single score, expressed in EcoPoints (Pt), resulting from the use of damage models and normalization of multiple impact scores [52]. The EcoPoints are simulated by the RES model for each scenario. The EcoPoint values are obtained from EBS model, which displays the EcoPoint values per energy unit. The EBS model obtained on his turn the values from the SimaPro model [61][62]. In order to simulate the value for the environmental impact, the EcoPoints per energy unit from EBS model are multiplied by the total energy requirements of every scenario. When a scenario has a certain energy oversupply, this energy is fed back into the grid, and the corresponding negative environmental impact is subtracted of the total environmental impact.

3.3 Financial feasibility (NPV)

The NPV is a commonly used method for measuring the economic feasibility [82]. The value of NPV indicates if the investment is whether or not attractive, when the NPV value is positive, it indicates it is attractive and when it is negative, it indicates it is not. Within the NPV the CAPEX, OPEX and revenues are included [82]. The CAPEX refers to the capital investments (e.g. digester, CHP), while OPEX represent the operational costs (e.g. purchase of electricity or gas) and revenues are the sales of the products (e.g. green gas, electricity). Further, there are costs like interest which have to be taken into account [16]. For the calculations of the CAPEX, it is assumed that all the equipment has a life expectancy of 25 years. Since the costs are presented in euro/year, the total CAPEX value is divided by 25 in order to change to the same expression. In order to determine the annual costs, the annual revenues are summed up with the CAPEX and OPEX. Table 13 and 14 in appendix section 13.4 shows the equipment and costs used in model.

4. Literature review milking methods

Literature review found a case study [20] which showed the energy demand for both milking methods (Table 1). This case study contains data sets (in the form of graphs), for both milking methods, that showed the energy consumption patterns, for 1 day, with an hourly temporal resolution. These data sets were adopted from this article; however, some modifications were made in order to fit into the model. The data was adjusted to a temporal resolution of 1 hour, in order to fit into the used models (this temporal resolution of 1 hour still provides a clear and accurate overview of the actual data, see Appendix 13.1). From the obtained data the averages of the hourly data points were summed in order to obtain a daily energy demand, in kWh. From this number the yearly energy demand was determined. This was done for both milking methods. However, these data sets did not contain the same number of cows in both systems. In order to compare these two data sets, the energy use per cow was determined and then multiplied by the total number of cows within the system. It is assumed that the daily energy consumption pattern was similar throughout the year, as the author stated [20].

Table 1. Energy use milking methods.

	Milking method		**Unit**	**Source**
	AMS	*CM*		
Energy demand	52,758.1	50,812.6	kWh/year	[20]

Figure 3 shows that there is a great contrast in hourly energy demand between the milking methods. Especially, a clear variation is seen in energy consumption over the day within the conventional milking (CM) method. As figure 3, for the conventional milking method shows, there are two periods during the day where the largest share of the total energy demand is needed. The automated milking system (AMS) method shows a more evenly distributed energy demand over the day. This variation in energy demand for both milking methods is explained in a case study done by Vandelannoote (2014) [20]. Nonetheless, the variation is shortly described below.

The two large peaks for the CM method are caused by two milking session that occur every day (Fig. 3). After these milking sessions, of about 3 hours each, there is mainly energy needed for cooling purposes. The required energy for this is significantly lower since the milk is already chilled at the required temperature and only need to be maintained at that temperature.

While, for the AMS method, the energy consumption is more evenly distributed over the day. The foremost reason for this is because using the AMS the milking process is continuous. Furthermore, the milk is cooled by a smaller amount at the same time, which levels the energy use. The small peaks indicate the start of the cooling cycle.

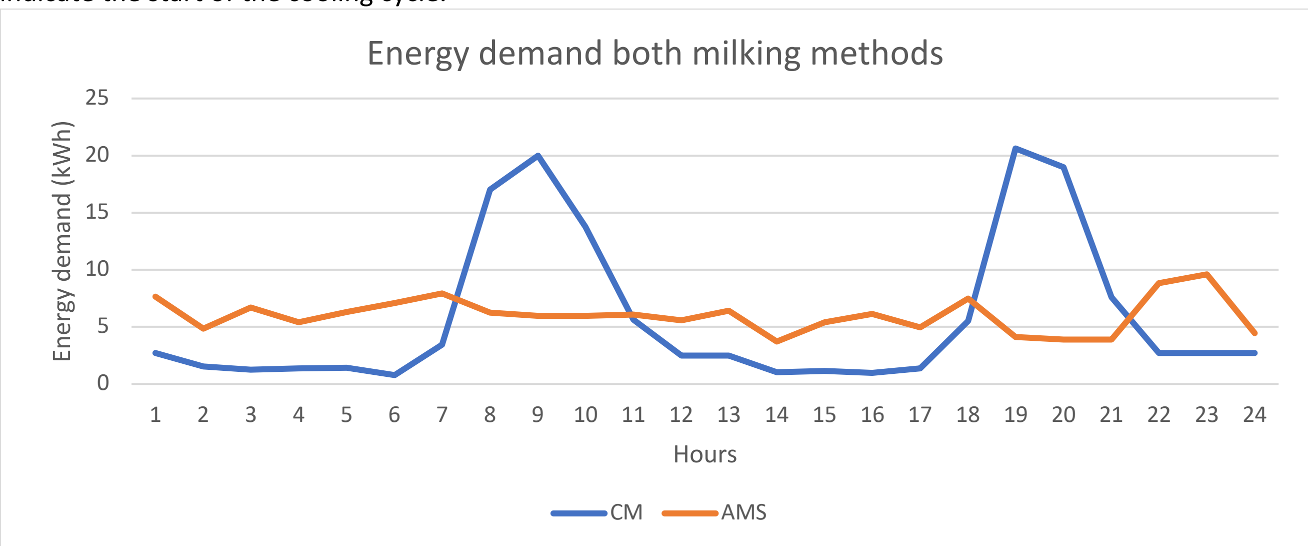

Figure 3. Energy demand both milking methods over the day.

5. Model construction

Within this chapter the use, structure and handling of the RES model is discussed. The Excel based 'Renewable Energy Source', or RES, model is developed to improve the balance between energy demand and supply, by AD from cow manure, on a small dairy farm (±120 cows), in order to increase sustainability and self-sufficiency. To do so, it is capable of determining the carbon footprint, environmental impact and costs. The results are expressed in three main indicators; the carbon footprint in Global Warming Potential 100-year scale (GWP100) using $kgCO_2$-eq as unit, the environmental impact in EcoPoints (Pt) and the economic feasibility in Net Present Value (NPV). Settings in the model can be removed, added or adjusted to fit more to the modeler's preferences. The RES model is composed around a clear methodology, containing a modular approach (section 5.1), model functioning description using Power Nodes (section 5.2.1) and main components used (section 5.3). Validation and sensitivity analysis are performed in order to validate the completeness of the RES model (Chapter 6). The modular approach increases the comprehensibility of the model by splitting up the energy production pathways. The most important variables are in the 'Database' and 'Scenario Results' tabs, which are described in detail in section 5.6.1. The main calculations, which are used to get to the end-results, are based on the validated EBS model and published literature. All used variables can be edited, when more recent data is available, to get more accurate results. The flexibility of the RES model opens up and widens the applicability of the RES model for other purposes within the agricultural sector. Furthermore, the three used expressions give a clear and understandable overview which scenario is most sustainable. Overall, the RES model can improve mismatches between energy demand and supply and can help shed insight to what extent AD is sustainable and feasible.

5.1 Modular approach

The RES model is built using a modular approach, in this way it is possible to add or remove individual modules to design the optimal production pathway. In the RES model, the main input is the number of cows, which produce manure, leading to biogas production.

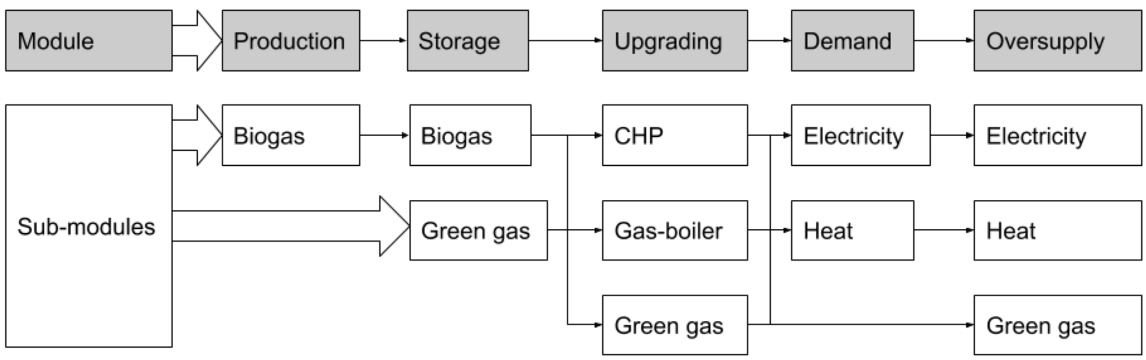

Figure 4. Main modules and sub-modules used in energy production pathways.

Each sub-module simulates the value in the corresponding expression (e.g. biogas production in Nm^3/hour). In order to simulate this value, mass and direct energy use flows are used. The mass flow is defined as Nm^3 biogas, the direct energy use is defined in kWh for electricity demand of the farm and MJ/hour for the heat demand of the AD. Since the values of the corresponding expression per sub-module are simulated in the modules and the SI-indicator values per energy source are known (Table 19-21), the total SI-indicator value (e.g. carbon footprint in $kgCO_2$, environmental impact in Pt and the costs in euro) can be determined. Section 5.4 goes into the mitigation pathway, which may have a mitigating effect on these values.

5.2 Description of RES model

The RES model is a model that balances energy demand and supply, thereby indicating the quantity of the mismatches. The main input in the RES model is the number of cows and the main outputs are the SI-indicators and the biogas production (Table 23 & 26). Within the RES model the energy supply is powered by converting cow manure into biogas with the use of an AD system. The simulated energy supply pattern is coupled to, the in section 4 described, energy demand patterns. Within the RES model, there is made use of 4 energy flows: green gas, biogas, heat and electricity flow. When the energy supply and demand patterns are coupled, potential mismatches can be located, using load duration curves (LDC), and the size of these mismatches can be determined. Which makes it possible to optimize the balance between the energy demand and supply in order to minimize energy waste and shortage. The LDCs are displayed in figures 19 and 20 in appendix section 13.5. When there is a surplus in energy, the surplus is fed into the electricity of gas grid and vice versa. This amount of electricity or gas is determined by the RES model and thereby the corresponding SI-indicator values. Figure 5 shows a clear overview of the used system within the RES model. Using scenarios, multiple optimization options are simulated to realize the most optimal scenario. These scenarios are described in chapter 7. Feed-in tariffs are added in order to simulate potential scenarios that might be more financially attractive. The functioning of the model is described into further detail in the following sections.

5.2.1 Model functioning

In this research there is made use of Power Nodes to describe the power system interactions. In figure 5 this Power Nodes system is illustrated; where arrows indicate the transport of the used energy flows in the system (e.g. heat, biogas, green gas, electricity). These energy flows are connected by nods, the function of these nods is explained in the legend of figure 5. Furthermore, clouds are used to indicate losses of energy flows. The RES model is based on this Power Nodes system (Fig. 5).

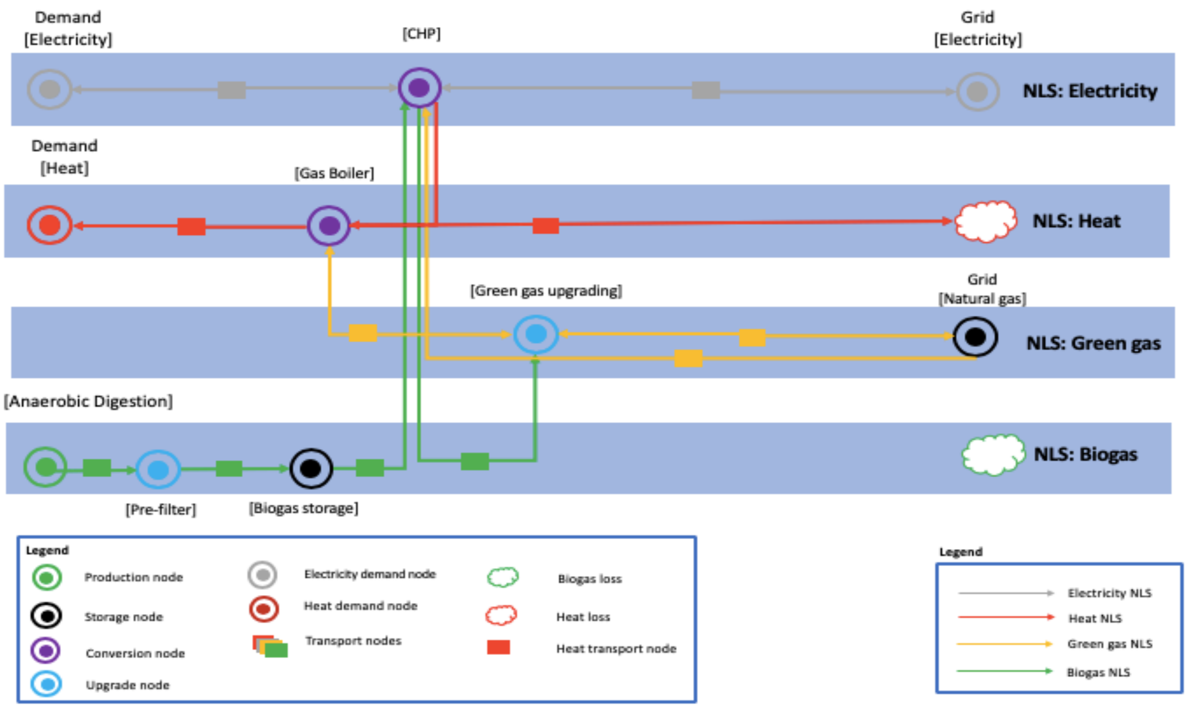

Figure 5. Conceptual framework of the RES model.

5.2.2 Model energy flow pathways

The farm has a manure fed anaerobic digester (AD), where biogas is generated. The manure is transported by a manure scraper on the floor of the barn, which sweeps the manure into a pit, where the manure is stored. This AD system is placed next to the barn and in direct contact with the manure pit. After anaerobic digestion, the biogas is filtered and stored in a biogas storage tank, subsequently converted to electricity with the use of a CHP to supply the electricity demand. Heat demand is supplied by heat recovery from the CHP unit. Additional heat requirement is met by the gas boiler, which is fed by biogas or gas from the gas grid. Remaining biogas is upgraded to green gas of similar quality of natural gas and stored in the national gas grid. Additional gas or electricity demand is imported from the national grid. Excess heat is discarded. Energy requirements for all processes are taken into account.

5.3 Main components of the RES model

The main components of the RES model are discussed in this section.

5.3.1 Biomass feedstock

The digester is solely fed by dairy cow manure. The methane yield per Mg manure is obtained from an article by Bekkering, J. et al [26]. The carbon footprint of the cows, which produce the manure, is not taken into consideration. The RES model determines the amount of biogas (and methane) that is produced with the set number of cows.

5.3.2 The Anaerobic Digester System

The digester is constantly stirred using electricity from the CHP system and kept at mesophilic temperature with heat generated by the CHP unit and biogas boiler. The retention time of the digester is 30 days. The volume of inflow of manure is equal to the volume of the outflow, in order to keep the same volume inside the digester. The digester in the model is built in a linear expandable way, meaning that the size of the digester can be adjusted to the quantity of the manure input and the results automatically linearly adapt [16]. The digester contains 4 mixers, which each have a lifespan of 10 years. The settings used for the anaerobic digester system are adopted from Pierie et al. 2015 [30].

5.3.3 Upgrader systems

Biogas that is generated in the digester is upgraded to green gas by an upgrader system (Fig. 5). But first, before the biogas enters the upgrader, some polluting gasses are removed from the biogas mixture by the pre-filter using active carbon. One of these gasses is hydrogen sulphide, which is highly corrosive and can hinder the upgrading process. This pre-filtered biogas is then redirected to the CHP unit, where heat and electricity are produced. When the CHP unit is unable to supply sufficient heat for to keep the AD at the required temperature, a share of the biogas is fed into the biogas boiler, which generates the remaining required heat. The remaining biogas flows through to green gas upgrader, this upgrader is a highly selective membrane that separates methane from carbon dioxide and other trace gasses [25]. The gas is now upgraded to green gas, which has a higher caloric value compared to biogas. This remaining green gas is stored in the national gas grid and recovered when needed.

5.3.4 CHP system

The combined heat and power (CHP) system can be fed in two ways, it can be fed directly from the digester or indirectly from the national gas grid. When the CHP unit is fed directly, the biogas is first pre-filtered in order to protect the equipment from corrosive pollutants. The CHP unit converts the green gas to electricity and heat. The generated electricity is used for internal purposes within the system and for powering the energy needs within the stable. The heat that is released by the CHP unit is used for maintaining the temperature of the digester and excess heat is discarded. See figure 5 for a schematic overview. Table 2 indicates the specifics of the used CHP system. It is assumed that the CHP unit runs on 80% of its maximal capacity. The size of the CHP unit is dependent on the scenario, table 9 shows the CHP unit sizes per scenario.

Table 2. Main values of the CHP unit.

CHP unit	Value	Unit	Source
Electric efficiency	38	%	[26]
Heat recovered from engine	80	%	[26]

5.3.5 Gas storage tank

The gas storage tank is directly linked to the digester and is filled when the biogas demand is lower than the supply. Vice versa, the gas inside the gas storage tank is used when biogas demand is higher than the digester is able to supply.

5.4 Mitigation pathways

The AD process can replace the energy supply from current suppliers (e.g. electricity grid, gas grid), thereby avoiding emissions and environmental impact. In the model this mitigation of emissions and environmental impact is calculated by subtracting the oversupply (e.g. not used energy) values per sub-module from the overall values (e.g. total $kgCO_2$ emissions by all energy source) in the demand sub-module.

5.5 Database

Within the RES model it is possible to adjust settings which makes the model flexible and accurate in use. Since the primary variables and values are linked to the sub-modules, the results in the sub-modules automatically adapt with the changed values. This makes it possible to expand the model or adjust values when necessary. Table 23 and 24 display the most prominent values regarding the biogas production. Tables 19-21 show the values used in order to determine the end results expressed in SI-indicator values (e.g. carbon footprint in $kgCO_2$-eq/year). How to operate the RES model is described in chapter 14.

6. Model Validation

In this section, the validation and verification (V&V) of the RES model is researched. Since this is a self-made model, the accuracy of the results, simulated by the model, require validation and verification [72]. In order to make a model completely valid for the entire domain it requires a lot of resources, including time and money. Therefore, most models are constructed in a way that they simulate accurate results for the designed function [73]. The used methodology in the V&V process for the RES model is described by Balci et al. [74] and Sargent [73].

6.1 Accuracy of the RES model

The accuracy of the model is, as explained earlier, dependents on the development time of the model. The aim is for a high level of accuracy, with the lowest time requirements [75]. In this model validation the RES model is compared to the more accurate and complete EBS model. The aim is that the primary results (e.g. green gas production) from the RES model has an accuracy of at least 95%, which means that the RES results do not exceed more than 5% of the EBS results [75].

6.2 Validation of the RES model

The initial goal for designing a model is to provide answers to complex questions [75]. Therefore, it is of importance that the model is able to answer these questions. In order to check if the built model is able to provide this it has to accord with several statements. These statements are adopted from Pierie et al [75].

6.2.1 The model adds to scientific understanding or to societal benefit

The RES model increases the scientific understanding of balancing the energy demand of a dairy farm with generated energy supply (e.g. green gas) from manure. The RES model indicates (using graphs) any mismatches and the quantity of it between demand and supply. When a mismatch is observed, the model is able to determine the amount of gas or electricity that is needed to resolve the mismatch. The societal benefit of this model is the optimization of energy supply and demand, which increases the efficiency of energy use and thereby reducing the costs for energy use.

6.2.2 The model refers to clear answers which can be provided through modeling

The model refers to three main results (SI-indicators), the outcome of these results can be altered by changing either the initial input (the numbers of cows, which produce the manure where the methane is obtained from and thus the energy supply) or by changing the energy demand. By changing one of these values, the three main results will change with them, providing a clear answer.

6.2.3 Reviewed and verified by experts

During the development of the RES model multiple walkthrough sessions were arranged with Frank Pierie, which is an expert on the field of biogas production. During these sessions the functioning of the model was discussed and was deemed to function adequate for the intended purpose it was developed for. The structure of the model and the numerous amounts of calculations can, for non-experts, be confusing, however, when used by an expert the model is logical and transparent in use. Besides, with the use of the “working with the RES model” section (chapter 14), it should be possible for experts and non-experts to understand and operate the RES model.

6.3 Verification of the RES model

In order to verify the RES model, multiple verification techniques have been used. The used verification techniques are derived from Sargent [73], these techniques are described below.

6.3.1 Comparing to other models

In order to verify the accuracy of the RES model, the RES model is compared to the EBS model, which is a verified model, described into great detail by Pierie, F. et al [75]. The EBS model focusses on biogas production as is the RES model. Furthermore, both models use the same methods in calculating the biogas production. However, the completeness and the accuracy of the EBS model is higher compared to the RES model. To compare if both models have similar biogas (and green gas) outputs when same inputs are used, a comparison scenario is created.

Table 3. Main inputs comparison scenario models.

Main variables	***Value***	***Unit***
Operating hours	8760	hours/year
*Transport distance**	0	km
*Losses of biogas***	0	%
*Losses of biomass***	0	%
Time spent in stables	8040	hours/year
Manure input	1996	Mg/year FM
Organic dry matter (oDM)	6.4	%
Methane potential of manure	180	Nm^3/Mg.oDM
Energy content green gas	35	MJ/Nm^3

*A transport distance of 0 meter was used for comparison of both models (10 meter is used in EBS model).
**In order to fairly compare both models, losses of biogas and biomass from digester are in both models set to 0%.

The comparison between the two models show that the RES model performs adequate when looking to the main output (i.e. methane production). The models show a difference in output of 0.017%. This being said; the difference between the most prominent output in both models is well within the set boundary of 5%. With the use of this main output, all values of the three used indicators can be calculated. The same indicator values per energy unit (e.g. $kgCO_2$-eq/kWh) is used in both the RES as the EBS model, leading to similar results when similar scenarios are used.

Table 4. Output comparison between both models.

Outcome	***Unit***	***EBS model***	***RES model***
Green gas production	Nm^3/year	22986	22990

Since the EBS model is a more complete model it contains more data, like losses of biomass during collection and biogas loss during transport. These inclusions might have an impact on the methane production.

6.4 Discussion

At section 6.3.1 the models were compared, and the RES model showed a slightly (i.e. 0.017%) higher output. Even though this is within the set acceptable range of 5%, the actual number is likely to be even closer to the output of the EBS model. The main reason for this is since the EBS model incorporates several assumptions that take loss of biomass and biogas into account, which lowers the biogas yield.

7. Main parameters and scenarios

In this research, different energy supply pathways are compared in supplying the energy demand on a dairy farm. The supply pathways and scenarios are explained in further detail in this section. Furthermore, multiple optimization scenarios are compared to the reference scenarios. In the composed optimization scenarios manure is used as main feedstock for a green gas production pathway. The energy production pathways of the currently used methods and composed scenarios are discussed in this section.

7.1 Theoretical cases

In this chapter a reference case and an AD are described in order to get an idea of the currently existing case and the composed cases (e.g. composed scenarios). Figure 6 and 7 give a clear overview of both cases.

The reference case (e.g. reference scenario) is based on the current energy supply systems an averaged sized dairy farm, including 120 cows. Within this energy supply system all energy is imported in the form of electricity by the national grid. The produced manure is used as fertilizer and additional manure is exported (Fig. 6). The environmental impact, carbon footprint and costs of electricity are included (Tables 19-21). Table 1 shows the electricity demand for both milking methods. The energy demand over the day for both milking methods is displayed in figure 3.

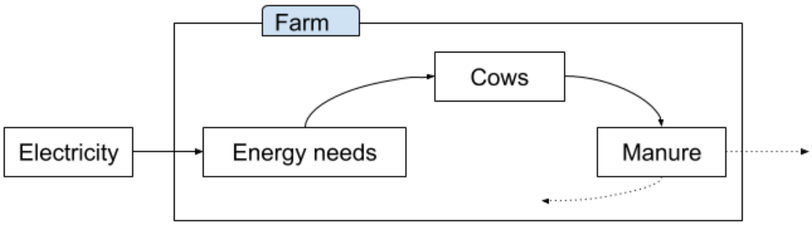

Figure 6. System overview reference case.

Within the AD case (e.g. composed scenarios), there is made use of an AD system, generating biogas from manure exclusively from within the farm itself, making the farm energy self-sufficient. The generated biogas is used as fuel to meet the energy demand of the dairy farm, creating a circular system (Fig. 7). Using different scenarios, the energy supply system is varied in order to determine the most sustainable scenario. These scenarios are described in section 7.4. The remaining digestate, after the AD process, is not taken into consideration. The environmental impact, carbon footprint and costs of all processes are included (Tables 19-21). Remaining energy requirements are imported. The revenues from selling leftover green gas and electricity is incorporated within the NPV calculations. Furthermore, leftover energy (e.g. electricity or green gas) which is fed into the national grid is included, as feeding in results in a decrease in carbon footprint and environmental impact.

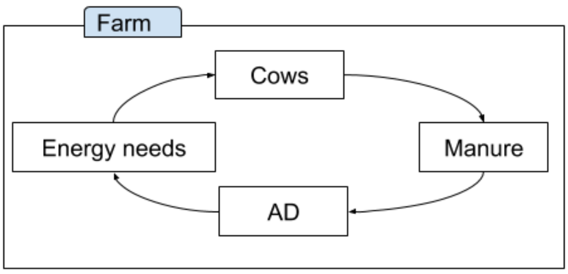

Figure 7. System overview AD case.

7.2 Biogas production pathway

Within all composed scenarios there is made use of the same manure as feedstock and same digestion plant set up, which is located on the farm near the barn where the manure is produced with a maximal manure input of 2500 Mg of fresh matter (FM) per year. Within all scenarios all harvested manure is put into the digester. The main product of the digestion plant is biogas which is first pre-filtered and subsequently fed into the CHP unit. The CHP unit feeds the energy needs for the digester in all scenarios. Specifics of the digestion plant are described in section 5.3.2. A share of the biogas is fed into the gas boiler in order to maintain mesophilic temperature for the digestion plant. Remaining biogas is upgraded by the upgrading system in order to upgrade the gas to the same quality as natural gas grid quality and then fed into the national gas grid, further specifics about the upgrading system are described in section 5.3.3. The energy use of systems including the production process, f.i. manure transport by a manure scraper is already incorporated in the total energy demand.

The values of these primary settings are similar for all optimization scenarios.

Table 5. Main values used in model.

Main components	Values	Unit	Source
Heat use digester	0.19	MJ/kg	[7]
Electricity use digester	0.026	MJ/kg	[7]
Pre-filter energy use	0.00065	MJ/Nm3	[81]
Gas boiler	0.34	MJ/hr	[55]
CHP internal use	2.511	kWh	Appendix 13.10
Electricity use membrane upgrader	0.304	kWh	[25]
Loss of methane in filtrate	0	%	[80]
Gas boiler heat efficiency	98	%	Appendix 13.10

7.2.1 Feedstock

The manure that is used for inside the AD system consists exclusively of dairy cow manure that is produced inside the barn. Table 6 shows the most relevant values regarding the feedstocks that are used in the model. The farm houses 120 dairy cows with a total annual manure production of 2,174,400 kg [34]. However, manure that is produced inside the barn and thus harvested is 1995,68 Mg [34] (See Appendix 13.2). In this model, all the manure that is produced inside the barn is fed in the AD system. In section 5.3.2 detailed specifications for the anaerobic digestion system is discussed.

Table 6. Most relevant values regarding the feedstocks used in the model.

	Manure	Unit	Sources
Biogas potential	350	Nm^3/Mg oDM	[7][54]
Methane potential	180	Nm^3/Mg oDM	[7][54]
Organic dry matter content (oDM)	6.4	%	[34]
Production of manure per cow per year	18.120	Mg/a	[34]
Number of cows	120	cows	-

7.3 Pathways and scenarios

Two reference scenarios are composed which accord with the electricity supply on modern dairy farm for both milking methods (table 7). The results of the reference scenario are compared to the made scenarios. The made scenarios are based on the most commonly used milking methods in the Netherlands and two different ways of supplying energy to them. All the scenarios are explained in further detail in this section. Figure 8 displays a clear overview of the made scenarios and pathways.

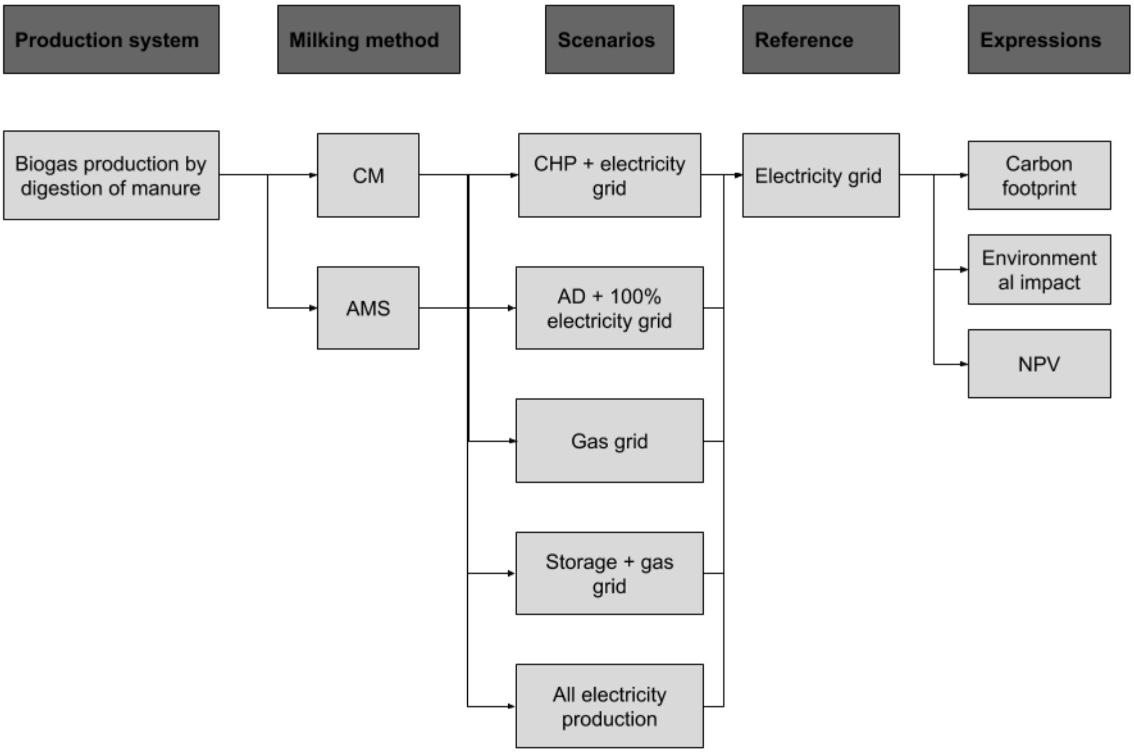

Figure 8. Pathways and scenarios used in this research leading to results.

7.3.1 Reference scenarios

In this section the reference scenarios are discussed. These scenarios represent the current energy supply on modern dairy farms for both researched milking methods.

Table 7. Reference scenarios used for comparison.

Reference Scenarios	Description
REF AMS	In this scenario, the dairy farm is 100% powered by electricity from the electricity grid. For the AMS milking method.
REF CM	In this scenario, the dairy farm is 100% powered by electricity from the electricity grid. For the CM method.

The global warming potential (GWP) of the reference scenario is based on the assumption that the dairy farms are currently for 100% powered by electricity from the electricity grid, with the corresponding GWP value of 177 kg CO_2-eq/GJ [55][56]. The remaining important values, based on the same assumption, are displayed in table 8.

Table 8. Relevant values for simulating the SI-indicator values for grey electricity.

	Value	Unit	Source
Carbon footprint	0.6372	kg CO_2-eq/kWh	[55][56]
Environmental impact	0.10152	Pt/kWh	[55][56]
Electricity price	0.22	Euro/kWh	[86]

7.4 Optimization scenarios

There are several optimization scenarios discussed in this section regarding the use of biogas. The results of multiple optimization scenarios are compared to the reference scenario (Fig. 8). The CHP unit sizes per scenario and milking method are displayed in table 9.

Table 9. CHP size per scenario and milking method.

Scenario	Milking method		Unit
	AMS	CM	
CHP + electricity grid	12.12	12.12	kWe
AD + 100% electricity grid	3.52	3.52	kWe
Gas grid	15.14	28.92	kWe
Storage + gas grid	15.14	28.92	kWe
All electricity production	12.12	12.12	kWe

7.4.1 CHP + electricity grid scenario

Within this scenario the electricity demand is powered by combusting the generated biogas in the CHP unit to generate electricity. Additional electricity demand is supplied by the electricity grid. Excess biogas is upgraded to green gas and fed into the national gas grid. Generated heat by the CHP unit is used for the heat demand. Additional heat requirements are supplied by the biogas boiler. This is done for both milking methods.

7.4.2 AD + 100% electricity grid scenario

Within this scenario all on-farm practices that require electricity are supplied by the electricity grid. The energy needed for the internal CHP and heat generation is supplied by the biogas generated from the digester. The remaining biogas is upgraded to green gas and fed into the national gas grid (Table 19-21). Generated heat by the CHP unit will be used to supply the heat demand. Additional heat requirements are supplied by the biogas boiler. This is done for both milking methods.

7.4.3 Gas grid scenario

Within this scenario the entire energy demand is supplied by a small CHP unit. The fuel for the CHP unit is provided by the green gas production pathway described in section 5.3.1. Additional required gas is supplied by the national gas grid (Table 19-21). When the energy demand is higher than the digester is able to supply biogas, gas from the grid is used to fill in this gap. Vice versa, when supply is higher than demand, excess biogas is upgraded to green gas and fed into the national gas grid. Generated heat by the CHP unit will be used to supply the heat demand. Additional heat requirements are supplied by the biogas boiler. This is done for both milking methods.

7.4.4 Storage + gas grid scenario

This scenario is similar to gas grid scenario (7.4.3), only in this scenario a gas storage tank is included. The gas storage tank is directly linked to the digester and is filled when the biogas demand is lower than the supply. Vice versa, the gas inside the gas storage tank is used when biogas demand is higher than the digester is able to supply. Additional required gas is supplied by the national gas grid (Table 19-21). Generated heat by the CHP unit will be used to supply the heat demand. Additional heat requirements are supplied by the biogas boiler. This is done for both milking methods.

7.4.5 All electricity production scenario

This scenario is similar to the CHP + electricity grid scenario (7.4.1), except in this scenario all the biogas is converted to electricity by the CHP unit and excess electricity is fed into the electricity grid. Generated heat by the CHP unit will be used to supply the heat demand. Additional heat requirements are supplied by the biogas boiler. This is done for both milking methods.

8. Results

In this section the results per expression as described in section 3 are discussed. The names used to present the scenarios are presented in Table 10. In section 8.1 – 8.3 notable observations per scenario for each SI-indicator are discussed, while in section 8.4 all SI-indicators are presented in one graph per scenario and an overall discussion of the results is presented.

Table 10. Scenarios indications for figures 9 - 11.

Scenarios	Milking method	
CHP + electricity grid	1 AMS	1 CM
AD + 100% electricity grid	2 AMS	2 CM
Gas grid	3 AMS	3 CM
Storage + gas grid	4 AMS	4 CM
All electricity production	5 AMS	5 CM
Reference	REF AMS	REF CM

8.1 Carbon footprint (kgCO_2-eq)

Figure 9 shows that all composed scenarios indicate, despite the higher energy requirements because of the AD process inclusion, a significant lower carbon footprint compared to the reference scenarios. This can be explained by the high carbon footprint per energy unit for grey electricity production which is used for both reference scenarios, while in the composed scenarios biogas, with a low carbon footprint, is used (Table 19). Besides, all scenarios, except 4 CM, have some surpluses in energy (electricity or green gas) leading to negative emissions and thence decrease the carbon footprint. A remarkable observation is the large difference in emissions between the milking methods for scenario 1. This large difference in emissions between the milking methods for scenario 1 can be explained by the amount of electricity from the grid that is imported, the conventional milking (CM) method imports significant more electricity, even though the total electricity demand is lower. This is since the CHP unit is unable to generate sufficient electricity at the peak demands for this milking method, due to lack of available biogas. During these peak demands, a lot of electricity is imported, which has a high carbon footprint per energy unit (Table 19). When scenario 2 is compared to the reference scenario, a large decrease in CO_2-eq emissions is seen, this decrease is exclusively achieved by the exporting green gas resulting in negative emissions (Fig. 9). The small difference in emissions within scenario 2 can be explained by the slightly higher energy demand of the AMS milking method. However, despite the lower energy demand of the CM method for all scenarios, a higher the carbon footprint is indicated using the CM method for scenarios 1, 3 and 4 (Fig. 9). This can be traced back to the higher total energy demand when the gas boiler is turned on, this occurs when the CHP unit is unable to supply sufficient heat to maintain mesophilic temperature for the AD, which is the foremost share of the day using the CM method (Fig. 19). Furthermore, the difference between the milking methods within scenario 3 can be explained by the large differences in gas that is imported and exported for both milking methods, so does scenario 3 AMS exports more gas than it imports. While vice versa for 3 CM automatically results in higher emissions. As figure 9 indicates is the emission of scenario 3 slightly higher compared to scenario 4, this small difference is due to the addition of storage capacity in scenario 4, which limits the natural gas import, which has a stronger influence on the CO_2-eq emissions than green gas (Table 19). The low carbon footprint of scenario 5 can be explained by the strong influence of exporting electricity, which has a high carbon footprint per energy unit, resulting in lots of negative emissions (Fig. 9). The difference in carbon footprint within this scenario can be explained by the higher energy demand of the AMS milking method, resulting in a lower net energy export for AMS.

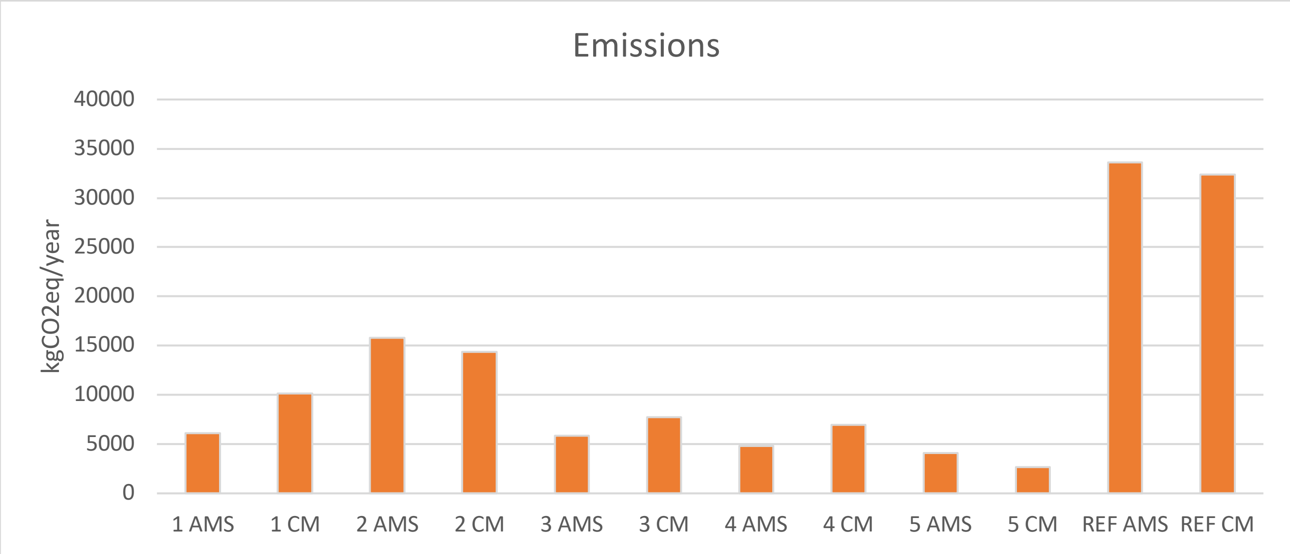

Figure 9. Carbon footprint per scenario.

8.2 Environmental Impact (Pt)

Despite the higher energy consumption of all made scenarios, is the environmental impact lower than the reference scenarios, this can be accounted to the large environmental impact resulting from grey electricity production which is used for the reference scenarios and the negative environmental impact points that arise for the made scenarios. There is a large discrepancy in environmental impact between the two milking methods for scenario 1 (Fig. 10), this discrepancy can be explained by the larger amount of grey electricity that is imported by 1 CM compared to 1 AMS (Fig. 27). The lower environmental impact of scenario 2 compared to the reference scenario (Fig. 10) is the result of the biogas production by the AD plant, which result in negative environmental impact points. The small difference in environmental impact within scenario 2 can be explained by the slightly higher energy demand of the AMS milking method. However, despite the lower energy demand of the CM method for all scenarios, a larger environmental impact is indicated using the CM method for scenarios 1, 3 and 4 (Fig. 10). This can be traced back to the higher total energy demand when the gas boiler is turned on, this occurs when the CHP unit is unable to supply sufficient heat to maintain mesophilic temperature for the AD, which is the foremost share of the day using the CM method (Fig 20). The difference within scenario 3 between the milking methods (Fig. 11) can be explained by the large differences in gas that is imported and exported for both milking methods, so does scenario 3 AMS exports more gas than it imports. While vice versa for scenario 3 CM, resulting in a larger environmental impact. Scenario 4 has a slightly lower environmental impact compared to scenario 3 (Fig. 10), this can be explained by addition of a biogas storage tank, which limits the import of natural gas and thereby limiting the environmental impact. In scenario 5 all the remaining biogas is converted to electricity and fed into the electricity grid. By feeding this remaining energy in the form of electricity, a share of the grey electricity, which has a large environmental impact (Table 20), is replaced by green electricity, which has a lower environmental impact, thereby decreasing the overall environmental impact and resulting as the scenario with the lowest environmental impact.

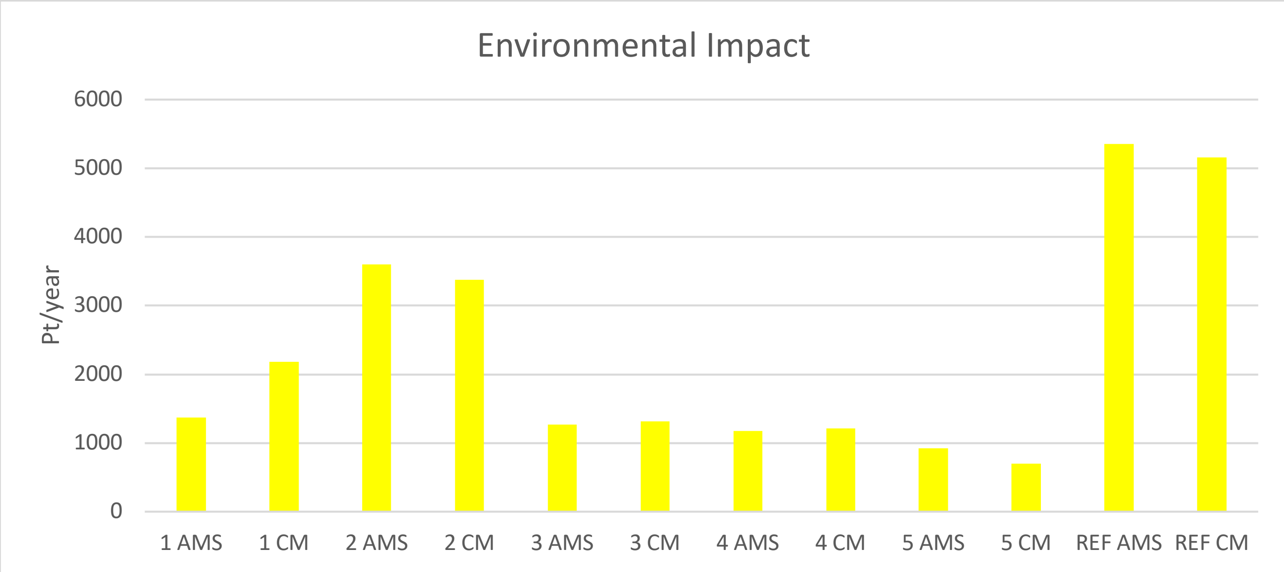

Figure 10. Environmental impact per scenario.

8.3 Financial feasibility (NPV)

Figure 11 displays the costs per year for all scenarios. All composed scenarios have much larger investments costs (e.g. digester, CHP unit etc.) compared to the reference scenarios (Table 33). However, since the annual energy costs are much lower for the made scenarios, all scenarios, except for scenario 2, indicate a smaller amount of total annual costs (Fig. 11). This can be explained by high energy costs that remain for scenario 2. In scenario 2, the same amount of electricity as the reference scenario is imported from the grid, which is a more expensive energy source compared to natural gas (Table 21). Even though there is an amount of green gas exported in scenario 2, the revenues are not enough to outweigh the imported electricity costs. Although the investment costs (CAPEX) are roughly similar for all composed scenarios, the annual costs using the automated milking system (AMS) are lower than the conventional milking (CM) method for the remaining scenarios (1, 3, 4, 5) (Fig. 11). This can be explained by the negative annual energy costs (higher revenues from exporting than costs from importing) for the AMS scenarios in contrast to the scenarios where is made use of the CM, where the net annual energy costs are positive (more imported than exported).

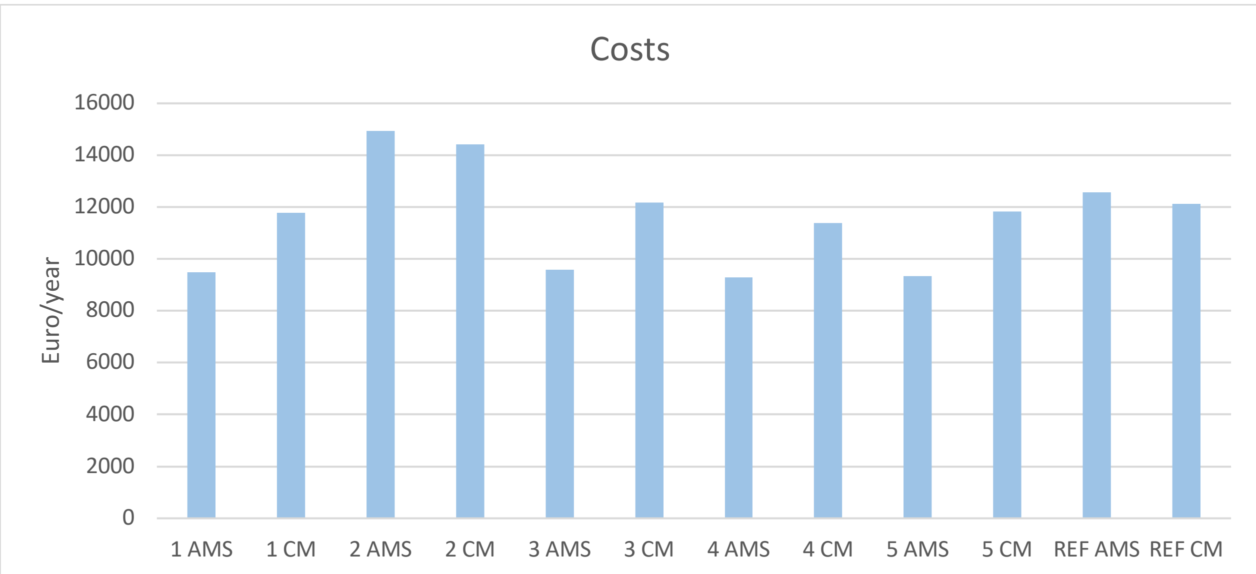

Figure 11. Costs per scenario.

8.4 Overall results

The carbon footprint and environmental impact have similar relative differences between the scenarios (Fig. 12), this can be traced back to the identical quantity of energy ((bio)gas or electricity) that is imported and/or exported into the grid.
Even though all composed scenarios have a higher energy demand compared to the reference scenarios; due to the incorporation of the energy demand of the AD process, the carbon footprint and the environmental impact are lower than the reference scenarios. The reason for this can be traced back to the large quantity of negative emissions that arise when excess energy (e.g. green gas or electricity) is exported into the grid and thereby replacing natural gas and grey electricity, with high carbon footprint and environmental impact (Table 19 & 20). Besides, grey electricity production has a large environmental impact and carbon footprint, which results in high overall impact and carbon footprint for the reference scenario, where exclusively grey electricity is used as energy source.
Furthermore, between scenarios, where only the energy carrier is varied, a large difference in carbon footprint and environmental impact is seen (Fig. 12). This can be traced back to the different carbon footprint and environmental impact values per energy source, so is in scenario 1, grey electricity used to fill in the energy demand gap, whereas in scenario 3 natural gas is used, which has a lower carbon footprint as environmental impact per energy unit (Table 19 & 20). Similar with scenarios 1 and 5, the main difference is in the energy carrier, which is fed into the grid. Since electricity has a larger influence on the environmental impact and the carbon footprint, the carbon footprint and environmental impact of scenario 5 are lower compared to scenario 1 (Fig. 12).

With the use of figure 12, all the values of the SI-indicators per scenario can be studied. The composed scenarios indicate a reduction of 88 to 92% for the carbon footprint and an 83 to 87% reduction for the environmental impact when traditional energy sources are replaced by AD from manure. While the costs analysis indicates the potential of overall annual costs reduction up to 26%. Showing that scenario 5 CM, has both the lowest environmental impact as carbon footprint, while the costs are lowest at scenario 4 AMS (Fig. 12).

Overall, when the energy demand for both milking methods are compared to the supply patterns of the AD, it is notable that the energy demand pattern of the AMS method is easier to match. This is due to the more equally distributed energy demand of the AMS method (Fig. 19 & 20). A notable observation is that scenario 4, using the AMS method, is the only combination where no additional energy is imported, making this the only optimization scenario that is completely energy self-sufficient and circular. This can be explained by the addition of the storage tank for this scenario. Besides, this scenario has the lowest annual costs, which also makes this the most economically attractive scenario.

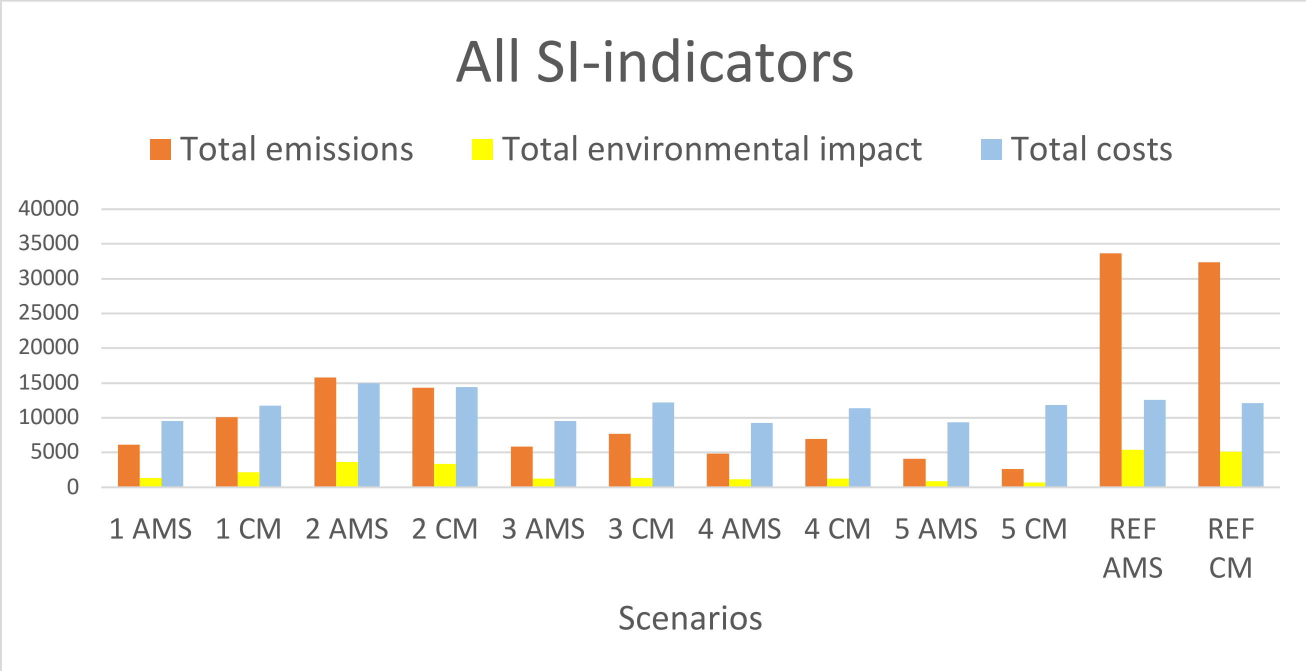

Figure 12. SI-indicator values for all scenarios.

9. Sensitivity Analysis

In this section, the sensitivity of the used variables in the model are tested. When scenarios are compared, identical settings eliminate sensitivities in the used values [16]. Table 26 shows the similar values that were used in all scenarios. Since the main output of the model (e.g. the biogas production per hour) is identical for every scenario, all variables are kept constant, except for one and so the sensitivity of this variable can be determined. Since there are three different energy sources (e.g. grey electricity, natural gas and green gas), which have differing SI-indicator values (kgCO_2-eq/GJ, Pt/GJ, euro/GJ), the corresponding values are varied in order to determine the sensitivity of each variable (Tables 15-17). Consequently, the sensitivity analysis was performed by varying all three SI-indicator values for each energy source together with the costs of the CHP unit and upgrader (Table 18), all these variables are varied by 10% (Appendix 13.7).

The values corresponding to grey electricity production show to be the most sensitive to changes for all three SI-indicators (carbon footprint, environmental impact and costs). This strong sensitivity can be explained by the high values per energy unit for all SI-indicators for grey electricity production. Especially in the scenarios where a lot of grey electricity is used (2 and REF) this is seen.

The sensitivity analysis shows that even in the worst-case scenarios both the carbon footprint as the environmental impact are lower compared to the reference scenarios (Fig. 13, 14). Furthermore, it shows that within the cost's variables, the grey electricity price is most dominant and that the costs for both the CHP unit as the upgrader do not have a large impact on the costs. For instance, in the worst case, scenarios (1 CM, 4 CM and 5 CM) the projected costs surpass the best case of the reference scenarios (Fig. 23), indicating some risks in the business case. However, for this to happen a decrease in electricity prices is needed.

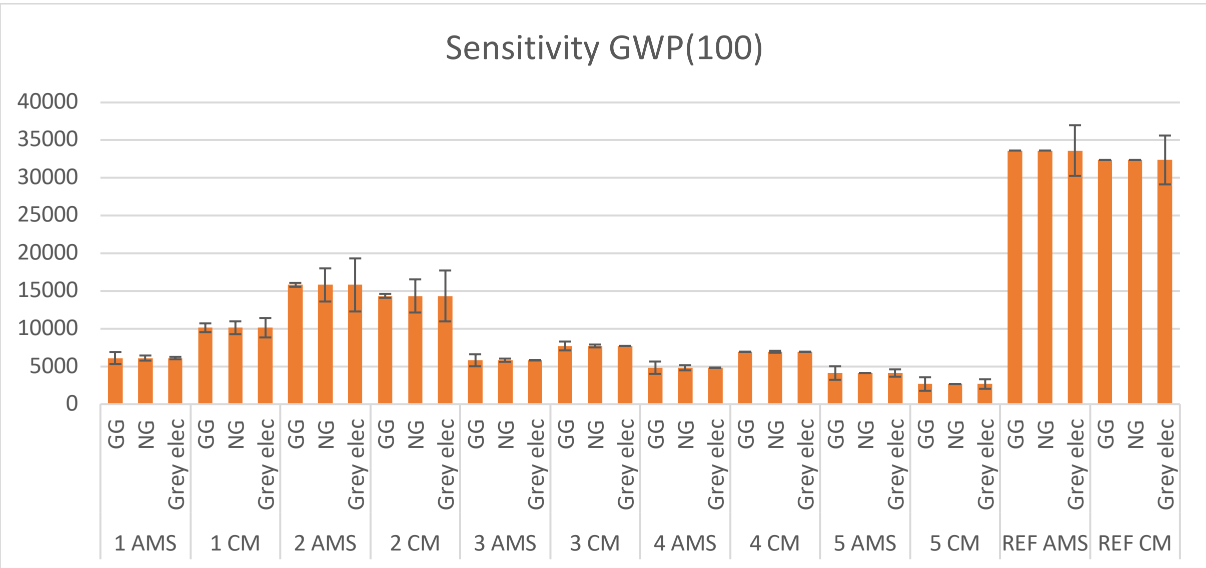

Figure 13. Sensitivity carbon footprint for all three energy sources (e.g. green gas (GG), natural gas (NG) and grey electricity (grey elec)).

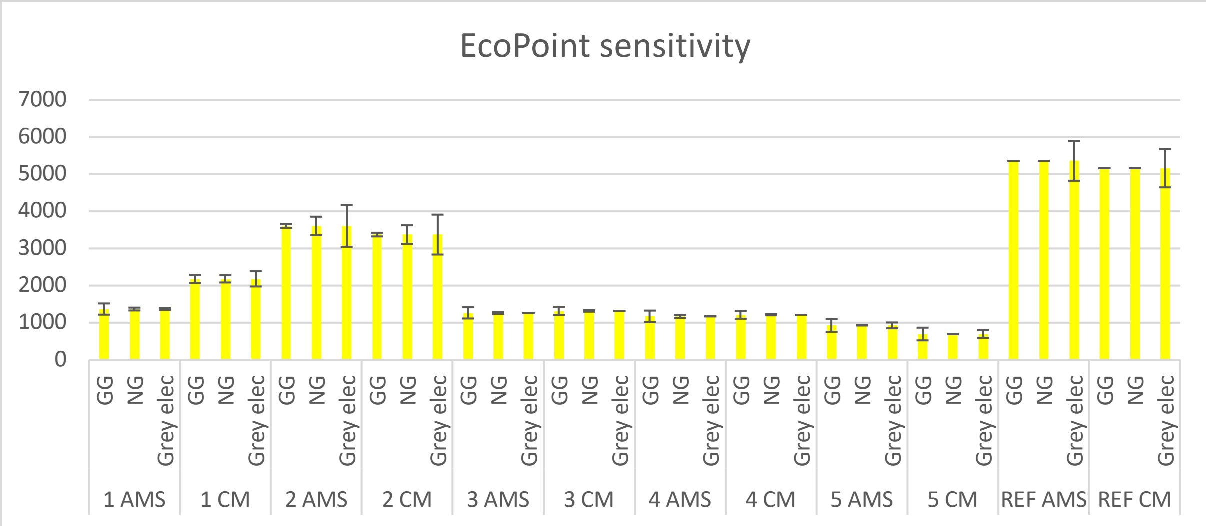

Figure 14. Sensitivity environmental impact all three energy source (e.g. green gas (GG), natural gas (NG) and grey electricity (grey elec)).

10. Discussion

There is existing research on re-using manure for energy purposes [16]; however, to the authors knowledge, the field of matching energy demand and supply patterns using locally produced manure is not explored yet. The findings of this study suggest that self-produced biogas, obtained from manure, has the potential to increase sustainability and feasibility, while obtaining energy self-sufficiency within a dairy farm. The results showed that the kind of energy (e.g. electricity or gas) and the corresponding carbon footprint and environmental impact is of great importance in determining which scenario is most sustainable. Furthermore, the results indicate a significant decrease in both carbon footprint and environmental impact for all composed scenarios. However, a decrease in annual costs was not seen in all scenarios. Nevertheless, potential subsidies are not taken into consideration, which might eventually improve economic feasibility. Subsidy policies may increase the feasibility to make investing in a digestion system more financially attractive, and thereby speeding up the energy transition and the circularity of the agricultural sector [94]. Nonetheless, one scenario indicated improvements in all three SI-indicators and also showing self-sufficiency, thereby meeting all specifications set in the introduction. These findings may help to mitigate the anthropomorphic carbon footprint and environmental impact caused by the agricultural sector, with the dairy sector in particular, while taken the costs into account to increase implementation.
The expressions used in this research to describe sustainability were used in order to increase transparency and obtain an overview; however, they lack the ability to give a specific interpretation regarding individual environmental impacts (e.g. eutrophication). In this research it is assumed that the environmental impact and carbon footprint decrease as the produced renewable energy is exported back into the grid. However, in practice the total amount of energy production (e.g. grey electricity production) is not automatically levelled, like a smart-grid, which makes this assumption less favourable than assumed. Nevertheless, future developments may solve this issue. Furthermore, the carbon footprint and environmental impact of grey electricity production is most likely to be lower in the future, due to increased percentage of green energy in the total energy mix. However, this was researched in the sensitivity analysis and did not indicate any significant changes. As described in the results section; scenario 4 AMS is circular, self-sufficient and least costly, while scenario 5 CM show the lowest carbon footprint and environmental impact. Therefore, a consideration has to be made, which factor is more important; sustainability, self-sufficiency or feasibility.

Assumptions and limitations

In order to model the system used in this research, some simplifications were made. First of all, losses were neglected within the system. Further, any energy requirements for heat and gas transport were not taken into account. Besides, an important assumption, which indicates the residence time of the cows inside the barn and therefore the amount of manure that is able to be gathered, was assumed to be equal over the entire year. However, the time spent in the stables by the cows is not evenly distributed over the year. Thence, it is possible that the biogas generation is not constant over the year, as is assumed in the model. Furthermore, any practices that interrupt the AD process, like maintenance, is not taken into consideration, which has a lowering output on the biogas production. Moreover, it was assumed that the heat demand for the AD was constant over the year. However, the heat demand is very dependent on the ambient temperature and therefore varies during the year. In this research there is made use of the EBS model, which provides the values for the SI-indicators per energy unit. This model is validated with a minimum input of 2000 tons of manure. However, in this research there is made use of a manure input of 1996 tons, which is slightly below the minimum threshold. Nonetheless, it is assumed that the model is still valid, even though the input is below the input threshold. Furthermore, the purchase costs for the milking methods are not included in the economic analysis. This was not done because this could give the dairy farmer a misleading perspective of the annual costs, since the purchase costs are processed into the annual costs. In this way an existing

dairy farmer has a more transparent view which scenario has the most beneficial findings. In table 22 the purchase costs of both milking methods are presented. Nonetheless, the costs calculation of the CHP unit, upgrader and green gas injection system were simplified. In the model it is assumed that the prices grow linear with size, which is in practice reasonable, however, the calculation lacks an initial starting value, causing an unrealistically low value for small CHP sizes. Moreover, the grid connection costs are not included in the cost's analysis, which may have an influence on the annual costs and therefore on the decision which scenario is financially most attractive.
Furthermore, the energy demand patterns of both milking methods are based on data from the same source [20]. However, the number of cows is not equal for both milking methods, which results in a different total energy consumption. Nevertheless, since the energy demand pattern is of importance, which remains similar, the source was considered to be reliable. Furthermore, mitigation through harvesting and storage of manure, instead of methane losses from untreated manure is not take into account, which decrease the carbon footprint and environmental impact [95].

Implementation and future research

This model framework can be used in defining and understanding similar systems. Alongside, since the RES model is flexible in use, it can be used in future research, for instance this research provides insight in the potential of locally produced manure for energy usage with the use of mono-digestion. However, other feedstocks (e.g. pig manure, chicken manure) and co-digestion and/or a combination with other renewable energy sources like solar and wind energy may increase the potential of energy self-sufficiency and sustainability and thereby increasing the circularity of other sectors as well. However, the RES model has a certain level of complexity that only experts in the field of modeling and biogas systems have the knowledge and experience to use and understand the model properly. Therefore, it is advised to consult an expert when using the RES model. The RES model can be used, in expert hands, to match energy demand and supply with the use of an AD, to increase the level of self-sufficiency and increasing sustainability within the agricultural sector. Further, implementation of re-using waste streams like the re-use of heat (e.g. from digestate) can increase the efficiency of energy and reduce the total energy demand. Future research may reveal if addition of electrical storage units has any potential in increasing the sustainability and circularity of the agricultural sector and the dairy sector in particular.

11. Conclusion

This research aimed to identify the possibilities in increasing the sustainability and circularity of the agricultural sector, with a focus on the dairy sector. Therefore, the following research question was introduced:

“To what extent is self-produced biogas, obtained from manure, a more sustainable, feasible and self-sufficient energy supplier for a dairy farm compared to electricity from the grid?”

The answer to this question consists of several parts, the question if using biogas obtained from AD of manure is more sustainable compared to the currently used energy supply methods, is evidently indicated in the results, showing an improvement in sustainability for all scenarios. Further, a large variety of possibilities that improves sustainability is seen, which are strongly dependent on the used energy carrier and the potential of storage. On the part of feasibility, most scenarios showed an improvement when comparing to the reference scenarios, indicating a financially more attractive scenario. This can be allocated to the significant reduction in energy import expenditures.
To answer the question what the possibilities are for energy self-sufficiency of the dairy farm, the used milking method and the potential of storage is of great importance. The results indicate that a combination of the automated milking system (AMS) in combination with biogas storage is the only scenario (scenario 4 AMS) that no additional imported energy is required and exclusively energy is exported, making the farm entirely autarkic and circular. While scenario 5 CM showed to be the most sustainable scenario. Overall, the results indicate a potential of 88 to 92% in carbon footprint reduction, 83 to 87% reduction in environmental impact and a costs reduction up to 26%.
The methods used in this research briefly and clearly display the results, with the option of including additional data to get more accurate and/or focussed results. The final results exceeded initial expectations, which are more conclusive than previously anticipated. During the progress of the research, additional improvement scenarios were added in order optimize and find the most sustainable and feasible combination, resulting in 5 scenarios which were compared to the reference scenarios. This research shows the possibilities in matching energy demand and supply patterns with the sole use of locally obtained feedstock, thus stimulating circularity, to produce renewable energy. Thence, showing that there is potential in shaping the agricultural sector in a more circular and autarkic sector and thereby achieving the future set goals.

12. References

[1] Pearce D.W. Turner, R.K. Economics of natural resources and the environment. JHU Press; 1990.

[2] Kuiphuis, D. July 2018. '*Elektrificatie van erfwerkzaamheden in de melkveehouderij*'

[3] Lanigan, G., 2017. Reducing Greenhouse Gas Emissions from Agriculture. Retrieved from https://www.teagasc.ie/publications/2017/reducing-greenhouse-gas-emissions-from-agriculture.php

[4] Korhonen, J., Honkasalo, A., Seppala, J. Circular Economy: The Concept and its Limitations. EcoI Econ 2018l 143:37-46.

[5] Lazarevic, D., Valve, H. Narrating expectations for the circular economy: Towards a common and contested European transition. Energy Research & Social Science 2017.

[6] Gebrezgabher SA, Meuwissen MPM, Oude Lansink AGJM. Energy-neutral dairy chain in the Netherlands: An economic feasibility analysis. Biomass Bioenergy 2012; 36: 60-8.

[7] Berglund M, Börjesson P. Assessment of energy performance in the life-cycle of biogas production. Biomass Bioenergy 2006; 30: 254-66.

[8] Gissén C, Prade T, Kreuger E, Nges IA, Rosenqvist H, Svensson S, et al. Comparing energy crops for biogas production – Yields, energy input and costs in cultivation using digestate and mineral fertilisation. Biomass Bioenergy 2014; 64: 199-210.

[9] Wei, D.; Cameron, E.; Harris, S.; Prattico, E.; Scheerder, G.; and Zhou, J. (2016) The Paris Agreement: What it Means for Business; We Mean Business; New York.

[10] Rijksoverheid, 28 June 2019. Den Haag. *Klimaatakkoord.*

[11] RVO, 2014a. *Energie en klimaat in Agrosectoren.*

[12] CBS, 2015. Centraal Bureau voor de Statistiek. Elektriciteit in Nederland.

[13] Richards, M.B., Wollenberg, E., Buglion-Gluck, S., 2015. Agriculture's Contributions to National Emissions. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen.

[14] Sulewski, P., Majewski, E., Was, A., 2017. The importance of agriculture in the renewable energy production in Poland and the EU. DOI: 10.5604/00441600.1232992

[15] Pedroli, B., Langeveld, H., 2011. Impacts of Renewable Energy on European Farmers. Final Report for the European Commission Directorate-General Agriculture and Rural Development, AGRI-2010-EVAL-03.

[16] Pierie, F., & Moll, H., 2018. How to measure and optimize the sustainability of complex (renewable) energy production pathways: Applied to farm scale biogas production pathways (Doctoral dissertation, 2018). University of Groningen.

[17] Berglund M, Börjesson P. Assessment of energy performance in the life-cycle of biogas production. Biomass Bioenergy 2006; 30: 254-66.

[18] CHBC, 2015. Power to Gas: The Case for Hydrogen White Paper; California Hydrogen Business Council: Los Angeles, CA, USA, 2015.

[19] Tappen SJ, Aschmann V, Effenberger M. Lifetime development and load response of the electrical efficiency of biogas-driven cogeneration units. Renewable Energy 2017; 114: 857-65.

[20] Vandelannoote, L., 2014. P2G voor een landbouwbedrijf. Boerenbond. http://docplayer.nl/4811678-P2g-voor-een-landbouwbedrijf.html

[21] Upton John, Michael Murphy, Padraig French & Pat Dillon, 2010. Dairy Farm Energy Consumption. Livestock Systems Department, Animal & Grassland Research and Innovation Centre, Teagasc Moorepark, Fermoy, Co. Cork.

[22] Upton, John & Humphreys, James & Groot Koerkamp, P.W.G. (Peter & French, P & Dillon, P & Boer, I.J.M., 2013a. Energy demand on dairy farms in Ireland. Journal of dairy science. 96. 10.3168/jds.2013-6874.

[23] RVO, 2018. Stikstof- en fosfaatproductiegetallen per melkkoe 2018 (drijfmest en vaste mest), Tabel 6. Mestbeleid 2018. https://www.rvo.nl/sites/default/files/2018/01/Tabel-6-Stikstof-en-fosfaatproductiegetallen-per-melkkoe-2018.pdf

[24] RVO, 2019. Berekenen werkelijk gebruik stikstof uit dierlijke mest | RVO.nl. Visited on 24 january 2019, from https://www.rvo.nl/onderwerpen/agrarisch-ondernemen/mestbeleid/mest/gebruiksnormen/dierlijke-mest/berekenen-werkelijk-gebruik

[25] Lems, R., Langerak, J., Dirkse, E.H.M., 2008. "Next generation biogas upgrading using highly selective gas separation membranes": Showcasing the Poundbury project 2008.

[26] Bekkering, J., Broekhuis, A.A., van Gemert, W.J.T., 2010. Optimisation of a green gas supply chain – A review. Bioresource Technology; 101: 450-6.

[27] Tauseef, S., Premalatha, M., Abbasi, T., & Abbasi, S., 2013. Methane capture from livestock manure. Journal of Environmental Management, 117, 187-207. doi:10.1016/j.jenvman.2012.12.022

[28] Pierie, F., Austin, D., Christian, E., René, M., Wim, J., & Henri, C., 2017. Improving the sustainability of farming practices through the use of a symbiotic approach for anaerobic digestion and digestate processing. Resources, 6(4), 50-50. doi:10.3390/resources6040050

[29] FrieslandCampina, 2019. Weidegang: koeien in de wei. Retrieved March 4, 2019, from http://www.frieslandcampina.com.nl/duurzaamheid/mvo-in-de-praktijk/weidegang-koeien-in-de-wei/

[30] Pierie, F., Bekkering, J., Benders, R., Van Gemert, W., & Moll, H. (2016). A new approach for measuring the environmental sustainability of renewable energy production systems: Focused on the modelling of green gas production pathways. *Applied Energy, 162*, 131-138.

[31] Mori K, Christodoulou A. Review of sustainability indices and indicators: towards a new City Sustainability Index (CSI). Environ Impact Assess Rev 2012;32:94-106.

[32] Pierie, F.; van Someren, C.E.J.; Bekkering, J.; Benders, R.M.J.; van Gemert, W.J.T.; Moll, H.C. The Development Validation and Initial Results of an Integrated Model for Determining the

Environmental Sustainability of Biogas Production Pathways. *Eur. Biomass Conf. Exhib.* ***2016,*** *1411,* 1411-1421.

[33] Haberl H, Weisz H. The potential use of the materials and energy flow analysis (MEFA) framework to evaluate the environmental costs of agricultural production systems and possible applications to aquaculture 2007; FAO/WFT Expert Workshop, 24–28 April 20 (TRUNCATED).

[34] Wageningen UR Livestock Research. *Kwantitatieve Informatie Veehouderij 2013-2014 ed.*; Wagening UR Livestock Research: Wageningen, The Netherlands, 2013. (In Dutch)

[35] KNMI, 2019. Daggegevens van het weer in Nederland. Database. https://www.knmi.nl/nederland-nu/klimatologie/daggegevens

[36] NCCO, North Carolina Climate Office. (2019). Temperature Gradient | North Carolina Climate Office. Retrieved March 4, 2019, from https://climate.ncsu.edu/edu/Gradient

[37] Lydia, M., Kumar, S., Selvakumar, A., & Prem Kumar, G., 2014. A comprehensive review on wind turbine power curve modeling techniques. Renewable and Sustainable Energy Reviews, 30, 452-460.

[38] EAZwind, 2019. E.A.Z. Wind Product from: https://www.eazwind.com/nl/product/ visited on 21 january 2019.

[39] EU, 2010 April. European Union. European Standard. Edict of Government. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.4.2005.pdf

[40] KNMI, july 2015. Klimaatdata en -advies. Metadata KNMI-stations. Eelde (06280) https://projects.knmi.nl/klimatologie/metadata/eelde.html

[41] Ragheb, M., 2018. Wind shear, roughness classes and turbine energy production. Available at : http://mragheb.com/NPRE%20475%20Wind%20Power%20Systems/Wind%20Shear%20Roughness%20Classes%20and%20Turbine%20Energy%20Production.pdf
Accessed at 05-06-2019.

[42] Juchuan, Dai & Liu, Deshun & Wen, Li & Long, Xin., 2016. Research on power coefficient of wind turbines based on SCADA data. Renewable Energy. 86. 206-215. 10.1016/j.renene.2015.08.023.

[43] Shelquist, R., 2009 Equations - Air Density and Density Altitude

[44] KNMI, 2017. Weerstatistieken Eelde - 2017. https://weerstatistieken.nl/eelde/2018

[45] EU, 2010 April. European Union. European Standard. Edict of Government. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.4.2005.pdf

[46] Milieucentraal, CE Delft & Stichting Stimular, 2017. co2factor stroomverbruik https://www.co2emissiefactoren.nl/co2emissiefactoren/co2-factor-stroomverbruik-20-11-2017/

[47] Shortall, J., O'Brien, B., Sleator, R., & Upton, J. (2018). Daily and seasonal trends of electricity and water use on pasture-based automatic milking dairy farms. *Journal of Dairy Science, 101*(2), 1565-1578. doi:10.3168/jds.2017-13407

[48] Upton, J., Murphy, M., Shalloo, L., Groot Koerkamp, P., & De Boer, I. (2014). A mechanistic model for electricity consumption on dairy farms: Definition, validation, and demonstration. *Journal of Dairy Science, 97*(8), 4973-4984. doi:10.3168/jds.2014-8015

[49] GroenKennisnet, 18 december 2018. Meer melk met minder koeien. https://www.groenkennisnet.nl/nl/groenkennisnet/show/Meer-melk-met-minder-koeien.htm

[50] Bakker, K. 21 Januari, 2018. *Welke provincie heeft de meeste melkveebedrijven?* (In Dutch) https://www.boerenbusiness.nl/melk/artikel/10877043/welke-provincie-heeft-de-meeste-melkveebedrijven

[51] Pierie, F.; van Someren, C.E.J.; Liu, W.; Bekkering, J.; Hengeveld, E.J.; Holstein, J.; Benders, R.M.J.; Laugs, G.A.H.; van Gemert, W.; Moll, H.C., *An Intergrated Approach fort he Validation of Energy and Environmental System Analysis Models: Used in the Validation of the Flexigas Excel BioGas Model;* Hanzehogeschool Groningen: Groningen, The Netherlands, 2016.

[52] Pierie, F., Van Someren, C., Benders, R., Bekkering, J., Van Gemert, W., & Moll, H. (2015). Environmental and energy system analysis of bio-methane production pathways: A comparison between feedstocks and process optimizations. *Applied Energy, 160*, 456-466.

[53] FrieslandCampina, 2019. Weidegang: koeien in de wei. Retrieved March 4, 2019, from http://www.frieslandcampina.com.nl/duurzaamheid/mvo-in-de-praktijk/weidegang-koeien-in-de-wei/

[54] Pöschl, M., Ward, S., Owende, P. Evaluation of energy efficiency of various biogas production and utilization pathways. Appl Energy 2010;87:3305-21.

[55] Pre. The attributed Life Cycle Analysis Model SimaPro 2013; 2013.

[56] Ecoinvent. Ecoinvent: Database of consistent, transparent, and up-to-date Life Cycle Inventory (LCI) data; 2014.

[57] Golub, G., Lukach, V., Ikalchyk, M., Tesliuk, V., & Chuba, V., 2018. Experimental study into energy consumption of the manure removal processes using scraper units. Eastern-European Journal Of Enterprise Technologies, 4(1 (94)), 20-26. doi:http://dx.doi.org/10.15587/1729-4061.2018.139490

[58] Murphy, D., Hall, C., Dale, M., Cleveland, C., 2011. Order from Chaos: a preliminary protocol for determining the EROI of fuels. Sustainability 3, 1888–1907.

[59] Rehl, T. Lansche, J. Müller, J. Life cycle assessment of energy generation from biogas – attributional vs. consequential approach. Renew Sustain Energy Rev 2012;16:3766-75.

[60] EBN, 2018. *Energie in Nederland.* (In Dutch). Retrieved on 28-10-2019 from: https://www.ebn.nl › uploads › 2018/01 › EBN-Infographic-2018-pdf

[61] Goedkoop, M., Schryver de, A., Oele, M., Durksz, S., Roest de, D. Introduction to LCA with SimaPro 7. 4.5; 2010.

[62] PRé Consultants, RIVM, CML, Radboud Universiteit Nijmegen. This site presents the ReCiPe methodology for Life Cycle Impact Assessment (LCIA); 2014.

[63] Goedkoop, M. Spriensma, R. SimaPro Database manual. The Eco-indicator 99 A damage-oriented method for life cycle impact assessment; 22 June, 2001.

[64] Hall, A.S.C., Balogh, S., Murphy, J.R.D. What is the minimum EROI that a sustainable society must have? Energies 2009;2:25-47.

[65] Hall, C., Lambert, J., & Balogh, S. (2014). Eroi of different fuels and the implications for society. *Energy Policy, 64*, 141-152. doi:10.1016/j.enpol.2013.05.049

[66] Hall, C., Lambert, J., & Balogh, S. (2013). *EROI of Global Energy Resources. Status, Trends and Social Implications.*

[67] Hall, C., Klitgaard, K., 2012. Energy and the Wealth of Nations: Understanding the Biophysical Economy. Springer Publishing Company, New York, USA.

[68] BP, 2019. *Statistical Review of World Energy, 2019*. 68th edition.

[69] CBS, 2015. Noorwegen passeert Rusland als belangrijkste olieleverancier.

[70] 2019, March 28. SimaPro. *Understanding electricity in SimaPro.* Retrieved on 05-11-2019 from https://simapro.com/2019/understanding-electricity-in-simapro/

[71] Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renew. Sustain. Energy Rev. 28, 555–565.

[72] Hahn, H.A., The Conundrum of Verification and Validation of Social Science-based Models. Procedia Computer Science 2013; 16: 878-87.

[73] Sargent, R.G., Verification and validation of simulation models. Journal of Sim 2013; 7: 12-24.

[74] Balci, O. Golden Rules of Verification, Validation, Testing, and Certification
 />of Modeling and Simulation Applications. SCS M&S Magazine – 2010 / n4 (Oct); October: 1-7.

[75] Pierie, F., van Someren, C., Liu, W., Bekkering, J., Hengeveld, E. J., Holstein, J., ... Moll, H. C. (2016). *An integrated approach for the validation of energy and environmental system analysis models: used in the validation of the Flexigas Excel BioGas model*. Hanzehogeschool Groningen.

[76] Singhal, S., Agarwal, S., Arora, S., Sharma, P., & Singhal, N. (2017). Upgrading techniques for transformation of biogas to bio-cng: A review. *International Journal of Energy Research, 41*(12), 1657-1669. doi:10.1002/er.3719

[77] Boerenbond, 4 september 2015. *Stroom en warmte met kleinschalige vergisters.*

[78] Knauer, T., Scholwin, F., & Nelles, M. (2018). Maximizing the energy output from biogas plants: Optimisation of the thermal consumption of biogas systems. *Waste and Biomass Valorization, 9*(1), 103-113. doi:10.1007/s12649-017-9920-2

[79] Liebetrau, J., Reinelt, T., Agostini, A., Linke, B. (2017). Methane emissions from biogas plants: Methods for measurements, results and effect on greenhouse gas balance of electricity produced. *IEA Bioenergy.*

[80] REINELT,T., DELRE, A., WESTERKAMP, T., HOLMGREN, M. A., LIEBETRAU, J., SCHEUTZ, C. (2017) Comparative use of different emission measurement approaches to determine methane emissions from a biogas plant. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.05.053

[81] Drijfmesttechniek. *Elektrische mestmixer*. Visited on 26-11-2019 from https://www.drijfmesttechniek.nl/elektrische-mestmixer/

[82] Brealey, R.A., Myers, S.C., Allen, F. (2013). Principles of Corporate Finance - Global Edition with Connect Plus; McGraw-Hill Education: New York City, NY, USA, 2013.

[83] Blokhina, Y., Prochnow, A., Plöchl, M., Luckhaus, C., & Heiermann, M. (2011). Concepts and profitability of biogas production from landscape management grass. *Bioresource Technology, 102*(2), 2086-2092. doi:10.1016/j.biortech.2010.08.002

[84] Amon B, Kryvoruchko V, Amon T, Zechmeister-Boltenstern S. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric , Ecosyst Environ 2006; 112: 153-62.

[85] Bekkering J, Hengeveld EJ, van Gemert WJT, Broekhuis AA. Will implementation of green gas into the gas supply be feasible in the future?. Appl Energy 2015; 140: 409-17.

[86] Milieucentraal. *Energierekening 2019.* Visited on 04-01-2020. Retrieved from: https://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/energierekening-2019/

[87] RVO, 2018. SDE+ Spring 2018. *Instructions on how to apply for a subsidy for the production of renewable energy.* Visited on 04-01-2020 from: https://english.rvo.nl/sites/default/files/2018/02/Brochure-SDE-Spring-2018.pdf

[88] Ebinger, J., 2008. *Mestrobot zorgt voor meer dan maar alleen schone koeien*. Visited on 08-01-2020 from: https://maken.wikiwijs.nl/bestanden/109183/Mestrobot.pdf

[89] KWIN, 2013-2014. Kwantitatieve informatie Veehouderij, Page 96

[90] HoSt bio-energy installations. *Energie uit mest met de Microferm monomestinstallatie van HoSt.* Visited on 10-01-2020 from: https://www.host.nl/nl/host-jumpstart-monomestvergisting/

[91] Zevenbergen, G. 30-05-2018. Veehouderij Techniek. *De prijs van een Lely Astronaut A5.*

[92] Inge van Schie-Rameijer. Maart 2013. Veehouderij Techniek. *Melksysteem bepaalt arbeidsproductiviteit.*

[93] Grant, M. Investopedia.com. Last updated: 25/06/2019. Retrieved on 29-01-2020 from: https://www.investopedia.com/terms/s/sustainability.asp

[94] Braakman, J. Boerderij.nl. *Kamp: geen denken aan vermindering subsidie mestvergisting.* Last updated: 07-09-2017. Retrieved on 05-02-2020 from: https://www.boerderij.nl/Home/Nieuws/2017/9/Kamp-geen-denken-aan-vermindering-subsidie-mestvergisting-181071E/

[95] Elands, M., 26-11-2019. *Methaan reduceren? Mest zo snel mogelijk in opslag.* Nieuweoogst.nl Visited on: 11-02-2020 from: https://www.nieuweoogst.nl/nieuws/2019/11/26/methaan-reduceren-mest-zo-snel-mogelijk-in-opslag

[96] Addition to [10]. "Dit is een achtergrondnotitie ten behoeve van de sectortafel Landbouw en landgebruik"

[97] RIVM, 10-09-2018. *CO2-uitstoot in 2017 gelijk aan die in 1990.* Rijksinstituut voor Volkgezondheid en Milieu. Visited on: 20-03-2020 from: https://www.rivm.nl/nieuws/co2-uitstoot-in-2017-gelijk-aan-die-in-1990

13. Appendix

13.1 Validation of actual data and Excel modelled data.

In this section the graph that belongs to the actual dataset provided by Vandelannoote [20], is compared to the Excel modelled graph.

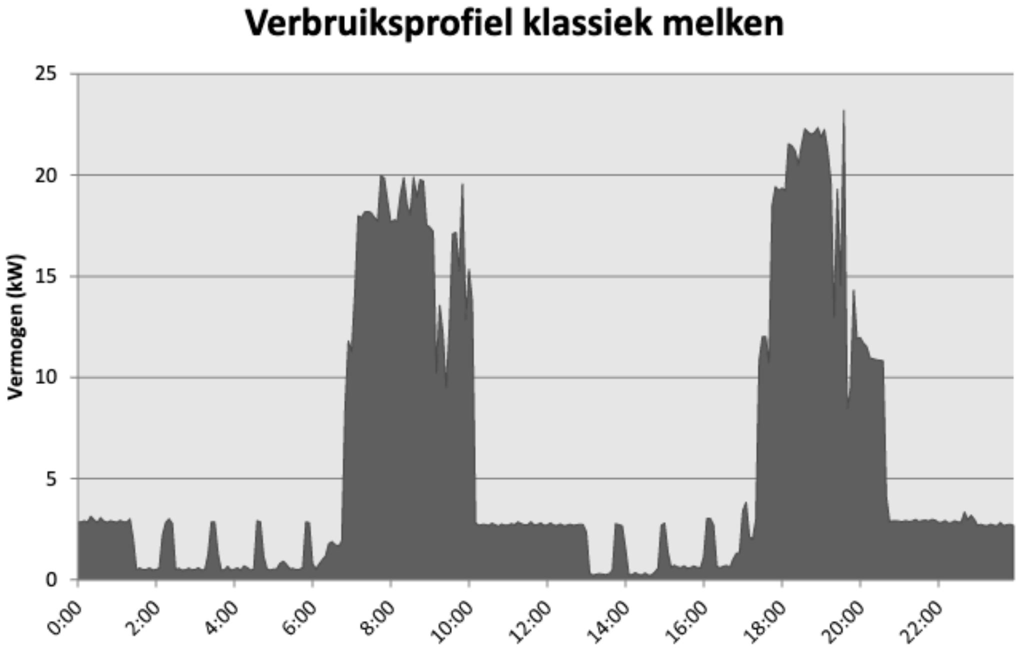

Figure 15. Energy demand conventional milking method for 120 cows.

Figure 15 shows the original dataset/graph with the energy demand for 120 cows for the conventional milking method, obtained from Vandelannoote [20].

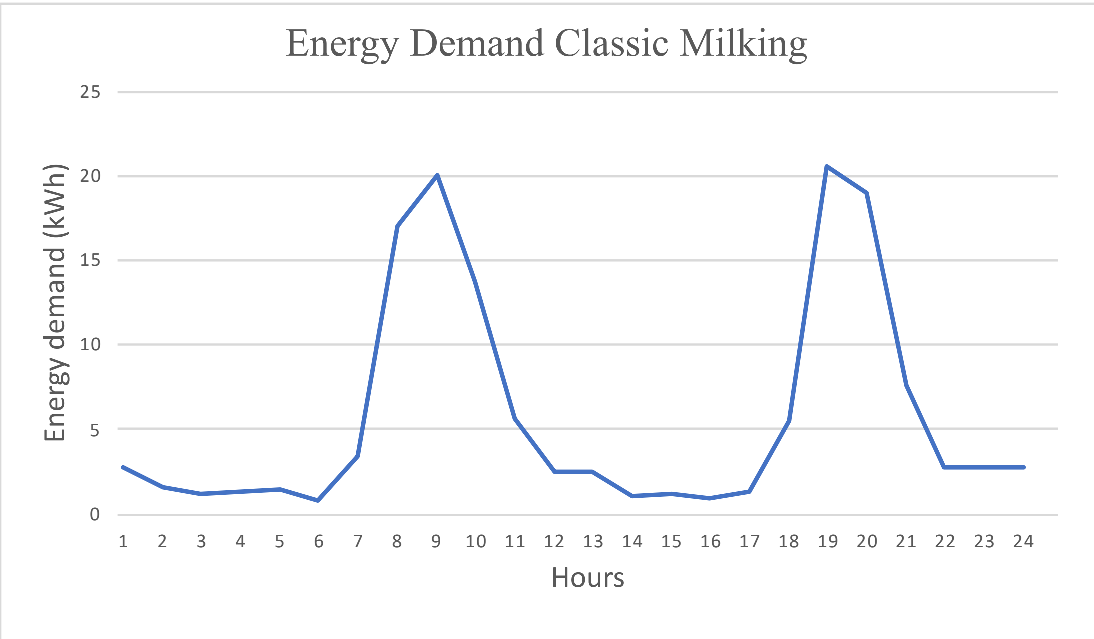

Figure 16. Energy demand conventional milking method for 120 cows hourly averaged.

Figure 16 shows the graph that is used in the Excel based model. When figure 22 and 23 are compared, the graphs are for the foremost share similar for some negligible part it is not.

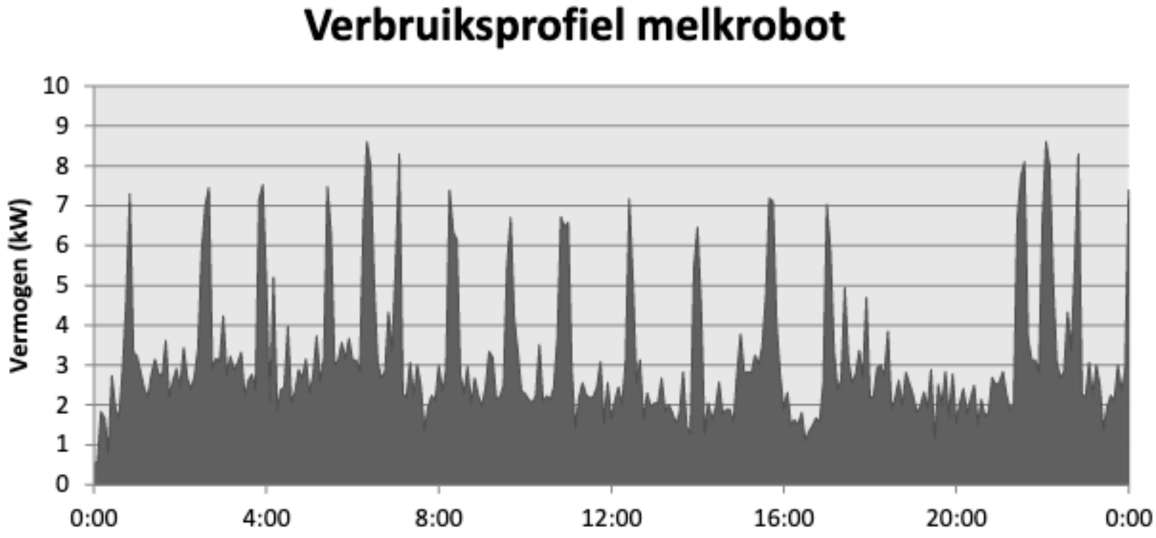

Figure 17. Energy demand AMS method for 60 cows.

Figure 17 shows the original dataset/graph with the energy demand for 60 cows for the AMS method, obtained from Vandelannoote [20].

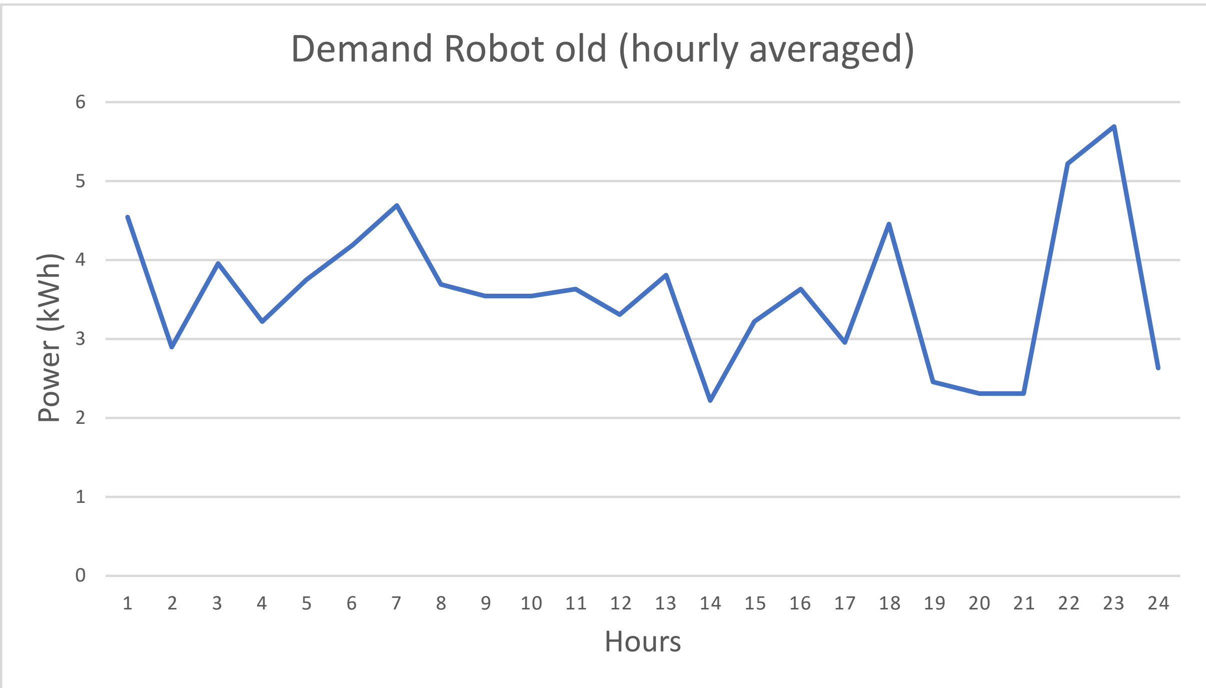

Figure 18. Energy demand AMS method for 60 cows hourly averaged.

Figure 18 shows the graph that is used in the Excel based model. When figure 24 and 25 are compared, the patterns seem not to be very complementary. This can be explained by the chosen temporal resolution of 1 hour, which was necessary in order to compare these values with the solar irradiation and wind speed values.

13.2 Calculations manure productions

18.12 Mg/cow/year manure production [34]

2,174.4 Mg year for 120 cows total manure production

2,174.4 Mg * (8040/8760) = 1,995.68 Mg manure per year INSIDE the barn.

The remaining 720 hours is because FrieslandCampina, one of the largest dairy companies in the Netherlands, encourage farmers by incentives to let the cows out of the barn for at least 6 hours for 120 days a year [53].

13.3 Values changed in EBS model

Table 11. Updated values in "Specific database" tab used in EBS model.

Main components	Values	Unit	Source
Heat use digester	108.85	MJ/Mg	[78]
Electricity use digester	31.44	MJ/Mg	[78]
Loss of biogas digester	0.044	%	[80]
Electricity use membrane upgrader	0.9	MJ/Nm^3	[76]
Loss of methane in filtrate	0	%	[80]
Manure scraper	1.26	MJ/Mg FM	[57]
Manure storage mixer	0.24	MJ/min FM	[81]

Table 12. Values used in "Professional settings" tab in EBS model.

Main components	Value	Unit	Source
Time spent in stables by cows	92	%	[53]
Collection transport distance	0	km	Assumption
Loss of manure during collection	0	Kg	Assumption
Green gas injection Loss of green gas (methane)	0.001	%	[16]

13.4 Costs values

Table 13. CAPEX

	Value	Unit	Source
CHP	946.16	Euro/kWe	[83]
Digester	53.64	Euro/Mg FM.year	[85]
Mixers digester	5800	Euro/piece	[89]
Pre-filter	10325	Euro	[26]
Upgrader	4024.88	Euro/(Nm^3/hr)	[85]
Manure scraper	15200	Euro	[88]
Gas boiler	13000	Euro	
Green gas injection system	550	Euro/(Nm^3/hr)	[85]

Table 14. OPEX

	Value	Unit	Source
Mixers digester	5800	Euro/piece	[89]
Gas grid connection			
Electricity grid connection			

13.5 Net Load Duration Curve (NLDC)

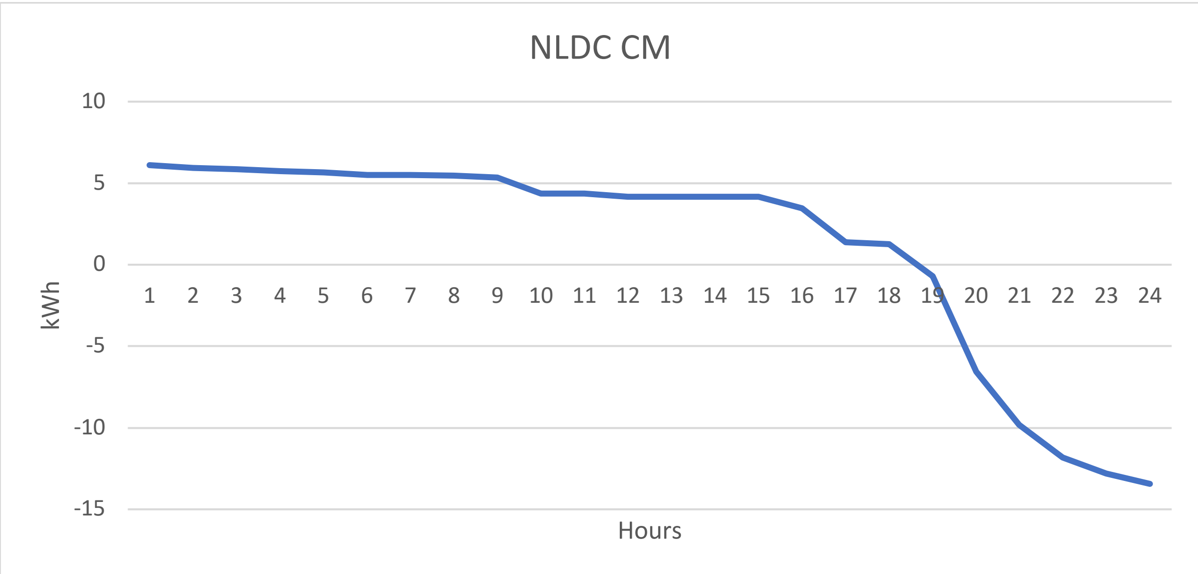

Figure 19. Net load duration curve of scenario 1 CM.

Figure 19 shows the net load duration curve of conventional milking (CM) method. When the energy supply is higher than the energy demand (oversupply), the curve is above the X-axis and when the supply is smaller than the demand (shortage) the curve is below the X-axis. Figure 26 shows that there is a shortage of electricity for 6 hours a day. During this period is additional energy is needed, the form of energy is dependent on the scenario.

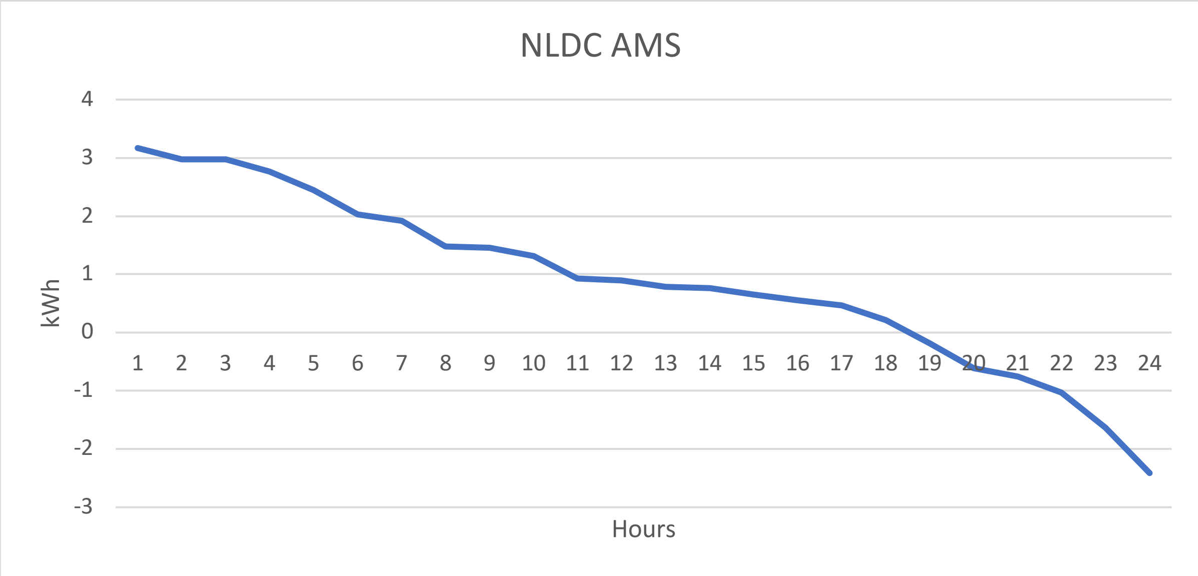

Figure 20. Net load duration curve of scenario 1 AMS.

Figure 20 shows the net load duration curve of the automated milking system (AMS) milking method. It shows that there is a shortage of electricity for 6 hours a day. During this shortage additional energy is needed, the kind of energy is dependent on the scenario.

13.6 Sensitivity analysis

Table 15. Adjusted values for simulating the SI-indicator values for grey electricity mix.

SI indicators	Original value	-10%	+10%	Unit	Source
Carbon footprint (GWP 100)	0.6372	0.5735	0.7009	kg CO_2-eq/kWh	[55,56]
Environmental impact	0.10152	0.0914	0.1128	Pt/kWh	[55,56]
Electricity price	0.22	0.198	0.242	Euro/kWh	[86]

Table 16. Values used for natural gas of the Netherlands.

SI indicators	Original value	-10%	+10%	Unit	Source
Carbon footprint (GWP 100)	1.911	1.720	2.102	$kgCO_2/Nm^3$	[55,56]
Environmental impact	0.217	0.195	0.239	Pt/Nm^3	[55,56]
Costs	0.77	0.693	0.847	$Euro/Nm^3$	[86]

Table 17. Adjusted values used for green gas.

SI indicators	Original value	-10%	+10%	Unit	Source
Carbon footprint (GWP 100)	1.036	0.932	1.140	$kgCO_2/Nm^3$	[26]
Environmental impact	0.196	0.176	0.216	Pt/Nm^3	[16]
Costs (feed-in tariff)	0.622	0.56	0.684	$Euro/Nm^3$	[87]

Table 18. Adjusted values used for CHP unit and upgrader.

	Original value	-10%	+10%	Unit	Source
CHP unit	946.16	851.54	1040.78	Euro/kWe	[83]
Upgrader	4024.88	3622.39	4427.37	Euro/(Nm^3/hour)	[85]

13.7 SI-indicator values per energy unit

Table 19. Carbon footprint per energy source.

Carbon footprint	Value	Unit	Source
Green gas	0.101656	kg CO_2-eq/kWh	[55][56]
Natural gas	0.19656	kg CO_2-eq/kWh	[55][56]
Grey electricity	0.6372	kg CO_2-eq/kWh	[55][56]

Table 20. Environmental impact per energy source.

Environmental Impact	Value	Unit	Source
Green gas	0.02016	Pt/kWh	[55][56]
Natural gas	0.02232	Pt/kWh	[55][56]
Grey electricity	0.10152	Pt/kWh	[55][56]

Table 21. Costs per energy source.

Costs	Value	Unit	Source
Green gas (sell)	0.064	Euro/kWh	[87]
Natural gas	0.0792	Euro/kWh	[86]
Grey electricity	0.22	Euro/kWh	[86]

13.8 Sensitivity Analysis graphs

'GG' indicating Green Gas
'NG' indicating Natural Gas
'Grey elec' indicating grey electricity mix

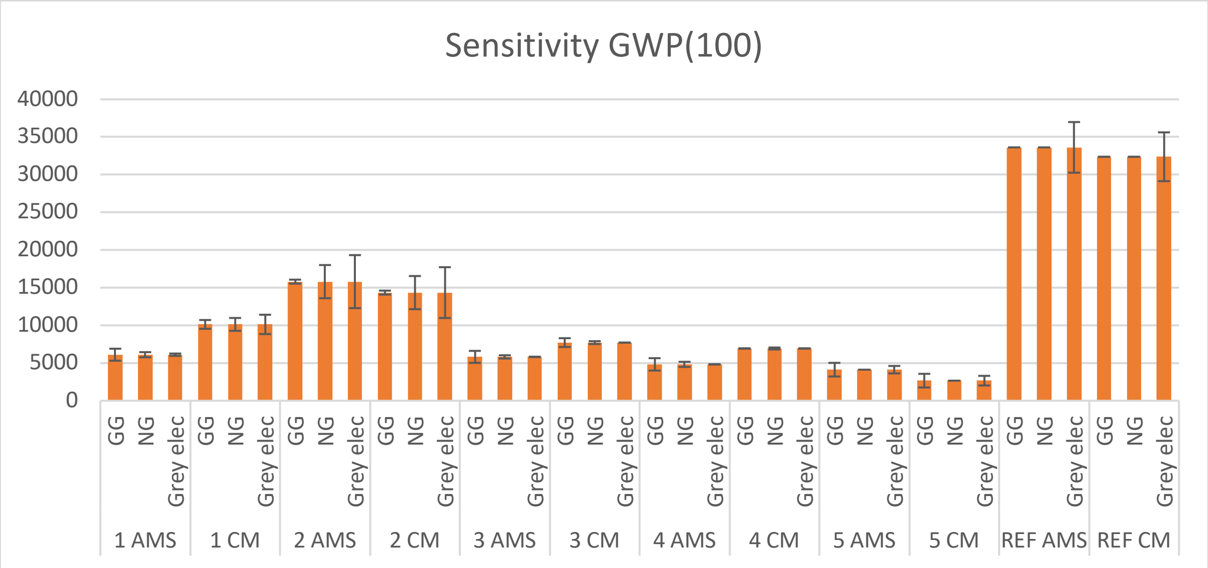

Figure 21. Sensitivity analysis on GWP(100).

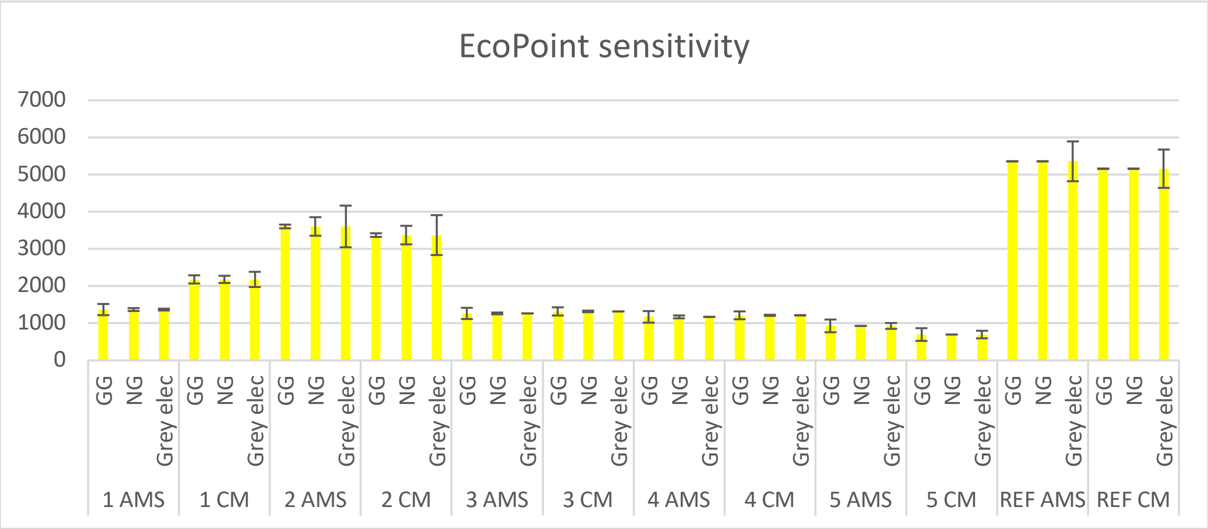

Figure 22. Sensitivity analysis on environmental impact.

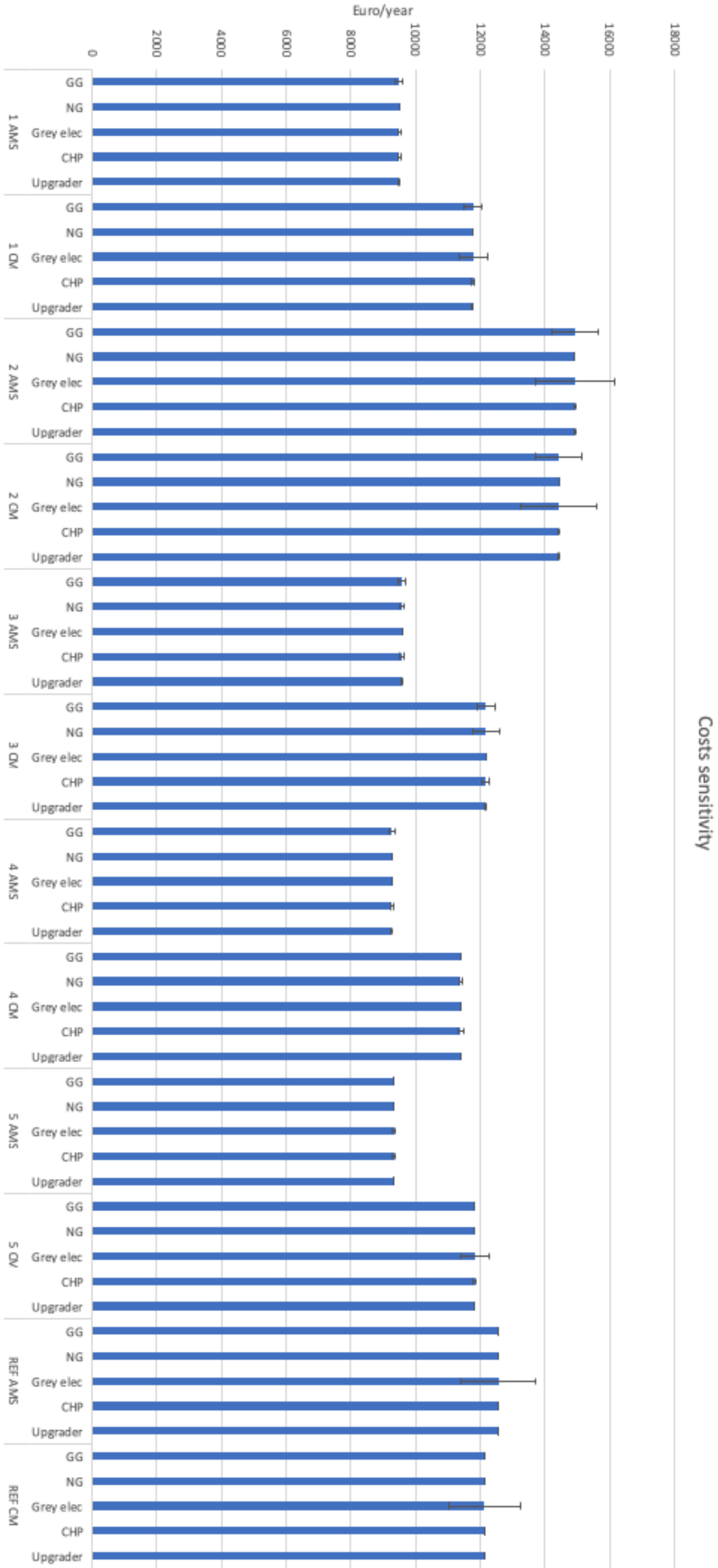

Figure 23. Sensitivity analysis on costs.

13.9 Milking methods

Table 22. Costs milking methods.

Milking method	Min value	Max value	Unit	Source
Conventional milking (CM)	85.000	150.000	Euro	[92]
Automated milking system (AMS)	110.000	180.000	Euro	[91]

13.10 Adopted values of EBS model

2.511 kWe internal use CHP to supply sufficient energy to run AD system, in 'energy saver' tab.

98% efficiency biogas boiler adopted from the EBS model, 'professional settings' tab.

13.11 RES model overview as described in chapter 5

Primary variables				**Results/Outputs**		
		Unit				Unit
Cows	120	st		Biogas production	5.1031143	Nm3/hour
				Green gas production	2.6244588	Nm3/hour
Inside barn	8040	Hours/year		Green gas that can be used	2.6244588	Nm3/hour
Outside	720	Hours/year		Electricity production	9.6959171	kWh/hour
Time spent in stables	91.78%	%		Internal use green gas (DIGESTER)	0.1692359	Nm3/hour
CHP efficiency (elec)	38%	%		Internal use (DIGESTER)	1.6453493	Kwh/hour
CHP efficiency (heat)	80%	%	0.011914293	Electricity demand digester	5.9232576	MJ/hour
Share green gas used of total produced	38%	%	0.031268571	Heat demand digester	43.285344	MJ/hour
Active carbon efficiency (pre-filter)	99.8%	%		Heat fed by CHP (recovered heat)	45.560604	MJ/hour
Membrane filtering efficiency (upgrader)	99.5%	%		Heat fed by gas boiler	-2.27526	MJ/hour
CHP size all gas conv.	9.695917133	kWe		Input gas boiler	-2.321694	MJ/hour
CHP size (100%)	12.11989642	kWe				
Primary database				Cash flow		Euro/hour
		Unit		Energy input		MJ/hour
Green gas injection system	550	euro/(Nm3/hour)		Carbon footprint		kg CO2eq/hour
Upgrader	4024.88	euro/(Nm3/hour)		EcoPoint		Pt/hour
Pre-filter	0.00065	MJ/Nm3	Number of mixers	4		
Pre-filter	10325	euro		**Primary input**		
Digester costs	134100	euro				Unit
Production per cow	18120	kg/year		Biomass production	2174.4	Mg FM/year
oDM content	6.4%	%		Biomass flow in digester	1995.6822	Mg FM/year
Energy content Green gas	35	MJ/Nm3			127.72366	Mg DM/year
	9.722222222	kWh/Nm3			0.2278176	Mg FM/hour
Green gas content manure	180	Nm3/Mg DM	11.52		0.0145803	Mg DM/hour
Biogas content manure	350	Nm3/Mg DM	22.4	Digester size	2500	Mg FM/year
Total hours in year	8760	Hours		Energy content manure	403.2	MJ/Mg manure
CHP costs	946.16	Euro/kWe			40.32	MJ/euro (manure)
Internal electricity use digester	0.026	MJ/kg	0.026	0.03144	1.152	Nm3/euro
Internal heat use digester	0.19	MJ/kg	0.19	0.10885	11.2	kWh/euro
Gas boiler efficiency	98%	%	Gas boiler price	13000	€ 0.09	euro/kWh
Gas price	0.77	Euro/Nm3	0.0792	euro/kwh		
Electricity price	0.22	euro/kWh		0.061111111		
Electricity feed in tarrif	0.07	euro/kWh		61.11111111	euro/GJ	
Manure price	10	euro/Mg	Manure scraper	15200	CAPEX	
Energy use AMS	52768.1	kWh/year	Manure scraper	350	OPEX	
Energy use CM	50812.6	kwh/year	Mixers AD	5800	CAPEX/OPEX	
Gas price feed in tarrif	0.064	euro/kWh	0.622222222	euro/nm3		

Figure 24. The database tab within the RES model.

CHP + elec grid	Scenario 1							
AMS (internal use AD + farm + internal CHP) ELECTRIC			CHP SIZE!					
Hour	Demand elec (kWh)	Demand elec (MJ/h)	Supply elec (kWh) by CHP	Green gas used (Nm3)	Heat need digester (MJ)	Heat by CHP (MJ)	Heat needed by gasboiler (MJ)	Heat needed by gasboiler (MJ)
1	10.14770509	36.53173833	9.695917133	2.624458773	43.28534434	45.56060429	-2.275259953	0
2	7.667050197	27.60138071	7.667050197	2.075291783	43.28534434	36.02706535	7.258278996	7.258278996
3	9.481295053	34.13266219	9.481295053	2.566365578	43.28534434	44.55210644	-1.266762096	0
4	8.215542828	29.57595418	8.215542828	2.223755953	43.28534434	38.60440335	4.68094099	4.68094099
5	9.143761127	32.91754006	9.143761127	2.475003012	43.28534434	42.96605229	0.319292057	0.319292057
6	9.578116591	34.48121973	9.695917133	2.624458773	43.28534434	45.56060429	-2.275259953	0
7	10.42195141	37.51902507	9.695917133	2.624458773	43.28534434	45.56060429	-2.275259953	0
8	9.038281774	32.53781439	9.038281774	2.44645221	43.28534434	42.47041036	0.814933985	0.814933985
9	8.8062272	31.70241792	8.8062272	2.383640445	43.28534434	41.37999813	1.905346215	1.905346215
10	8.764035459	31.55052765	8.764035459	2.372220124	43.28534434	41.18174136	2.103602985	2.103602985
11	8.911706552	32.08214359	8.911706552	2.412191247	43.28534434	41.87564005	1.409704292	1.409704292
12	8.384309791	30.18351525	8.384309791	2.269437237	43.28534434	39.39743043	3.887913914	3.887913914
13	9.228144608	33.22132059	9.228144608	2.497843653	43.28534434	43.36256582	-0.077221479	0
14	6.527873194	23.5003435	6.527873194	1.76694312	43.28534434	30.67413257	12.61121178	12.61121178
15	8.236638698	29.65189931	8.236638698	2.229466114	43.28534434	38.70353173	4.581812608	4.581812608
16	8.932802422	32.15808872	8.932802422	2.417901407	43.28534434	41.97476843	1.310575909	1.310575909
17	7.772529549	27.98110638	7.772529549	2.103842585	43.28534434	36.52270727	6.762637072	6.762637072
18	10.000034	36.0001224	9.695917133	2.624458773	43.28534434	45.56060429	-2.275259953	0
19	6.928694732	24.94330104	6.928694732	1.875436168	43.28534434	32.55757188	10.72777246	10.72777246
20	6.717736028	24.1838497	6.717736028	1.818334564	43.28534434	31.56628803	11.71905631	11.71905631
21	6.717736028	24.1838497	6.717736028	1.818334564	43.28534434	31.56628803	11.71905631	11.71905631
22	11.32907384	40.78466581	9.695917133	2.624458773	43.28534434	45.56060429	-2.275259953	0
23	12.10962104	43.59463575	9.695917133	2.624458773	43.28534434	45.56060429	-2.275259953	0
24	7.245132789	26.08247804	7.245132789	1.961088574	43.28534434	34.04449765	9.24084669	9.24084669

Figure 25. Gas boiler tab within the RES model.

Primary database				
		Unit		Source
Carbon footprint	29.6	kgCO2/GJ	Green gas	EBS model
	1.036	kgCO2/Nm3	Green gas	
	0.10656	kgCO2/kWh	Green gas	
Environmental impact	5.6	Pt/GJ	Green gas	**5.6-1.8**
Carbon footprint	54.6	kgCO2/GJ	Natural gas	[55][56]
Carbon footprint	1.911	kgCO2/Nm3	Natural gas	[55][56]
Environmental impact	6.2	Pt/GJ	Natural gas	[55][56]
Carbon footprint	98.23	kgCO2/Mg	Manure	[56][84]
Environmental impact	2.03	Pt/Mg	Manure	[56][84]
Manure in digester	1995.682192	Mg FM/year		
carbon footprint	177	kgCO2/GJ	Grey elec	[55][56]
carbon footprint	0.6372	kgCO2/kWh	Grey elec	[55][56]
environmental impact	28.2	Pt/GJ	Grey elec	[55][56]
environmental impact	0.10152	Pt/kWh	Grey elec	[55][56]
Environmental impact	0.02016	Pt/kWh	Green gas	
Environmental impact	0.196	Pt/Nm3	Green gas	
Environmental impact	0.02232	Pt/kWh	Natural gas	[55][56]
Environmental impact	0.217	Pt/Nm3	Natural gas	[55][56]
Carbon footprint	0.19656	kgCO2/kWh	Natural gas	

Figure 26. SI-indicator values per energy source.

Scenario	1 AMS	1 CM	2 AMS	2 CM	3 AMS	3 CM	4 AMS	4 CM	REF AMS	REF CM	Unit	5 AMS	5 CM
Emissons done by CHP own gas	7969.26812	5837.38834	2627.70566	2627.70566	7969.26812	5837.38834	8227.02128	5624.55819	0	0	kgCO2/year	9050.8051	9050.8051
Buy elec	1541.294214	12831.2113	35179.2831	33721.1354	0	0	0	0	33623.8015	32377.7648	kgCO2/year	1541.29421	12831.2113
Buy gas	0	0	0	0	1251.18442	10416.0591	0	1311.81	0	0	kgCO2/year	0	0
Sell gas (neg. emmisions)	3398.365388	8536.61917	21997.2373	21997.2373	3398.36539	8536.61917	3398.36539	0	0	0	kgCO2/year	0	0
Sell elec (neg. emissions)											kgCO2/year	6467.29886	19215.3637
Manure											kgCO2/year		
Total emissions	6112.196946	10131.9805	15809.7515	14351.6037	5822.08715	7716.82832	4828.65589	6936.36819	33623.8015	32377.7648	kgCO2/year	4124.80046	2666.65269
					-2147.181	1879.43998							
											dif scen 1-5	-1987.3965	-7465.3278

Scenario	1 AMS	1 CM	2 AMS	2 CM	3 AMS	3 CM	4 AMS	4 CM	REF AMS	REF CM	Unit	5 AMS	5 CM
Emissons done by CHP own gas	1507.699374	1104.37077	497.133504	497.133504	1507.69937	1104.37077	1556.46348	1064.1056	0	0	Pt/year	1712.31448	1712.31448
Buy elec	245.562129	2044.29468	5604.83494	5372.51987	0	0	0	0	5357.01244	5158.49135	Pt/year	245.562129	2044.29469
Buy gas	0	0	0	0	142.075887	1182.77595	0	148.96011	0	0	Pt/year	0	0
Sell gas (neg. emmisions)	385.8949708	969.359686	2497.85479	2497.85479	385.894971	969.359686	385.894971	0	0	0	Pt/year	0	0
Sell elec (neg. emissions)											Pt/year	1030.38321	3061.43083
Total environmental impact	1367.366532	2179.30577	3604.11366	3371.79859	1263.88029	1317.78703	1170.56851	1213.06571	5357.01244	5158.49135	Pt/year		
												927.4934	695.178332
											dif scen 1-5	-439.87313	-1484.1274

Figure 27. Main results carbon footprint in kgCO2/year (orange) and environmental impact in Pt/year (yellow).

Scenario	1 AMS	1 CM	2 AMS	2 CM	3 AMS	3 CM	4 AMS	4 CM	REF AMS	REF CM	Unit	5 AMS	5 CM
Life span	25	25	25	25	25	25	25	25	25	25	Year	25	25
Life span mixer	10	10	10	10	10	10	10	10	0	0	Year	10	10
Buy elec	532.1480337	4430.11063	12146.0174	11642.5766	0	0	0	0	11608.971	11178.7638	Euro/year	532.148034	4430.11063
Buy gas	0	0	0	0	504.140242	4196.94691	0	528.568131	0	0	Euro/year	0	0
Sell gas	1106.508877	2779.52598	7162.30763	7162.30763	1106.50888	2779.52598	1106.50888	0	0	0	Euro/year	0	0
Sell elec												710.469115	2110.91566
Total energy costs	-574.3608431	1650.58464	4983.70977	4480.26892	-602.36863	1417.42093	-1106.5089	528.568131	11608.971	11178.7638	Euro/year	-178.32108	2319.19496
CAPEX													
CHP costs	458.698368	458.698368	133.219328	133.219328	572.994496	1094.51789	572.994496	1094.51789	0	0	Euro/year	458.698368	458.698368
Digester costs	5364	5364	5364	5364	5364	5364	5364	5364	0	0	Euro/year	5364	5364
Pre-filter	413	413	413	413	413	413	413	413	0	0	Euro/year	413	413
Upgrader	32.682721	82.0982769	211.551581	211.551581	32.682721	82.0982769	32.682721	0	0	0	Euro/year	0	0
Manure scraper	608	608	608	608	608	608	608	608	608	608	Euro/year	608	608
Gas boiler	520	520	520	520	520	520	520	520	0	0	Euro/year	0	0
Green gas injection system	4.466095026	11.2187326	28.9085313	28.9085313	4.46609503	11.2187326	4.46609503	0	0	0	Euro/year	0	0
Mixers AD	2320	2320	2320	2320	2320	2320	2320	2320	0	0	Euro/year	2320	2320
Gas storage tank	0	0	0	0	0	0	200	200	0	0	Euro/year	0	0
Total CAPEX	9720.847184	9777.01538	9598.67944	9598.67944	9835.14331	10412.8349	10035.1433	10519.5179	608	608	Euro/year	9163.69837	9163.69837
OPEX													
Manure scraper	350	350	350	350	350	350	350	350	350	350	Euro/year	350	350
Elec grid connection costs					0	0					Euro/year		
Gas grid connection costs	0	0	0	0			0	0	0	0	Euro/year	0	0
Total OPEX	350	350	350	350	350	350	350	350	350	350	Euro/year	350	350
Total costs													
	9496.486341	11777.6	14932.3892	14428.9484	9582.77468	12180.2558	9278.63444	11398.086	12566.971	12136.7638	Euro/year	9335.37729	11832.8933
AMS system	0	0	0	0	0	0	0	0	0	0	Euro/year	0	0
CM system	0	0	0	0	0	0	0	0	0	0	Euro/year	0	0
Storage tank	5000										Euro		
AMS system	0	180000									Euro		
CM system	0	85000									Euro		

Figure 28. Costs file in the scenario results tab within the RES model.

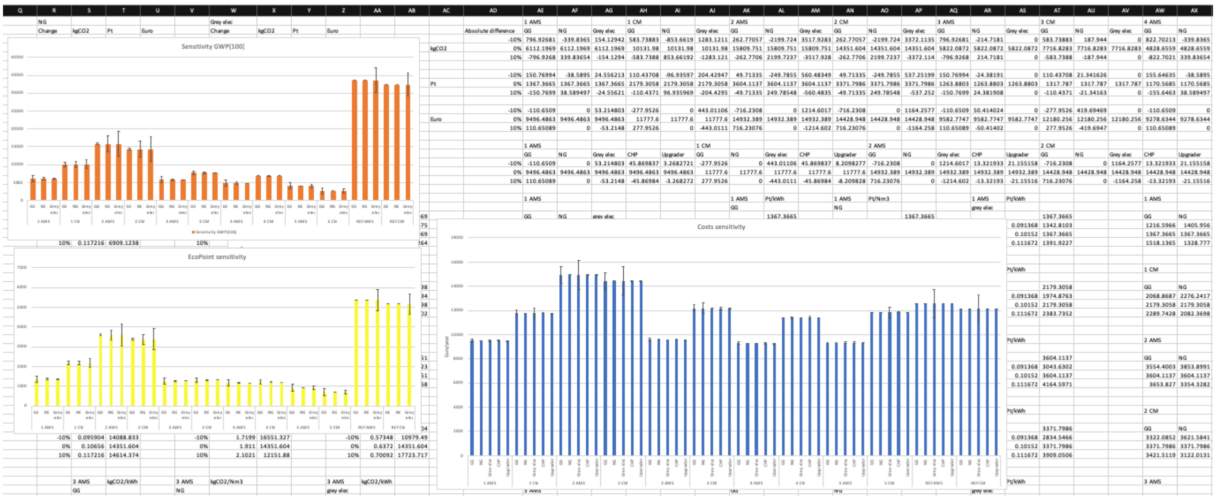

Figure 29. Sensitivity analysis tab in RES model.

14. Working with the RES model

The construction of the model is comprehensible when some background knowledge of the topic is known. Therefore, an expert in the field of biogas production is able to operate the RES model. This section was developed in order to make the RES model more comprehensible for users. The RES model consists of 5 tabs (Fig. 30), each tab displays its own output, jointly resulting in the end-results. In order to increase comprehensibility of the RES model these tabs are described in the sections below.

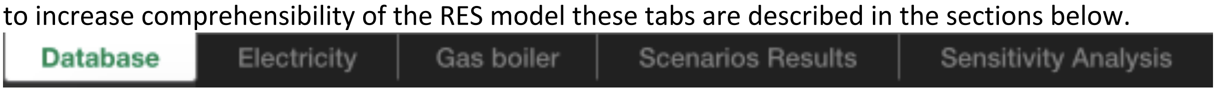

Figure 30. The main sheets in the RES model.

14.1.1 Database tab

The first tab is the 'database' tab, in this tab all the variables are presented, as described in figure 30. This tab consists of 4 different sub sections; 'primary variables', 'primary database', 'primary input' and 'results/outputs' (Tables 23 – 26). When values are changed within the 'primary variables', 'primary database' or 'primary input' sections, the values in the 'results/outputs' section automatically adjust with them. For instance, the number of cows can be altered in order to determine the available quantity of manure (Table 23). Besides, the most relevant output; the biogas production per hour, is presented in the database tab as well, but shown into a particular section into more detail (Table 26). Other used variables are presented in table 23, for example the CHP efficiency for heat and electricity. All 4 sub sections (e.g. 'primary variables', 'primary database', 'primary input' and 'results/outputs') are described into further detail in this chapter.
Overall, the 'database' tab can already give an indication in the hourly biogas production. However, in order to get to the main results (SI-indicators) a deeper look into the model is needed. In appendix section 13.11, figure 24 an overview of the 'database' tab is presented.

14.1.1.1 Primary variables section

The primary variables section contains data for calculating the amount of manure that is available for harvesting, for example the number of cows and the time spent in stables, indicated with red rectangular shape (Table 23). Furthermore, the CHP size; which is dependent on the total amount of manure input and the efficiency for heat and electricity are displayed here. These results are consequently indicated in the 'results/outputs' section (Table 26). All the used variables in this database can be changed.

Table 23. Primary variables section in RES model.

Primary variables		
		Unit
Cows	120	st
Inside barn	8040	Hours/year
Outside	720	Hours/year
Time spent in stables	91.78%	%
CHP efficiency (elec)	38%	%
CHP efficiency (heat)	80%	%
Share green gas used of total produced	38%	%
Active carbon efficiency (pre-filter)	99.8%	%
Membrane filtering efficiency (upgrader)	99.5%	%
CHP size all gas conv.	9.695917133	kWe
CHP size (100%)	12.11989642	kWe

14.1.1.2 Primary database section

The primary database section contains literature-based data including energy flows and the related costs, so are the corresponding energy uses for processes within the system shown here, for example the internal energy use of the AD system, indicated with red rectangular shape (Table 24). Further, data about manure production and content, for example the organic dry matter (oDM) fraction of manure, is presented here. The energy content and the biogas and green gas content per ton of oDM manure are shown. In order to determine the feasibility, the costs for all used energy sources were included, for example the gas price per 1 Nm^3 (Table 24). These values are, together with the primary variables, used to simulate the values presented in the 'results/outputs' section (Table 26). These values (Tables 23 & 24) are flexible in use and can be adjusted when more, accurate and/or updated values are available.

Table 24. Primary database section in RES model.

Primary database		
		Unit
Green gas injection system	550	euro/(Nm3/hour)
Upgrader	4024.88	euro/(Nm3/hour)
Pre-filter	0.00065	MJ/Nm3
Pre-filter	10325	euro
Digester costs	134100	euro
Production per cow	18120	kg/year
oDM content	6.4%	%
Energy content Green gas	35	MJ/Nm3
	9.722222222	kWh/Nm3
Green gas content manure	180	Nm3/Mg DM
Biogas content manure	350	Nm3/Mg DM
Total hours in year	8760	Hours
CHP costs	946.16	Euro/kWe
Internal electricity use digester	0.026	MJ/kg
Internal heat use digester	0.19	MJ/kg
Gas boiler efficiency	98%	%
Gas price	0.77	Euro/Nm3
Electricity price	0.22	euro/kWh
Electricity feed in tarrif	0.07	euro/kWh
Manure price	10	euro/Mg
Energy use AMS	52768.1	kWh/year
Energy use CM	50812.6	kwh/year
Gas price feed in tarrif	0.064	euro/kWh

14.1.1.3 Primary input section

The primary input section contains data for calculating the amount of biogas/green gas production, which is finally displayed in the 'results/outputs' section (Table 26). The data within the 'primary input' section is a result of both the primary variables (Table 23) and the primary database (Table 24) values combined, for example the Biomass production (indicated with red rectangular shape) as shown in Table 25, is a multiplication of the number of cows (Table 23) by Production per cow (Table 24).

Table 25. Primary input section in RES model.

Primary input		
		Unit
Biomass production	2174.4	Mg FM/year
Biomass flow in digester	1995.68219	Mg FM/year
	127.72366	Mg DM/year
	0.2278176	Mg FM/hour
	0.01458033	Mg DM/hour
Digester size	2500	Mg FM/year

14.1.1.4 Results/outputs section

The results/outputs section contains data which is a result of multiplying multiple values presented in the previously described sections within the Database tab (e.g. 'primary variables', 'primary database' and 'primary input'). For example, the biogas production (indicated in red rectangular shape) as presented in table 26, is a multiplication of biogas content of manure (Table 24) by biomass flow in digester in Mg DM/hour (Table 25).

Table 26. Results/Outputs section in RES model.

Results/Outputs		
		Unit
Biogas production	5.10311428	Nm3/hour
Green gas production	2.62445877	Nm3/hour
Green gas that can be used	2.62445877	Nm3/hour
Electricity production	9.69591713	kWh/hour
Internal use green gas (DIGESTER)	0.16923593	Nm3/hour
Internal use (DIGESTER)	1.64534935	Kwh/hour
Electricity demand digester	5.92325765	MJ/hour
Heat demand digester	43.2853443	MJ/hour
Heat fed by CHP (recovered heat)	45.5606043	MJ/hour
Heat fed by gas boiler	-2.27526	MJ/hour
Input gas boiler	-2.3216938	MJ/hour

14.1.2 Electricity tab

In the 'electricity' tab, the electricity demand and supply for every hour in a day per scenario is displayed. Furthermore, the tab displays the amount of the surpluses and/or shortages of electricity or gas per hour. With the use of this data, the total surplus and/or shortage can be determined (e.g. amount of gas that is exported in combination with the amount of electricity that is imported). In this tab it is possible to add scenarios, which eventually are adopted in the remaining tabs.

14.1.3 Gas boiler tab

In the 'gas boiler' tab, is similar to the electricity tab only now the energy requirement of the gas boiler is added, which is then translated back into the additional required amount of biogas or natural gas. The gas boiler is added, since the re-use of heat from the CHP unit is not sufficient during the entire day. This makes the gas boiler tab a more extensive and thereby more accurate part of the model than the electricity tab. Furthermore, the gas boiler tab also displays the amount of the excess heat, which is eventually discarded. Tables 27 and 28 present a small part of the gas boiler tab, in these tables the energy demand (in kWh) (table 27) and additional heat demand (in MJ) that is supplied by the gas boiler (table 8) for one scenario for the first 2 hours are presented, both indicated in red rectangular shape.

In table 27 the electricity demand of the first 2 hours in one scenario is displayed. Showing the amount of green gas (in Nm^3) that is used to meet the demand, indicated in green. Further, the heat demand of the digester (Heat need digester) and the heat supply by the CHP unit (Heat by CHP) for these hours are shown in table 28. In the last tab, the additional heat requirement supplied by the gas boiler is shown. The required amount of gas (e.g. Green gas need for boiler; in table 29) or the excess amount ('not used gas') is shown in table 29. When the total daily surplus is determined this value can be used in the scenario results section (section 14.1.4). Figure 25 in appendix section 13.11 shows the entire gas boiler tab.

Table 27. First part, of one scenario for 2 hours, in the gas boiler tab in the RES model.

Hour	ɔemand elec (kWh)	ɔemand elec (MJ/h)	Supply elec (kWh) by CHP	Green gas used (Nm3)
1	5.515	19.854	5.51	1.492781955
2	4.365	15.714	4.36	1.181503759

Table 28. Second part, of one scenario for 2 hours, in the gas boiler tab in the RES model.

Heat need digester (MJ)	Heat by CHP (MJ)	Heat needed by gasboiler (MJ)	Heat needed by gasboiler (MJ)
43.28534434	25.91469474	17.3706496	17.37064961
43.28534434	20.51090526	22.7744390	22.77443908

Table 29. Third part of, one scenario for 2 hours, in the gas boiler tab in the RES model.

Green gas need for boiler (Nm3)		not used gas	Gas dat over is na aftrekken van gasbenodigdheden CHP
0.506432933		1.131676818	0.625243885
0.663977816		1.442955013	0.778977198

14.1.4 Scenario results

In the 'scenario results' tab, the results for each scenario per SI-indicator are displayed (Table 31 & 32) and the SI-indicator values per energy source and unit are displayed (Fig. 25 appendix 13.11). To get to the results presented in tables 31 and 32, the results from the gas boiler tab (e.g. left-over green gas in Nm^3 or shortage, shown in the last tab of table 29) are multiplied by for example the SI-indicator value displayed in table 30, depending on the energy source, for example the carbon footprint in kgCO_2/Nm^3. This is done for all three SI-indicators, resulting in the values displayed in tables 31 and 32. All values are shown in figure 26 in appendix section 13.11.

Table 30. Carbon footprint for natural gas in kgCO_2/Nm^3.

Carbon footprint	1.911	kgCO2/Nm3	Natural gas	[55][56]

In table 31, scenario 1 AMS is shown. In order to determine the carbon footprint and the environmental impact, the 'emissions done by CHP own gas' are summed up with the amount of electricity and gas that is bought ('buy elec' & 'buy gas'). Next, the value that is sold ('sell gas' and 'sell elec') is subtracted from the summed values ('emissions done by CHP own gas' & 'buy elec' & 'buy gas'), resulting in total emissions/environmental impact (table 31). Figure 27 in appendix section 13.11 show the entire tab for both SI-indicators.

Table 31. Main results carbon footprint in kgCO2/year (orange) and environmental impact in Pt/year (yellow) for scenario 1 AMS).

Scenario	1 AMS
Emissons done by CHP own gas	7969.26812
Buy elec	1541.294214
Buy gas	0
Sell gas (neg. emmisions)	3398.365388
Sell elec (neg. emissions)	
Manure	
Total emissions	6112.196946

Scenario	1 AMS
Emissons done by CHP own gas	1507.699374
Buy elec	245.562129
Buy gas	0
Sell gas (neg. emmisions)	385.8949708
Sell elec (neg. emissions)	
Total environmental impact	1367.366532

The NPV table is split up into multiple tables in order to provide a clear overview. Calculations, as is done for the carbon footprint and environmental impact, is done for the costs, however CAPEX and OPEX are now included (Tables 33 & 34), which are summed up to the costs of gas and electricity ('total energy costs'), shown in table 32. In the model the costs calculations are based on an NPV costs analysis with a technical lifespan of 25 years as described in chapter 3. Additional costs or revenues (e.g. subsidies, interest) can be programmed into the model.

Table 32. Main results NPV in euro/year for one scenario .

Scenario	1 AMS
Life span	25
Life span mixer	10
Buy elec	532.1480337
Buy gas	0
Sell gas	1106.508877
Sell elec	
Total energy costs	-574.3608431

Table 33. CAPEX in RES model for one scenario.

CAPEX	
CHP costs	458.698368
Digester costs	5364
Pre-filter	413
Upgrader	32.682721
Manure scraper	608
Gas boiler	520
Green gas injection system	4.466095026
Mixers AD	2320
Gas storage tank	0
Total CAPEX	9720.847184

Table 34. OPEX and total costs for one scenario.

OPEX	
Manure scraper	350
Elec grid connection costs	
Gas grid connection costs	0
Total OPEX	350
Total costs	
	9496.486341
	-2281.113681

14.1.5 Sensitivity analysis

Constructing the ‘sensitivity analysis’ tab, the ‘scenario results’ tab is copied and the influence of each energy source per scenario is determined. This is performed by using the ‘What-If-Analysis’ option in MS Excel. In the ‘sensitivity analysis’ tab it is possible to add additional scenarios, perform an additional sensitivity analysis on other variables and vary the values used in the sensitivity analysis. Table 15 displays the sensitivity analysis for all three SI-indicators (displayed as: $kgCO_2$, Pt, Euro) for scenario 1 AMS and 1 CM. Subsequently, these values are plotted in figures 21-23 in appendix section 13.8. ‘GG’ indicates green gas, ‘NG’ natural gas and ‘Grey elec’ indicates grey electricity.

Table 35. Part of the sensitivity analysis tab in RES model.

		1 AMS			1 CM		
	Absolute difference	GG	NG	Grey elec	GG	NG	Grey elec
	-10%	796.926812	-339.83654	154.129421	583.738834	-853.66192	1283.12113
kgCO2	0%	6112.19695	6112.19695	6112.19695	10131.9805	10131.9805	10131.9805
	10%	-796.92681	339.836539	-154.12942	-583.73883	853.661917	-1283.1211
	-10%	150.769937	-38.589497	24.5562129	110.437077	-96.935969	204.429468
Pt	0%	1367.36653	1367.36653	1367.36653	2179.30577	2179.30577	2179.30577
	10%	-150.76994	38.5894971	-24.556213	-110.43708	96.9359686	-204.42947
	-10%	-110.65089	0	53.2148034	-277.9526	0	443.011063
Euro	0%	9496.48634	9496.48634	9496.48634	11777.6	11777.6	11777.6
	10%	110.650888	0	-53.214803	277.952598	0	-443.01106