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THE POTENTIAL OF GREENHOUSE GAS EMISSIONS REDUCTION IN THE AGRO-INDUSTRIAL SECTOR:

A CASE STUDY OF BIOGAS SYSTEMS IN URUGUAY

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Abbreviations and acronyms

Institutions

GEF	Global Environment Facility
IPCC	International Panel for Climate Change
MGAP	Ministry of Farming, Agriculture and Fishing *Ministerio de Ganadería, Agricultura y Pesca*
MIEM	Ministry of Industry, Energy and Mining *Ministerio de Industria, Energía y Minería*
MVOTMA	Ministry of Housing, Land Management and Environment *Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente*
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations International Development Organization
UTE	State power company *Administración Nacional de Usinas y Trasmisiones Eléctricas*

Acronyms

CC	Climate Change
CDM	Clean Development Mechanism
CH_4	Methane
CO_2	Carbon dioxide
DLUC	Direct land use change
EF	Emission factor
GDP	Gross Domestic Product
GHG	Greenhouse gas
GWP	Global warming potential
ILUC	Indirect land use change
INDC	Intended Nationally Determined Contribution
LCOE	Levelized Cost of Energy
LUC	Land Use Change
LULUCF	Land Use and Land Use Change and Forestry
MCF	Methane Conversion Factor
N_2O	Nitrous Oxide
RE	Renewable Energy
SD	Sustainable Development
SDG	Sustainable Development Goals

Physical units

J	Joule (energy unit)
MJ	Megajoule (equivalent to 1,000,000 J)
GJ	Gigajoule (equivalent to 1 x 10^9 J)
EJ	Exajoule (equivalent to 1 x 10^{18} J)
W	Watt (power capacity unit)
kW	Kilowatt (equivalent to 1,000 W)
MW	Megawatt (equivalent to 1,000,000 W)
GW	Gigawatt (equivalent to 1,000,000,000 W)
Wh	Watt hour (energy unit)
kWh	Kilowatt hour (equivalent to 1.000 Wh)
MWh	Megawatt hour (equivalent to 1,000,000 Wh)
GWh	Gigawatt hour (equivalent to 1,000,000,000 Wh)
V	Volt (electric potential unit)
kV	Kilovolt (equivalent to 1000 V)
kg	Kilogram (weight unit)
ton	Metric ton (equivalent to 1000 kg)
Gg	Gigagrams (equivalent to 1,000,000 kg)
m3	Cubic meters (volume unit)
℃	Degrees Celsius (temperature unit)
toe	Ton of oil equivalent (energy unit)
ktoe	Kiloton of oil equivalent (equivalent to 1000 toe)
CO_2eq	Carbon dioxide equivalency

Exchange rate

1 Uruguayan Peso = 0,034947 US Dollar (consulted: 8th of August 2017)

***NOTE:**

The English numeral system will be used in this document to separate numbers. The "," (comma) will be employed as the thousands separator; while the "." (dot) will be used as the decimal separator.

Abstract

Greenhouse gas emissions from the agro-industrial sector contribute significantly to Climate Change. The implementation of renewable energy technologies can contribute to the reduction of GHG emissions. The most favorable RE technology for the agro-industrial sector is the production of biogas through anaerobic digestion of animal manure and other residues generated in the sector. The Uruguayan economy is strongly based on the agro-industrial sector and is therefore highly vulnerable to climate change.

In the present research, the GHG emissions reduction potential through biogas systems in the agro-industrial sector in Uruguay has been identified. Based on primary data generated by the government of the Oriental Republic of Uruguay, the amount of residues generated in the sub-sector feedlots, poultry production, dairy cows and pig industry have been calculated. The results served as input to calculate the Methane and Nitrous oxide emissions of the different sub-sectors using the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The potential electricity generation for each sub-sector was assessed, as well as a feasibility analysis conducted.

The analyses show that there is a high potential for reduction of GHG emissions in the agro-industrial sector. Approximately 46.76% of the total GHG emissions could be avoided, accounting to 2,573,394 tonCO2eq/year.

The electricity generation from biomass did not lead to a reduction of fossil fuels, due to the considerable amount of electricity currently generated from renewable sources. However, the installation of biogas systems can avoid CH_4 and N_2O emissions, lowering the overall GHG emissions of Uruguay and at the same time fulfilling the emission reduction goals defined in the country’s INDC, for methane and contributing to those of nitrous oxide.

Keywords: Biogas, anaerobic digestion, greenhouse gases, Climate Change, agro-industrial sector, Uruguay

Resumen

Las emisiones de gases de efecto invernadero del sector agroindustrial contribuyen significativamente al cambio climático. La implementación de energías renovables puede contribuir a la reducción de emisiones de GEI. La tecnología más favorable para el sector agroindustrial es la producción de biogás a través de la digestión anaeróbica de estiércol animal y otros residuos generados por el sector. La economía uruguaya se basa fuertemente en el sector agroindustrial y por lo tanto el país es muy vulnerable al cambio climático.

La presente investigación ha identificado el potencial de reducción de emisiones de GEI a través de la implementación de sistemas de biogás en el sector agroindustrial en Uruguay. Usando datos primarios generados por el gobierno de la República Oriental del Uruguay, se ha calculado la cantidad de residuos generados en los subsectores engorde a corral, producción avícola, vacas lecheras y la industria porcina. Los resultados sirvieron como insumo para calcular las emisiones de metano y óxido nitroso de los diferentes subsectores, usando las Guías del IPCC para los Inventarios Nacionales de Gases de Efecto Invernadero (IPCC, 2006). Se evaluó el potencial de generación de electricidad para cada subsector, y se llevó acabo su respectivo análisis de factibilidad.

Los análisis muestran que existe un alto potencial de reducción de las emisiones de GEI en el sector agro-industrial, pudiéndose evitar un aproximado de 46.76% de las emisiones totales de GEI, equivalentes a 2,573,394 tonCO2eq/año.

La generación de electricidad a partir de biomasa no resulta en una reducción de combustibles fósiles, debido a la significativa cantidad de electricidad actualmente generada a partir de fuentes renovables. Sin embargo, la instalación de sistemas de biogás puede evitar las emisiones de CH_4 y N_2O generados por el sector agro-industrial, reduciendo las emisiones de GEI de Uruguay y al mismo tiempo cumpliendo con los objetivos de reducción de emisiones definidos en las Contribuciones Previstas Nacionalmente Determinadas (INDC) del país para el metano y contribuir a los mismos del óxido nitroso.

Palabras clave: Biogás, digestión anaeróbica, gases de efecto invernadero, cambio climático, sector agroindustrial, Uruguay

Zusammenfassung

Treibhausgasemissionen aus dem agroindustriellen Sektor tragen wesentlich zum Klimawandel bei. Der Einsatz von erneuerbaren Energie Technologien kann zur Reduzierung der Treibhausgasemissionen beitragen. Die vorteilhafteste Technologie für den agroindustriellen Sektor ist die Produktion von Biogas durch anaerobe Vergärung von Dung und anderen organischen Materialien, die von diesem Sektor erzeugt werden. Der agroindustrielle Sektor ist wichtiger Teil der uruguayischen Wirtschaft und das Land ist daher durch den Klimawandel sehr gefährdet.

In der vorliegenden Arbeit wurde das Potenzial zur Reduzierung der Treibhausgasemissionen durch Biogassysteme im agroindustriellen Sektor in Uruguay identifiziert. Mit Hilfe von Primärdaten, die von der Regierung Uruguays erhoben wurden, wurde die Menge der organischen Materialien berechnet, die in den Teilsektoren Mastrinder, Geflügelproduktion, Milchkühe und der Schweineindustrie erzeugt wurden. Die Ergebnisse dienten für die Berechnung der Methan- und Distickstoffmonoxidemissionen der verschiedenen Teilsektoren nach den IPCC-Richtlinien für nationale Treibhausgasinventare (IPCC, 2006). Die potenzielle Stromerzeugung für jeden Teilsektor wurde berechnet, sowie eine Wirtschaftlichkeitsstudie durchgeführt.

Die Analysen zeigen, dass es ein hohes Potenzial zur Reduzierung der Treibhausgasemissionen im agroindustriellen Sektor gibt. Im Durchschnitt könnten 46,76% der gesamten Treibhausgasemissionen vermieden werden, das entspricht 2,573.394 tonCO2eq/Jahr.

Die Stromerzeugung aus Biomasse konnte jedoch nicht zu einer Verringerung der fossilen Brennstoffe beitragen, da in Uruguay bereits eine erhebliche Menge Strom aus erneuerbaren Quellen gewonnen wird. Allerdings kann die Installation von Biogas-Systemen die CH_4 und N_2O-Emissionen vermeiden und somit zur allgemeinen Verringerung von Treibhausgasen beitragen. Gleichzeitig können so die Emissionsreduktionsziele, die in den INDCs des Landes definiert sind, für Methan erfüllt werden. Weiterhin wird zur Reduktion von Distickstoffmonoxid beigetragen.

Schlüsselwörter: Biogas, anaerobe Vergärung, Treibhausgase, Klimawandel, agroindustrieller Sektor, Uruguay

1. Introduction

Nowadays, Climate Change has become one of the primary concerns for humanity, causing extreme weather phenomena, affecting ecosystems and fostering environmental degradation. Human activities caused a significant increase in the greenhouse gas concentrations over the last centuries, which can be mainly attributed to the burning of fossil fuels for energy purposes. However, emissions from other sectors such as the agro-industrial sector have also contributed significantly to the greenhouse gas emissions, making their mitigation a priority for many countries. The main emissions of the sector are methane from enteric fermentation and methane and nitrous oxide from manure management. It is very difficult to achieve a mitigation of the emissions from enteric fermentation without reducing the livestock itself, therefore, it is of great significance to achieve a reduction of emissions through enhanced manure management systems. The implementation of renewable energy technologies represents not only a sustainable solution to replace fossil fuels, but can also be an important mitigation strategy for GHG emissions, such as methane and nitrous oxide. The most beneficial renewable energy technology for the agro-industrial sector is the generation of biogas through the anaerobic digestion of manure and other agro-industrial residues. This approach increases the value of materials previously considered as waste, converting them into an asset that generates economic profits through the production of biogas, generation of electricity and reduction of GHG emissions.

In the present work, the GHG emissions reduction potential through biogas systems will be analyzed. The chosen study case is the agro-industrial sector of Uruguay. Having an economy strongly based on food production, the country's CH_4 and N_2O emissions are significant and therefore its vulnerability to climate change is high.

The selected methodology includes a quantitative research that evaluates the primary data collected by an internationally funded biomass project. The following objectives were established to guide the investigation: (1) identify and compare the residues generated in the different sub-sectors, as well as their GHG emissions, (2) analyze the agro-industrial sub-sectors with the most GHG emissions reduction potential, (3) evaluate the contribution of biogas systems to the energy matrix, (4) analyze the economic feasibility of biogas systems and (5) evaluate the contribution of a biogas system to the INDCs of the country.

This document intends to demonstrate and quantify the potential GHG emissions reduction of the agro-industrial sector in Uruguay through the implementation of biogas systems, serving as a reference for parties interested in the mitigation of Climate Change.

2. Climate Change and the role of Greenhouse Gas Emissions

Ecosystems are the basis of life on Earth, providing not only the habitat for all species on the planet but also inter alia regulating the climate, supplying fresh air and clean water, mitigating floods, ensuring soil productivity and preventing erosion. Humanity is strongly dependent on its services, like food, fiber and energy and therefore human security and well-being is strongly connected to maintaining ecosystems and avoiding environmental degradation. (Associated Programme on Flood Management 2006, 29)

Since the 1970s, the annual demand for resources is exceeding the regenerating capacity of Earth. Humanity has now an ecological deficit of 1.7 Earths, meaning that the natural resources of 1.7 Earths are necessary to satisfy the demand of the current population. This is putting ecosystems under serious stress and fostering environmental degradation through overfishing, overharvesting forests and the emission of more carbon dioxide into the atmosphere than forests can capture. (Global Footprint Network, 2017)

A consequence of this environmental degradation is the alteration of the atmospheric composition, which leads to (anthropological) Climate Change.

The two most recognized definitions of Climate Change used by the scientific community are:

> "Climate change in **IPCC** usage refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the **United Nations Framework Convention on Climate Change (UNFCCC)**, where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and that is in addition to natural climate variability observed over comparable time periods."
>
> (IPCC, 2007, p. 30.)

Climate Change (CC) due to its implications on the planet has become one of the primary concerns for humanity in the 21st century. (Panwar, Kaushik, & Kothari, 2011, p. 1514) Increased temperatures, the rise in sea levels and extreme weather conditions, like droughts, intense rainfall, heat waves or cold fronts, are only some examples of change, ecosystems are suffering.

The causes for CC can be divided into two categories: natural and anthropological. Among the natural causes are volcanic activity, solar output and the Earth's orbit around the sun; anthropological causes refer to human activities, such as burning of fossil fuels and land use changes for agriculture and forestry. (Government of Canada)

The author acknowledges the definition of IPCC and considers Climate Change to be caused both by natural variability and human activity. However, the present work will refer to climate change attributed to human activity, either directly or indirectly (as defined from UNFCCC).

Physical drivers of Climate Change attributed to human activities are among others, Greenhouse Gases (GHG). The most common anthropologic GHG is carbon dioxide (CO_2), in 2010 it constituted 76% of the total anthropogenic GHG emissions, followed by methane (CH_4) with 16%, N_2O with 6.2% and fluorinated gases, so called F-gases with 2.0%. (IPCC 2015, 46) In 2010, the sector with the highest GHG emissions was the energy sector (35%), followed by agriculture, forestry and other land use (AFOLU) with 24% (net emissions), the industry sector (21%), transport (14%) and the building sector (6.4%). (IPCC 2015, 46)

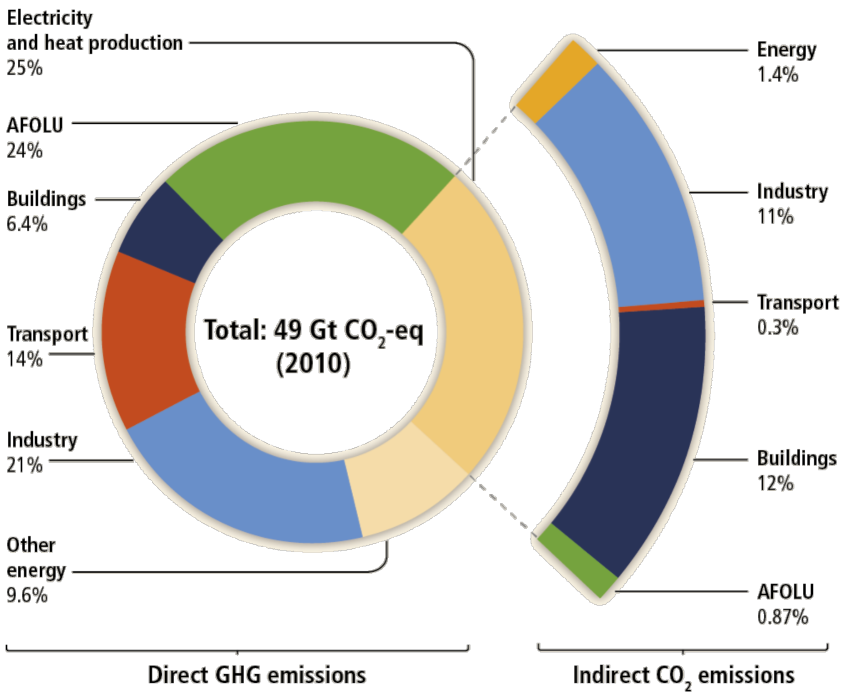


Figure 1: Greenhouse gas emissions by economic sectors (IPCC 2015, 46)

The prospects for the future show that by 2030 due to population expansion and economic growth, the global demand for energy (and water) will increase by 40% and the demand for food by 50%. With the use of resources already exceeding the biocapacity of the planet to restore itself, it is now indispensable to implement new strategies to reduce the use of resources and fossil fuels, to mitigate Climate Change. (FAO, 2011, p. 12)
Future GHG emissions depend highly on the development of several key forces, such as among others population expansion, economic growth, energy demand, resource use, as well as the implementation of mitigation policies. (IPCC, 2012, p. 130)

2.1. The Greenhouse Effect

Short-wave solar radiation can penetrate the atmosphere relatively unimpeded, once it reaches the Earth, a part of this radiation is absorbed, warming the surface, another part is re-emitted (as long-wave terrestrial radiation). This long-wave radiation is partly emitted back into space and partly trapped in molecules of trace gases, which scatter it and reflect it back to Earth, provoking a further warming of the Earth and lower atmosphere. This effect is the so called natural greenhouse effect. (IPCC, 2001, p. 93)
To maintain the temperatures at a constant level, the amount of absorbed energy has to be the same, as the amount of energy emitted back into space. However, emissions from human activities (mainly the burning of fossil fuels) increase the concentration of gases (greenhouse gases) in the atmosphere and therefore enhance the greenhouse effect, leading to an additional warming of the surface. (IPCC, 2001, p. 93)
Atmospheric concentrations of GHGs are also affected by several other factors. Plants are one example for this; they convert CO_2 and water through photosynthesis into carbohydrates; this carbon sequestration reduces atmospheric CO_2 concentrations. The deforestation of forests is, therefore, an important factor which adds GHGs to the atmosphere.
The most important GHGs are carbon dioxide (CO_2), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) (long-lived gases), as well as methane (CH_4). Although all of those gases are GHGs, they have different Global Warming Potentials (GWP). The GWP indicates how much longwave radiation gas traps in the atmosphere over a specific time horizon.
For a 100-year time horizon, carbon dioxide (CO_2) has a standardized value of 1; methane has 25 times the GWP of CO_2 and nitrous oxide 298 times.

Greenhouse Gas	Chemical formula	GWP values for 100-year time horizon
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298

Table 1: Global Warming Potential, IPCC, 2007, p. 30

To stabilize the concentrations of the long-lived gases at today's levels, a reduction in emissions from human activities of over 60% would be required and to stabilize the concentration of methane, an emissions reduction of 15-20% is necessary. If this reduction levels cannot be achieved, the consequences would be a significant increase in the global mean temperature and the rise in the sea levels, putting in danger not only ecosystems but also humans. In order to stabilize the GHG concentrations in the atmosphere and at the same time provide sustainable and clean energy, renewable energy technologies have been introduced. (Hussain et al., 2017, p. 12)

2.2. Renewable energy sources

The increasing use of fossil fuels has already negative implications on climate and the environment. The effects are environmental degradation, increased health issues, ozone depletion, climate change and increased global warming. At the same time, however, the demand for energy, especially in developing and emerging countries, is growing steadily. By 2035 the global primary energy demand is expected to rise by 40% (BMZ, 2014, p. 23), if this rising demand would be met with fossil fuels, it would cause a significant increase in the GHG concentrations in the atmosphere, affecting the environment and climate further. (Hussain, Arif, & Aslam, 2017, p. 12)

Nevertheless, access to energy is the driving force behind the development and growth of a country and in 2012 1.3 billion people, especially in rural areas, still had insufficient or no access to energy. In addition to that, over 2.7 billion people use traditional biomass for cooking, causing 3.5 million estimated deaths per year from indoor air pollution. (IEA, 2015, p. 103)

Provide energy access, secure the energy supply to meet the growing demand and reduce the GHG emissions are the major global energy challenges of the 21st century. Renewable energies

(RE) play a major role in overcoming these difficulties in developing countries, as well as in industrialized countries.
In developing countries energy is required to stimulate production, often the rural population suffers the most from energy poverty because a connection to the national grid is not feasible due to high infrastructure costs and a very low prospected profit margin. Due to their decentralized character, RE can facilitate the connection of rural population to energy services. Therefore, RE are an important facilitator for income generation and social development. Another important aspect is the contribution to the improvement of the health conditions. If traditional cooking and lighting from sources, such as wood, charcoal, and dung, are replaced with RE sources, serious health problems, as for example, respiratory diseases can be reduced. For industrialized countries RE are mainly seen as an opportunity for achieving energy security, reducing GHG emissions to mitigate Climate Change and the creation of jobs. (IPCC 2012, p. 40)

Definition:

> "Renewable energy is any form of energy from solar, geophysical or biological sources that are replenished by natural processes at a rate that equals or exceeds its rate of use. Renewable energy is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar energy, geothermal heat, hydropower, tide and waves, ocean thermal energy and wind energy." (IPCC, 2012, p. 38.)

While RE have a theoretical potential, which exceeds the current and projected global energy demand by far, for many RE technologies the levelized cost of energy (LCOE) is still higher than the costs for traditional energy sources, however, RE technologies are getting more competitive and some already reached grid parity. The biggest challenge, however, is to exploit the potential of RE for a cost-effective energy generation. (IPCC, 2012, p. 39)
For many countries, the decarbonization of the energy sector through RE deployment is an essential element of their strategy of Climate Change mitigation. Particularly in the energy sector, the use of RE has a great potential to reduce GHG emissions. 22% of the total global electricity is already generated from renewable power plants. Hydropower plants are the biggest contributor, but also other RE sources such as wind, solar and bioenergy are increasing steadily. In 2012, with the use of renewables 3.1 $GtCO_2e$ of emissions could be avoided, which

would have been emitted from non-renewable based power generation. (Sen & Ganguly, 2017, p. 1173)

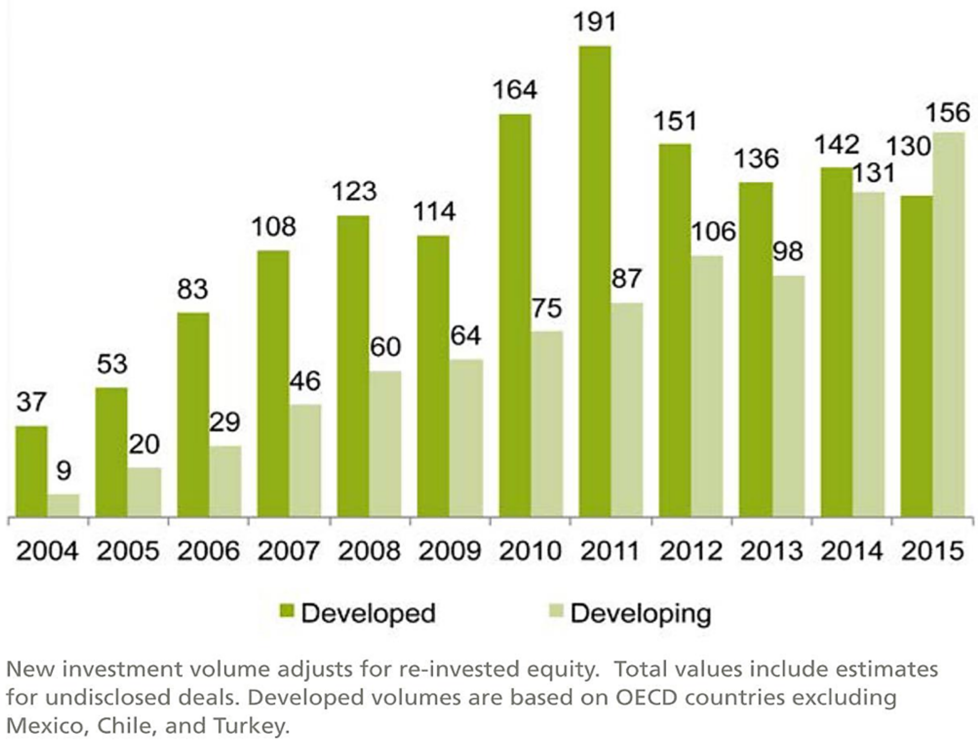


Figure 2: Global new investment (billion USD) in renewable energy: developed vs. developing countries, 2004-2015 (McCrone, 2016, p. 15)

The global new investments in RE reached 286 billion USD, a six-time higher investment than 2004 and the sixth year in a row being higher than 200 billion USD. In 2015, installation of wind and solar photovoltaic reached record figures with 62 GW and 56 GW respectively. The investment in RE in 2015, was for the first time higher in developing countries than in developed countries. Figure 2 shows that the investment in developed countries dropped 8% to 130 billion USD in 2015 and in developing countries investments rose 19% to 156 billion USD. The single largest investor was China, but also India raised its commitment to RE in 2015. However, even by excluding China, India, and Brazil, developing countries invested 30% more in 2015, raising the investment to an all-time high of 36 billion USD. The countries investing the most into clean power were South Africa (4.5 billion USD), Mexico (4 billion USD) and Chile (3.4 billion USD). In Uruguay, Turkey and Morocco investment was for the first time higher than 1 billion USD. (McCrone, 2016, p. 12f)

A growing number of RE policies have pathed the way for investments and an escalated growth in RE technologies, (IPCC, 2012, p. 44) which can not only provide energy services in a sustainable manner but also play a major role in mitigating climate change. (IPCC, 2012, p. 33)

2.3. Sustainable development

Origin of SD

The Brundtland report "Our common future" of 1987 by the World Commission on Environment and Development (WCED) is often seen as the origin of sustainable development and defines it as:

> "Development that meets the needs of the present without compromising the ability of future generations to meet their needs."
> (Elum & Momodu, 2017, p. 74)

Societies require energy services to meet basic human needs, such as cooking, lighting, communication, transportation, as well as to complete productive activities. For development to be sustainable, energy services, need to be provided with low environmental impact and low GHG emissions. (IPCC, 2012, p. 33)

The concept of sustainable development (SD) addresses the interconnection of nature and human society. It has the premise to enable development without compromising the environment. RE can provide energy services in a sustainable way, exploiting natural resources without harming ecosystems. (IPCC, 2012, p. 119)

To accomplish a sustainable socioeconomic development, a reliable and cost-effective energy supply with low environmental impacts and low GHG emissions is needed. Still, nowadays, 85% of the total global primary energy demand is met by conventional fossil fuel combustion, emitting 56% of all anthropogenic GHG emissions. Using RE for energy generation means the supply of sustainable and clean energy and at the same time fulfills goals for CC mitigation. (Sen & Ganguly, 2017, p. 1170)

RE can contribute to achieving several important SD goals, such as social and economic development, energy access, energy security and CC mitigation, as well as the reduction of environmental and health impacts. (IPCC, 2012, p. 119) As numbers of 2015 already indicated, most of the expansion in future RE production will happen in developing countries. Once overcome the challenge of high LCOEs of RE technologies it is likely that developing countries can leapfrog emissions-intensive development. (IPCC, 2012, p. 127)

Barriers and opportunities for RE in the context of SD

To implement RE technologies and at the same time pursue a SD it is important to take into account environmental, social and economic effects.

In developing countries, there can often be observed a lack of information concerning available and appropriate RE technologies, affecting the deployment of RE. Integrated planning and policies favoring the integration of RE into existing energy systems can help to overcome barriers to and incentive the development of RE. (IPCC, 2012, p. 129)

To evaluate the economics of RE in the context of SD, it is essential to take into account also the social costs and benefits. Several quantifiable criteria such as cost effectiveness, regional appropriateness and environmental and distributional consequences should be measured in this context. If a RE project is economically viable and competitive, often depends on the grid size and the choice of technology to be implemented. In most cases to expand the rural energy access, smaller off-grid and mini-grid applications are used. These decentralized solutions frequently have many benefits over the connection to the national grid, which is usually associated with high costs. If the deployment of RE is economically viable, still other barriers could hinder its deployment. From a financial perspective, high investment costs for RE technologies are frequently identified barriers. From a political point of view, it is essential to put in place policies that support RE deployment.

However, strategies for SD at international, national and local levels can help overcome those barriers and create opportunities for the deployment of RE. One important approach is the internalization of environmental and social externalities, which often leads to changes in the ranking of energy sources and technologies, such as the Clean Development Mechanism (CDM), implemented under the Kyoto Protocol, it is a mechanism that internalizes environmental and social externalities and promotes RE technologies to foster a SD. (IPCC, 2012, p. 129)

Another way to evaluate SD options is the principal of resource cascading; it aims to achieve the exploitation of the full potential of biological resources and to improve the efficiency of material use. Therefore, the principle of resource cascading contributes to the sustainability of the production chain, giving priority to the higher value uses, which allow reuse and recycling of products and raw materials, only promoting energy use when there are no other options, and preferably those energy-uses with co-products (for example compost and nutrients).

The technology of anaerobic digestion can increase the sustainability of biomass cascades and contribute to closing material cycles. (Wellinger et al., 2013, p. 170)

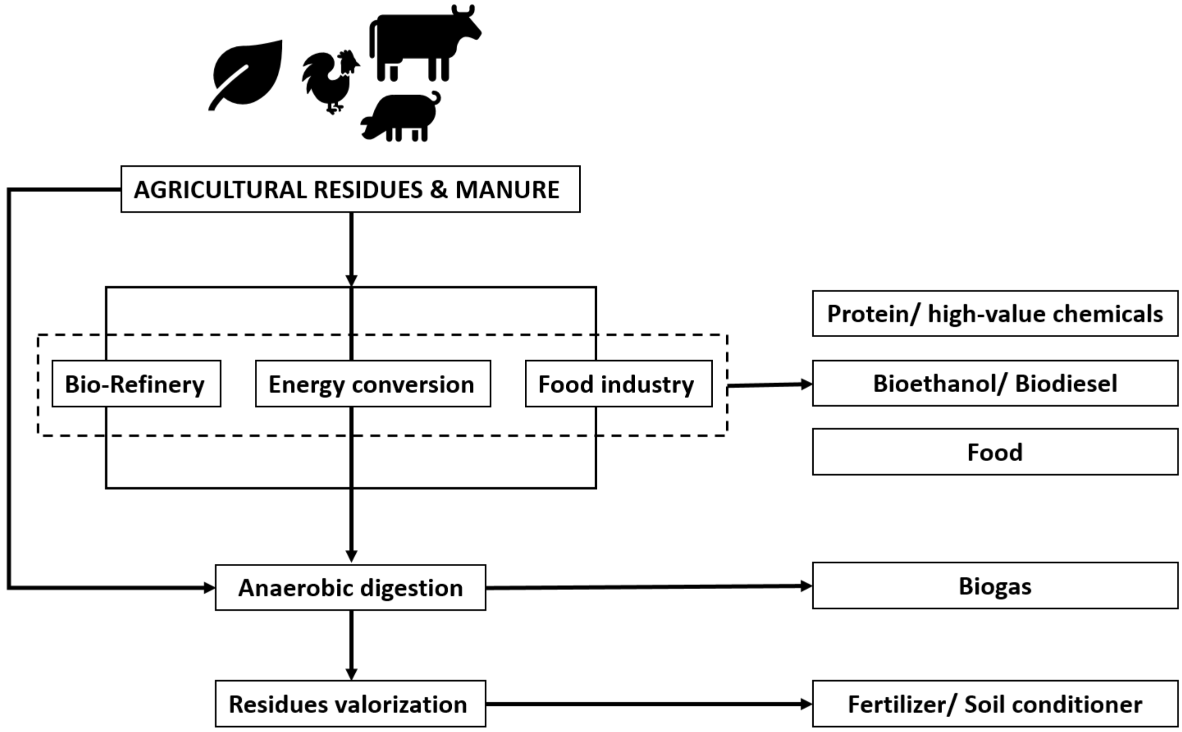


Figure 3: Possible biogas cascade configurations having anaerobic digestion as a key element. Adapted from Wellinger et al., 2013, p. 169

3. Biomass as a renewable energy source in developing countries

Biomass can be defined as:

> "Biomass (feedstock) comprises any organic matter of either plant or animal origin constituting a renewable energy source. Biomass energy or bioenergy is the stored solar energy, carbon and hydrogen – captured initially through photosynthesis into chemical bonds – that is available on demand within that organic matter." (Achterbosch et al., 2013, p. 13)

Biomass is widely used for energy purposes and in 2008 biomass supplied about 10% (50 EJ) of the global annual primary energy consumption. There is still a significant potential to expand the use of biomass for energy generation, especially for high-efficiency modern bioenergy uses, producing biogas from residues and waste. (Wellinger et al., 2013, p. 19)

Major biomass uses can be divided into two broad categories: low-efficiency traditional biomass and high-efficiency modern bioenergy.

Low-efficiency traditional biomass is generally used by low-income households in developing countries. The main biomass applications are cooking, lighting and heating, combusting wood, straw, dung and other manures. This use of biomass is highly unsustainable and has several negative implications for humans as well as for the environment. The burning of biomass can lead to serious negative health issues, mainly because of the emission of smoke, leading to poor air quality and provoking respiratory illnesses, especially in women and children who suffer the most exposure to the smoke. Another problem is the impact on the environment. The use of wood is not only poorly efficient (90% of the energy is lost during combustion), but also leads to deforestation and consequently to higher concentrations of GHGs in the atmosphere.

In contrast to that, **high-efficiency modern bioenergy** refers to the use of solids, liquids, and gases derived from biomass as secondary energy sources. The main applications of this form of energy are the generation of heat, electricity, combined heat and power (CHP) and fuels. For this high-efficiency applications, biomass can be treated through anaerobic digestion, generating primarily methane, which is either used for the generation of electricity and/or heat or purified for the use as a transportation fuel. Solid biomass can be used in boilers for electricity generation (Rankine cycle) or through gasification directly be converted to a gas. (IPCC, 2012, p. 46)

Using biomass for energy production has many benefits over the use of fossil fuels. First of all, the use of biomass instead of fossil fuels can contribute to a significant reduction of GHG emissions. Under the Clean Development Mechanism, which was defined in the Kyoto Protocol in 2007, these savings in GHG emissions could become an interesting economic incentive, especially for developing countries. Also, energy generation with biomass can encourage rural development, providing a decentralized self-sufficient energy supply for industries, which in turn can potentially create jobs. Finally, the use of biomass also helps to prevent environmental problems, related to the inadequate handling of waste and manure, which otherwise could lead to inter alia eutrophication of lakes as well as an excess of nitrate in the soil. (Wellinger et al., 2013, p. 167)

3.1. Biomass technologies

For using biomass for energy purposes, it has to be converted. There are three main conversion processes:

- Direct conversion,
- Thermochemical conversion and
- Biochemical conversion.

The process of **direct conversion** is the traditional method of the use of biomass. It has a very low efficiency, as almost 90% of the energy is lost by burning organic matter.

In contrast to that, **thermochemical conversions** are high-efficiency processes, based on the use of heat. The main thermochemical conversion processes are combustion, pyrolysis, and gasification.

During the process of combustion, the biomass is almost completely oxidized at very high temperatures between 800 and 1000°C; this reaction releases water, carbon dioxide, ashes, and heat. The main applications are domestic and industrial heating or electricity generation.

The process of pyrolysis is an incomplete combustion of biomass in an anaerobic environment at temperatures of around 500°C and is typically used for charcoal production. Through this process, a low-energy gas is produced, which is mainly composed of a mixture of carbon monoxide and dioxide, hydrogen and light hydrocarbons. The gas has low calorific value can be used as a fuel for diesel engines, for electricity generation or as a vehicle fuel.

The third main thermochemical conversion process is gasification. During the process of gasification, an incomplete combustion of biomass at high temperatures of between 700 and

1200°C takes place. The primary product is a combustible gas composed of hydrogen, methane and carbon monoxide. The efficiency of this process is higher as the combustion of biomass in a boiler, but the principal problem of this process of gasification is the purification of the gas. One of the advantages of this process is that the produced gas is more versatile and it can be used for the same purposes as natural gas; another benefit is that it can be burned to produce heat, steam and for powering internal combusting engines as well as gas turbines for electricity generation.

The processes of **biochemical conversion,** are also high-efficiency conversion methods. They take advantage of the characteristics of the biomass and the metabolism of microbial organisms to produce gaseous and liquid fuels. Biochemical conversion processes are more appropriate for the conversion of wet biomass. The most important products are alcohol fuels, biodiesel, gas from landfills and biogas.

Alcohol fuels are liquid fuels, that can be produced for example through the fermentation of sugars, such as ethanol or can be obtained by the destructive distillation of wood, such as methanol. This technology has been used for the production of liquors and, more recently, it is used to generate substitutes for fossil fuels for transportation. These fuels can be used in pure form or mixed with others, for transport or running machines.

Biodiesel is composed of fatty acids and alkaline esters, obtained from vegetable oils, animal fat and recycled fats. Through the process of transesterification, oils are combined with alcohol and chemically altered to form fatty esters, such as ethyl or methyl ester. Those can be mixed with diesel or used directly as fuels in conventional motors. The biodiesel is usually used as an addition to normal diesel, in the proportion of 20%, but it is also possible to use different amounts, depending on the costs and expected benefits. The biggest advantage of using biodiesel is the considerable reduction of emissions, exhaust gases, and odor.

Gas from landfills is formed by the fermentation of solid urban waste. The gas is a mixture of methane and carbon dioxide, and its formation is a natural, common process in the landfills, however, normally this gas is not exploited. The exploitation of this gas has several advantages besides the generation of energy; it contributes considerably to the reduction of contamination, the risks of explosions and emissions of GHG. (Fernández Castaño, 2017, p. 1-4).

Biogas is produced through a process called anaerobic digestion. Biomass (normally manure and/or organic waste) is fed into a digester, where bacteria degrade the organic material. The outputs of this digestion process are an odorless effluent and biogas, which consists mainly of methane (50-75%), carbon dioxide (25-50%) and other gases such as nitrogen, oxygen (2-8%). (Wellinger et al., 2013, p. 2)

The anaerobic digestion of renewable sources is a technology with great potential to produce clean and sustainable energy. One of the main sources for biogas generation is organic matter from the agro-industrial sector, such as agricultural residues and animal manure. (Abdeshahian et al., 2016, p. 714) One reason for this is that activities of the sector produce biomass in large quantities, by converting this biomass into different forms of energy, the range of its applications can be extended. For example, by converting it into biogas, not only can it be burned directly and used for cooking and heating, but it also can be used as a source for generating electricity, for CHP generation as well as (after an upgrade process) for the production of fuels. (United Nations Foundation, pp. 47–48) Besides the use as an energy source, anaerobic digestion is also a very effective waste treatment method. Often there is no proper management of the residues in the agro-industrial sector, which has negative implications for the environment. For example, animal manure has high concentrations of nitrogen (N) and phosphorus (P), if it is applied directly to the soil, it can lead to its' degradation or imbalances of nutrients or the pollution of water bodies. Another serious problem is microorganisms in the manure, without adequate treatment they can possess a danger for humans concerning the transmission of diseases. In addition to that, other harmful substances such as heavy metals, growth hormones, and antibiotics can be contained in manure. (Abdeshahian, Lim, Ho, Hashim, & Lee, 2016, p. 715) During the process of anaerobic digestion, the number of organic contaminants is reduced, and the odor is eliminated, converting the introduced residues in a safe, odorless effluent, which can be used as fertilizer. Therefore, the technology of anaerobic digestion has three main benefits: 1) to provide renewable energy, 2) to improve sanitary conditions by pollution control and 3) to produce a bio-fertilizer. (MINENERGIA/PNUD/FAO/GEF, 2011, p. 9)

3.2. Bioenergy and food security

It is important to make a distinction between the different origins of the substrates used for biogas generation. The main distinction is whether residues or energy crops are used as input for the anaerobic digestion process. (Wellinger et al., 2013, p. 2)
In the years 2007 and 2008 the food crisis led to a debate over the competition between food and energy, raising concerns about bioenergy, especially biofuels, competing with food security. (Achterbosch et al., 2013, p. 10) Food security according to the definition of the FAO exists:

> "[…] Food security exists when all people, at all times, have physical, social and economic access to sufficient amounts of safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. There are four dimensions to food security as it relates to bioenergy: availability, access, stability, and utilization." (FAO, 2010b, X)

Nowadays, the development of a bioenergy sector represents a high priority on many countries' agendas, seeking to improve their energy security, access to energy and mitigate the emissions of greenhouse gases. Nevertheless, bioenergy caused serious concerns regarding its sustainability and implications regarding food security for poor households (FAO, 2010a, p. 9) and it is said to be additional pressure on agricultural production and the environment. (FAO, 2010b, p. 3)
Sustainable food production can be compromised by the production of biomass for bioenergy in several ways. The first is land, a land use change (LUC) can be either direct, (DLUC) using the land for bioenergy production, that was not used before for agricultural purposes or indirect (ILUC) using the land for bioenergy production, that was used for food production before. Food production is negatively affected by the ILUC if agricultural land designated to food production is now used to produce biomass for bioenergy. The second is the food prices because they are likely to increase if food as a commodity decreases on the market, which would result in increases in food import expenses. Particularly for the poor, it is important that the relation of income and food prices does not get in misbalance. If food is available on the market, but too expensive for poor households to afford, it will lead to food insecurity. (Achterbosch et al., 2013, p. 21)
There are many options to minimize the effects of DLUC and ILUC. The first would be, intensifying land use or integrating food and energy production. Secondly, using abandoned or

degraded lands to produce bioenergy. Moreover, finally, by using waste and residues for bioenergy production. In that way, it would be possible to reduce the impacts and competition arising from bioenergy production on food security. (Achterbosch et al., 2013, p. 21)
Bioenergy developments have local, national, regional and global impacts across interlinked social, environmental and economic domains. (FAO, 2010a, p. 9) If expanded, bioenergy production is likely to provoke greater competition for access to land and water, posing a threat to people depending on it. (Achterbosch et al., 2013, p. 32) Furthermore, bioenergy projects have the ability to improve resilience, by reducing vulnerabilities that lead to food insecurity. (Kline et al., 2016, p. 7)
In the present work, only the production of biogas from agro-industrial residues is analyzed.

3.3. Biogas and Biogas by-products

The biomass sources suitable for biogas production can be grouped firstly, according to the taxonomic rank of their origin, being vegetal (Plantae) or animal (Animalia) and secondly, according to the sector, which produced the biomass source. The three most important sectors and their biomass sources are: manure and slurries, vegetable by-products and residues, plants, harvest residues, as well as energy crops from the **agricultural sector**; organic wastes, by-products and residues from agro-industries and food and brewery industries, wastewaters from industrial processes, by-products and residues from biofuel production and bio-refineries from the **industrial sector**; and organic household waste, municipal solid waste and food residues, sewage sludge, among others from the **municipal sector**. The organic matter of these biomass value chains is the most suitable feedstock for biogas generation. (Wellinger et al., 2013, p. 20)
The application of biogas has mainly two target groups, which can be characterized by income and productivity. In the first target group, productivity and income are rather low. This group consists of farmers in marginal rural areas or medium-scale producers with limited access to conventional energy sources and no grid connection. For this group, the bio-digester has to have a very low cost as well as an easy maintenance, because of that the digester has a low efficiency and generates less energy. The second target group consists of medium and high-income producers from the agricultural and agro-industrial sector. The main objective of this target group is reaching a high efficiency of the bio-digester to generate heat and electricity. This implies higher investment costs, and it makes the operation and maintenance of the plant more difficult. (Ing. A. M.Sc. Hilbert, Jorge A., 2015, pp. 2–3)

The present work will focus on medium income producers from the agro-industrial sector.

3.3.1. The process of anaerobic digestion

Biogas consists mainly of methane (CH_4) (50-75%), carbon dioxide (CO_2) (25-50%), and small amounts of hydrogen (H), hydrogen sulfide (H_2S) and nitrogen (N), which normally rank between 2% and 8%. (Abdeshahian et al., 2016, p. 715)

The process of anaerobic digestion entails four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. (Panwar et al., 2011, pp. 1517–1518)

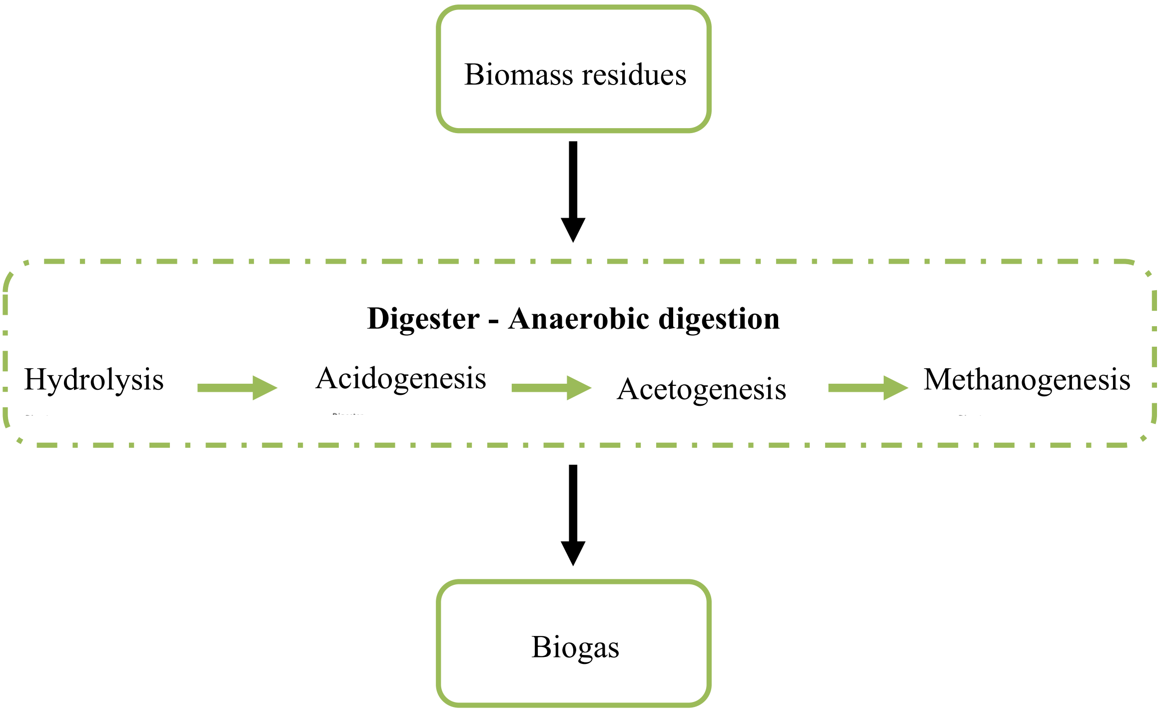


Figure 4: The process of anaerobic digestion. Adapted from Panwar et al., 2011, pp. 1517–1518

The bacteria responsible for the biogas production can only survive in the total absence of oxygen and have a high sensitivity to environmental conditions. Therefore it is important to maintain parameters such as temperature and humidity inside the digester at constant levels. Temperatures between 29°C and 35°C are ideal for methane production because it allows the microbial activity to take place. (Ing. A. M. Sc. Hilbert, Jorge A., 2015, pp. 4–6)

After introducing the biomass into the digester, the first stage of the anaerobic digestion, the **hydrolysis**, takes place. The bacteria, mostly facultative anaerobes, break down long, complex organic molecules into simpler chains of amino acids, fatty acids, and sugars. During this process, hydrogen and carbon dioxide are liberated.

In the second stage, the **acidogenesis**, the process of acidification takes place. The acidogenic bacteria transform the polymers into short chain volatile acids, alcohols, ketones, hydrogen, and carbon dioxide. The principal products are among others, propionic, butyric, formic, lactic and acetic acid, as well as ethanol and methanol. From those, the hydrogen, carbon dioxide and acetic acid skip the third stage (acetogenesis) and are utilized directly by the methanogenic bacteria in the final stage.

The other products of the acidogenesis are transformed into hydrogen, carbon dioxide and acetic acid in the third stage, the **acetogenesis**, by acetogenic bacteria. These bacteria are obligate syntrophs, which must act together with bacteria in a different trophic group to digest a substrate. (Murphy, 2013, p. 104–108)

The third stage is called **methanogenesis**. It is the last stage of the formation of methane. The bacteria involved belong to the group of achibacterias and are strictly anaerobe, meaning that they only can survive in the total absence of oxygen. The final reaction in this stage has as main substrate acetic and other short-chain organic acids. The final products are methane and carbon dioxide. The two main pathways to create methane are:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2H_2O$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

(Ing. A. M. Sc. Hilbert, Jorge A., 2015, p. 4–6)

3.3.2. Digester

The process of anaerobic digestion, namely the microbial activity and the transformation of organic matter to biogas, takes place in the digester. The processing options depend on the feeding system, the reactor type, and temperature, the number of phases and the agitation system. (Bachmann, 2013, p. 197)

Technology	Key parameters	Options
Feeding system	Digester type and matter content of feedstock	- Discontinuous feeding for batch digester - Continuous or semi-continuous feeding for plug-flow or continuously stirred tank reactor (CSTR) - Solid or liquid feeding system depending on dry matter content of the substrate
Reactor type	Dry matter content of feedstock	- CSTR for liquid substrates - Plug-flow or batch digester for solid substrates
Reactor temperature	Risk for pathogens	- Mesophilic temperature (25-45°C) when no risk for pathogens - Thermophilic temperature (50-58°C) when risk for pathogens
Number of phases	Composition of substrates, acidification risk	- One phase systems: no acidification risk - Two phase systems: acidification risk (substrates with a high content of sugar, starch or proteins)
Agitation system	Dry matter content of feedstock	- Mechanical agitators for high solids concentrations in the digester - Mechanical, hydraulic or pneumatic agitation systems for low solids concentration in the digester

Table 2: Processing options. Adapted from: Bachmann, 2013, p. 193

For agro-industrial by-products such as manure and harvest residues, normally a one phase system in the mesophilic temperature range is used. This can vary due to requirements of the degree of digestion, the digestion speed and the risk of pathogens. (Wellinger et al., 2013, p. 3) In addition to that, the volume of the digester needs to be adapted to the quantity of feedstock and its degradation rate. (Bachmann, 2013, p. 197)

3.3.3. By-product

The effluent of the digester, the digestate, is a valuable biofertilizer. Its composition and quality depend strongly on the feedstock used for the anaerobic digestion process. However, it has many benefits in comparison to the direct application of raw animal slurries to the field and even the use of synthetic fertilizers. (Wellinger et al., 2013, p. 268) The direct application of raw manure to the field, poses a danger to humans and animals, due to the pathogens contained in the manure. In addition to that, it emits a strong odor and attracts flies and other insects, compromising not only the health of people living close to the field but also lowering their living standards.

The main danger of the application of synthetic fertilizer is the contamination of the groundwater with nitrate (N). Furthermore, N together with phosphorus (P) can lead to eutrophication of rivers, lakes, and seas. (Mulvaney et al., 2009, p. 2295–2296) Although eutrophication is a natural process in which the lake is enriched with nutrients or organic material, fertilizer with a high amount of N and P accelerate this, normally gradual, process significantly due to an excess of nutrients that lead to an increase in the population of phytoplankton and a decrease of the dissolved oxygen in the water causing the death of fish and aquatic plants. (Loehr, 1978, p. 265–266)

Another important issue of the use of synthetic fertilizer is the conversion of fertilizer N to N_2O–N. N_2O is a GHG with almost 300 times the GWP of CO_2. Therefore it has the potential to accelerate Climate Change drastically. Besides, the application rates of N often exceed the crop requirements, due to the missing knowledge of the right amount and time. Applying too much synthetic fertilizer can have negative consequences on soil fertility and lead to a decrease in the crop productivity rate. (Mulvaney et al., 2009, p. 2295–2296)

The process of anaerobic digestion, not only reduces the amount of nutrients in the digestate, but also eliminates the pathogens and the odor, making the digestate an environmentally safe fertilizer. (Wellinger et al., 2013, p. 267) However, there are still countries with missing legislation on the use and commercialization of the digestate as fertilizer.

4. Case study: The agro-industrial sector of Uruguay

The Oriental Republic of Uruguay has a population of 3.4 million (2015), and its Gross Domestic Product (GDP) accounted for 53.44 billion USD in 2015. Uruguay is one of the most socially sustainable countries in Latin America regarding various measures of well-being, e.g. in the region; it ranks first in the Democracy Index, the Global Peace Index, and the Prosperity Index.

Unlike other countries in Latin America Uruguay has an egalitarian society, high per capita income levels, a low degree of inequality and poverty and almost no extreme poverty. Moderate poverty decreased from 32.5% in 2006 to 9.7% in 2015, while extreme poverty practically disappeared (from 2.5% to 0.3%). In 2013, the World Bank ranked Uruguay as a high-income country. Two years later, the national gross per capita income reached 15,720USD; it is the highest in the region. (The World Bank Group, 2015) Besides that, the country grew at an average annual rate of 4.4% between 2006 and 2016 and is, therefore, one of the fastest growing countries in the region. (Uruguay XXI, 2016b, p. 2)

The growth of Uruguay's economy is directly related to the export-orientated agro-industrial sector, which is continuously growing (between 2002 and 2015 at a rate of 2.8% per year) and accounted for 78% of all exported goods in 2016, producing food for 28 million people and making the country one of the main food exporting regions in the world. (Uruguay XXI, 2016b, p. 2)

Another particularity of the country is the scarcity of fossil energy resources, Uruguay has no oil, no natural gas, and no coal reserves. Thus, the Uruguayan primary energy mix in the years from 2001 to 2006 was characterized by energy imports, which accounted for 63% of the total energy matrix. Besides that, the country had a high climate dependence as hydropower constituted 20% of the primary energy matrix and therefore was subject to high variations due to precipitation. (Uruguay XXI, 2016a) In the last decade, the energy market in Uruguay went through a deep transition and made a shift towards the integration of renewable energies into its energy matrix.

Historical Background

From 2000-2006 Uruguay was strongly dependent on energy imports. In average petroleum derivatives accounted for about 56% of the energy matrix (hydroelectric generation 20%, firewood 15%). Uruguay has no oil or gas reserves, and the hydroelectric generation capacity was almost entirely utilized. The country was strongly dependent on imports of oil, fuel oil and gas oil for thermal generation. (Honoré, 2004, p. 36) One of the major imports came from Argentina in the form of natural gas, and Uruguay even planned to expand those imports, but in 2004 serious gas shortages and power cuts hit Argentina, and the country reduced its energy exports drastically. Uruguay was supplying one-fifth of its electricity consumption from Argentina at that time, so as Uruguay's state power company (UTE) threatened to take legal action against Cammesa (Argentines wholesale market administrator) for cutting the power exports, the Kirchner government agreed to restart power exports to Uruguay in June 2004. (Honoré, 2004, p. 36)

Shift to the integration of RE into the energy matrix

In 2005, Uruguay developed an "Energy Policy 2005-2030", which in 2010 became state policy, and therefore independent of changes in the government. It held a strong commitment to the diversification of the energy matrix and the incorporation of renewables in the latter. The policy included short term (2015), medium term (2020) and long-term goals (2030). (MIEM, 2015a, p. 2)

To provide a secure supply of primary energy without being dependent on energy imports, Uruguay invested in the period from 2009 to 2014 3.53 billion USD in the diversification of their energy matrix, mainly in domestic renewable resources. By the end of 2015, Uruguay had accomplished a significant change in its primary energy matrix.

Wind, for example, became an important source of energy, in 2005 there were no wind farms installed in Uruguay, and by 2015 the country had 26 wind farms (with a total power of 850 MW), of which 19 were installed between 2013 and 2015. This represented a 15% share of wind energy in the power generation matrix in 2015. (MIEM, 2015a, p. 3) Windfarms now even feed into hydropower plants so that dams can maintain their reservoirs longer after the rainy seasons is over. According to Ramón Méndez (head of climate policy), this has reduced vulnerability to drought by 70%; this is a remarkable improvement considering that a dry year used to cost the country nearly 2% of its GDP. (Global Climatescope, 2014)

In (the forecast of) 2016, 62% of the Uruguayan primary energy was supplied by local renewable energy sources, and only 38% of the energy was imported. (MIEM, 2016)

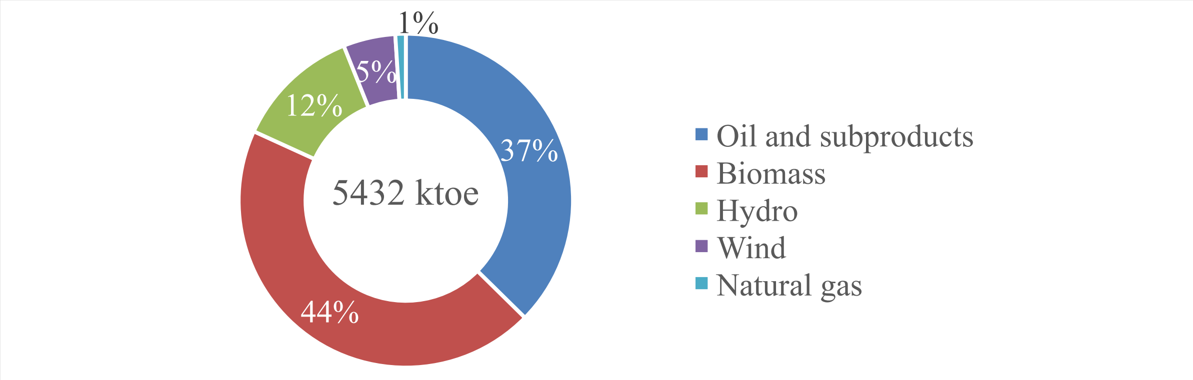


Figure 5: Energy supply Uruguay 2016 (in ktoe). Adapted from MIEM, 2016

The country's primary energy matrix, had a net growth of 129% between 1990 and 2015, recording a record value in 2015 (5230 ktoe) and a 9% increase over the previous year. At the end of 2015, Uruguay had a total installed capacity of 4058.7 MW. Large hydro stays at a constant level of 1538 MW, wind, however, experienced an immense increase from only 40.6 MW in 2010 to 856.8 MW in 2015. Solar accounted for 64.4 MW, biomass, and waste for 424.6 MW and oil and diesel for 1174.9 MW. Considering the power installed by source, 72% corresponded to renewable energy (hydro, biomass, wind and solar), while the remaining 28% consisted of non-renewable energy (diesel and fuel oil). Furthermore, 2015 was the third consecutive year, without a commercial import of electricity. (MIEM, 2015a, p. 2)

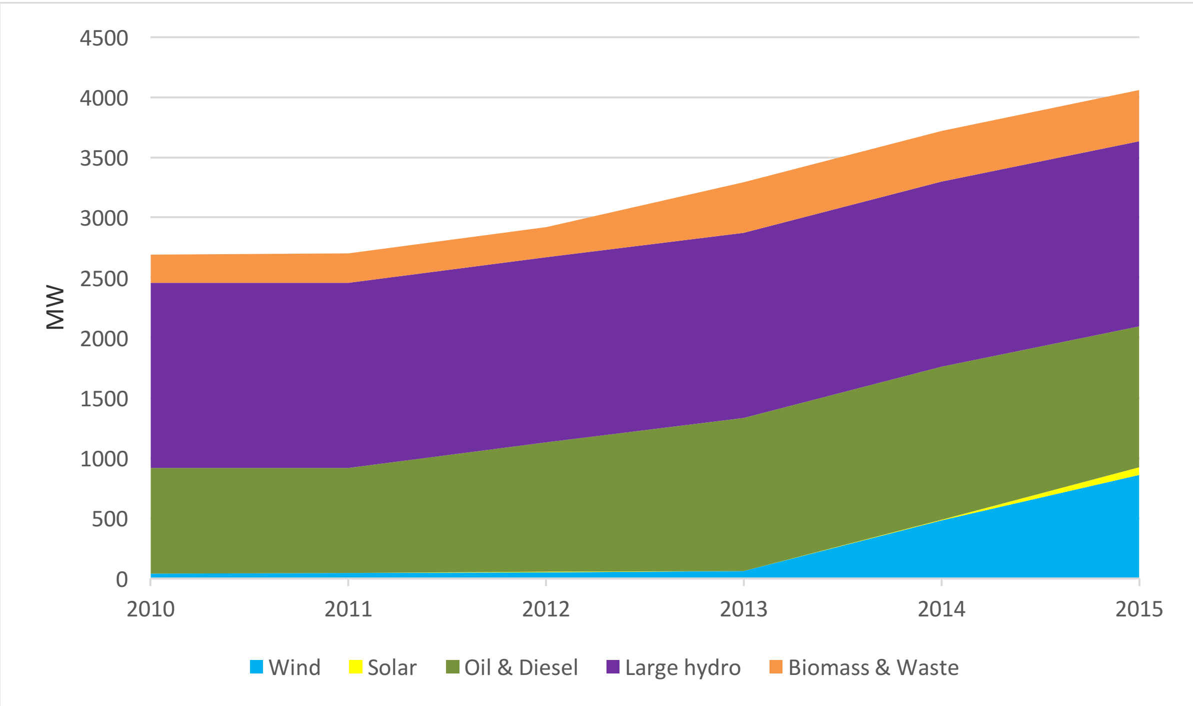


Figure 6: Installed capacity Uruguay (MW/year). Adapted from MIEM, 2015b

These achievements can be attributed to the success of the guidelines implemented under the energy policy since 2005. The main objective of this policy was to reach energy independence with the diversification of the primary energy matrix using renewable and indigenous sources. (IRENA, 2015, p. 1) The short-time goal until 2015 of supplying 50% of the country's energy from renewables, was even surpassed and renewables accounted for 57% in the energy supply matrix of Uruguay in 2015.
In a decade, Uruguay has achieved to become the country with the highest proportion of electricity generated from wind energy in Latin America and one of the main in relative terms worldwide. (MIEM, 2015a, p. 3) There is still no official data yet, but the government estimates more than 90% of electricity generated by renewable energy in 2016, mainly from hydro and wind. (MIEM, 2015a, p.4)
Despite the high energy independence, the country's energy supply is still vulnerable to climate variations, due to the high generation of electricity from hydro and wind. The use of biomass for electricity generation can provide a higher energy security, supplying a constant rate of energy, independent from changes in the climate.

The Uruguayan energy demand reached 4399 ktoe in 2015. The industrial sector has the highest energy demand with 1853 ktoe, 62% of the demand is covered by biomass, followed by the transport sector with a demand of 1235 ktoe of that 48% is covered by gasoil and 46% by petrol. Renewables play an irrelevant role in the transport sector yet, bioethanol and biodiesel accounted for only 3% in 2015. Third, with an energy demand of 796 ktoe is the residential sector, 45% of this demand is covered by electricity and 37% of biomass. The Business/Service/Public sector has a demand of 299 ktoe, of which electricity covers 83% and the lowest demand has the Agricultural/Fishing/Mining sector with 216 ktoe, diesel oil and gasoil cover 66%. (MIEM, 2015b, p.3)

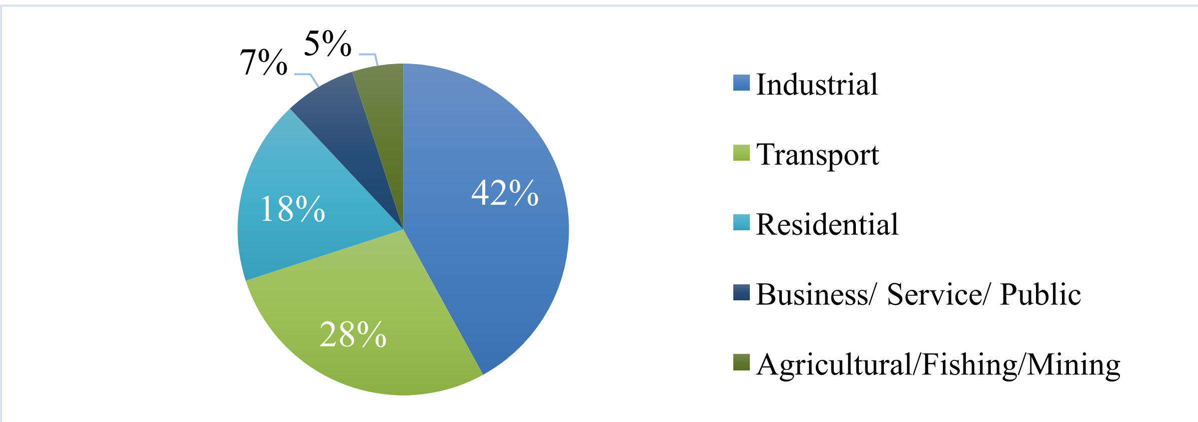


Figure 7: Energy demand per sector 2015. Adapted from MIEM, 2015b

In 2015, the final energy consumption per capita was 1292 toe per 1,000 inhabitants, and the electricity consumption per capita reached 3039 kWh. (MIEM, 2015b, p. 2)

4.1. Political framework related to renewable energies

The main instrument that Uruguay used for the promotion of renewable electricity was auctions, in which the state-owned national electric company (UTE) grants power purchase agreements (PPAs) to successful bidders. This mechanism was especially used for the installation of wind farms. However, the country also implemented several other instruments, inter alia net metering, which was implemented in 2010 by Decree 173/010 for small wind power, solar, biomass and mini-hydro systems; and by Decree 367/010 a feed-in tariff to promote electricity generation from biomass; as well as a hybrid instrument to promote solar PV, containing elements of auctions as well as feed-in tariffs. (IRENA, 2015, p. 3f)

In 2010, Uruguay implemented a National Action Plan for Environmentally Sustainable Production and Consumption (2010-2015), in which inter alia actions for the promotion of sustainable/ cleaner production practices in two agro-industrial sub-sectors, namely the meat production and the dairy cow industry, were defined. For the primary dairy cow industry, the goals are to promote the sustainable management of resources, to avoid pollution, and to conserve the soil, reducing nutrient and CO_2 losses to the atmosphere. To achieve these goals, the National Action Plan highlights the importance of an environmentally sustainable management of effluents and residues of the dairy cow stables and an establishment of guidelines for the soil management. (PNUMA, 2010, p. 85–87) For the meat production, one of the goals is to promote the environmentally sustainable management of effluents and solid waste, with the implementation of environmentally sound management systems and the generation of energy from residues of the sector. (PNUMA, 2010, p. 88–91)

International agreements

In 2015, Uruguay submitted its Intended Nationally Determined Contribution (INDC) to the UNFCCC, which contained a commitment to implement a low-carbon growth agenda with targets addressing both climate change mitigation and adaptation. (FAO & New Zealand Agricultural Greenhouse Gas Research Centre, 2017, p. v)

Gas	Sector/Activity		2030 Targets Percentage emission reduction targets from **base year 1990**	
			With domestic resources	**With additional means of implementation**
CO_2	***Net CO_2 removal by 2030 with domestic resources*** by means of the targets listed to the right	**LULUCF**	Remove 13200 Gg annually	Remove 19200 Gg annually
		Energy (Accounts for 94% of CO_2 emissions in 2010)	Reduce emission intensity per unit of GDP by 25%	Reduce emission intensity per unit of GDP by 40%
			Keep power generation emissions below 40 gCO_2/kWh	Keep power generation emissions below 20 gCO_2/kWh
		Industrial Processes (Accounts for 6% of CO_2 emissions in 2010)	Keep the intensity of emissions per unit of GDP at the reference value	Reduce emission intensity per unit of GDP by 40%
CH_4	**Beef Production** (Accounts for 78% of CH_4 emissions by 2010)		Reduce emission intensity per kilogram of beef by 33%	Reduce emission intensity per kilogram of beef by 46%
	Waste (Accounts for 7% of CH_4 emissions by 2010)		Reduce emission intensity per unit of GDP by 44%	Reduce emission intensity per unit of GDP by 68%
	Other sectors and activities (Accounts for 15% of CH_4 emissions by 2010)		Reduce emission intensity per unit of GDP by 45%	Reduce emission intensity per unit of GDP by 60%
N_2O	**Beef Production** (Accounts for 61% of N_2O emissions by 2010)		Reduce emission intensity per kilogram of beef by 31%	Reduce emission intensity per kilogram of beef by 41%
	Other sectors and activities (Accounts for 39% of N_2O emissions by 2010)		Reduce emission intensity per unit of GDP by 40%	Reduce emission intensity per unit of GDP by 55%

Table 3: Contribution of Uruguay to international mitigation efforts, Oriental Republic of Uruguay, 2015

In 2010, considering the CO_2 emissions, 94% had its origin in the energy sector, and 6% were emitted from industrial processes. The "National Energy Policy 2005-2030", lead to a share of about 60% of renewable energies in the primary energy matrix of Uruguay (83% in the industrial sector and 93% for power generation) and therefore the country's total emissions of the energy sector are with 111g CO_2 very low. In its INDC submitted, Uruguay wants to achieve an additional 25% intensity reduction (from 1990 values) by 2030 by means of domestic resources.

GHG emissions from the power sector will be reduced to 17 g CO_2/kWh this year, achieving an absolute emissions reduction of 88% compared to the annual average for the period 2005 to 2009.

The emissions from beef production constituted 78% of all CH_4 emissions in 2010 of the country, but the biological origin and the importance of this sector for the economy, present a challenge for the mitigation. However, Uruguay wants to reduce CH_4 by one-third per kilogram of beef (from 1990 values) by means of domestic resources by 2030. 15% of the CH_4 emissions were emitted from other sectors and activities, of which 9% of were from other livestock and the dairy production. Uruguay wants to achieve a reduction of the emission intensity per unit of GDP by 45%.

Emissions from waste accounted for 7% of the CH_4 emissions in 2010, even though the country already implemented several emissions reducing strategies, there is an additional reduction potential of 44% per unit of GDP. (Oriental Republic of Uruguay, 2015)

Although Uruguay already achieved a high contribution of renewable energies to their primary energy matrix, the INDC show, that there is still a great potential for the reduction of emissions, especially in the agro-industrial sector.

4.2. The agro-industrial sector

The agro-industrial sector has been one of the most important drivers of the economic growth of the country in the last decade. In 2016, it accounted for 78% of all exported goods and in 2015 for 12.4% of the country's GDP, (6.2% is attributed to the primary sector and 6.2% to agro-related industries) generating a profit of 6.44 billion USD. (Uruguay XXI, 2016b, p. 2, 7, 40)

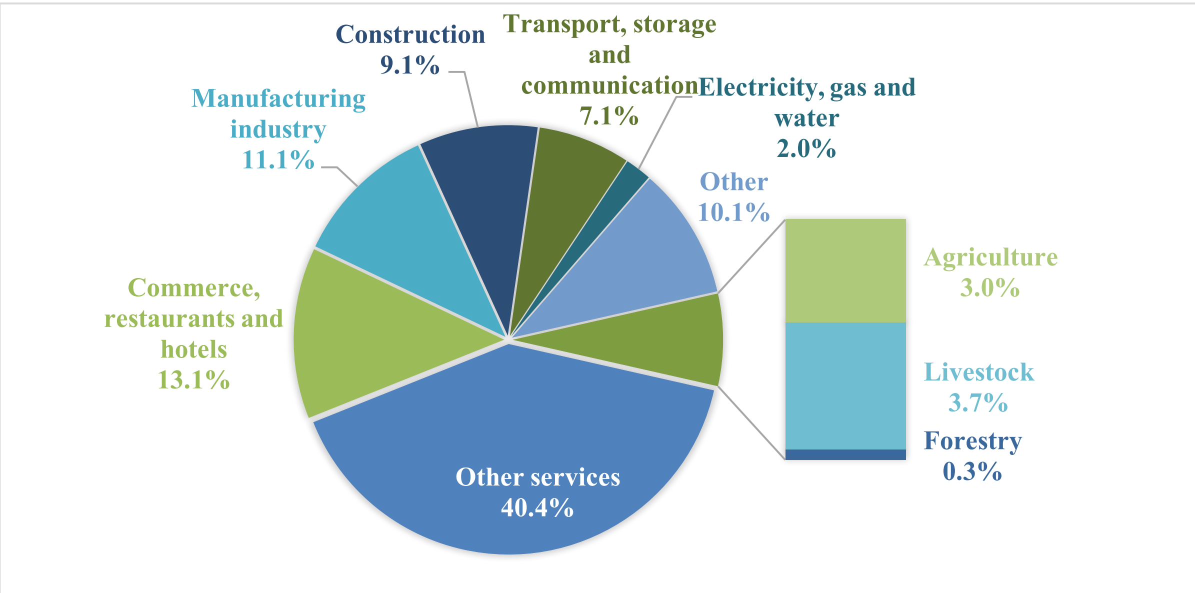


Figure 8: GDP per sector 2015. Adapted from Uruguay XXI, 2016b

The food production of Uruguay is expected to grow in the future as a response to the increasing international demand for food, especially meat. The country has a significant comparative advantage in international food production, due to that 95% (16.4 million hectares) of its land is suitable for agricultural use and besides that, Uruguay has a great potential to increase its agro-industrial production. Having a population of only 3.48 million people, the country is already producing food for 28 million people. (Uruguay XXI, 2016b, p. 2)

The main exported products from the agro-industrial sector in 2016, were beef (23%), cellulose (mainly forestry products, 19%), soy (13%) and dairy products (9%). (Uruguay XXI, 2016b, p. 8)

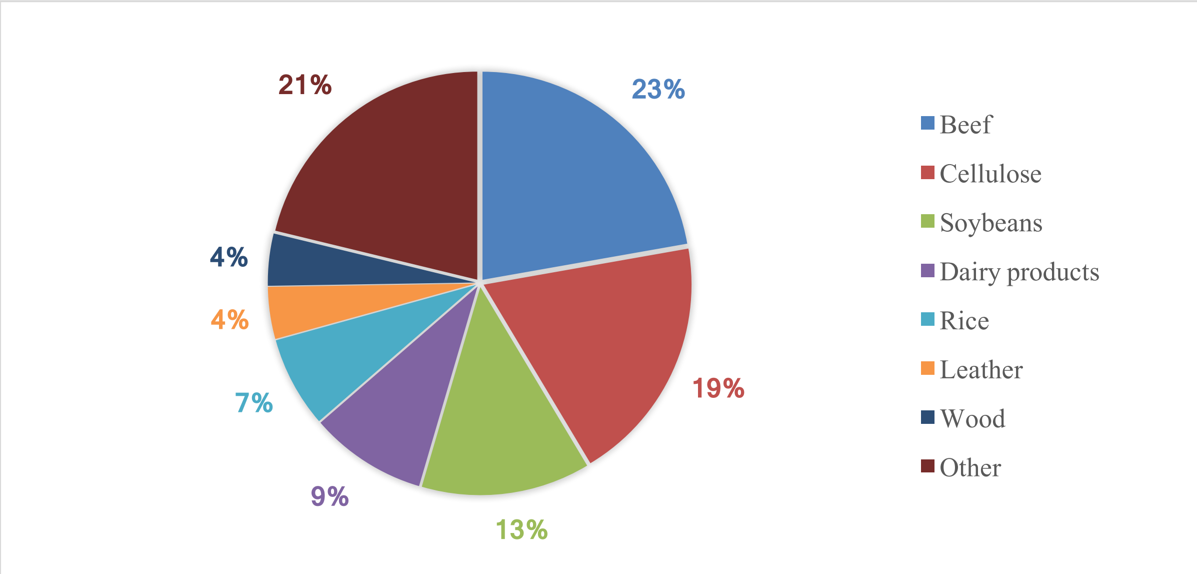


Figure 9: Agro-industrial exports – main products 2016. Adapted from Uruguay XXI, 2016b

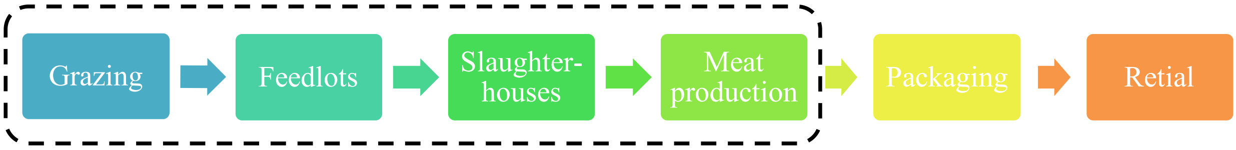
For this work, the primary sectors, namely the sub-sectors: feedlot, poultry production, dairy cows and pig industry were selected. Due to their character of primary production and the manure management systems, those sectors not only have a high estimated potential for GHG emissions but also for energy generation and environmental safeguarding. The energetic valorization of the residues through anaerobic digestion can, therefore, respond to several issues at the same time.

In the following the primary agro-industrial production chains are presented (in a very simplified way), taking into consideration the different production steps. The black dotted line symbolizes the boundary of the agro-industrial sector.

Beef production

Beef production is the most important activity in the agro-industrial sector. In 2015, there was a total of 11,099,000 animals. (Ministerio De Ganadería, Agricultura Y Pesca, 2016, p. 34) In the year 2015/2016, beef production reached 1.1 million tons of live cattle and slaughter accounts for 2.2 million heads of cattle, generating a revenue of USD 1.443 bn. Having even higher stock levels this year, the country expects an increase in the levels of slaughter and in the export of live cattle. (Uruguay XXI, 2016b, p. 20, 42)

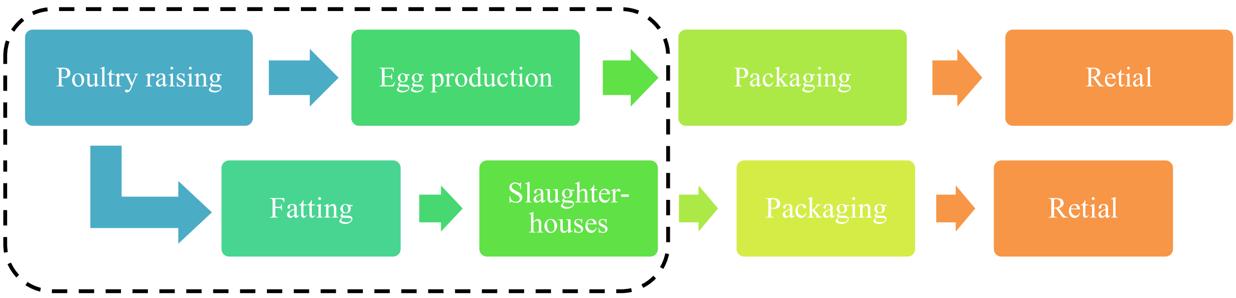
The animals are held outside and graze all year round, only for the final fattening (day 90 to day 120) the animals are taken to feedlots, to reach their final slaughter weight.



Poultry production

The poultry sector is comprised of two sub-sectors, one dedicated to the production of laying hens (for egg production), the other to broiler chickens. Both breeding lines begin their production process in farms, where hens and roosters are raised. During the primary production, the animals are usually held in closed sheds, and the main waste generated in this stage are beds and excreta.

In 2015, the production of eggs accounted to 2.34 million boxes containing 360 eggs each and to 106,700 tons of slaughtered roosters. (Ministerio De Ganadería, Agricultura Y Pesca, 2016, p. 70)



Dairy cows

The dairy sector was constituted of 783,000 animals in 2015, and 73% of the animals were being milked (Ministerio De Ganadería, Agricultura Y Pesca, 2016, p. 51). 70% of the milk produced is destined for export, accounting for a revenue of USD 567 million in 2016. From 2014, prices for dairy products began to decline, caused by an increase in international supply and a decrease in demand from several key countries (especially China). Nevertheless, with the increase in demand, which is expected in developing countries, also prices are expected to rise again. (Uruguay XXI, 2016b, p. 25, 42)

The dairy cows are held outside and graze all year round; they are only taken inside for the milking process. First, they are placed into a holding pen and later into the milking parlor.

Pig industry

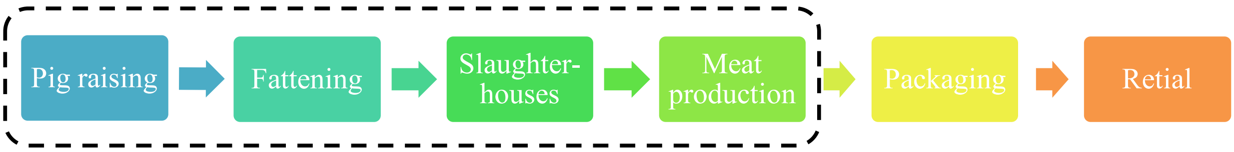
In 2015, there were 216,000 animals in Uruguay, and 16,000 tons of meat was produced. (Ministerio De Ganadería, Agricultura Y Pesca, 2016, p. 67)

There are mainly three different production systems for pigs.

Extensive system (on the field): groups of pigs are produced in pens with drinking fountains and shelters, which may or may not have vegetation cover. This system is mostly used from small to medium-scale establishments. They require low levels of investment per hectare but use large areas.

Intensive system (enclosure): all categories of pigs are held in fully enclosed premises. This system is mainly used in establishments of large scale production; it requires high investment, but a less large area.

An intensive system with pasture or grazing access: the animals spend most of the time in the enclosure, but have controlled access to pens or grazing areas.



5. Methodology

The present work was developed in the context of the project BIOVALOR of the Uruguayan government[1], namely the Ministry of Industry, Energy and Mining (MIEM), the Ministry of Housing, Land Management and Environment (MVOTMA) and the Ministry of Farming, Agriculture and Fishing (MGAP), financed by the GEF (Global Environmental Facility) and implemented by UNIDO (United Nations Industrial Development Organization).

Four main methodological steps were employed: **1) Analysis of theoretical background** (secondary data). The first step was to analyse the theoretical background of the present thesis, this is including the detailed understanding of Climate Change and the role of GHG emissions for global warming, as well as the function of biomass as a renewable energy source, biomass technologies, the possible risk of bioenergy for food security and finally the production of biogas through the process of anaerobic digestion. The aim of collecting secondary data is to obtain a general overview of the current situation involving all aspects surrounding the research. This can be achieved through literature review and consultation of relevant institutions.

2) Definition of baseline scenario (secondary and primary data). Through a literature review, the national legal framework related to renewable energies as well as the current energy matrix of the country was identified. In a second step, the sub-sectors with the most pollution potential, namely the sub-sectors concentrated on primary production were analyzed regarding the mitigation viability, including an analysis of the origin of the emissions and the living conditions of the animals. Using this data, their residues generation was calculated, using factors defined by the BIOVALOR project team. The previous results serve as input to calculate the GHG emissions of the different sub-sectors using the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The purpose of the primary data collection was, to identify specific situations in the study area, such as the factors, which were established by the project team. The primary data was obtained from the review of BIOVALOR project

[1] After the definition of the Energy Policy 2005-2030, the country had international financing through some projects that facilitated its implementation. The most important are the Wind Energy Project in Uruguay (PEEU), the Electric Energy Generation Project from Forest Biomass (PROBIO) and the Waste Energy Recovery Project (BIOVALOR). These projects had the aim to generate information, break down barriers, build capacities, develop additional regulations to the existing one, and fund some small-scale pilot projects. The project BIOVALOR implemented several small-scale pilot projects and generated information, which was analyzed in the present work.

information from UNIDO and semi-structured qualitative interviews with the responsible project coordinator in Uruguay and the Ministry of Industry, Energy and Mining (MIEM).

3) Evaluation of GHG emissions reduction potential. The third step was to analyze the amount of GHG emissions from the different sub-sectors, using descriptive statistics. Later, with the analysis of different scenarios and a projection of the increase in GHG emissions until 2030, the potential of GHG emissions reduction in the different sub-sectors was evaluated. For this an economic feasibility study for the installation of a biogas plant was conducted for each sub-sector, taking into account the different scenarios. **4) Interpretation of data**. The final step of this thesis was to compare the amount of the GHG emissions of the status-quo, the projection until 2030 and the potential reduction with the installation of biogas plants in each of the sub-sectors.

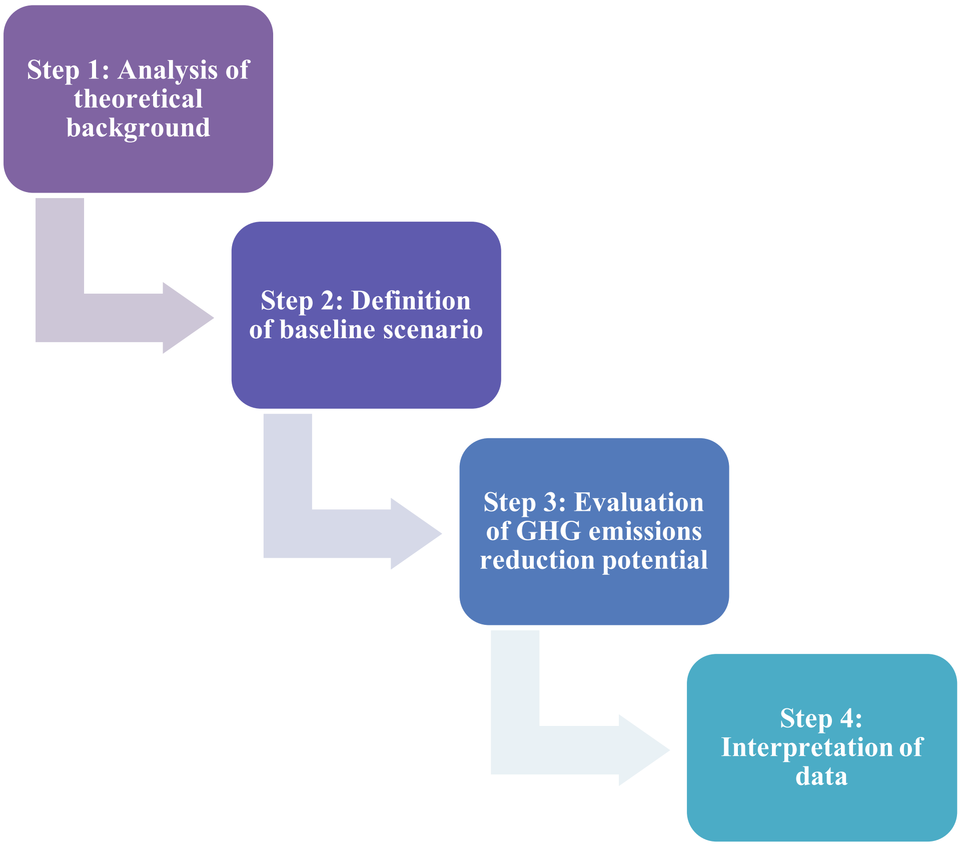


Figure 10: Methodological steps, own elaboration.

6. Results and discussion

6.1. GHG emissions in the agro-industrial sector

In 2011, 25% of the global GHG emissions related to agriculture and cattle raising were produced in Latin America and the Caribbean, meaning that in this region the emissions from the sector are very significant. (Witkowski & Medina, 2016, p. 20) In Uruguay the high agro-industrial production also influences in great amount the GHG emissions of the country, constituting 76% of the total national GHG emissions in 2015. (FAO & New Zealand Agricultural Greenhouse Gas Research Centre, 2017, p. v)

The two main emissions from the agro-industrial sector are methane (CH_4) and nitrous oxide (N_2O). (Olivet, 2014, p. 26) The main emitter of methane is the cattle industry through enteric fermentation, but also manure left on soils or other types of manure management, such as solid storage and the treatment in an uncovered anaerobic lagoon, emit high levels of methane. A reduction of emissions from enteric fermentation is almost not possible; little can be achieved by dietary changes of the cows, the only effective method is a reduction of the livestock itself. However, beef production is an economic priority of Uruguay, and therefore a reduction of the livestock is not feasible. For reducing methane emissions, a change in the management system of the manure has to be implemented.

The second main emission is nitrous oxide, emitted from the application of synthetic fertilizer to agricultural soils. In the last years, the need for greater crop yields led to an increase in the use of synthetic fertilizers and consequently to an increase in the nitrous oxide emissions. Furthermore, the direct application of manure as fertilizer on the soil can also result in massive emissions of nitrous oxide. (Olivet, 2014, p. 26)

The installation of a biogas system is a solution for the reduction of emissions, without having to reduce the livestock. Anaerobic digestion of the residues is an excellent manure management system, preventing not only GHG emissions and the pollution of the soil, but also producing energy on site, which can be used for production processes.

For the estimation, of how many GHG emissions can be avoided, installing a biogas plant, first, the generated residues in the four agro-industrial sub-sectors have to be estimated. Following this estimation, the GHG emissions resulting from the residues and the corresponding treatment (manure management system), will be calculated. In a third step, the energetic valorization potential of the produced biogas will be analyzed and the possible revenues calculated.

6.1.1. Residues generated in the different sub-sectors

The agro-industrial sector is composed of various sub-sectors, generating residues which can be treated anaerobically for biogas production.

The total amount of residues generated in the prioritized sub-sectors are:

Agro-industrial sub-sectors	Identified residues with valorization potential	Total Solids (tons/year dry basis)
Feedlots	Manure	13,773,859.00
Poultry production	Manure	27,650.72
	Bedding	103,652.00
Dairy cows	Manure	1,091,451,105.00
Pig industry	Manure	38,631.60

Table 4: Total residues generated in different sub-sectors, own calculation.

However, not all of the residues can be used for the anaerobic digestion process. Therefore it is important to consider their production reality.

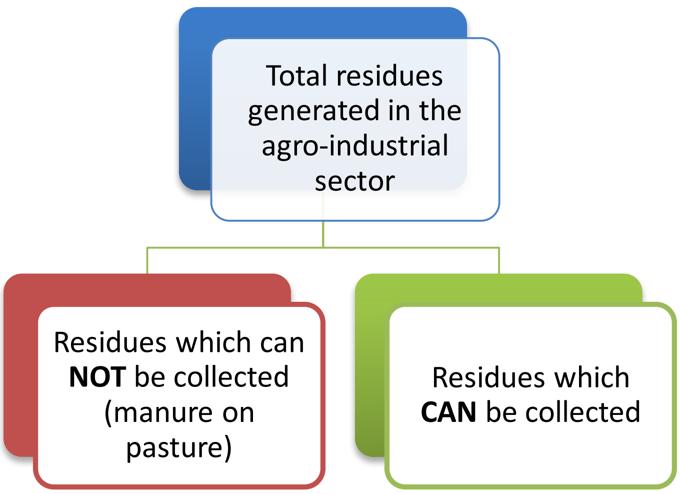


Figure 11: Residues in the agro-industrial sector, own elaboration.

For example, the beef industry is the sub-sector with the highest number of animals, but considering the production system of beef in Uruguay (see **4.2**), only a very small amount of the generated residues can be collected, because the animals live almost all their lives outside and are fed on natural pastures. Only the 30 last days before the slaughter of the animals, they are brought into a feedlot, where the manure can be collected and used for biogas production.

In the primary poultry and egg production, the chicken broilers, as well as the laying hens, are usually hold in closed sheds, and therefore the generated residues of the beds and excreta can be collected.

In the milk production industry, the collection of the residues of the dairy cows is also not possible in large amounts. The animals are held outside and graze all year round and are only taken inside for the milking process, during the time the animals are waiting in the holding pen, the residues can be collected.

The pig industry uses different production systems. In the system, which 82.42% of the producers in Uruguay use, the pigs are held in fully enclosed premises, therefore the collection of the pig manure is possible.

With this analysis and some factors, which were developed by the BIOVALOR project team, the amount of the generated residues in each sub-sector, was calculated. It is important to mention that in the following analysis and calculations only the residues, which can be collected are considered. This does e.g. not include the manure left on soil from cows or pigs raised in not confined systems.

Agro-industrial sub-sectors	Identified residues with valorization potential	Total Solids (tons/year dry basis)
Feedlots	Manure	1,132,098.00
Poultry production	Manure	27,650.72
	Bedding	103,652.00
Dairy cows	Manure	125,178.21
Pig industry	Manure	31,840.16

Table 5: Residues which can be collected for use in a biogas plant, own calculation.

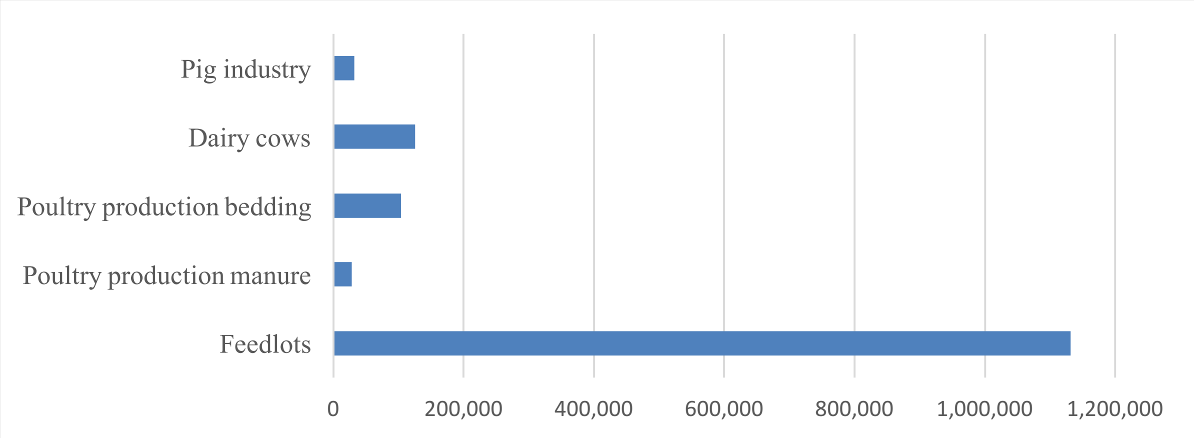


Figure 12: Residues generated in different sub-sectors, total solids (tons/year dry basis).

After taking a closer look at the estimated residues generation, two main observations can be made. The first is that the primary agricultural sectors are the ones with the highest residues generation (all four sub-sectors over 30,000 tons/year dry basis), which are almost entirely constituted of animals excrete, such as cow and pig manure, as well as chicken manure and bedding. The second observation, which can be made, is that almost all of the residues are applied on the land, some direct others after a pretreatment. In the sub-sectors of cattle raising, dairy cows, and the pig industry 100% of the generated residues are applied on the land, only in the poultry industry, 20% of the generated residues are used for compost production.

The direct application of manure on the land can cause serious environmental pollution (see **3.1**), to avoid this, a treatment of the residues is required. The anaerobic digestion process provides not only such treatment but also allows the energetic valorization of the residues. (Moreda, 2016, p. 1589)

6.1.2. Calculation of GHG emissions

With the estimated residues production, the GHG emissions of the different residues can be calculated. For this calculation, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and other land use, Chapter 10: Emissions from Livestock and Manure Management are used.

The formulas, which were applied for the calculation of CH_4 and N_2O emissions are:

EQUATION 10.23

CH_4 EMISSION FACTOR FROM MANURE MANAGEMENT

$$EF_{(T)} = \left(VS_{(T)} \bullet 365\right) \bullet \left[B_{o(T)} \bullet 0.67\, kg/m^3 \bullet \sum_{S,k} \frac{MCF_{S,k}}{100} \bullet MS_{(T,S,k)} \right]$$

Where:

$EF_{(T)}$ = annual CH_4 emission factor for livestock category *T*, kg CH_4 animal^{-1} yr^{-1}

$VS_{(T)}$ = daily volatile solid excreted for livestock category *T*, kg dry matter animal^{-1} day^{-1}

365 = basis for calculating annual VS production, days yr^{-1}

$B_{o(T)}$ = maximum methane producing capacity for manure produced by livestock category *T*, m^3 CH_4 kg^{-1} of VS excreted

0.67 = conversion factor of m^3 CH_4 to kilograms CH_4

$MCF_{(S,k)}$ = methane conversion factors for each manure management system *S* by climate region *k*, %

$MS_{(T,S,k)}$ = fraction of livestock category *T*'s manure handled using manure management system *S* in climate region *k*, dimensionless

Equation 1: CH_4 Emission Factor from manure management (IPCC, 2006, p.41)

EQUATION 10.25

DIRECT N_2O EMISSIONS FROM MANURE MANAGEMENT

$$N_2O_{D(mm)} = \left[\sum_S \left[\sum_T \left(N_{(T)} \bullet Nex_{(T)} \bullet MS_{(T,S)} \right) \right] \bullet EF_{3(S)} \right] \bullet \frac{44}{28}$$

Where:

$N_2O_{D(mm)}$ = direct N_2O emissions from Manure Management in the country, kg N_2O yr^{-1}

$N_{(T)}$ = number of head of livestock species/category *T* in the country

$Nex_{(T)}$ = annual average N excretion per head of species/category *T* in the country, kg N animal^{-1} yr^{-1}

$MS_{(T,S)}$ = fraction of total annual nitrogen excretion for each livestock species/category *T* that is managed in manure management system *S* in the country, dimensionless

$EF_{3(S)}$ = emission factor for direct N_2O emissions from manure management system *S* in the country, kg N_2O-N/kg N in manure management system *S*

S = manure management system

T = species/category of livestock

44/28 = conversion of $(N_2O\text{-}N)_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions

Equation 2: Direct N2O emissions from manure management (IPCC, 2006, p.54)

For the calculation of the CH_4 and N_2O emissions, the following data[2] is needed:

Sub-sectors	Identified residues	Humidity %	Total (tons/year dry matter)	VS (%TS)	B_0[3] ($m^3CH_4/kgVS$)	N (kgN/kgVS)
Feedlots	Manure	85%	3,396,294	80	0.2	0.043
Poultry production	Manure	80%	27,651	80	0.28	0.069
	Bedding	50%	103,652	70	0.16	0.071
Dairy cows	Manure	85%	125,178	80	0.2	0.043
Pig industry	Manure	90%	31,840	80	0.45	0.106

Table 6: Data for calculation of CH_4 and N_2O emissions in different sub-sectors (BIOVALOR).

The residues generated in these agro-industrial sub-sectors are treated with different manure management systems.

Sub-sectors	Identified residues	Share of Residues by Management System (%)				
		Solid storage	**Pasture/ Range/ Paddock**	**Uncovered anaerobic lagoon**	**Dry lot**	**Daily spread**
Feedlots	Manure	60	10	30	0	0
Poultry production	Manure	60	0	30	10	0
	Bedding	100	0	0	0	0
Dairy cows	Manure	20	10	40	0	30
Pig industry	Manure	11	0	0	0	89

Table 7: Manure Management Systems (in %) present situation (BIOVALOR).

[2] Data obtained from BIOVALOR.
[3] Oxford Dictionary Science Definition: "STP Standard Temperature Pressure formerly known as NTP (Normal Temperature and Pressure). The standard conditions used as a basis for calculations involving quantities that vary with temperature and pressure. These conditions are used when comparing the properties of gases. They are 273.15°K (0°C) and 101325Pa (or 760mmHg)" DAINTITH, J. & MARTIN, E. (eds.) 2010. A Dictionary of Science Oxford, Oxford University Press

Manure management system	MCF (%)
Solid storage	4
Pasture/Range/Paddock	1.5
Uncovered anaerobic lagoon	75
Dry lot	1.5
Daily spread	0.5

Table 8: Methane Conversion Factors (MCFs) (IPCC, 2006, p.44) with average annual temperature of 16° Celsius (http://usclimatedata.com/climate/uruguay/uy).

Manure management system	EF (kgN2O-N/kgN)
Solid storage	0.005
Pasture/Range/Paddock	0.02
Uncovered anaerobic lagoon	0
Dry lot	0.001
Daily spread	0.02

Table 9: Emission Factor (EF) for direct N_2O emissions (kgN2O-N/kgN) from manure management system (BIOVALOR).

The manure management system with the highest MCF is the uncovered anaerobic lagoon. In the sub-sectors feedlots and dairy cows, 30% of the residues are treated with this manure management system, generating the highest methane emissions.

With this data, the CH_4 emissions and the N_2O emissions of the residues, which can be used for biogas production in the different sub-sectors were calculated. For being able to calculate the total GHG emissions (tCO_2e) of each of the sub-sectors, the CH_4 emissions, and the N_2O emissions were multiplied with their corresponding Global Warming Potential (GWP) and summed.

Sub-sectors	Emissions CH_4 (ton CH_4/year)	Emissions N_2O (ton N_2O/year)	GHG emissions (tCO_2e/year)
Feedlots	30,400.91	305.99	851,207.67
Poultry production	1,350.65	47.91	48,043.91
Dairy cows	4,173.34	60.90	122,482.03
Pig industry	67.97	77.86	24,900.78
TOTAL	**96,794.68**	**1,104.64**	**2,749,049.71**

Table 10: CH_4, N_2O and GHG emissions (tCO_2e) of the sub-sectors, own calculation.

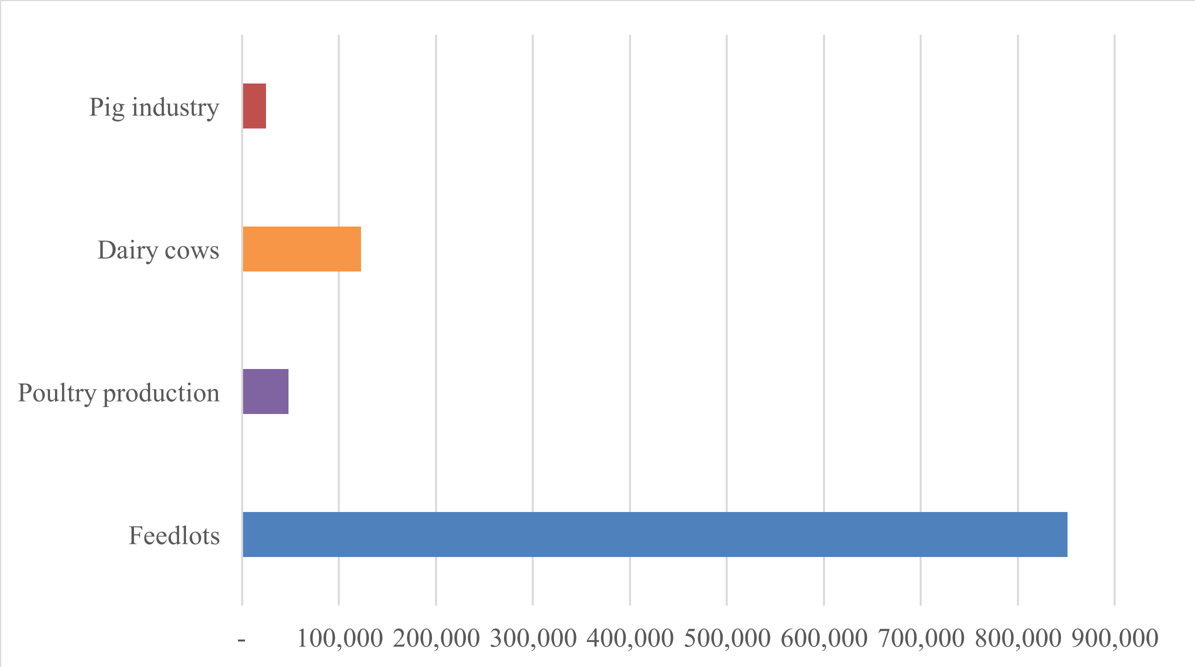


Figure 13: GHG emissions (tonCO_2eq) of the sub-sectors, own calculation

The calculations show that the GHG emissions from the feedlots sub-sector are the highest, followed by the emissions of the dairy cows, the pig industry, and the poultry production. The feedlots sub-sector accounts for almost twice of the emissions of the pig industry and poultry production together. And the dairy cows' sub-sector emits about three times as much as the pig industry or the poultry production.

6.2. Scenarios

In the following, different scenarios will be presented. The first scenario is a projection of the business as usual until 2030, describing the increase in GHG emissions if no mitigation strategies are employed. The following scenario analyzes the potential of GHG emissions reduction if all residues generated in the sub-sectors are used for biogas production, considering different tariff regimes. In the scenarios 3, 4 and 5 only a part of the residues will be considered for biogas generation, taking into account the current manure management systems.

6.2.1. Scenario 1: Business as usual

The agro-industrial sector had an annual growth rate of 2.8% between 2002 and 2015. (Uruguay XXI, 2016b, p. 2) This rate was used for the estimations of the increase of the GHG emissions in the different sub-sectors.

Feedlots

	2015	2016	2017	2018	2019	2020	2025	2030
Total number of animals (heads/year)	11,099,000	11,409,772	11,729,246	12,057,664	12,395,279	12,742,347	14,629,012	16,795,022
Animals with possible residues use (heads/year)	11,099,000	11,409,772	11,729,246	12,057,664	12,395,279	12,742,347	14,629,012	16,795,022
Residues generation (kg/year dry matter)	3,396,294,000	3,491,390,232	3,589,149,158	3,689,645,335	3,792,955,404	3,899,158,156	4,476,477,691	5,139,276,664
Volatile Solids (%TS) (kg/year)	2,717,035,200	2,793,112,186	2,871,319,327	2,951,716,268	3,034,364,323	3,119,326,525	3,581,182,153	4,111,421,331
Methane generation (tons/year)	91,203	93,756	96,382	99,080	101,855	104,706	120,210	138,008
Nitrous oxide generation (tons/year)	918	944	970	997	1,025	1,054	1,210	1,389
Total GHG emissions (tCO2e/year)	**2,553,623**	**2,625,124**	**2,698,628**	**2,774,190**	**2,851,867**	**2,931,719**	**3,365,797**	**3,864,146**

Table 11: GHG emissions projection until 2030 for the sub-sector of feedlots, own calculation

Poultry production

	2015	2016	2017	2018	2019	2020	2025	2030
Total number of animals (heads/year)	3,030,216	3,115,062	3,202,284	3,291,948	3,384,122	3,478,878	3,993,969	4,585,327
Animals with possible residues use (heads/year)	3,030,216	3,115,062	3,202,284	3,291,948	3,384,122	3,478,878	3,993,969	4,585,327
Residues generation (kg/year dry matter)	131,302,721	134,979,197	138,758,615	142,643,856	146,637,884	150,743,745	173,063,257	198,687,455
Volatile Solids (%TS) (kg/year)	94,676,977	97,327,932	100,053,114	102,854,601	105,734,530	108,695,097	124,788,777	143,265,329
Methane generation (tons/year)	1,351	1,388	1,427	1,467	1,508	1,551	1,780	2,044
Nitrous oxide generation (tons/year)	47.9	49.3	50.6	52.0	53.5	55.0	63.1	72.5
Total GHG emissions (tCO2e/year)	**48,044**	**49,389**	**50,772**	**52,194**	**53,655**	**55,157**	**63,324**	**72,700**

Table 12: GHG emissions projection until 2030 for the sub-sector of poultry production, own calculation

Dairy cows

	2015	2016	2017	2018	2019	2020	2025	2030
Total number of animals (heads/year)	783,000	804,924	827,462	850,631	874,448	898,933	1,032,031	1,184,837
Animals with possible residues use (heads/year)	571,590	587,595	604,047	620,960	638,347	656,221	753,383	864,931
Residues generation (kg/year dry matter)	125,178,210	128,683,200	132,286,329	135,990,347	139,798,076	143,712,423	164,990,859	189,419,836
Volatile Solids (%TS) (kg/year)	100,142,568	102,946,560	105,829,064	108,792,277	111,838,461	114,969,938	131,992,687	151,535,869
Methane generation (tons/year)	4,173	4,290	4,410	4,534	4,661	4,791	5,501	6,315
Nitrous oxide generation (tons/year)	60.9	62.6	64.4	66.2	68.0	69.9	80.3	92.2
Total GHG emissions (tCO2e/year)	**122,482**	**125,912**	**129,437**	**133,061**	**136,787**	**140,617**	**161,437**	**185,340**

Table 13: GHG emissions projection until 2030 for the sub-sector of dairy cows, own calculation

Pig industry

	2015	2016	2017	2018	2019	2020	2025	2030
Total number of animals (heads/year)	216,000	222,048	228,265	234,657	241,227	247,982	284,698	326,851
Animals with possible residues use (heads/year)	178,027	183,012	188,136	193,404	198,819	204,386	234,648	269,391
Residues generation (kg/year dry matter)	31,840,165	32,731,689	33,648,177	34,590,326	35,558,855	36,554,503	41,966,858	48,180,580
Volatile Solids (%TS) (kg/year)	25,472,132	26,185,351	26,918,541	27,672,260	28,447,084	29,243,602	33,573,486	38,544,464
Methane generation (tons/year)	68.0	69.9	71.8	73.8	75.9	78.0	89.6	102.8
Nitrous oxide generation (tons/year)	77.9	80.0	82.3	84.6	87.0	89.4	102.6	117.8
Total GHG emissions (tCO2e/year)	**24,901**	**25,598**	**26,315**	**27,052**	**27,809**	**28,588**	**32,820**	**37,680**

Table 14: GHG emissions projection until 2030 for the sub-sector of pig industry, own calculation

All sub-sectors:

	2015	2016	2017	2018	2019	2020	2025	2030
Total GHG emissions (tCO2e/year)	2,749,049.72	2,826,023.11	2,905,151.76	2,986,496.00	3,070,117.89	3,156,081.19	3,623,378.81	4,159,865.74

Table 15: GHG emissions projection until 2030 for all sub-sectors, own calculation

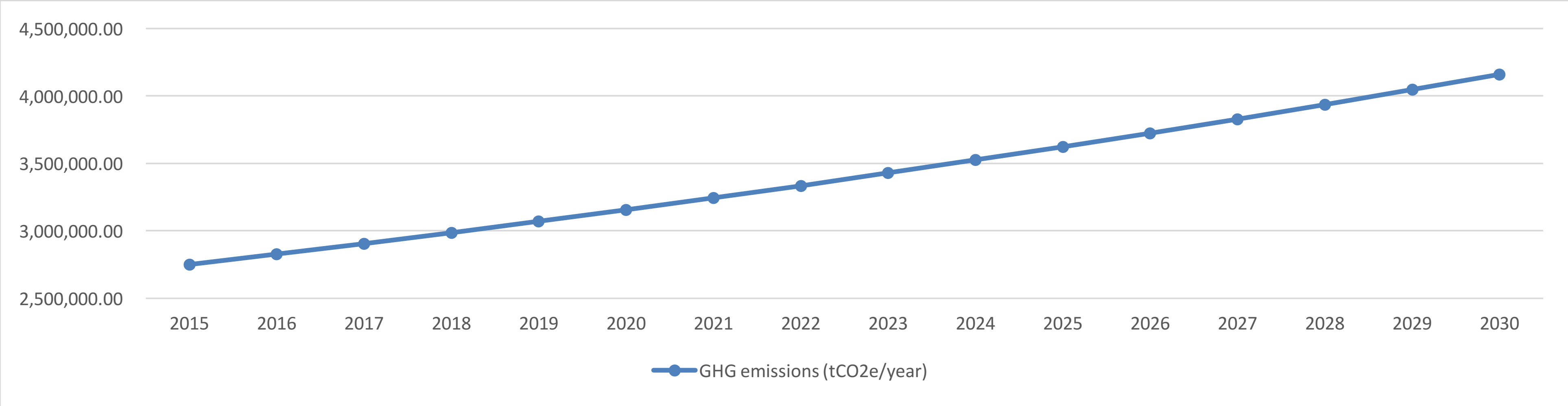


Figure 14: GHG emissions projection until 2030 for all sub-sectors, own calculation

This projection shows that, if the agro-industrial sub-sectors continue to grow (at a rate of 2.8%), the total GHG emissions will rise 66% until 2030.

6.2.2. Scenario 2: All residues used for biogas production

For calculating the reduction potential of the GHG emissions, with the installation of a biogas plant, first the potential biogas production for each sub-sector was calculated:

Sub-sectors	Total Solids (kg/year dry matter)	VS (%TS)	Volatile Solids (kg/year)	B_0 (m^3CH_4/kgVS)	Methane generation (m^3CH_4/year)
Feedlots	3,396,294,000	80%	2,717,035,200	0.2	543,407,040
Poultry production	27,650,719	80%	22,120,576	0.28	6,193,761
	103,652,000	70%	72,556,400	0.16	11,609,024
Dairy cows	125,178,210	80%	100,142,568	0.2	20,028,514
Pig industry	31,840,165	80%	25,472,132	0.45	11,462,459

Table 16: Potential biogas production in different sub-sectors, own calculation

Sub-sectors	Electricity generation (kWh/year)	ktoe
Feedlots	1,625,330,457	139.75
Poultry production	53,248,130	4.58
Dairy cows	59,905,284	5.15
Pig industry	34,284,216	2.95
TOTAL	**1,772,768,087**	**152.43**

Table 17: Potential electricity generation (kWh/year) in different sub-sectors, own calculation

The total electricity generation (with the factor $1m^3$ $CH_4 \approx 9.97$ kWh and 30% efficiency of the internal combustion motor), considering the use of all the residues generated in the four agro-industrial sub-sectors, could reach **1,772,768 MWh**. The electricity consumption per inhabitant accounted for 3039 kWh in 2015 (MIEM, 2015a, p. 2). Therefore, the electricity production from the generated biogas has the potential to cover **17% of the electricity demand** of the population (583,339 people).

In 2015, the energy demand reached 4399 ktoe in Uruguay, of which the Agricultural/Fishing/Mining sector accounted for 216 ktoe. Diesel oil and gasoil still cover 66% of the sectors energy demand. (MIEM, 2015a, p.3) With the energy production of the biomass valorization, **152.43 ktoe** can be generated. This accounts for 3% of the total energy demand or 70.57% of the energy demand of the Agricultural/Fishing/Mining sector.

In this scenario, as all the residues are used for biogas production, the avoided emissions account for 100% of the business as usual scenario, and the possible electricity generation also reaches 100% in this scenario.

	Total Methane Emissions (tons/year)	**Total N2O Emissions (tons/year)**	**Total GHG Emissions (tonCO2eq/year)**	**Possible electricity generation (kWh/year)**
Current situation	96,795	1,105	2,749,050	1,772,768,087
Scenario 1	0	0	0	1,772,768,087
Avoided emissions	**96,795**	**1,105**	**2,749,050**	**-**

Table 18: Avoided emissions – Scenario 2, own calculation

<u>Economic feasibility:</u>
For analyzing the economic feasibility of the installation of a biogas plant, three factors were considered: the estimated profit, the costs of the investment and the payback period.
The profit can be calculated on the basis of the Decree 173/2010, which enables the net-metering of electricity produced from biomass through micro-generation. In this context, the electricity generated that exceeds the own consumption of the establishment can be fed into the low voltage grid and will be remunerated with the same tariffs as the energy consumed by the establishment. After the signing of the contract with UTE, this agreement is valid for the duration of 10 years. In this way, regardless of the existence or not of electrical demand for the production process of the sub-sector, the valorization of the residues is ensured. (IRENA, 2015, p. 3f)
For the following analysis, the tariff for medium consumers with medium tension level (6.4 – 15 – 22 kV) is used.

Tariff for medium consumers (MC):

1. Tariff according to energy consumption:

Tariff	Tension level kV	Electricity prices (USD/kWh)		
		Low	Medium	High
MC 1	0.23 – 0.40	0.07	0.15	0.34
MC 2	6.4 – 15 – 22	0.07	0.14	0.26
MC 3	31.5	0.07	0.14	0.23

Table 19: Electricity tariff for medium consumers. Administración Nacional de Usinas y Transmisiones Eléctricas (UTE), 2017, p. 5

2. Tariff according to time periods depending on demand (tariff differentiation):
   For the period of standard time (UTC/GMT -3):
   - High: from 18:00 to 22:00
   - Medium: from 07:00 to 18:00 and from 22:00 to 24:00
   - Low: from 00:00 to 07:00

The following calculations were made, for analyzing the economic feasibility for establishments with 500, 1000, 1500, 2000, 3000, 4000 and 5000 animals, assuming that there is a constant feed-in of electricity into the grid for 24 hours per day, with the MC 2 tariff and considering four hours (18:00 to 22:00) of 0.26USD per kWh, 13 hours (07:00 to 18:00 and 22:00 to 24:00) of 0.14USD per kWh and seven hours (00:00 to 07:00) of 0.07USD per kWh. The installation of a biogas plant would be economically feasible if the payback period is less than 10 years (due to the duration of the net-metering contracts of 10 years). The investment costs of the biogas plants were obtained from the BIOVALOR project team.

Scenario 2.1.:

Feedlots:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	24,480	48,960	73,440	97,920	146,880	195,840	244,800
Electricity generation (kWh/year)	73,220	146,439	219,659	292,879	439,318	585,757	732,197
Estimated profit (USD/year)	10,040	20,080	30,120	40,161	60,241	80,321	100,401
M&O Costs (USD/year)	24,480	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(14,440)	7,330	14,820	22,311	37,291	52,271	67,251
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	20.5	12.1	9.4	7.2	6.3	5.8

Table 20: Economic feasibility for the sub-sector of feedlots with 24 hours feeding into national grid, own calculation

Poultry production

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	2,938	5,875	8,813	11,750	17,625	23,500	29,375
Electricity generation (kWh/year)	8,786	17,572	26,359	35,145	52,717	70,290	87,862
Estimated profit (USD/year)	1,205	2,410	3,614	4,819	7,229	9,638	12,048
M&O Costs (USD/year)	10,625	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(9,420)	(10,340)	(11,686)	(13,031)	(15,721)	(18,412)	(21,102)
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	Never	Never	Never	Never	Never	Never

Table 21: Economic feasibility for the sub-sector of poultry production with 24 hours feeding into national grid, own calculation

Dairy cows:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	17,520	35,040	52,560	70,080	105,120	140,160	175,200
Electricity generation (kWh/year)	52,402	104,805	157,207	209,609	314,414	419,219	524,023
Estimated profit (USD/year)	7,186	14,371	21,557	28,742	43,113	57,485	71,856
M&O Costs (USD/year)	10,625	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(3,439)	1,621	6,257	10,892	20,163	29,435	38,706
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	92.5	28.8	19.3	13.4	11.2	10.1

Table 22: Economic feasibility for the sub-sector of dairy cows with 24 hours feeding into national grid, own calculation

Pig industry:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	32,193	64,386	96,579	128,772	193,158	257,544	321,930
Electricity generation (kWh/year)	96,289	192,579	288,868	385,157	577,736	770,314	962,893
Estimated profit (USD/year)	13,204	26,407	39,611	52,814	79,221	105,628	132,035
M&O Costs (USD/year)	19,210	23,630	25,107	26,584	29,538	32,491	35,445
Annual estimated cash flow	(6,006)	2,777	14,504	26,230	49,684	73,137	96,590
Investment	226000	278000	295375	312750	347500	382250	417000
Payback period	Never	100.1	20.4	11.9	7.0	5.2	4.3

Table 23: Economic feasibility for the sub-sector of pig industry with 24 hours feeding into national grid, own calculation

The calculations show that the installation of a biogas plant would only be economically feasible in the sub-sectors feedlots, from 2000 animals up and in the pig industry, from 3000 animals up. Due to the production reality in Uruguay, an assumption of more than 5000 animals is not realistic.

Consequently, the installation of a biogas plant in the sub-sectors poultry industry and dairy cows is not feasible.

However, another calculation can be made, assuming, that the electricity produced from the biogas plant, would be only fed into the grid during the price regime of the highest tariff (0.26 USD) from 18:00 until 22:00.

This would lead to the following results:

Scenario 2.2.:

Feedlots:

Number of animals	**500**	**1000**	**1500**	**2000**	**3000**	**4000**	**5000**
Methane production (m3/year)	24,480	48,960	73,440	97,920	146,880	195,840	244,800
Electricity generation (kWh/year)	73,220	146,439	219,659	292,879	439,318	585,757	732,197
Estimated profit (USD/year)	19,271	38,543	57,814	77,086	115,629	154,171	192,714
M&O Costs (USD/year)	24,480	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(5,209)	25,793	42,514	59,236	92,679	126,121	159,564
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	5.8	4.2	3.5	2.9	2.6	2.4

Table 24: Economic feasibility for the sub-sector of feedlots with 4 hours feeding into national grid, own calculation

Poultry production:

Number of animals	**500**	**1000**	**1500**	**2000**	**3000**	**4000**	**5000**
Methane production (m3/year)	2,938	5,875	8,813	11,750	17,625	23,500	29,375
Electricity generation (kWh/year)	8,786	17,572	26,359	35,145	52,717	70,290	87,862
Estimated profit (USD/year)	2,313	4,625	6,938	9,250	13,875	18,500	23,125
M&O Costs (USD/year)	10,625	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(8,312)	(8,125)	(8,362)	(8,600)	(9,075)	(9,550)	(10,025)
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	Never	Never	Never	Never	Never	Never

Table 25: Economic feasibility for the sub-sector of poultry production with 4 hours feeding into national grid, own calculation

Dairy:

Number of animals	**500**	**1000**	**1500**	**2000**	**3000**	**4000**	**5000**
Methane production (m3/year)	17,520	35,040	52,560	70,080	105,120	140,160	175,200
Electricity generation (kWh/year)	52,402	104,805	157,207	209,609	314,414	419,219	524,023
Estimated profit (USD/year)	13,792	27,585	41,377	55,169	82,754	110,338	137,923
M&O Costs (USD/year)	10,625	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	3,167	14,835	26,077	37,319	59,804	82,288	104,773
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	39.5	10.1	6.9	5.6	4.5	4.0	3.7

Table 26: Economic feasibility for the sub-sector of dairy cows with 4 hours feeding into national grid, own calculation

Pig:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	32,193	64,386	96,579	128,772	193,158	257,544	321,930
Electricity generation (kWh/year)	96,289	192,579	288,868	385,157	577,736	770,314	962,893
Estimated profit (USD/year)	25,343	50,687	76,030	101,373	152,060	202,747	253,433
M&O Costs (USD/year)	19,210	23,630	25,107	26,584	29,538	32,491	35,445
Annual estimated cash flow	6,133	27,057	50,923	74,790	122,523	170,255	217,988
Investment	226000	278000	295375	312750	347500	382250	417000
Payback period	36.8	10.3	5.8	4.2	2.8	2.2	1.9

Table 27: Economic feasibility for the sub-sector of pig industry with 4 hours feeding into national grid, own calculation

With the reduction of the feed-in time to only the period of the highest tariff, the economic feasibility can be improved. The installation of a biogas plant in the sub-sector feedlots becomes feasible with only 1000 animals and the pig industry with 1500 animals. In addition to that, also the installation of a biogas plant in the dairy sector for establishments from 1500 animals, becomes economically feasible. Despite assuming the feed-in during the most profitable tariff and the use of all of the residues for biogas generation, an installation of a biogas plant in the poultry industry is still not economically feasible. Therefore it will no longer be considered in the following scenarios.

This scenario considered that all of the generated residues were used for biogas production. However, this is a best-case scenario, and therefore the following scenarios will be orientated closer to the production reality of the country, taking into account only the residues which are already being collected by the farmers, in the manure management systems: uncovered anaerobic lagoon, daily spread, and solid storage. The author assumes that no additional effort will be needed for the feeding of those residues into the biodigester.

6.2.3. *Scenario 3: Residues treated in an uncovered anaerobic lagoon used for biogas production*

For the third scenario, the residues generated in the sub-sectors feedlots and dairy cows, which at the moment are treated in an uncovered anaerobic lagoon, are being considered for biogas production. In the sub-sector feedlots, these residues account for 30% of the total residues, and in the sub-sector dairy cows, they account for 40%.

	Total Methane Emissions (tons/year)	**Total N2O Emissions (tons/year)**	**Total GHG Emissions (tonCO2eq/year)**	**Possible electricity generation (kWh/year)**
Current situation	96,795	1,105	2,749,050	1,772,768,087
Scenario 3	10,850	1,105	600,441	511,561,251
Avoided emissions	**85,944**	**-**	**2,148,608**	**-**

Table 28: Avoided emissions – Scenario 3, own calculation

<u>Feedlots:</u>

Number of animals	**500**	**1000**	**1500**	**2000**	**3000**	**4000**	**5000**
Methane production (m3/year)	7,344	14,688	22,032	29,376	44,064	58,752	73,440
Electricity generation (kWh/year)	21,966	43,932	65,898	87,864	131,795	175,727	219,659
Estimated profit (USD/year)	5,781	11,563	17,344	23,126	34,689	46,251	57,814
M&O Costs (USD/year)	7,344	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(1,563)	(1,187)	2,044	5,276	11,739	18,201	24,664
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	Never	88.1	39.8	23.0	18.1	15.8

Table 29: Economic feasibility for the sub-sector of feedlots – Scenario 3, own calculation

Dairy cows:

Number of animals	**500**	**1000**	**1500**	**2000**	**3000**	**4000**	**5000**
Methane production (m3/year)	7,008	14,016	21,024	28,032	42,048	56,064	70,080
Electricity generation (kWh/year)	20,961	41,922	62,883	83,844	125,766	167,687	209,609
Estimated profit (USD/year)	5,517	11,034	16,551	22,068	33,101	44,135	55,169
M&O Costs (USD/year)	10,625	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(5,108)	(1,716)	1,251	4,218	10,151	16,085	22,019
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	Never	143.9	49.8	26.6	20.5	17.7

Table 30: Economic feasibility for the sub-sector of dairy cows – Scenario 3, own calculation

The calculations show, that although the feed-in with the highest tariff is considered, neither for the feedlots nor for the dairy cows, would an installation of a biogas plant be economically feasible to reach this, higher amounts of residues are necessary.

6.2.4. *Scenario 4: Residues treated in an uncovered anaerobic lagoon and from daily spread used for biogas production*

For the fourth scenario, the residues generated in the sub-sectors feedlots and dairy cows, which at the moment are treated in an uncovered anaerobic lagoon and in the sub-sectors dairy cows and pig industry, which is spread on a daily basis on the field, are being considered for biogas production. In the sub-sector feedlots, these residues account for 30% of the total residues, in the sub-sector dairy cows, they account for 70%, and in the pig industry, 89% of the residues are included in this scenario.

	Total Methane Emissions (tons/year)	Total N2O Emissions (tons/year)	Total GHG Emissions (tonCO2eq/year)	Possible electricity generation (kWh/year)
Current situation	96,795	1,105	2,749,050	1,772,768,087
Scenario 4	10,796	989	564,478	560,045,788
Avoided emissions	**85,999**	**116**	**2,184,571**	**-**

Table 31: Avoided emissions – Scenario 4, own calculation

Feedlots:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	7,344	14,688	22,032	29,376	44,064	58,752	73,440
Electricity generation (kWh/year)	21,966	43,932	65,898	87,864	131,795	175,727	219,659
Estimated profit (USD/year)	5,781	11,563	17,344	23,126	34,689	46,251	57,814
M&O Costs (USD/year)	7,344	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(1,563)	(1,187)	2,044	5,276	11,739	18,201	24,664
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	Never	88.1	39.8	23.0	18.1	15.8

Table 32: Economic feasibility for the sub-sector of feedlots – Scenario 4, own calculation

Dairy cows:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	12,264	24,528	36,792	49,056	73,584	98,112	122,640
Electricity generation (kWh/year)	36,682	73,363	110,045	146,726	220,090	293,453	366,816
Estimated profit (USD/year)	9,655	19,309	28,964	38,618	57,928	77,237	96,546
M&O Costs (USD/year)	10,625	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(970)	6,559	13,664	20,768	34,978	49,187	63,396
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	22.9	13.2	10.1	7.7	6.7	6.2

Table 33: Economic feasibility for the sub-sector of dairy cows – Scenario 4, own calculation

Pig industry:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	28,652	57,304	85,955	114,607	171,911	229,214	286,518
Electricity generation (kWh/year)	85,697	171,395	257,092	342,790	514,185	685,580	856,974
Estimated profit (USD/year)	22,556	45,111	67,667	90,222	135,333	180,445	225,556
M&O Costs (USD/year)	19,210	23,630	25,107	26,584	29,538	32,491	35,445
Annual estimated cash flow	3,346	21,481	42,560	63,639	105,796	147,953	190,111
Investment	226000	278000	295375	312750	347500	382250	417000
Payback period	67.6	12.9	6.9	4.9	3.3	2.6	2.2

Table 34: Economic feasibility for the sub-sector of pig industry – Scenario 4, own calculation

As in the previous scenario, the amount of residues taken into consideration for biogas production from the sub-sector feedlots is too small to be economically feasible. However, considering now not only the residues from the dairy cow sub-sector, which are being treated in an uncovered anaerobic lagoon but also those spread on a daily basis on the land, the installation of a biogas plant is economically feasible with 3000 animals and more. In addition to that, in the pig industry, the installation of a biogas plant, which feeds on the residues of the daily spread, is already economically feasible from 1500 animals.

6.2.5. Scenario 5: Residues treated in an uncovered anaerobic lagoon, from daily spread and solid storage used for biogas production

In this scenario, the biogas production from the residues generated in the sub-sectors feedlots and dairy cows, which at the moment are treated in an uncovered anaerobic lagoon and in the sub-sectors dairy cows and pig industry, which are spread on a daily basis on the field, as well as the residues which are managed in a solid storage in the sub-sectors feedlots, dairy cows and pig industry are taken into consideration. From the sub-sectors feedlots, 90% of the residues are included in this scenario, from the dairy cows 90% and from the pig industry 100%.

	Total Methane Emissions (tons/year)	**Total N2O Emissions (tons/year)**	**Total GHG Emissions (tonCO2eq/year)**	**Possible electricity generation (kWh/year)**
Current situation	96,795	1,105	2,749,050	1,772,768,087
Scenario 5	1,917	429	175,655	1,550,996,382
Avoided emissions	**94,878**	**676**	**2,573,394**	**-**

Table 35: Avoided emissions – Scenario 5, own calculation

Feedlots:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	22,032	44,064	66,096	88,128	132,192	176,256	220,320
Electricity generation (kWh/year)	65,898	131,795	197,693	263,591	395,386	527,182	658,977
Estimated profit (USD/year)	17,344	34,689	52,033	69,377	104,066	138,754	173,443
M&O Costs (USD/year)	22,032	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	(4,688)	21,939	36,733	51,527	81,116	110,704	140,293
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	Never	6.8	4.9	4.1	3.3	3.0	2.8

Table 36: Economic feasibility for the sub-sector of feedlots – Scenario 5, own calculation

Dairy cows:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	15,768	31,536	47,304	63,072	94,608	126,144	157,680
Electricity generation (kWh/year)	47,162	94,324	141,486	188,648	282,973	377,297	471,621
Estimated profit (USD/year)	12,413	24,826	37,239	49,652	74,478	99,304	124,131
M&O Costs (USD/year)	10,625	12,750	15,300	17,850	22,950	28,050	33,150
Annual estimated cash flow	1,788	12,076	21,939	31,802	51,528	71,254	90,981
Investment	125,000	150,000	180,000	210,000	270,000	330,000	390,000
Payback period	69.9	12.4	8.2	6.6	5.2	4.6	4.3

Table 37: Economic feasibility for the sub-sector of dairy cows – Scenario 5, own calculation

Pig industry:

Number of animals	500	1000	1500	2000	3000	4000	5000
Methane production (m3/year)	32,193	64,386	96,579	128,772	193,158	257,544	321,930
Electricity generation (kWh/year)	96,289	192,579	288,868	385,157	577,736	770,314	962,893
Estimated profit (USD/year)	25,343	50,687	76,030	101,373	152,060	202,747	253,433
M&O Costs (USD/year)	19,210	23,630	25,107	26,584	29,538	32,491	35,445
Annual estimated cash flow	6,133	27,057	50,923	74,790	122,523	170,255	217,988
Investment	226000	278000	295375	312750	347500	382250	417000
Payback period	36.8	10.3	5.8	4.2	2.8	2.2	1.9

Table 38: Economic feasibility for the sub-sector of pig industry – Scenario 5, own calculation

This scenario takes into account three different manure management systems, uncovered anaerobic lagoon, daily spread, and solid storage, as possible resources for the biogas production.

Taking into account 90% of the residues generated by the feedlots (those currently treated in an uncovered anaerobic lagoon and those designated to solid storage), the sector already reaches economic feasibility with 1000 animals. The sub-sector of the dairy cows reaches in this scenario economic feasibility already at 1500 animals (half of the animals compared to scenario 4). This scenario also favors the pig industry, improving the payback period for a biogas plant for 1500 animals from 6.9 to 5.8 years.

6.3. Reduction potential through installation of biogas plant

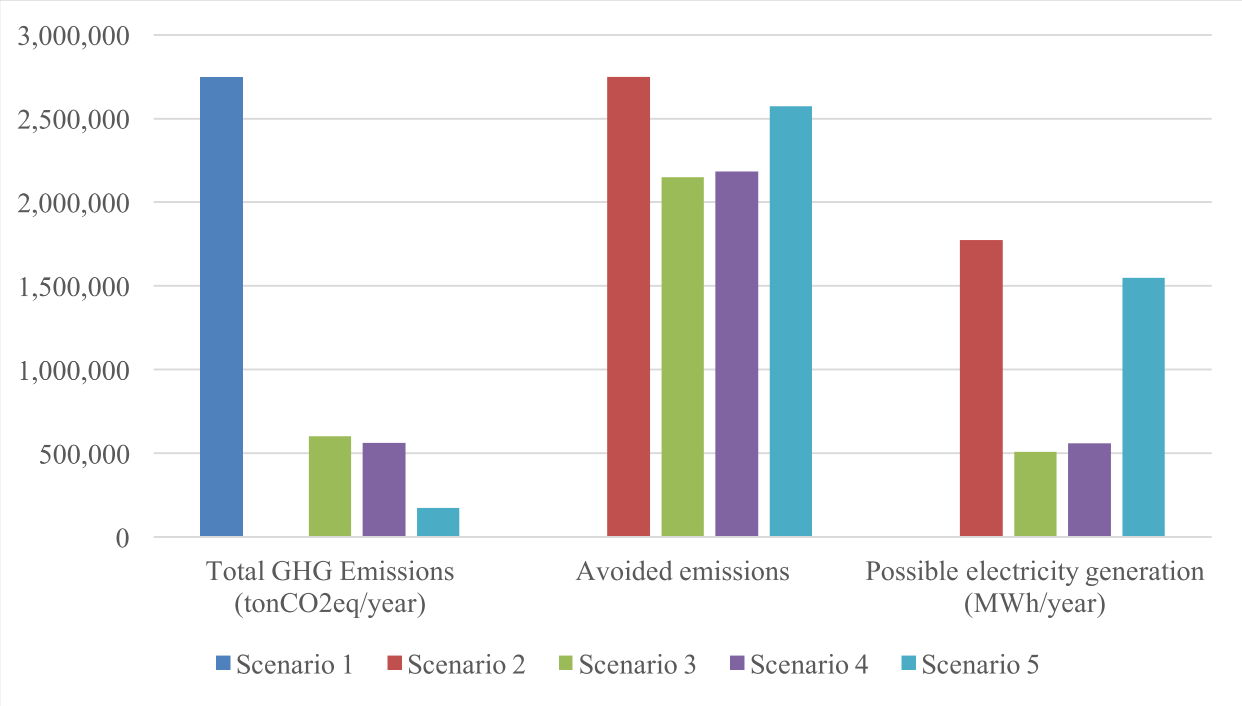


Figure 15: Total GHG emissions, avoided GHG emissions and possible electricity generation for all sub-sectors, own calculation

The installation of biogas plants in the agro-industrial sector has several benefits. The most important are: GHG emissions can be avoided, the residues are energetically valorized through biogas production and the electricity production creates economic profits through net-metering.

The analysis indicates that a change in these sub-sectors is urgently needed to reduce the GHG emissions of the country. The projection of scenario 1 shows that otherwise until the year 2030 the GHG emissions will rise 66% (assuming an annual growth of 2.8%, see 6.1) in comparison to the values of 2015.

After analyzing the different scenarios, it is clear that an installation of a biogas plant is potentially feasible in the sub-sectors feedlots, dairy cows, and the pig industry. The results proved, that the more residues are used for biogas production, the more methane can be produced and consequently, the higher is the electricity generation and the profits from selling electricity to the grid.

However, if the feed into the grid would be for 24 hours/day, the average price per kWh would be 0.1552 USD, resulting in an investment not feasible for the sub-sectors dairy cows and poultry production. By feeding the produced electricity into the grid during the highest tariff (18:00 –

22:00), the economic feasibility improves remarkably in the sub-sectors feedlots, as well as the pig industry and even proves economically feasible for the dairy cows.

This can be seen in scenario 2.2. (all residues are used for biogas production and electricity is fed into the grid at the highest tariff), which avoids the most GHG emissions and generates the most electricity, however, it is also the less realistic option. Scenarios 3, 4 and 5, in contrast, are more realistic, considering that only a part of the residues will be used for biogas production. The scenarios take into account the part of the residues, which is already being collected on the farms, so no additional effort has to be made for feeding the biodigester. Of the before mentioned, scenario 5 has the potential to avoid the most emissions, namely 93.6% of the total estimated GHG emissions (emitted from the current) manure management systems in the selected sub-sectors and produce the most electricity. Estimating the profit generated from net-metering, it is also the scenario with the shortest payback period for all sub-sectors (except poultry production).

Considering the total amount of residues (residues, which cannot be collected (manure left on pasture) and residues, which can be collected) generated in the sub-sector of the feedlots and the total GHG emission of the former, if the scenario 5 would be implemented 36.4% of the GHG emissions can be avoided.

	Total residues of feedlots	Residues with mitigation potential of feedlots
Total Solids (tons/year)	13,773,859	3,396,294
Total CH_4 emissions (tonsCO2eq/year)	2,697,246	2,280,068
Total N_2O emissions (tonsCO2eq/year)	3,617,005	273,555
Total GHG emissions (tonsCO2eq/year)	6,314,251	2,553,623
Avoided emissions (Scenario 5)	-	36.4%

Table 39: Comparison – Feedlots: Total residues generated and residues with mitigation potential, own calculation.

In the sub-sector of the dairy cows, the implementation of the scenario 5, would lead to a reduction of 23.32% of the GHG emissions.

	Total residues of dairy cows	Residues with mitigation potential of dairy cows
Total Solids (tons/year)	1,091,451	125,178
Total CH_4 emissions (tonsCO2eq/year)	143,177.70	104,333.50
Total N_2O emissions (tonsCO2eq/year)	329,463	18,148
Total GHG emissions (tonsCO2eq/year)	472,641	122,482
Avoided emissions (Scenario 5)	-	23.32%

Table 40: Comparison – Dairy cows: Total residues generated and residues with mitigation potential, own calculation.

In the sub-sector pig industry, implementing scenario 5, 80.56% of the total GHG emissions could be avoided.

	Total residues of pig industry	Residues with mitigation potential of pig industry
Total Solids (tons/year)	38,632	31,840
Total CH_4 emissions (tonsCO2eq/year)	2,313.45	1,699.25
Total N_2O emissions (tonsCO2eq/year)	28,595	23,202
Total GHG emissions (tonsCO2eq/year)	30,909	24,901
Avoided emissions (Scenario 5)	-	80.56%

Table 41: Comparison – Pig industry: Total residues generated and residues with mitigation potential, own calculation.

6.4. Discussion

The analysis shows, that there is a high potential for the reduction of GHG emissions in the agro-industrial sector, although, not all residues can be collected an average of 46.76% of the total GHG emissions could be avoided, implementing scenario 5. In addition to that, the installation of biogas plants (implementing scenario 5), can meet the INDCs of Uruguay related to the beef industry. The scenario reduces 76.08% of CH_4 emissions emitted for the sub-sector feedlots, surpassing the goal of 33% per kilogram beef (with domestic resources) and even the goal of 46% (with additional means of implementation), defined in the countries INDCs. However, the reduction goal for N_2O cannot be achieved by the installation of biogas plants in the analyzed sub-sectors. The sub-sector feedlots only achieves a reduction of 6.81% of N_2O (emission reduction goal of 31% per kg of beef defined in the INDCs), the reason for this is that the majority of the residues cannot be collected and is left in the pasture.

Considering the economic aspect, the country implemented the net-metering of electricity produced from biomass with the Decree 173/2010, regulating the energetic valorization of residues through biogas generation. The establishment of a contract for net-metering has several advantages over other incentives, as for example government subsidies for biogas plants. Lessons learned from Germany, and Austria indicate that subsidies do not promote a sustainable development and often the plants were deactivated after the end of the subsidies. Therefore, the decree 173/2010 seems to be a good instrument to incentivize the investment in biogas plants. However, the differentiated price structure encourages the farmers to only feed electricity into the grid, at the time of highest profit. This is beneficial for the farmers, allowing them to generate higher profits and reduce the payback period of the biogas plant significantly, but for the state power company (UTE) this could mean significant losses. Yet, surplus energy could also be sold to neighbors (Argentina and/or Brazil).

Even though the net-metering contract after the initial 10 years, would not allow the feed into the grid only during the highest tariff regime anymore, the investment would still be beneficial for farmers. After paying off the initial investment, the profits would be higher than the costs for operation and maintenance, generating additional income for the lifetime of the plant (between 15 and 25 years).

Moreover, the produced biofertilizer could also constitute an additional income source. The Ministry of Industry, Energy, and Mining (MIEM) is currently working on a law for transporting

the digestate. If this law gets approved, the biofertilizer could be sold on the national market, and therefore be converted to a value-added product, improving the net profitability of the farmers.
Another benefit of the installation of a biogas plant is that the treatment of the agro-industrial residues through anaerobic digestion is a recognized method for soil protection. At the moment, the country is redefining its plans for soil protection, soon the enhanced treatment of residues could become obligatory. This could lead to an additional economic benefit for the owners of biogas plants. Not only could they earn money injecting electricity into the grid, but also by treating manure and other agro-industrial residues of other farmers.
The electricity generation from biomass didn't lead to a reduction of fossil fuels, due to the considerable amount of electricity already generated from renewable sources, accounting for over 90% in Uruguay. Although there is a high reduction potential for GHG emissions implementing the recommended scenario, the installation of biogas plants in the agro-industrial sector of a country with similar economic orientation and lower contributions of RE in its primary energy matrix could additionally achieve a reduction in CO_2 emissions, replacing fossil fuels used for electricity generation.

7. Conclusions and Recommendations

In the government's forecast for the year 2016, renewable energies, mainly hydro and wind, accounted for over 90% in the Uruguayan power sector (MIEM, 2016) which means, that (almost) no fossil fuels will be replaced with the generation of electricity from biomass, resulting in no direct reduction of fossil fuel emissions.

However, the installation of a biogas system has other important functions. Due to the economic importance of the agro-industrial sector in Uruguay, it is almost impossible to mitigate emissions from enteric fermentation. That's why the mitigation of emissions from manure management is even more important. Through the installation of a biogas plant, CH_4 and N_2O emissions can be avoided, lowering the overall GHG emissions of Uruguay and at the same time fulfilling the emissions reduction goals for Methane and contributing to those of Nitrous oxide, defined in the INDCs of the country.

Another significant benefit of the generation of electricity with biogas is the sustainable diversification of Uruguay's energy matrix and its contribution to the energy security of the country. The electricity generated can be used for supplying base load energy, minimizing the risks of electricity production variations of hydro plants or wind parks, due to changing weather conditions. The policies in place create a beneficial environment for the investment in biogas systems, and if the laws concerning environmental protection and digestate transportation are implemented, the investment will be even more profitable.

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