Politecnico di Torino

Master's Degree in Energy and Nuclear Engineering

Master's Degree Thesis

Integrated LCA analysis of food and energy: the case study of milk and biomethane production

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Abstract

In a world in which food and energy needs go on increasing, the development of methodologies that limit the impact of their production is more important every day. A correct evaluation of the impact is fundamental to obtain an actual reduction in emissions from the systems. This thesis presents an integrated Life Cycle Assessment of dairy and biomethane production chains, with the goal of identifying the most influential choices and factors in their Carbon Footprints and exploring how they interact. After an analysis of the relevant regulations, a scenario-based approach was adopted to assess the effects of different farming choices on emissions from the system. The internal subdivision of emissions has been identified as highly influential on the Carbon Footprint of the Products. Particular attention has been given to the role of allocation techniques, with four analysed frameworks (IDF2015, IDF2022, Economic and FAO) applied and compared. Calculations have been performed using OpenLCA Software with the ecoInvent 3.10 database. The analysis of the different scenarios has shown that productivity, feed characteristics, and composition of the herd can be highly influential on the emissions from the dairy cycle, with variations up to over 100% of milk Footprint in the different scenarios. Allocation techniques have proved to be incredibly significant on the impact associated with the various products, with the footprint of milk varying up to 43% inside the same scenario. The allocation effect is limited in the biomethane field, in which there is a detachment from the agronomical practices, with no input emissions from manure following the Renewable Energy Directives. The hypothetical introduction of an input impact associated to manure generated an increase in the final Biomethane Footprint of up to 26% while providing a decrease of Milk Footprint up to 33%. The implementation of anaerobic digestion has shown to reduce emissions from the whole dairy operations by nearly 27% when confronted with the storage on-site and field application of manure. The use of digestate as fertilizer has been found to decrease the emissions of the agronomical system, with a reduction of milk Footprint in the standard scenario between 13% and 18%, depending on the selected allocation method. If considering the Carbon Stock generated with the use of Digestate in the cultivation, the reduction of emissivity by the system increases significantly. The study emphasizes two main conclusions: that agronomic and structural choices in farm management have a fundamental impact on total emissions from the system; and that different allocation methodologies profoundly change the resulting Carbon Footprints of the products. These factors underline how different the emissivity from systems producing the same agronomically originated goods can be, and how the current regulatory frameworks are partially unable to effectively represent the variations. A harmonized and transparent methodology is needed to prevent misleading reductions in product-level emissions and to support more effective strategies for the reduction of emissions in integrated food-energy systems.

Contents

List of Tables

List of Figures

List of Abbreviations

AD	Anaerobic Digestion
AF	Allocation Factor
CH_4	Methane
CO_2	Carbon Bioxide
DM	Dry Matter
FPCM	Fat and Protein Corrected Milk
FU	Functional Unit
GHG	Greenhouse Gas
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LED	Light Emitting Diode
LHV	Lower Heating Value
MED	Medium
NDF	Neutral Detergent Fiber
NOx	Nitrogen Oxides
NTK	Total Kjeldahl Nitrogen
OESFR	Organisation Environmental Footprint Sector Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Category Rules
PR	Parmigiano Reggiano
RED	Renewable Energy Directive
SOC	Soil Organic Carbon
ST	Total Solids
STND	Standard
TOC	Total Organic Carbon
VS	Volatile Solids

Chapter 1

Introduction

The production of biogas from anaerobic digestion has experienced a strong growth over the last 20 years. In the years from 2000 to 2017 the biogas production in the world has more than quadrupled from 78 to 364 TWh [1]. The biggest producers of biogas globally are Europe 54%, Asia 31% and the Americas 14% [2]. The increase in production in Europe was strongly propelled by the incentives policy of the Union, starting with the Renewable Energies Act of 2000 [3]. The obligation for energy supply companies to buy renewable energy at fixed tariffs, combined with strong incentives for energy crops cultivation augmented the sector [2]. As a standard at the time and currently the main technology for the utilization of biogas is the valorisation on site through a CHP (88.5% of total biogas in 2018) [4]. While there has been an increase in number and capacity, Anaerobic digestion plants have undergone a major change in the supply chain. The change has occurred because the substantial utilization of energy crops for the production of biogas pushed by the positive tariffs caused the landscape to change, with the so called “maizification”, an abnormal increase in maize monoculture, not dedicated to feed but to energy [2]. The effects caused by the phenomena on environment and society (an increase in price for food and feed) decreased the beneficial environmental effects of biogas production, leading to the maize-cap. This is one of the measures applied against the indiscriminate use of energy crops, adopted in Germany before the start of 2012. The amendment limited the use of maize and cereal as a substrate for new biogas plants, limiting funding for the projects, to then totally abandon public funding of energy crops in 2014 [5]. The production of biogas in the union has had a decrease in increase around 2017, when the Tariffs ceased [2] and a change in the sector occurred. From energetic crops, the biogas production shifted to the ‘residues’ or wastes (the definition will be fully analysed in the following chapters), intended as organic municipal solid waste, sewage sludge, industrial waste and agricultural residues [6]. The strong increase in the number of new plants running on agricultural residues is pushing the development of the specific technologies and the formation of related supply chains. The animal slurries/manures constitute the majority of the inputs (60% in Italy [7]) for new plants. An outlook on the substrates adopted in new built plants in the EU is presented in figure 1.1 [6]. Since 2020 the use of energy crops in new plants has been limited and as they are not utilizable as the main feedstock in biogas production.

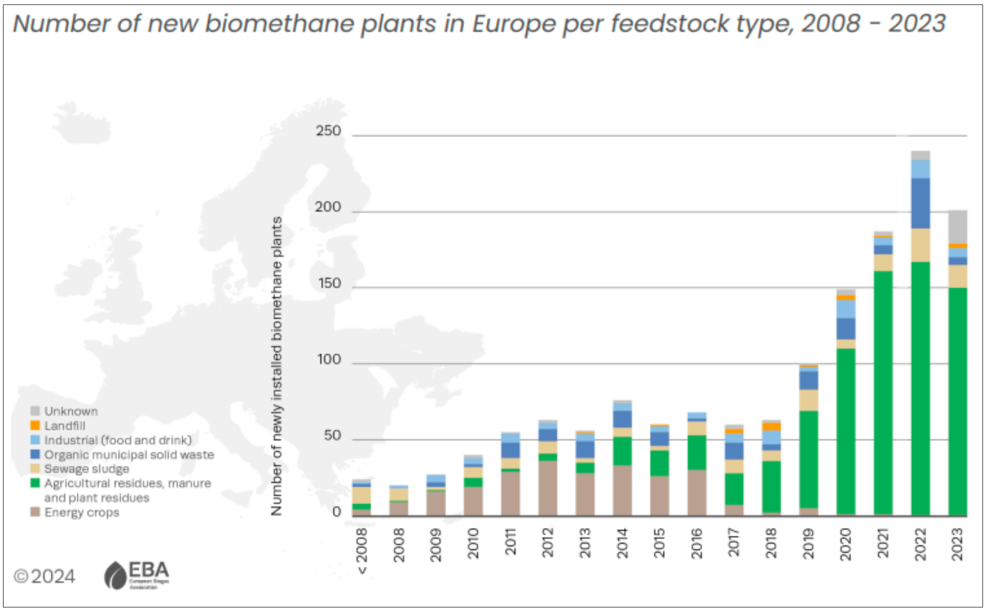


Figure 1.1: Number of new Anaerobic Digestion plants in Europe [6]

In the Italian context the bio energies are in evolution, but still represent a small part of the production [8]. In the production of biogas Italy stands as the fourth worldwide producer, with 2200 operative plants, of which 1730 using agricultural substrates [8]. Biomethane production is still in the initial steps of its progress, with 35 operating plants up to 2022. The productive potential to 2030 is expected to reach 11-13% of the total natural gas consumption in the country [8]. The main producers are Piedmont, Lombardy, Emilia Romagna and Veneto, with Lombardy having the largest capacity 34.6% of total [7]. The production is associated with the high farming activity in the zone, with 65% of total cattle, 78% of poultry and 88% of pigs produced in the territory. The biogas and biomethane production do not only represent a possibility of economic income for the farmers (related to a decrease in costs for manure management, not only to the biomethane production), but is a key option in the reduction of ammonia and general nitrogen emissions [7]. The dairy farming and related processes, on their own, account for around 60% of the total nitrate emissions in Northen Italy [7]. While the whole sector undoubtedly reduces its impact with digestion, the way the reduction affects emissions associated with the farming products and to anaerobic digestion products is extremely variable and dependent on the chosen methodology and conditions. In the general methodology to account for emissions, the nitrates from dairy farming are accounted and related to the products exiting the farms (mainly meat and milk), a reduction of emissions from manure management will lead to a reduction in emissions of the cited products. The entity and proportion of the reduction is not univocally defined. Methodologies to obtain the equivalent CO2 impact associated with the various products of the supply chain are of interest to analyse, trying to highlight the main physical and normative variables that cause the results to vary. In Chapter 2 a first outlook on typical emissivity of Milk and Biomethane (obtained from agronomical inputs) is presented. Then the main regulatory frameworks defining the methodologies of calculation are analysed and compared, highlighting methodological inconsistencies and incongruences.

1.1 Cycle LCA

In the study of the impact related to the production and use of biomethane, an assumption is encountered that connects the production process of biomethane with the agricultural process of cattle farming. The connection is given by the consideration of the input impact related to the manure/slurry used in the digester as null [9] (in the following chapters it will be highlighted how the impact is actually negative, with bonuses linked to the use of manure). This assumption determines a fundamental disconnection between the various agricultural and productive practices in farming and the production of biomethane, thus not taking into consideration the different CO_{2eq} loads that could be associated with the manure input. The study attempts to outline an allocation method more in line with the real energy cycles under analysis and consequently to connect the cycle related to milk production and that related to biomethane production. In carrying out this connection, however, the different regulatory context under which the quantification of the emissions related to milk or biomethane fall must be considered, with methodologies that are defined in different regulatory frameworks. Attention will therefore be directed at obtaining an analysis that best represents the real cycles while still remaining consistent with the emission quantification methods. The definition of the production cycle under examination is presented in Figure 1.2. In this, the most influential input and output flows constituting the cycle are represented. They are not univocal in all situations, and are extremely dependent in quantity and characteristics on the location and agricultural methods adopted. In section 3.1.10 it is better explained for what reasons some inputs and processes theoretically belonging to the system may be ignored in the analysis, in addition to a more specific analysis of the same. The system consists of two main production processes that can be summarized as "Dairy Farming" and "Anaerobic Digestion", followed by the processes of cleaning and upgrading of biogas. The manure/slurry constitutes the connection between the two parts of the cycle, being a product of the farming phase and a raw material of the anaerobic digestion phase. This does not only constitute the meeting point of the two systems, but also goes on to define the connection between two different regulatory contexts. In food production, in fact, the guidelines of the PEF methodology [10] are followed, while for biofuels a different regulatory framework is referred to, defined in the RED2 directives [9]. The two regulatory systems and the possibility to relate them consistently are studied in the following chapter. The aim of the study is to evaluate the environmental impact of the various products in the considered cycle, understood as kg of CO_{2eq} relative to the functional unit of product. Other aspects of environmental impact are consequently left aside as they are not the subject of the study, although they may be influential on the feasibility of implementing the cycle and on the actual environmental impact of the same, not exclusively dependent on CO_{2eq}. The allocation among the various products of the emissions deriving from the farming phase represents one of the main factors under analysis.

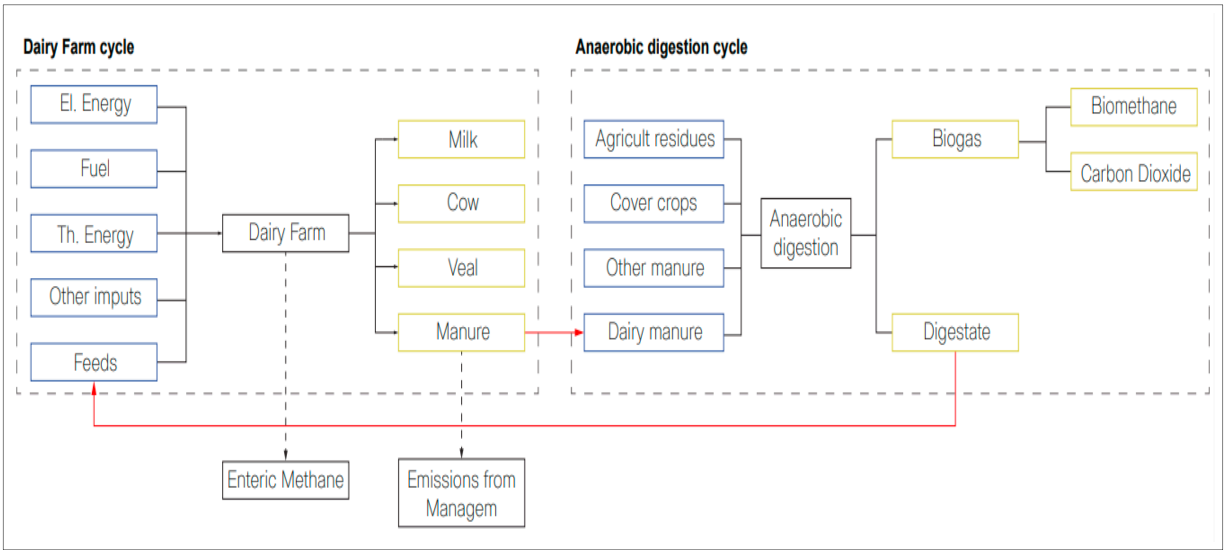


Figure 1.2: Representation of main involved flows and processes

Chapter 2

LCA studies

In the chapter, an outlook on the state of the art of the study on the emissivity of Milk and Biomethane is presented, and then the analysis of the regulations themselves is addressed.

2.1 LCA of Milk

The Carbon Footprint of milk is a fundamental information for consumers [11] and market entities. The determination of the footprint is though characterised by many variables which can strongly influence the final results. With a market so expanse and globalized it could be expected to have stable and strong methodologies for dairy farming, standardized and characterized by very similar methodologies. The situation is different, with very strong variability of expected emissions based on geography and connected techniques. The dairy farming practices strongly vary based on the socio-economic situation in which they are implemented: in Europe and Usa it is expected to have high yielding cows (over 9000kgmilk/year [12]) in high density intensive farms, while in south America, for example, a medium yielding system is expected (around 6000 kgmilk/year [13]) but characterized by increased grazing activity and less concentrated feeds [14], characteristics that, as will be analyzed in the following chapters can be extremely influent on Milk Footprint. Not only the agronomical techniques influence possibly influence the Footprint, the methodology with which it is calculated strongly influences its value. Already in 2011 there are studies pointing out how a standardized methodology is fundamental to give the possibility to compare the different footprints [15]. Many evolutions have been implemented to try and standardize the PEF methodologies, for milk in particular (analyzed in paragraph 2.3.1) however, despite four decades of development [16], the methods lack of a fully harmonized approach. The hypothesis and choices that the analyzer implements united to the data used can lead to different results from the same subject matter [a critical review]. Even if the problem has been cited many times, not many comparative studies have been performed, especially if compared to beef [14]. The study from Mazzetto et all [13] tried to compare various studies considered as representative for the milk pef in many countries. The results are presented in figure 2.1 [13] and confirm the great variability in results.

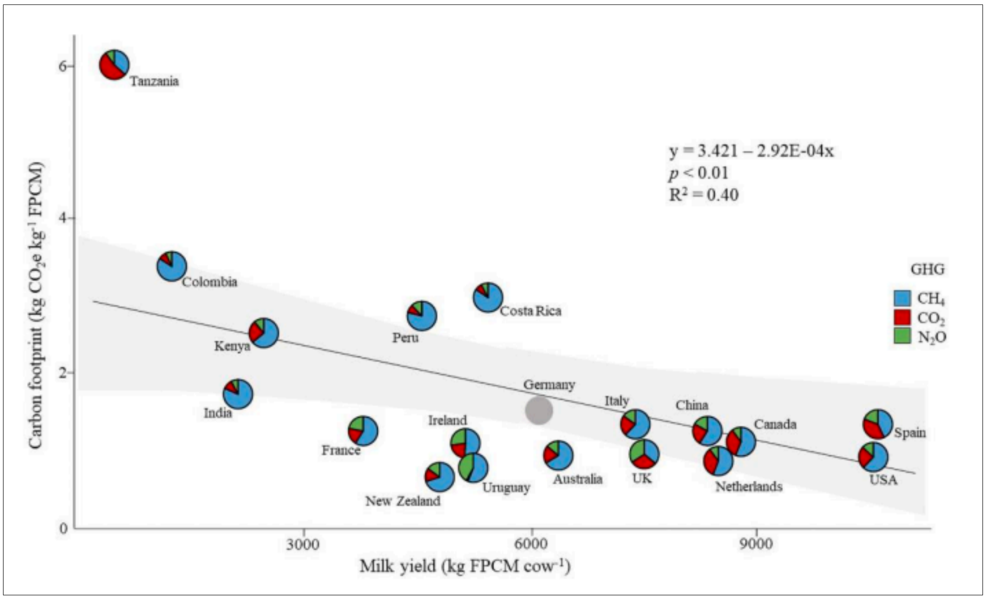


Figure 2.1: Variability of Milk CF [13]

The trend expected, knowing the PEF bases is that with the increase in production of the FU, the pef associated at that product, produced by the same system, should decrease. Translating it to the analyzed situation the emissivity of the single kg of milk should decrease with the growth in production by the cow. In figure 2.1, the results do not follow the expected trend, at least not in a statistically acceptable range. It is interesting to notice how, for the same production of around 5000 kgfpcm/year, the emissivity from the Uruguayan studies is less than one third of the ones from Costa Rica or Peru, even if the farming organization is not expected to be very different. In the division between the 3 considered polluting gasses contribution the differences are even greater, with a noticeable difference in the attribution of emissions from many states. This factor highlights how the standardized methodologies are still extremely dependent on national assumptions and general data estimation and collection, united to the allocation methodology implemented [13]. It is then of interest to perform an analysis that considers the different methodologies of allocation that can be implemented and how different agricultural techniques interact with them. In fact the many different methodologies to calculate the carbon footprint are expected to be differently perturbed by a change in the inputs, generating an inconsistency.

2.2 Emissivity of Biomethane

The definition of the Footprint connected to a determinate way of producing biomethane is incredibly important in the definition of how much the use of the biomethane decreases emissions compared to the use of the same quantity of natural gas [17]. As will be analysed in the following paragraphs that is the main objective when defining the footprint from bio-fuels in the European Union. The emissions from Anaerobic Digestion are strongly dependent on different factors as: substrate selection, pretreatments, technology and operational practices chosen, other than production scale and design [18]. As for Milk also for Biomethane the allocation methodologies strongly impact the emissivity of Biomethane, with Digestate being an important co-product if used in agriculture [9]. In any case many studies attest emissivity from Biomethane to be in the order of grams or tens of grams of equivalent carbon dioxide for MJ [18] [19]. The results are confirmed in RED 2-3 standard emission factors, with biomethane from maize stovers as as example, example, varying from 73 to 30 gCO2eq/MJ depending on digestion technology and digestate post treatment [9]. The substrate selection has a greater influence than it would for a standard LCA study: the incoming biomasses do not only directly influence the emissions with their associated impacts and contributions to the processes, but are characterised by different possibilities for bonuses and credits [9]. In this sense the utilization of manure as a substrate acquires an important role, having an associated bonus of 45g of CO2eq/MJ manure (the bonus will be analysed and recalculated during the development of the thesis). The presence of a negative CO2 input opens to the possibility to have a total negative Footprint for Biomethane. Typical values allocated to Biomethane from digestion of pure manure are presented as negative in RED2, with a value of −100gCO2/MJ biomethane for the best possible technology. The digestion of manure is though rarely performed as single substrate and is usually characterised by a mix of biomasses [20]. Based on the manure content of the mix and the characteristics of the cycle adopted, as the treating of digestate [20], the emissivity of biomethane can be expected to be negative [9]. In any case manure origin and characteristics and the agronomical practices from which it is generated are not a matter of study, as the value associated to its utilization is directly defined in the normative. In the progress of the study the eventual effects that the variation of manure impacts could have on the final emissivity by biomethane is analysed.

2.3 Emissions from the farming side

In the paragraph, the methodology to follow in the quantification of the impacts of the farming phase of the cycle is treated. The procedures for this purpose could be countless, for this reason in 2013 the Commission issued Recommendation 2013/179/EU [10] to promote the use of common methods to measure and communicate the environmental performance of the life cycle of products and organizations. In the pilot phase, the elaboration of specific rules for product (Product Environmental Footprint Category Rules, PEFCR) and for sector (Organisation Environmental Footprint Sector Rules, OEFSR) was experimented, resulting in the drafting of 19 PEFCR and 2 OEFSR [21]. The results of the pilot phase were presented in the 2019 Commission staff working document «Sustainable Products in a Circular Economy — Towards an EU Product Policy Framework contribution to the Circular Economy» [22]. In the same working document, possible uses of the environmental footprint methods in the development of policies at EU level are also indicated. The European Green Deal [23] aims to mobilize industries for a clean and circular economy and underlines that, to enable buyers to make more sustainable decisions and reduce the risk of greenwashing, reliable, comparable and verifiable information is necessary. In the communication «A new Circular Economy Action Plan. For a cleaner and more competitive Europe» [24], the Commission underlined the need for companies to provide further elements in support of their environmental claims, using «the so-called methods to measure the environmental footprint of products and organisations», and committed itself to testing the integration of these methods into the EU Ecolabel.

2.3.1 Regulatory framework for the evaluation of CF in the Dairy sector

Numerous regulations partially or fully deal with the evaluation of the environmental impact in the dairy sector. The regulatory landscape develops in mutual respect of the regulations, which mostly go to define different aspects of the study. The main ones referred to in the study can be divided into two types:

1. General guides for the evaluation of the Carbon Footprint:
    - ISO 1400 series. They constitute the main common rules at international level, with every other regulatory form that must be based on them. They do not have direct references to the dairy industry, but they are limited to establishing a basic normative frame for the definition of footprint. The main ones are:

ISO 14040 [25], establishes the principles of the LCA study and its structure, going to define its constitutive phases (treated in section 2.3.2). However, it does not provide practical-methodological information on the drafting of the same;

ISO 14044 [26], guide to the 4 constitutive phases and to the methodology of communication of the study results. It also gives the method for the evaluation of an LCA study by a third party.

ISO 14067 [27], establishes the guidelines for the actual quantification of the Carbon Footprint.

- Ghg Protocol [28], provides the methodology for almost all the GHG evaluation standards, also giving the bases for the drafting of the ISO standards. An important aspect is the non-limitation to the evaluation of the carbon footprint but rather the possible quantification of every greenhouse gas.
- PEF Recommendations [10], represents the European standard for impact evaluation.

2. Specific guides for the evaluation of dairy products:

   - FOA LEAP, initiative with the aim to improve the livestock sector sustainability giving the access to homogenized methods and datasets. It supplies a number of guides specific for different phases and tipologies of livestock production. The most influent ones in the study are given by: ”Environmental performance of large ruminant supply chains” [29], ”Enviromental performance of animal feeds supply chains” [30], “Measuring and modelling soil carbon stocks and stock changes in livestock production systems” [31].
   - PEFCR Dairy [32], gives a specific vision of how the environmental footprint of products in the sector should be defined. Defines the categories of impact to consider and a set of datasets to use in absence of specific data. It considers a Cradle-to-Grave dairy LCA as mandatory in the definition of the footprint. In the study the LCA will not comprehend all the phases of the life of milk, that is because the aim is to define a possible relation in environmental impacts of the products under exam, not to follow each to its end of life.
   - IDF Global Carbon Footprint standard for the dairy sector [11], analyzes all the dairy value chain, developing in more detail the regulamentory framework for specific situations. Aims to give a unified and more simple method of definition of impacts, ”providing a valuable resource on which then global dairy sector can evaluate, manage and reduce climate impacts in a responsible way.”

3. - IPCC, represents the United Nations entity responsible for assessing the science related to climate change. It redacts regular scientific assessments in which future risks for climate change and possible mitigation options are studied. It doesn't conduct its own research, but produces assessment reports that are neutral, policy-relevant but not prescriptive. The main reports of interest in the study are: “AR6” [33], “2006 IPCC Guidelines for National GHG Inventories” [34], “Refinement to the 2006 IPCC Guidelines for National GHG Inventories” [12].

Different norms and regulations have been implemented in the analysis of the various processes under study, basing tho the framework on the two most specific guides for the goal: PEFCR Dairy [32] and the IDF guide [11]. They both are a development, from the metodological and organizative point of view, of the PEF Raccomandation [10].

2.3.2 Principles and steps of the LCA study

To have a complete study of the environmental footprint 5 principal phases can be detected:

1. Goal definition
2. Scope definition
3. LCI
4. Analysis of impact of life cicle assestment
5. Interpretation and comunication of results

Since the study does not have the objective of drafting a complete PEF analysis, but rather of evaluating the relation between the footprints of the different products under examination, the fifth point is not treated exhaustively. The other phases of the study are addressed remaining faithful to the contents necessary for the analysis, but not in the form that would be required in the case of drafting an official PEF document.

2.3.2.1 Goal definition

Defining the objective is the first step in the study of a PEF, it gives the possibility to understand the general context and to have all the partecipants to the study on the same vision of the analysis. It is important to ensure the coherence between methods and results of the study. The applications and depth of the study have to be detected giving the possibility to select the right limitations in the scope definition phase. To have a complete objective definition the study needs:

- Intended applications;
- Reasons for carrying on the study and context decision;
- Audience;
- Commissioner;
- Verifier;

In Table 2.1, the goal definition of the study is summarized. As this is not a formal PEF document, some details, such as the verifier, are hypothetical and included for illustrative purposes.

Table 2.1: Goal definition of the study

To define	**Definition**
Intended applications	Provide information on product to customer; provide information on relation between products of the cycle
Reasons for carrying on the study and context decision	Necessity to better represent carbon and energy cycles for the considered system
Audience	Technical audience
Commissioner	Politecnico di Torino
Verifier	Independent external verifier, Dr. Ing. Prussi

2.3.2.2 Scope definition

The scope definition consists in the description of the system to analyse in full detail. All technical detail must be evaluated in this phase, accordingly with the goal previously defined. The main passages are the definition of:

- **Functional Unit (FU) and Reference Flow:** Functional Unit represents the reference product: it has to define from the quantity and quality point of view the functions and lifespan of the product under analysis. The reference flow is the base quantity of the product necessary for the function analysed, the number at which all input and output flows will relate to in quantity. A complete analysis of the functional units of the main reference flows in the system is provided in Chapter 3;

- **System Boundary:** defines which part of the LCA of products and what stages and processes belong to the system analysed, that are necessary to comply to the product scope. Some parts of processes can be excluded (following rules treated in section 3.1.10), but a complete justification and documentation is necessary. The boundary is defined following a supply-chain logic, following all the steps in the lifespan of the product, from the acquisition of raw materials to the end life treatment. Co-products, by-products and wastes must be identified. A system boundary diagram is requested in the PEF report, indicating which activities and processes are included and which are excluded from the analysis;

- **Impact Categories:** they cover many aspects of possible impact from the supply chain or the usage of a product. The only category considered in the study is *Climate Change, total (GWP100).* Other impact categories that can be considered in studies are presented in section 2.3.2.4;

- **Additional Information:** All the information on the equipment or materials used that have not been treated should be included. No additional information is provided in the document;

- **Assumptions and Limitations:** to overcome some of the limitations that arise, assumptions will be made. All of limitations and assumptions must be reported transparently and motivated.

1.3.2.3 Life Cycle Inventory

An inventory of all inputs and outputs of material, energy and waste and of all emissions into air, water or soil for all the supply chain is necessary as a basis of the PEF. The flows can be elementary or non-elementary (or complex) flows. For the PEF study it is required for all complex flows to be modelled up to elementary flows level apart from the product flow for the product scope. The life cycle is divided in stages, the default ones are:

1. **Raw material acquisition and pre-processing**: The acquisition of all materials, pre-processing (including production of parts and components) have to be included in the stage. It is comprehensive of all the processes that go on before the products components enter through the gate of the production facility, including the eventual transport to the facility. All inputs and outputs are studied in Chapter 3.

2. **Manufacturing**: The stage begins in the moment in which the components enter the production site and end when the finished product leaves the production site. The manufacturing wastes has to be included in the stage, applying the circular footprint formula. The transport of semi-finished products is included in this phase of Life cycle inventory.

3. **Distribution**: It comprehends all the supply chain that is included between the output from the factory gate and the entry in the consumer home. It also has to include the losses in the process, default rate losses during distribution and storage and at the consumer.

4. **Use**: The use is the functional phase of the product, it starts at the beginning of use and ends when the product leaves its place and enters the End of Life stage. In absence of other information the standard use is considered following the manufacturer indications of use. It includes all additional products, activities and energy expenditures necessary for the utilization. All wastes generated are part of the End of Life stage (like the water used to boil pasta). Many processes can be involved in the use of a product, but attention must be put on the distinction between product independent processes and product dependent processes. The first are not influenced by the product (energy to boil half litre of water to have a tea) and should be excluded from the boundaries of PEF studies, with just a qualitative characterization. Product dependent processes must be described and quantified, because they are strictly influenced by the characteristic of the single product (an example is that different kinds of pasta, produced by the same producer, although are comprehended in the same subgroup have different cooking times, therefore having different energy consumptions). Another important factor in analysing the use of a product is given by the consideration of only the components relative to the main function of a product (main function approach) or taking into account all the impacts that the use of the product could have on other products (delta approach). Considering only the energy necessary to heat a cup of milk is the main function approach, while considering the impact of the subsequent cleaning of the mug represents the added delta impact. All the impacts more than the one caused by only the actuation of the principal function are considered inside the delta.

5. **End of life**: The stage includes all the actions and consumptions that bring the product from the end of use from the user to be returned to nature or enter another product production cycle. The recovery and transportation from the user location to the recycling or dismantling facility have to be included. This stage should be excluded for intermediate products.

These phases constitute Cradle to grave LCI, but in the analysis of dairy products *"Depending on the scope, in some cases life cycle stages can be omitted from the CF study"* ([11], p.29). It is then possible to define an inventory that is defined as "Crade-to-Farm Gate", which will comprehend only the stages up to milk collection in the farm, not considering the following distribution and usage phases. An even stronger limitation of the considered phases is given by the "Gate-to-Gate" approach, in which just the phases strictly executed on farm are studied. The chosen method is the last, this will limit the data about the actual environmental impact of the product life (intended as the single case product), but is useful in the case in consideration, in which the focus is on the relation between the different co-products of the farming side of the system. This consideration gives the possibility to detach the analysis from the different variables specific to single situations and try and give a general outlook.

2.3.2.4 Impact Evaluation

Once the emissions and resources associated with the life cycle of a product are compiled and documented in the **Life Cycle Inventory**, an **impact assessment** can be performed, in general cases considering three main areas of protection: *human health*, *natural environment* and issues related to *natural resource use.*

Impact categories typically included in a Life Cycle Impact Assessment are **climate change**, **ozone depletion**, **eutrophication**, **acidification**, **human toxicity** (cancer and non-cancer related), **respiratory inorganics**, **ionizing radiation**, **ecotoxicity**, **photochemical ozone formation**, **land use**, and **resource depletion** (materials, energy, water).

The emissions and resources of the inventory are assigned to each impact category and then converted into quantitative indicators using characterization factors. The categories presented have an associated characterization factor related to the quality of indicator: *"Level I"* (recommended and satisfactory), *"Level II"* (recommended but in need of some improvements) or *"Level III"* (recommended, but to be applied with caution). *"Interim"* indicates that a method was considered the most promising among others for the same impact category, but still immature to be recommended. This does not indicate that the impact category would not be relevant, but that further efforts are needed before any recommendation can be given [35]. In table 2.2, extracted from [35], some of the main categories are presented.

Table 2.2: Some of the main ILCD2011 impact chategories

LCIA method Rec	**Level**	**Flow property***	**Unit group data set (with reference unit)**
Climate change; midpoint; GWP100; IPPC2007	I	Mass CO2-equivalents	Units of mass (kg)
Climate change; endpoint - human health; DALY; ReCiPe2008 interim	interim	Disability Adjusted Life Years (DALY)	Units of time (a)
Ozone depletion; midpoint; ODP; WMO1999	I	Mass CFC-11-equivalents	Units of mass (kg)
Cancer human health effects; midpoint; CTUh; USEtox II/III	II/III	Comparative Toxic Unit for human (CTUh)	Units of items (cases)
Non-cancer human health effects; midpoint; CTUh; USEtox II/III	II/III	Comparative Toxic Unit for human (CTUh)	Units of items (cases)
Non-cancer human health effects; endpoint; DALY; USEtox interim	interim	Disability Adjusted Life Years (DALY)	Units of time (a)
Ionizing radiation; midpoint - human health; ionising radiation potential; Frischknecht et al. (2000)	II	Mass U235-equivalents	Units of mass (kg)
Ionizing radiation; midpoint - ecosystem; CTUe; Garnier-Laplace et al (2008) interim	interim	Comparative Toxic Unit for ecosystems (CTUe) *	Units of volume*time (m3*a)
Ionizing radiation; endpoint- human health; DALY; Frischknecht et al (2000) interim	interim	Disability Adjusted Life Years (DALY)	Units of time (a)

Table 2.2 –

LCIA method Rec	**Level**	**Flow property***	**Unit group data set (with reference unit)**
Photochemical ozone formation; midpoint - human health; POCP; Van Zelm et al. (2008)	II	Mass C2H4-equivalents	Units of mass (kg)
Eutrophication terrestrial; midpoint; Accumulated Exceedance; Seppala et al.2006, Posch et al 2008	II	Mole N-equivalents	Units of mole
Eutrophication marine; midpoint; N equivalents; ReCiPe2008	II	Mass N-equivalents	Units of mass (kg)
Eutrophication freshwater; endpoint; PDF; ReCiPe2008 interim	interim	Potentially Disappeared number of freshwater species * time	Units of items* time (1*a)
Ecotoxicity freshwater; midpoint; CTUe; USEtox II/III	II/III	Comparative Toxic Unit for ecosystems (CTUe) *	Units of volume*time (m3*a)
Resource depletion-mineral, fossils and renewables; midpoint; abiotic resource depletion; Van Oers et al (2002)	II	Mass Sb-equivalents	Units of mass (kg)

Although many of these categories affect the environmental impact of the products in the analysed system, they will not be considered in the study. As stated in previous sections, the only impact category considered is **Climate Change, GWP100**, representing the Global Warming potential in a span of 100 years from emission. To obtain it the data of the different emitting substances are converted by multiplying the emission for single substance with the relevant impact characterization factor (principal of interest presented below). Summing all the equivalent CO_2 and dividing it by the number of functional units produced generates the final Carbon Footprint. The GWP factors have evolved in the last couple of decades, changing value in different studies. The most recent are presented in “The physical science basis” volume of IPCC 2021 report on climate change [36] and reported under:

- 1 kg of fossil CH_4 (CH_4 fossil) = 29.8 kg of CO_2 e
- 1 kg of non-fossil CH_4 (CH_4 non-fossil) = 27.0 kg of CO_2 e
- 1 kg of N_2O (N_2O) = 273 kg of CO_2 e

Outside of the Climate Change GWP100 the main other impact categories affected in the cycle are [11]:

- Ecotoxicity, freshwater
- Particulate matter

- Acidification
- Eutrophication, terrestrial
- Eutrophication, marine
- Resource use, fossils
- Water use

2.4 Methodology for the calculation of Biomethane Footprint

2.4.1 The Renewable Energy Directives

One of the main points of interest for European decarbonization is the energy production system. It accounts for the majority of the GHG emissions in Europe, as shown in figure 2.2, referred to emissions in 2019. The percentage in the picture considers the emissions from transport sector included in the energy and accounting for roughly one third of total emissions of the sector [37].

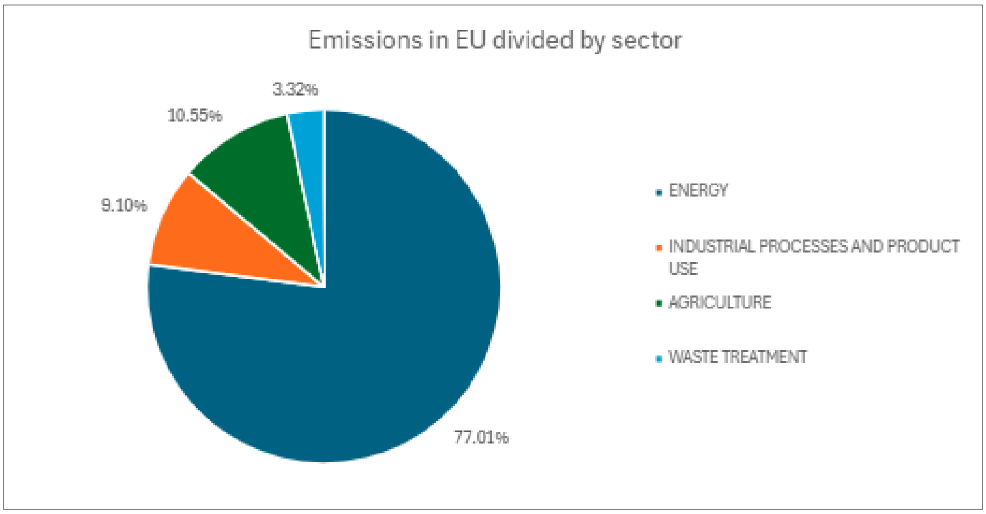


Figure 2.2: GHG emissions in EU, divided by sector (2019)

It has become increasingly important to reduce emission related to the energetic sector, with various directives implemented during the course of the last decades. The normative background is in constant evolution, trying to follow the newest and most accurate scientific considerations. The increase in renewable energy production has been identified as the key to the achievement of the reduction in GHG gasses emissions. To impose and incentivize emission reduction the Renewable Energy Directives have been developed. RED 2 (2001/2018 [9]) imposed that the share of renewable energy in Europe final gross consumption of energy had to be at least equal to 32% in 2030. The review of the directive (2413/2023 [17]) has moved the minimum share to reach by 2030 to 42,5% , with the collective commitment from the Member countries to try and reach 45% [17]. In any case the share of renewable energy has to be kept over the baseline indicated in the third column of the table shown in table 2.3 [9].

Table 2.3: Share of energy from renewable sources in gross final consumption

Country	Share of energy from renewable sources in 2005 (%)	Target for share of energy from renewable sources in gross final consumption of energy, 2020 (%)
Belgium	2,2	13
Denmark	17,0	30
Germany	5,8	18
Greece	6,9	18
Spain	8,7	20
France	10,3	23
Italy	5,2	17
Netherlands	2,4	14
Portugal	20,5	31

To perform the calculation of the share of renewable energy the gross final consumption from renewable is considered as the sum between:

- Gross final consumption from renewable electricity, quantified as the total renewable electric energy produced in the Member country;
- Gross final consumption from renewable in cooling and heating;
- Final consumption of renewable energy in the transport sector, the standard values on the energetic content for transport fuels are considered in calculations.

In plants that use different fuels, some of which are renewable, the renewable share will have to be assessed considering the energetic content of the different fuels and dividing accordingly the electricity generated [9]. In any case all definitions and methodology for the calculation of the shares are provided in Regulation N 1099/2008 [38].

The transport sector is also addressed independently at the regulatory level due to its specific characteristics regarding emissions. In this case between the first publication of RED II in 2018 [9] and the 2023 modifications [17] the rules have changed, with a differentiated approach to the emission reduction. In the RED II original version the only interest was on the share of renewable energy out of the total energy dedicated to transport, that was imposed to be at least of 14% in 2030. The amendment to the Directive gives instead two different possibilities one of wich has to be ensured by 2030:

- A minimum share of 29% for renewable energy in transport; or
- A minimum reduction of greenhouse gas intensity of at least 14,5% compared to the baseline.

The introduction of the second condition gives the possibility to distinguish the actual effects on emissions of different renewable fuels added to the mix. The biogas injected in the national net may be considered in the calculations, even if the final use is unknown [17].

2.4.2 Emission equation

Many factors account in the emissions for the production of biomethane. Equation 2.1 from the RED appendix VI [9] gives the possibility to evaluate the emissions of CO_2 connected with the product. **E** represents the emissivity of the biomethane, intended as $kgCO_2eq/MJ$.

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{cc} \tag{2.1}$$

In the context under investigation this equation is slightly modified, with a weighting factor referred to the various biomass composing the substrate for anaerobic digestion. The evolved equation is studied in Chapter 3. An outlook on the various factors affecting the contributions to the equation is now presented.

2.4.2.1 Extraction or cultivation of the raw material IMM

e_{ec} represents the emissions generated in extraction or cultivation of the raw material. The value can be directly calculated or estimated in different ways depending on quantity and quality of data available. The EU countries can present relations on the evaluation of the typical GHG gasses emissions for the different cultivations on the territory. The data must be referred to an area classified as level 2 or 3 following the nomenclature of territorial units for statistics. The NUTS levels are defined in article 3 (2) of Regulation (EC) No 1059/2003 (updated in January 2024) [39], the division is shown in Table 2.4, the population is intended as stationary resident on the territory.

NUTS level	Minimum population	Maximum population
1	3 million	7 million
2	800,000	3 million
3	150,000	800,000

Table 2.4: NUTS levels and relative population ranges

To accept the values the methodology and data used must be indicated in the study and compliant with regulations, including at least information on the soil, the climate and the expected raw material yield. For territories outside the European Union the values can be accepted but the data has to follow the same rules and be referred to a territory with a maximum of 3 million residents. To adopt the data the reports must pass the examination procedure described in article 5 of EU regulation 182/2011 [40]. After a positive vote from the committee they can be used in emissions evaluation.

In any case the default values provided in annex VI par C of the directive 2018/2001 of the EU parliament [9] and presented in figure 2.3 can be implemented in calculations. The emissions for cultivation or extraction have to include the emission from the actual extraction or cultivation process, the harvest, drying and storage of materials besides losses and waste generated. If in both the default values and eventual relations the data needed is not available, a mean value of the data from a group of local farms can be implemented in the calculation.

Biomethane production system	Technological option		TYPICAL VALUE [g CO_2eq/MJ]						DEFAULT VALUE [g CO_2eq/MJ]					
			Cultivation	Processing	Upgrading	Transport	Compression at filling station	Manure credits	Cultivation	Processing	Upgrading	Transport	Compression at filling station	Manure credits
Wet manure	Open digestate	no off-gas combustion	0,0	84,2	19,5	1,0	3,3	– 124,4	0,0	117,9	27,3	1,0	4,6	– 124,4
		off-gas combustion	0,0	84,2	4,5	1,0	3,3	– 124,4	0,0	117,9	6,3	1,0	4,6	– 124,4
	Close digestate	no off-gas combustion	0,0	3,2	19,5	0,9	3,3	– 111,9	0,0	4,4	27,3	0,9	4,6	– 111,9
		off-gas combustion	0,0	3,2	4,5	0,9	3,3	– 111,9	0,0	4,4	6,3	0,9	4,6	– 111,9

Figure 2.3: Default and typical values for different techniques of Biomethane production [9]

In which for **'no off-gas combustion'** the categories of technologies for biogas upgrade considered are: Pressure Swing Adsorption (PSA), Pressure Water Scrubbing (PWS), Membranes, Cryogenic, and Organic Physical Scrubbing (OPS). With **off gas combustion** the technologies for upgrade considered are: Pressure Water Scrubbing (PWS) when water is recycled, Pressure Swing Adsorption (PSA), Chemical Scrubbing, Organic Physical Scrubbing (OPS), Membranes and Cryogenic upgrading. In the first case an emission of 0,03 MJ CH_4/MJ in the off gasses is considered, in the second, burning them, there is no residue.

2.4.2.2 e_l, annualized emission from carbon stock changes caused by land use change

El represents the total carbon stock delta over 20 years divided by the years. It can be quantified using Equation 2.2

$$e_l = (CS_R - CS_A) \cdot \left(\frac{3{,}664}{20 \cdot P}\right) - e_b \tag{2.2}$$

Where:

CS_R, represents the carbon stock in tonn per surface unit associated to the destination of use the terrain had in -January 2008 or 20 years before the raw material collection, if after 2008;

CS_A, represents the actual stock of carbon in the soil. If the stock increases for a period longer than one year, the value after 20 years or at the maturation of cultivation can be estimated, based on the shorter of the two;

P, yield. Intended as the quantity of energy obtained by the fuel on the surface unit every year;

e_b, bonus of 29 g CO_2eq/MJ if the cultivation recovered degraded terrains. Those can be terrains that were not cultivated in January 2008 or highly degraded soils, having very high salinity, very low organic matter or with very high erosion. The bonus decurrs after 20 years of cultivating.

The method to implement to define the carbon stock in the soil is described in point 5 of EU Commission decision (2010/335/UE). The rule to apply is:

$$CS = (SOC + C_{VEG}) \cdot A \tag{2.3}$$

In which:

CS is the carbon stock per unit area;

SOC is the Soil Organic Carbon (mass of C per hectare);

$\mathbf{C}_{VEG}$ represents the carbon stock from vegetation both above and beneath the ground;

A is a factor scaling the area considered to hectars.

The definition of cultivated land follows the IPCC principles [41].

2.4.2.3 e_p, emission from production

To define the emissions generated during the actual production process of the biogas Equation 2.4 can be considered. External to the standard factor but to consider in the production of the biomethane for transportation are the emissions related to upgrading and compression of the gas, indicated as e_{up} and e_{comp} in Equation 2.5.

$$e'_p = e_{process} + e_{leak} + e_{waste} + e_{chem} \tag{2.4}$$

$$e_p = e'_p + e_{up} + e_{comp} \tag{2.5}$$

In the factor e_{chem}, all the emissions from chemicals and other substances in the process are evaluated, considering as emitted as CO_2 all Carbon from fossil origin, even if it is not combusted in the process. The electricity needed by the process, in the case it is not produced locally inside the plant, can be assumed with emissions equivalent to the medium emission for electricity from the net in that zone.

2.4.2.4 e_{td} emissions from transport and distribution

Emissions from transport and distribution comprehend all the transport processes of intermediate products and the end product, starting from the process start. The transport and distribution emissions on the agricultural side or, in general, connected to the sourcing of raw materials has to be considered in e_{ec}.

2.4.2.5 e_u emission for fuel use

The fuel use emissions account for the impact from fossils used in the production. The emission evaluation should comprehend the three main GH gasses, being CO_2, CH_4 and N_2O. They have to be considered in proportion to the effects, defined by [28](treated in 2.3.2.4). For what concerns the biomass based fuels the emissions from combustion are considered to be 0 [9].

2.4.2.6 e_{sca}, emission savings from soil carbon accumulation via improved agricultural management

The factor accounts for the change in the management of agricultural land and activities. Increasing carbon stock in soil is one of the methodologies pushed by the European Union to remove and store some of the atmospheric CO_2. Many techniques have been developed and considered to have a positive impact on carbon stock, some of the most influent are presented in Table 2.5

Table 2.5: Soil management techniques and their effects

Technique	**Effects**
Pasture management	More biomass production, less soil erosion
Grazing management	More biomass production, less soil erosion
Cover crops	More biomass production, good ground cover, less soil erosion
Pasture cropping	More biomass production, less soil disturbance
Adding Carbon rich materials	Addition of organic matter
Stubble retention	Less biomass reduced, surface protected by residues from erosion

Implementing these techniques is not sufficient to quantify the e_{sca} factor. Solid evidence has to be presented proving the soil carbon has increased or is expected to in the cultivation period of the raw materials. Measurement of soil carbon as presented in Section 1.4.2.2 can be used as evidence. Measurements should be taken before cultivation starts and at regular intervals throughout the years. An estimation can be performed before the second measurement, based on representative experiments or soil models. In the European Directives [9], Anaerobic Digestion is recognized as a positive practice, causing a reduction in emissions with respect to the standard methods implemented to treat manure. A bonus is therefore assigned to manure undergoing Digestion. It consists of -45g of CO_2eq/MJ manure to be added in e_{sca} factor. An outlook on the effects and reasons that characterize the bonus is presented in Chapter 4.

2.4.2.7 e_{ccs}, emission savings for geological capture and storage

Quantifies the savings in CO2 emissions for geological storage related to the extraction, transport, processing (if not accounted in ep factor) and distribution of biomass fuel. To be acceptable in the factor the capture and storage should respect the rules imposed by the Directive 2009/31/EC [42].

2.4.2.8 e_{ccr}, emission savings from CO2 capture and replacement

It refers directly to the process of production of the biomass fuel under investigation. It quantifies the avoided emissions due to CO2 capture of biomass originated Carbon that is substituting the CO2 generated by fossil Carbon used to produce commercial products and services.

2.5 Relation between the normative

Both the [10] and the directive RED 2 [9]/3 [17] explain the methodologies for the emission quantification connected to a certain product. The RED 2 is only specific to fuels or, more in general, energy carriers. To obtain a combined LCA study, considering all the different products, the possibility of complying with the rules of both norms has to be studied. Although the methodologies consider a similar range of aspects, different approaches to situations are presented. The analysis has the goal to find the methodology that, for the specific situation, better complies with the rules, or that represents in the best way the situation. For this reason various options of analysis will be presented for the fundamental points, to then judge the effects of different operative behaviors on the final output. It is important to underline how similar the methodologies are, with the main points of disagreement being given by the different goals the rules have. In the next paragraphs a brief analysis of the main difference points is presented. It is important to highlight how some of the differences are conceptual and modify the operating behavior, others are not influential on the final output in numbers but are important to consider for other aspects.

2.5.1 Legislative aspect

The methodologies for PEF definition are displayed in the Recommendations 2021/2279. It is a non-legislative act that in Art 1.3 states: *'This Recommendation does not apply to the implementation of EU mandatory legislation that foresees a specific methodology for the calculation of the life cycle environmental performance of products or organizations. This Recommendation may however be referred to by EU legislation or policy as a method for the calculation of the life cycle environmental performance of products or organizations'*([43], p.4). Although it poses some strong bases, the PEF recommendation can be modified through the PEFCR's as already presented in Section 2.3.1 or in general with any other regulatory specific. In fact the 'recommendations' fall under the Non-legislative acts of EU. The RED Directives, on the other hand, are Legislative acts and cannot be ignored, they constitute a part of the EU binding laws. The power of the two regulatory frameworks is then different, making clear that, in case of a disagreement between the two, the RED 2 has to prevail. In general, legislative acts create the core of EU law and are adopted through a democratic process involving both the Parliament and the Council, whereas non-legislative acts are more procedural and detailed, ensuring that the laws are correctly implemented and applied.

2.5.2 Purpose of implementation

The difference in the regulative role is highlighted by analysing the goals of the texts. While for PEF Recommendation the goal is to *'promote the use of the Environmental Footprint methods in relevant policies and schemes related to the measurement and/or communication of the life cycle environmental performance of all kinds of products, including both goods and services, and of organizations.'* ([43], p. 3). For the RED Directives the goal is to establish a mechanism to *'implement strategies and measures designed to meet the objectives and targets of the Energy Union and the long term Union greenhouse gas emissions commitments consistent with the Paris Agreement, and for the first ten-year period, from 2021 to 2030, in particular the Union's 2030 targets for energy and climate'* ([44], p. 13). The first is addressed to any organization or country to give the possibility to establish the life cycle performance of the intended product, just with the scope of measurement, or to communicate the results publicly or privately. The evaluation of the product PEF is performed to obtain different forms of certifications, which can have practical outcomes, first of all from the incentives point of view. The RED, on the other hand, sets binding targets to respect. The different goals will give a different approach to the frameworks. The RED is in fact based on the comparison between the standard emissions from a traditional fuel and the emissions of the new production system or fuel. The PEF Recommendations do not push for a change in the product's life cycle, just attest what the environmental impacts are, while in RED a change is promoted, not just on a regulatory basis, but laying down the rules for financial support of improved techniques.

2.5.3 The multiplicative factors

The Carbon Footprint obtained through the PEF methods is performed by trying to comply with the actual physical relations in place. The final footprint depends on the total impact of the system and the eventual allocation strategies. Even if some inputs or factors can be neglected or ignored, that can only happen if they are irrelevant to the final output (1% rule [32]). In the definition of the total impact, the final use of a product is irrelevant: the emissions related to the action itself are considered, but different uses do not change the emissivity of the production chain. In the RED the approach is different: to be compliant with the objectives, some contributions are multiplied by different factors depending on the origin of the biomass and the final use of the fuel. So different final uses will cause a difference in practical impact and bonus possibilities, even for the same product(fuel). The main 'multiplication bonuses' present for transport fuels are presented [17]:

- Twice the energy content can be considered for the biofuels and biogas if produced starting from feedstocks present in Annex IX of RED2 (the argument of origin of biomass will be analyzed in the following paragraph);
- The share of electric energy for road vehicles is considered 4 times, and the one intended for rail transport is considered 1,5 times;
- Energy for marine and aviation sectors (excluding if the feedstock is of food/feed origin) should be considered 1,2 times.

The possibility of increasing the 'renewable impact' of different energy carriers highlights the conceptual difference present between the regulatory frames in analysis: the RED Directives are made to incentivize the use and production of renewable energy sources, imposing binding goals and bonuses to reach them; PEF Raccomandations are written to describe the relation between inputs and processes and their products, not trying to encourage some forms of production or methods, just to assess the differences between them.

2.5.4 Origin of biomass

In the definition of the Product Environmental Footprint there is no particular attention paid to the origin of the biomass or its category. The impact depends on the footprint of inputs and processes, not impacted by the presence of different feedstocks. So the origin of the biomass will influence the process, in the sense that different feedstocks generated through different methodologies will carry an unequal impact, but no bonus or malus will be given based on what kind of biomass is used. For the RED methodology origin of biomass constitutes an important aspect. A binding objective has been imposed, with a minimum share of the transport sector fuels that have to be generated by biomass in Annex IX of RED2. The limit was firstly posed at 1% for 2025 and 3,5% for 2030 in [9], then increased to 5% by 2030 in [17]. Additionally, the feedstocks in Annex IX of RED2 allow a x2 multiplier, as described in the previous paragraph. The main biomass in Annex IV are:

- Algae if cultivated on land in ponds or photobioreactors;
- Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC;
- Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry;
- Straw;
- Animal manure and sewage sludge;
- Palm oil mill effluent and empty palm fruit bunches;
- Bagasse;
- Grape marcs and wine lees;
- Nut shells;
- Husks;
- Cobs cleaned of kernels of corn;
- Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre-commercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil;
- Other non-food cellulosic material;
- Other ligno-cellulosic material except saw logs and veneer logs.

The list is updated every two years following the instructions in paragraph 28.6 of RED2 [9]. An important aspect that underlines the incentive-based philosophy of RED2 is given by the fact that the list can be amended, modifying the contents, but only by adding feedstocks and not removing the present. This protects eventual investments in some forms of biofuels, giving a security of incentives in the long term. It could seem as a not so influent aspect of the Directives but it has a big intrinsic importance: even if some technologies or feed stocks prove to not be that efficient in reducing emissions or in general become obsolete they cannot be removed, protecting the investments but not fully representing the physical reality of systems.

2.5.5 Manure as waste

How wastes are treated in the analysis is one of the points in which more inconsistencies between the frameworks can be detected. In both the PEF Recommendations and the RED Directive, the definition of waste follows the one described in [45]: *"waste means any substance or object which the holder discards or intends or is required to discard"*(Article 3.1). As a rule for allocation of emissions wastes should have no carbon emissions (punto 18, pag 74 [9]).

The two documents seem to be coherent for what concerns definition and how to treat them, but are not in the practical application of rules. In the PEF analysis, manure can be considered as different entities based on the definition of wastes and co-products:

(a) **Residual (default option)**: if manure does not have an economic value at the farm gate, it is regarded as residual without allocation of an upstream burden. The emissions related to manure management up to the farm gate are allocated to the other farm outputs where manure is produced.

(b) **Co-product**: when exported manure has an economic value at the farm gate, an economic allocation of the upstream burden shall be used for manure by using the relative economic value of manure compared to milk and live animals at the farm gate. However, biophysical allocation based on IDF rules shall be applied to allocate the remaining emissions between milk and live animals.

(c) **Manure as waste**: when manure is treated as waste (e.g., landfilled), the circular footprint formula shall be applied.

The PEF Recommendations give the possibility of different allocations of emissions connected to the different possible roles of manure. This, added to the different allocation rules described in the following point, leads to the possible allocations described in Section 2.2. In the RED Directive, a bonus is assigned to manure if it is used in the production of biogas or biomethane: the manure bonus. It consists of 45g CO2eq/MJ manure that can be assigned to the e_{sca} factor (negative in the total sum). This is connected to the improved agricultural and manure management. It is assigned indifferently whether the manure had an economic value at the farm gate or not. A possible contradiction is generated: if in a farm the produced manure is exported with an associated economical value, for the PEF, it should have some of the process emissions allocated (depending on the price or not, based on what allocation method is chosen) while for the RED 2, the same product should have a negative emission input on the system it is entering. In this scenario, some miscount of emissions is plausible, opening the door to 'emission leakage'.

In RED it is stated that: *Co-products are different from residues and agricultural residues, as they are the primary aim of the production process.* It is therefore appropriate to clarify that agricultural crop residues are residues and not co-products. This has no implications on the existing methodology but clarifies the existing provisions.

2.5.6 Allocation of impacts

When treating multifunctional systems, the emissions should be divided between the various products of the cycle.

In the PEF methodologies, a decision hierarchy is provided following the ISO rules [26]:

- **Subdivision or system expansion**,

  It is the first option to apply if possible, avoiding allocation. In subdivision, the multifunctional processes are disaggregated, isolating the input flows associated with each co-product. In the expansion, additional functions connected to co-products can be considered.

- **Allocation based on relevant physical relationship**,

  The emissions allocation should represent a relevant, quantifiable underlying physical relation between the products. It can be based on energy, Lower Heating Value or other relations as Carbon or Protein balances, if they properly represent the system.

- **Allocation based on other relations**,

  Before the application, the inability to use the two previous options should be justified. If no other relation is applicable or representative of the system, non-physical relations can be implemented, the most typical of which is the economic allocation. The emissions will be divided based on the economic values of output streams.

For the RED directives, only one allocation method is possible and acceptable: energy allocation. The discrepancy with the EN ISO 14044:2006 [26] is justified as follows: *'The substitution method is appropriate for the purposes of policy analysis, but not for the regulation of* *individual economic operators and individual consignments of transport fuels. In those cases, the energy allocation method is the most appropriate method, as it is easy to apply, is predictable over time, minimizes counter-productive incentives and produces results that are generally comparable with those produced by the substitution method.'* ([26], p. 99) and more: *'The established method of using energy allocation as a rule for dividing greenhouse gas emissions between co-products has worked well and should be continued. It is appropriate to align the methodology for calculating greenhouse gas emissions coming from the use of combined heat and power (CHP) when the CHP is used in processing biofuels, bioliquids and biomass fuels to the methodology applied to a CHP being the end-use.'* ([26], p. 99).

The difference in the methodologies brings, as in the case of manure consideration, to possible miscounts of emissions. To be coherent from the methodological point of view, if a product of a system enters the biofuel production, the whole PEF evaluation of the product must be executed following the RED rules.

Chapter 3

Dairy Farm

3.1 Modelization

The main variables affecting the LCA of a fictitious Dairy farm are analysed. A full consideration of all of the agronomical inputs and main choices in farming is fundamental for the analysis of the impact from them. The main variables considered when varying farm characteristics are the number of animals, feed characteristics and productivity levels. The analysis is intended to represent some typical Farms that could be found on Italian territory, without actually representing a single case study. It is brought on following the indications by IPCC 2019 [12], the calculations are then not based on measurements or estimates but directly on the regulatory framework. All equations used in the modelization section are extracted from IPCC 2019 if not differently indicated. The methods used in the calculations have been chosen to respect at least Tier 2 level. Some of the inputs have been varied and considered at different levels to generate the scenarios implemented in the analysis.

3.1.1 Composition of the herd

The analysis has been performed generating a fictitious herd. For the Italian system, it is quite complex to define a standard herd dimension and composition. The dairy farming activities are spread in all the national territory and are characterised by a high heterogeneity in terms of dimensions of herd and farm and of production and final uses of milk [46]. In the last 10 years a yearly reduction of 3% in the number of milk farms has verified in Italy [46]. The percentage of small farms (less than 50 heads) has decreased from 61% to 53% in favour of farms with between 100-500 heads, which represent 25% of the total farms and have more than half the total animals [47]. Today nearly 80% of total cows is bred in farms with over 100 heads, with the big dimension farms concentrated in Northen Italy, in the specific Lombardia, Emilia Romagna, Veneto and Piedmont [47]. In figure 3.1 [46], the distribution of milk farms in Italy is presented.

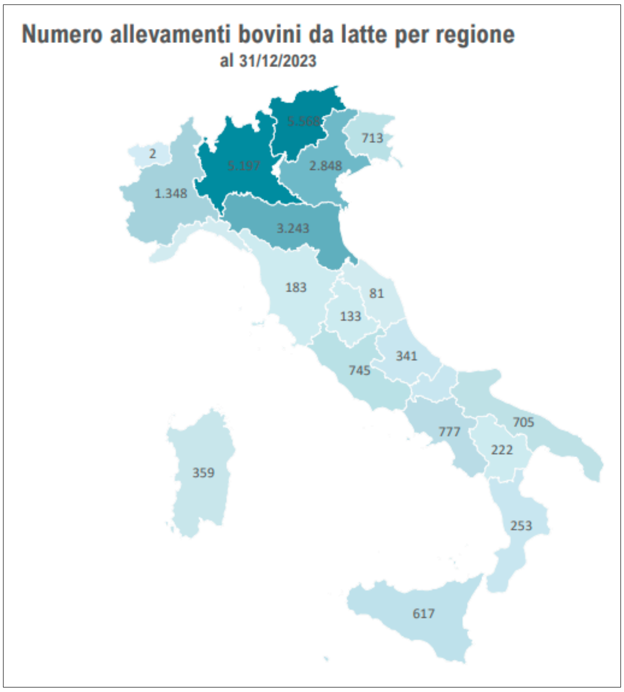


Figure 3.1: Distribution of Dairy farms in Italy [46]

The decrease in the number of farms and increase in the dimensions of the others can be related to the entry of milk in the free market, with the end of the so-called 'milk quotas'. The milk quota system, which remained in force until 31 March 2015, was a regulatory framework designed to curb milk and dairy overproduction within the EU. Its primary objective was to stabilize the market by aligning supply with demand, enabling Member States with production surpluses to distribute their output to those with shortages. Under this mechanism, each Member State was allocated a 'national reference quantity,' representing the maximum allowable milk production before triggering EU market intervention measures. [48].

The concentration of production in some centres has brought the medium dimensions for a farm from 85 heads in 2014 to 111 in 2023 [46]. In figure 3.2, an outlook on the evolution of farm dimensions is proposed [47].

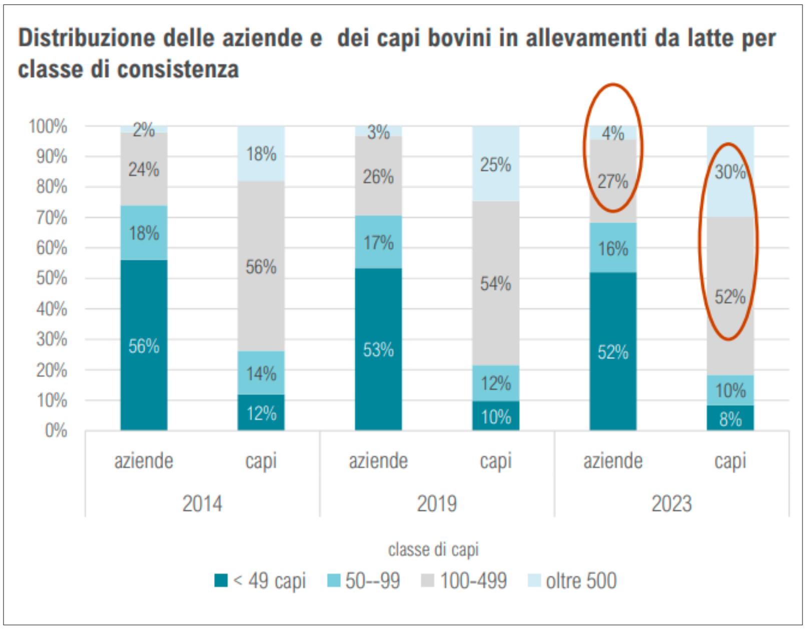


Figure 3.2: Distribution of Italian Dairy farms by dimension of herd [47]

More than half the farms are small but over 50% of the cows are bred in medium-big farms. The number of productive cows for the standard herd has been posed at 100. This number has been chosen to give a relatable result in composition of herd for small farms, while analyzing a medium herd. Starting from the number of productive cows the herd dimension and composition is derived. In Figure 3.1 the total presence in every day of the year of the different categories of cows is showed. To be consistent in the evaluation of the herd numbers some factors typical of the Italian breeding system have been considered.

To have 100 productive cows in every day of the year it is necessary to keep in the farm 120 potentially productive cows in total, of which 20 will be in the 'dry period'. This number originates from Equation 3.1, considering as a standard lactating period for cows 305 days [49].

$$N_{\text{cows, adult}} = N_{\text{cows, latt}} \cdot \frac{365}{N_{\text{days, latt}}} \tag{3.1}$$

Once the total number of adult animals has been estimated, an evaluation of the number of younger cows necessary for a stable production can be assumed. In equation 3.2 the number is obtained starting from the principle that around 30% of productive animals will have to be substituted every year (B in the equation, breeding rate) and no big influence of mortality is present between the first and second year of life [50].

$$N_{\text{cows, 1–2 years}} = N_{\text{cows, adult}} \cdot B \tag{3.2}$$

The number of cows between 0 and 1 year is assumed the same as the ones between 1-2 years, to maintain the stability of the herd. The standard composition of the herd is presented in figure 3.3.

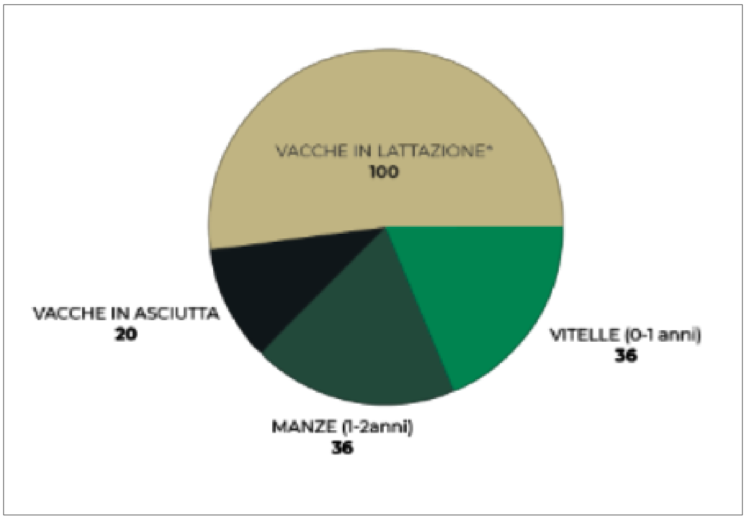


Figure 3.3: Composition of the standard herd

3.1.2 Animal exiting fluxes

Defining the composition of the standard herd gives the possibility to calculate the fluxes of animals exiting the system. There are three different groups of cattle that can be estimated leaving the system: un-productive old cows, male calves, and the remaining female calves, not necessary to stabilize the number of the herd.

- Unproductive cows that are substituted in the herd will be sold to the meat production facilities. The number of animals exiting every year is equivalent to the new productive cows entering the system, calculated in equation 3.2. The standard weight for the adult animals is considered as 602.7 kg [51], considered the live weight of the cattle leaving the farm;

- The number of male calves exiting the system can be obtained with equation 3.3, in which fertility (f) is considered 92% [51], unsuccessful births (b,n) are 5% [12] and the division between male and female calves (rm/f) at birth can be considered 50%(rm/f) [12].

$$N_{\text{calves, male}} = N_{\text{cows, adult}} \cdot f \cdot r_{\text{mf}} \cdot (1 - b_n) \tag{3.3}$$

  The number of male calves born on the farm ca be assessed at 52 every year. There are various options for the destiny of the calves depending on farm objectives and organization. The veal will pass some time in the farm, minimum 2 weeks, to then be sold to a fattening facility. Once there it can be butchered for white meat veal or fattened to final weight. The weight of calves when leaving the farm is considered 42 kg [**?**], [52], not a normative limit, but the weight at which fattening facilities will accept the animal. In the analysis one scenario has been proposed in which the fattening process is brought on in the same spaces of milk production, giving the possibility to fatten the calves until 1 year of age.

- Female calves are, as the male ones, 52 every year. The farm has necessity of 36 new female cows that enter the system each year, leaving out 16 female calves. In the analysis they have not been considered separate from male calves because both are considered exported from the farm at the same weight. The destiny of the females can be both to enter another farm as milk producing cows or to be inserted in the fattening cycle.

Figure 3.4 summarizes the fluxes of animals exiting the system in the standard scenario.

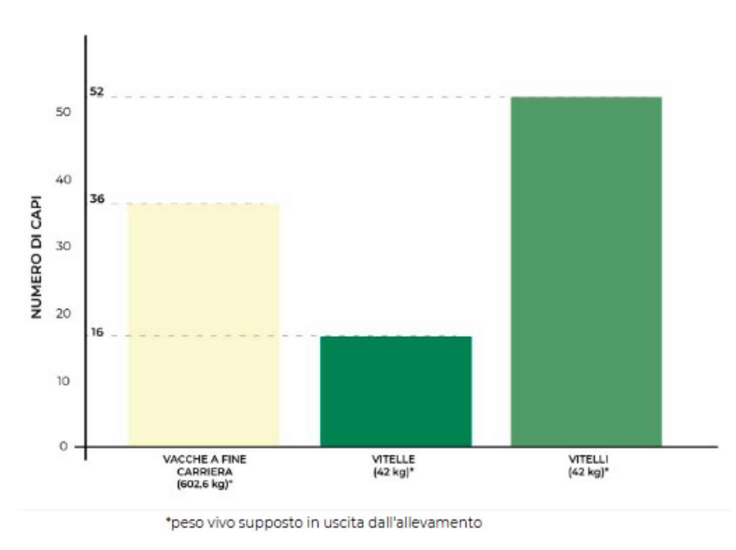


Figure 3.4: Number of animals exiting the system by category

3.1.3 Milk production

The quantity of milk produced is one of the main variables in the analysis. It strongly varies, when changing the farming practices. It can be dependent on many factors, some of the most influent are presented:

- **Genetics,** it affects the production in many ways, from the quantitative and qualitative point of view. Years of breed selection have brought to a constant increase in milk productivity. Different breeds have different milk productions, with for example Frisona Italiana that will have a maximum productivity of over 11000 kg of milk in one year while a Pezzata Rossa will produce around 2000 kg of milk per year (data from analysis of Aia database for Piedmont 2024 [53]). Different breeds will produce milk with different chemical characteristics, with Holstein cows that will usually produce more milk, but with lower quantities of fat and proteins compared to Jersey [54];

- **Feed,** quality and characteristics of the feed affect many aspects related to cow production. A wrong dietary recipe can bring to an important reduction in production, even 30% [55];

- **Herd management,** aspects like frequency and igene of milking processes, animal welfare, space and many variables related to the management of cow life can influence production;

- **Age and moment in lactation,** with cows at the first pregnancy that will tend to produce less than the ones at the second or third. The production of milk is not constant during the lactation period but will have a maximum around to then decrease until the end of lactating period [56]. An example of a lactating curve is presented in figure 3.5.

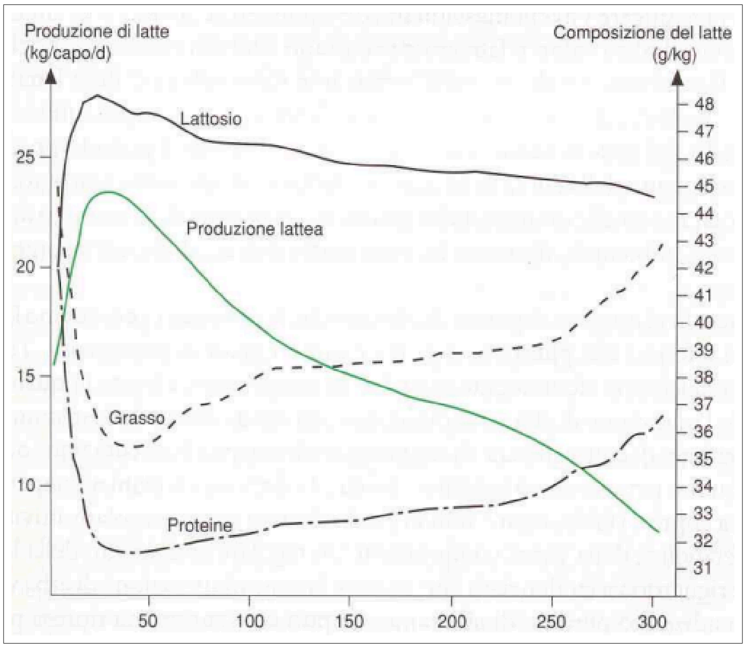


Figure 3.5: Lactation curve [56]

- **Climate,** in hot humid climates production could decrease significantly. Cows get stressed with temperatures over 25-30°C, with an important reduction of production. The right aeration and shade should be provided to avoid the problem [56]. Feed intake and energy for maintenance depend on the temperature too.

Some of the factors listed have been analyzed in more detail in the following chapters, trying to evaluate their impact on the emission of the single kg of milk. An increased management of farms and animal conditions and the optimization of the factors led to a big increase in productivity/head. Figure 3.6 [53] shows the evolution of milk production for each lactating period from 1962 to 2020.

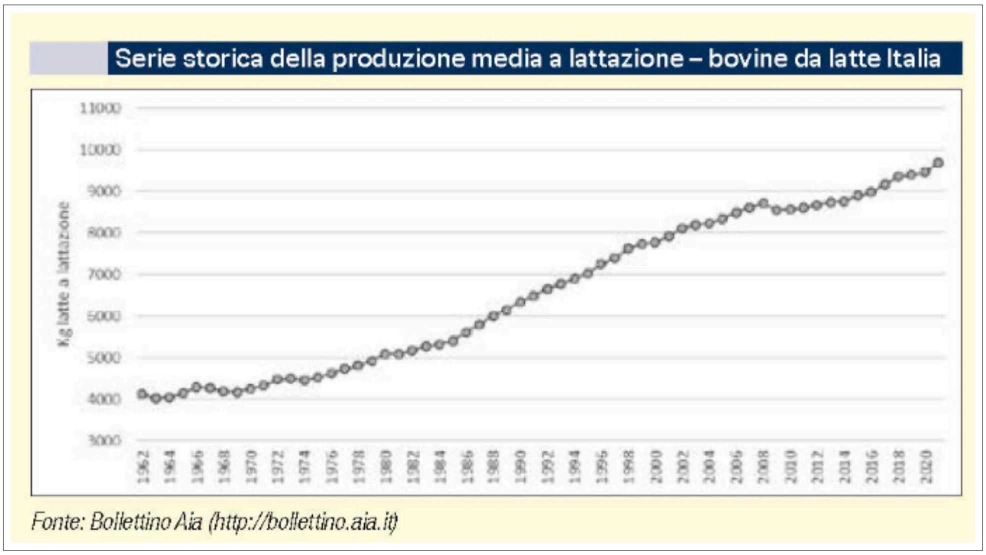


Figure 3.6: Evolution of medium yearly milk production [53]

In the standard scenario the milk produced by each cow is 9858 (the medium value of production for Piedmont in 2023 [57]). The standard protein content is 3,46% while fats attest at 3,90% [57]. These values are important for the definition of how much FPCM is produced.

1 kg FPCM is one of the functional units of the study and represents 1 kg of Fat and Protein Corrected Milk. It is a standardized kg of milk, having 4% of fat and 3,3% of true protein content [11]. It is used to assure an objective comparison between farms with different feeds and breeds. To pass from milk to FPCM equation 3.4 can be implemented.

$$\text{kg}_{\text{FPCM}} = \text{kg}_{\text{MILK}} \cdot (0.1226 \cdot \%\text{fat} + 0.0776 \cdot \%\text{prot} + 0.2534) \tag{3.4}$$

3.1.4 Need for feed

The feed necessary for maintenance and production from the cows is extremely dependent on a large number of factors, as feed base, genetics, purpose, production objectives and levels of inputs and outputs [12]. In an LCA study for a product, the quantities and characteristics of feed are one of the data necessary to complete the study. In this analysis, the energy intake necessary has been estimated, combining the IPCC formulas for feed intake estimation and the typical characteristics connected to Italian geography. The chemical profile of feed is extremely important for both the well-being and correct production and reduced emission. The total energy requirement can be estimated by relating the many factors accounting for every vital function of the animal with feed characteristics (equation 3.5). The main contributions are:

- **Energy for maintenance,** amount of energy to keep the body in equilibrium, can be estimated knowing the animal category (intended as if it is a productive cattle or not) and its live weight.

$$\text{NE}_m = C_f \cdot (\text{weight})^{0.75} \tag{3.5}$$

  Where Cf can be obtained from table 3.1, obtained from [12].

Animal Category	$\mathbf{C_f}$ **(MJ/day/kg)**
Cattle	0.322
Cattle lactating	0.386
Bulls	0.370

Table 3.1: C_f values by animal category

- **Energy for activity,** needed from the animals for the activity, it is intended as the energy needed to obtain water, food and shelter. It is more connected to the feeding techniques more than to the chemical characteristics of the feed. It is estimated starting from the maintenance energy through equation 3.6.

$$\text{NE}_a = C_a \cdot \text{NE}_m \tag{3.6}$$

  Where Ca is an empirical coefficient, depending on feeding situation and obtainable from table 3.2.

Situation	$\mathbf{C_a}$
Stall	0
Pasture	0.17
Grazing Large Areas	0.36

Table 3.2: Activity coefficient C_a by situation

- **Net Energy for growth,** energy necessary for the desired weight gain. The weight gain in cattle is a complex subject, with many studies analyzing effects of different feeds and techniques on the growth of calves. Breed is obviously a factor in the gain, with early maturing breeds that will gain weight at a different pace than slower ones [58]. Other factors that can affect the growth are the density of populations and feed characteristics, other than the period of the year in which the calf is born [58]. The process is not exactly linear, but, as shown in figure 3.7 [59], it can be assumed as so.

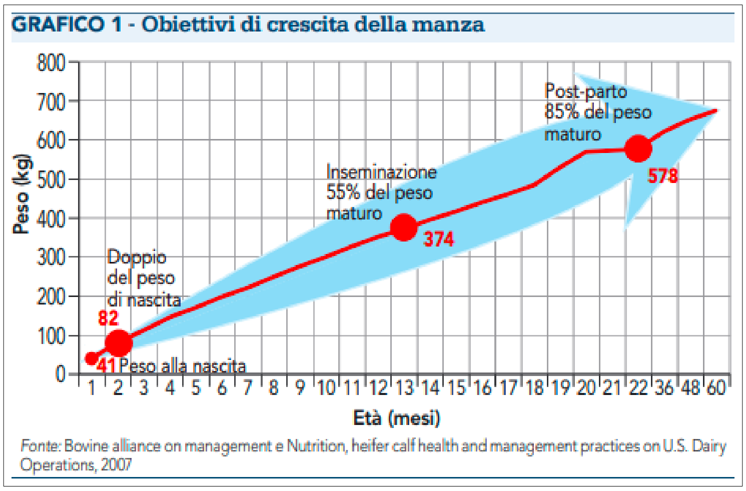


Figure 3.7: Evolution of cattle weight with growth [59]

In a specific study measures could be implemented to analyse the actual weight gain of the different animals, but for the objective of the present document the slight variations from a linear trend are not of interest and assumed as negligible. Weight gain has been assumed as constant through the two years, bringing the weight of the calves from 42kg to 602,5kg. The gain is of about 0,77kg/day (WG). Once defined the entity of weight gain equation 3.7 can be used.

$$\text{NE}_g = 22.02 \cdot (BWC \cdot MW)^{0.75} \cdot WG^{1.097} \tag{3.7}$$

In the equation, BW is the average live bodyweight, MW is the final weight at maturation, while C is an empirical coefficient obtained from [60] and can be:

Category	**C**
Females	0.8
Castrates	1.0
Bulls	1.2

Table 3.3: Correction coefficient C by animal type

- **Net Energy for lactation,** necessary for milk production. It depends on the amount of milk produced and the quantity of fats (%) in it. It can be calculated following equation 3.8.

$$\text{NE}_l = \text{milk} \cdot (1.47 + 0.40 \cdot \%\text{fat}) \tag{3.8}$$

- **Net Energy for Pregnancy,** required to bring on the pregnancy. For cattle the total energy necessary for the whole gestation period averaged on the year is considered to be 10% of maintenance energy requirement.

Two other factors account for the total energy requirements of cattle: energy for work and the increase in energy for maintenance caused by cold temperatures. The two are presented below but not accounted for in the final equations.

- **Net Energy for work,** estimates the energy required for the draft power of cattle. Estimation is dependent on many factors but has been simplified in equation 3.9.

$$\mathrm{NE}_w = \mathrm{NE}_m \cdot 0.10 \cdot \mathrm{hours} \tag{3.9}$$

  The factor has no impact in the studied scenarios because in Italian cattle farming it is unusual to use animals for work today. The use of cattle to work in the fields was very influent in all history of traditional agriculture until the 40es, but has become obsolete with the introduction of tractors [**?**]. The working hours are considered 0.

- **Coefficient for energy for maintenance in cold climates,** It substitutes to the coefficient present in equation 5, accounting for the energy used by the animals to resist to the cold. Many factors as wind and temperature account, but an estimation can be made through equation 3.10.

$$C_{f,\mathrm{cold}} = C_{f,i} + 0.0048 \cdot (20 - {}^{\circ}\mathrm{C}) \tag{3.10}$$

  Where cf,i are the values in Table 10.4 of IPCC 2019 refinement [12] and °C is the mean daily temperature during winter. The factor is referred to the maintenance during cold months for open-lot cattle. This doesn't correspond to the scenarios under study, not modifying the maintenance energy.

Once all the energy requirements are estimated, the factors taking into account feed characteristics should be analyzed. The main factor influencing the ability of the cows to absorb the energetic intake is the Digestibility of feed (DE, %). In the scenarios construction this factor has been varied, taking into account different diets with different feed characteristics. Two factors can be defined:

- Ratio of net energy available in diet for maintenance to digestible energy consumed (REM), estimated through equation 3.11

$$\mathrm{REM} = 1.123 - (4.092 \cdot 10^{-3} \cdot DE) + (1.126 \cdot 10^{-5} \cdot DE^2) - (25.4 \div DE) \tag{3.11}$$

- Ratio of net energy available for growth in a diet to digestible energy consumed (REG), estimated through equation 3.12.

$$\mathrm{REG} = 1.164 - (5.16 \cdot 10^{-3} \cdot DE) + (1.308 \cdot 10^{-5} \cdot DE^2) - (37.4 \div DE) \tag{3.12}$$

In the standard scenario digestibility of feed has been considered as 73.3% [51]. This is a high value but is what is expected in an Italian farm of high productivity cows with a diet based on 49.3% corn silage.The characteristics of feed are better treated in the following paragraph. Having estimated all the useful factors it is then possible to calculate the total energy request (GE). This represents the energy to introduce as feed, but the actual quantity of dry matter depends on the energetic content of it. For mixes that are not analyzable and where specific information is not available a typical value for feed energy content is 18,45 MJ/kg of dry matter [12]. GE can be estimated through equation 3.13.

$$GE = \left(\frac{\mathrm{NE}_m + \mathrm{NE}_a + \mathrm{NE}_l + \mathrm{NE}_p}{\mathrm{REM}} + \frac{\mathrm{NE}_g}{\mathrm{REG}} \right) \div DE \tag{3.13}$$

2.1.4.1 Feed mix

The characteristics of feed strongly influence many factors in dairy farming [pulina]. One of the most affected parameters is the quantity of feed intake, that, as shown in the previous paragraph, will decrease with an increase of the digestibility. This obviously is of extreme importance for the organizational and economical aspect of production, while conserving an indirect influence on emissions of the system. From the emissivity point of view the feed typology directly influences one of the flows: enteric fermentation. The modality and entity with which this flow is affected are analyzed in paragraph 2.1.4. To try and interpret the influences of the different agricultural practices it is then of interest to differentiate various feed typologies related to every scenario that will be analyzed. In the Italian dairy farming four main diets are identifiable [51]:

- **Corn Silage,** 49.3% of total dry matter given by corn silage and 32.8 Natural Detergent Fiber. It is caracterised by the highest digestibility of the four, equal to 73.3%;
- **Alfaalfa silage,** 26.8% of dry matter, with 27.1 NDF. The digestibility is 71.4%;
- **Wheat Silage,** 20% of dry matter by wheat, 33.7 NDF. The digestibility is 70.3%;
- **Parmigiano Reggiano (PR),** has 25.3% of both alfalfa and Italian Ryegrass. The Natural Detergent Fiber is 36.7, high with respect to the others, the digestibility is low, 64.5%. Farms that want to enter the Parmigiano Reggiano supply chain have to respect a specific regulation, outside the national norms. In the Disciplinare PR DOP [**?**] various aspects of farming are normed, from the spaces and activities allocated to each animal to feeds. Silages are not permitted in alimentation (and can not be present on the farm) and forages must be originated for at least 50% in a certain zone, inside the DOP territory.

The first three options fall under the high producing cows with DE>70% and NDF <=35%, while the PR diet falls in the high producing cows with DE>70% and NDF<35% in the IPCC 2019 Refinements [12]. In the analyzed scenarios one diet has been considered as standard, based on Corn Silage. This is selected as representative of the silage based diets, constituting 73% of total high producing systems in Italy [51]. The PR based diet is selected to represent the other 27% of milk production [51], dedicated to Parmigiano Reggiano or similar cheeses and with specific regulations. Once the basis of the diet has been defined, the whole recipe is formed based on elaboration of diets present in [61] and [62]. The diet selected for the standard scenario and the one referred to Parmigiano Reggiano production are presented in tables 3.4 and 3.5.

Standard	**%DM**
Maize silage	47.29
Hay	21.29
Loietto	2.77
Flour maize	17.11
Soy	7.58
Flour sunflower	3.96

Table 3.4: Dry matter percentage – Standard

PR	**%DM**
Alfalfa	25.3
Italian ryegrass hay	25.3
Maize flour	30.0
Barley flour	19.4

Table 3.5: Dry matter percentage – PR

It is obvious that these are not the standard diets for all the high producing cows, but are considered as a representative mix that includes, at least in little quantities, the main components of dairy feeds in Italy. In the identification of specific diets for the various scenarios, different from standard and Parmigiano Reggiano, ideal mixes, with variable quantities of the two, have been implemented.

Feed is though much more complex in modern diets, with additives and concentrates that are used, in small quantities, to increase energetic or protein contents of diets. In the last years the possibility to reduce emissions changing the feed inputs have been studied with, for example, Almeida et al. [63] identifying Macroalgae (-49%) and Nitrooxypropanol (-23%) as additives able to strongly reduce the emissions from enteric fermentation, interacting with the microbial activity. The various additives have not been considered in the present study.

3.1.5 Enteric Fermentation

Enteric fermentation is a process typical of ruminant animals, cattle and sheep in particular [12]. It is a major source of anthropogenic methane emissions, affecting the global greenhouse inventory. In 2022 in Italy enteric methane emissions constituted 69.5% of CH_4 emissions in the agricultural sector, in line with the values from 1990 (69.4%) [51]. Dairy cattle represents 44% of total enteric fermentation emissions, value in decrease from 1990(48,1%) [51]. Non dairy cattle account for 34.9%. Methane is produced during the microbial breakdown of feed in the rumen, a specialized stomach compartment where anaerobic fermentation occurs. During this process, complex carbohydrates such as cellulose are decomposed by methanogenic archaea and other microorganisms, producing volatile fatty acids (used as an energy source by the animal), carbon dioxide (CO_2), and methane. The CH_4 is primarily released through eructation and, to a smaller extent, respiration. The amount of methane emitted depends on several factors, including the animal's diet composition, feed intake, digestive efficiency, and physiological state [64]. To estimate the amount of methane emitted by the various animals of the herd many methodologies can be implemented, as for the feed intake IPCC 2019 [12] refinements have been followed. To try and be consistent with the results a second method of estimation has been carried on as a control value. The evaluation of total methane emissions passes for the definition of the emission factor (KG CH_4/YEAR/HEAD) for each animal category, in equation 3.14 the standard method is showed, in 3.15 the control one is in display.

$$EF = \frac{GE \cdot \left(\frac{Y_m}{100}\right) \cdot 365}{55.65} \tag{3.14}$$

In the equation 55.65 represents the energy content of methane (MJ/Kg). Ym is the methane conversion factor, representing the percentage of gross energy in feed that is converted to methane. The value of Ym depends on feed characteristics and productivity level of the animals. For the Italian production system in the conditions defined as standard (high productivity and high DE diets with low NDF) Ym is considerable 5.7% [51]. Since in the different analyzed scenarios the value considered will change with productive characteristics and feed an outlook on its possible values is presented in Table 3.6 [12].

$$EF = DMI \cdot \left(\frac{M_Y}{1000}\right) \cdot 365 \tag{3.15}$$

MY represents the methane yield, intended as g of CH4/Kg of DMI. The default values for MY is presented in Table 3.6

Once the EF is defined for all the different animals involved the total emissions from enteric fermentation are obtainable.

3.1.6 Manure Production

Manure is one of the Functional units of the study. It is the product that connects the two sectors of milk/meat production and the production of biomethane. Manure can have many different characteristics based on feed, breed and conditions. This big variability of characteristics, first of all humidity, makes it not of statistical value to consider manure in its totality. The dry substance in manure is then considered as the functional unit [11]. To obtain the dry substance it

Category	DE (%) and NDF (% DMI)	MY (g CH_4/kg DMI)	Y_m (%)
High-producing cows (>8500 kg/head/yr)	DE $\geq$ 70, NDF $\leq$ 35	19.0	5.7
High-producing cows (>8500 kg/head/yr)	DE $\geq$ 70, NDF $\geq$ 35	20.0	6.0
Medium producing cows (5000–8500 kg/yr)	DE 63–70, NDF > 37	21.0	6.3
Low producing cows (<5000 kg/yr)	DE $\leq$ 62, NDF > 38	21.4	6.5

Table 3.6: Methane yield factors by production level and diet quality.

is necessary to calculate the excretion of Volatile Solids from the animals. Many formulations on the estimation of VS are present in studies, being it of interest for the quantification of producible methane (the argument will be treated in following chapters) In the IPCC refinements [12] it is advised to use national values for excreted Volatile Solids in the study. In this case it is of interest to estimate the different productions of manure based on the different feed situations, so a tier 2 methodology has been implemented in equation 3.16.

$$\mathrm{VS} = \left(\mathrm{GE} \cdot \left(1 - \frac{\mathrm{DE}}{100}\right) + (\mathrm{UE} \cdot \mathrm{GE})\right) \cdot \frac{(1 - \mathrm{ASH})}{18.45} \tag{3.16}$$

The equation shows how the excretion of VS is highly dependent on the energy intake and feed digestibility. (UE*GE) represents the urinary energy expressed as a fraction of GE. In the study the default value 0.04 was implemented for UE [12]. ASH stands for the % of ashes in the dry matter of the feed and it is assumed as 8% [12]. Once the factors are defined the excretion of VS for all the categories of animals can be calculated. The relation between Dry substance and Volatile solid is again dependent on the characteristics of feed and can depend on other factors (cows age or breed), but it can be estimated between 0.65 and 0.85 [65], more precisely as 0.75 [66].

3.1.7 Methane from Manure management

In 2022 the emissions from manure management in Italy constituted 22% of total CH_4 emissions for the agriculture sector and 10.5% of the national total [51]. In particular emissions from management of cattle manure represent 49.6% of total CH_4 emissions connected to manure [51]. To quantify the emissions the methodology proposed in IPCC 2019 [12] is implemented through equation 3.17.

$$\mathrm{EF} = (\mathrm{VS} \cdot 365) \cdot \left(\frac{B_0 \cdot 0.67 \cdot \mathrm{MCF}}{100}\right) \tag{3.17}$$

While 0.67 represents the conversion factor between m_3 and kg's of methane, B0 and MCF are the main variables of the equation. B0 is the maximum methane that is producible from a determined animal's manure, in the case of cattle in Italy it is considered as 0.24 [51]. MCF quantifies the methane conversion for each manure management system, representing the degree of achievement of B0. The main factors influencing every manure management system are: the amount of volatile solids, the extent of anaerobic conditions, retention time of the manure and the temperature of the system [12]. In the standard scenario the manure is destined to anaerobic digestion. This practice strongly influences the emissions from manure management. Pit storage, for example, has an MCF up to 80% for long retention times in hot weathers but conserves a minimum of 4% even for short periods in cool climates while the implementation of anaerobic digestion can obtain a MCF of 1% if in high quality technology [12]. For sake of being coherent with real plants an MCF of 1.41% has been considered in the standard scenario, considering a good quality technology but with a slightly poorer storage. The influence of this factor on final emissions from the system will be evaluated in the following chapters.

3.1.8 NOx da Manure

N0x emissions are an influent factor in manure management. It is produced, directly and indirectly during the storage and treatment of manure before it is applied to land or used for feed, fuel or construction. A differentiation can be made between direct and indirect emissions:

- **Direct,** occur via combined nitrification and denitrification of nitrogen contained in manure. Nitrification will occur in storages if enough oxygen is provided, it does not verify in anaerobic conditions [12]. The main parameters on which it depends are nitrogen and carbon content of manure [12]. The Nitrogen excreted in manure can be calculated following IPCC methodologies, considering it as the difference the N intake connected to the diet and N retention in both tissues and produced milk. Based on the excretion rates the emissions are then obtainable. Equation 3.18 describes the calculation of N_intake.

$$N_{int} = \frac{GE}{18.45} \cdot \left(\frac{CP\%}{6.25} \right) \tag{3.18}$$

In the equation 6.25 represents the conversion factor from kg of protein to kg of N. CP% is the crude protein of the diet. Being diets variable and dependent on age and productive goal of animals this factor can assume various values. For Italian cattle in general it is suggested to use a medium value for diet of 14.22% CP [51]. This calculation does not take into account the different productive levels of the animals under study, not giving the possibility to analyze what eventual difference will arise with a different dietary composition. The value assumed for high producing animals is 16.1% [12], as suggested in IPCC 2019 refinements for western Europe dairy cattle and in line with 15.7-16 values presented in [67] for high producing dairy cows. Low producing cows will have lower values of crude dietary protein, around 13.9-14% [67]. The total Nitrogen retained can be derived from equation 3.19.

$$N_{ret} = \frac{MILK \cdot PR_{MILK,\%}}{6.38} + \frac{WG \cdot \left(268 - \left(7.03 \cdot \frac{NE_g}{WG}\right)\right)}{6.25} \tag{3.19}$$

Where MILK are the kg of milk produced every day and 6.38 is the conversion from milk protein to Nitrogen. WG represents the weight gain, with 268 and 7.03 constants from equations from [60]. The equation highlights the very different possible retentions connected to age and productivity of the animal. Subtracting the retained N from the assumed it is possible to obtain the excreted Nitrogen and from this, through equation 3.20 the total direct emissions are calculable.

$$N_2O_{dir} = N_{ex} \cdot EF_3 \cdot \frac{44}{28} \tag{3.20}$$

Equation 3.20 is a simplified version of Equation 10.25 in [12]. The simplification is due to a calculation not referred to national emissions and based on one manure management system at the time. 44/28 represents the passage between the passage from N emissions to N_2O emissions. EF_3 is the emission factor referred to the implemented manure management system. For anaerobic digestion it assumes a value of 0.0006 [12].

- **Indirect,** ammonia and NO_x from leaching and run-off, result of nitrogen volatile losses. The total indirect emissions consist in the sum of two factors: volatilization and leaching.

Volatilization is the result of microbial activity on Nitrogen compounds (NH_4+ in particular) in alternated aerobic-anaerobic conditions. Factors as temperature, O_2 presence, ph and C/N influence the extent of N_2O volatilization [68]. NO_x from volatilization are obtainable through equation 3.21.

$$\mathrm{N_{vol}} = \mathrm{N_{ex}} \cdot \mathrm{Frac_{GAS}} \tag{3.21}$$

$Frac_gas$ is accounts for the fraction of manure nitrogen that will volatilize in the manure system. It is considered as 19.88% for Italian management [51].

Leach off nitrogen accounts for the emissions in water and soil due to percolation or assimilable processes. In Italy national legislation imposes a waterproof bottom for manure storage containers, limiting in fact leaching. The factor accounts only for the losses occurred during manure heaps near fields. $Frac_leach$ in Equation3.22 is evaluated as 1% and referred to only the Nitrogen not volatilized, being considered a successive process [51].

$$N_{\mathrm{leach}} = (N_{\mathrm{ex}} - N_{\mathrm{vol}}) \cdot \mathrm{Frac_{leach}} \tag{3.22}$$

Through the combination of equations 3.23 and 3.24 the total indirect emissions from manure management are obtained.

$$N_2O_g = N_{\mathrm{vol}} \cdot EF_4 \cdot 4428 \tag{3.23}$$

$$N_2O_l = N_{\mathrm{leach}} \cdot EF_5 \cdot 4428 \tag{3.24}$$

EF_4 is the emission factor for atmospheric deposition of nitrogen on soils and water surfaces, it is given in chapter 11 of IPCC Vol 4 [69] and equal to 0.01. EF_5 represents leaching and runoff, is equal to 0.011 [69].

3.1.9 Energy Consumption

For all the operations in the farm various forms of energy are necessary. Based on farm type and goals the consumption referred to each head can be extremely variable. For the end of the study 3 different forms of energy are considered: electric, thermal and petrol. The use of petrol could be included in the thermal consumptions and it usually is in literature, but for the sake of clarity and better possibility of process separation in the allocations it is considered as separate.

- **Electrical energy,** electrical consumption is extremely variable through the literature. In the analysis we can pass from a minimum of 400 kwh/year/head for [70] in the Italian territory to a maximum of 1145 kwh/year/head for [71] in a highly automated farm in central Minnesota in the USA. Throughout Italian literature the study that is most implemented [72] [73] is Re Sole project [74]. It is an analysis requested by Emilia Romagna region, including 60 milk farms, of which 95% having more than 60 animals, with a medium number of 180, comparable with the dimension of the standard herd. The study is of particular interest because it divides the total consumption in the single consumption voices, opening to the possibility of process separation. In Table 3.7 an outlook of the consumption per UBA (Unità di Bovino Adulto, adult bovine head) is showed.

- **Thermal and petrol consumptions** Thermal consumption accounts for more than half the total [70]. It is constituted by both energy as heat and as petrol. As stated in the preface it is of interest to treat them separately. As for electrical consumption it is affected by a very high variability. Moreover a part of the thermal energy is connected to the agronomical side of the cycle being in the middle between farming and cultivating operations [74]. In the analysis of the consumptions for the standard scenario the thermal energy used to distribute manure on the fields is excluded from the consumption voices. Table 3.8 [74] includes the division between the various applications of energy.

Category	kWh/year	% of tot
Feeding	79.3	17.16
Ventilation	93.2	20.17
Milking	76.1	16.47
Milk cooling	55.8	12.08
Manure removal	38.2	8.27
Manure treatments	84.8	18.35
Lighting	34.7	7.51

Table 3.7: Electrical consumptions

Category	kWh/year	% of tot	Kind
Feeding	437.2	70.04	Petrol
Milking	54.3	8.70	CH_4
Housing	57.1	9.15	Petrol
Manure removal	41.2	6.60	Petrol
Manure treatment	34.4	5.51	CH_4

Table 3.8: Thermal consumptions

3.1.10 Possible exclusions

All of the inputs should be considered in the screening phase, but the cut-off rule can be applied. One input is excludable if it accounts for less than 1% of all impact categories [21]. The sum of the total excluded inputs should account for less than 5% of total. In the [32] some of the inputs are excluded for because of an absence of methodology in their quantification or due to their minimal contribution. A list is provided:

- medicines;
- antibiotics;
- Cattle insemination;
- Cleaning products at the dairy farm;
- Refrigerants at the dairy farm
- Lactic ferments production
- Rennet production
- Yeast and bacteria production
- Transportation of input products to the dairy processing unit accounting for less than 1% in mass
- Solid waste at the dairy processing unit
- Capital goods at the dairy processing unit
- Capital goods at distribution center and at retail
- Ambient storage at the consumer home
- Cutlery for dairy products consumption at consumer home
- pesticides, even if the eco toxicity factor could be influent;
- water use, influent on the voice of water scarcity but not important for CF.

Pesticides and water are excluded following the possibilities presented in the International Dairy Federation Carbon Footprint Standard [11]. The factors could be effective on the LCA assessment, but are not influent on the carbon footprint of the products. All the exclusions have been implemented. This due to the goal of the study: not getting the most complete PEF declaration of milk but studying the relation between possible allocations and products in the system and finding the most convenient agricultural techniques.

3.2 Allocation methods

Dairy farms produce, as a main reference product, milk. This is not the only product flow exiting the system at farm gate, with meat generated from surplus calves and culled dairy cows important co-products. Additionally, in some cases, *'manure can also be exported off-farm, and if so, this needs to be considered as a co-product'*(IDF 2022, pag 41 [11]). As already defined the previous chapter, the methodologies of allocation of impacts allowed in the definition of the footprint of products are not univocal. *'There are various ways to handle co-products, with some methods more pragmatic and others more scientific, but there is no single, common or established method.'*(IDF2015, pag26 [75]). The optionality of declaration of impact on many products leaves the possibility of different interpretations, based on data quantity and quality and on different factors. The analysis of the various allocation methods is then crucial in the study of the stability and coherence of calculations. Literature and interpretations on the argument evolved in the last decades, with different visions of the problem proposed. In the study 4 allocation methodologies have been analyzed, from the theoretical and mathematical point of view to try and interpret the different results there could be. All the methodologies respect the rules imposed in ISO 14044 [26] and are, consequentially, acceptable.

3.2.1 IDF 2015

The first difference of influence in the evolution of the allocation recommended methodologies is the change in functional units considered. The functional units considered in the methodology proposed in 'A common carbon footprint approach for the dairy sector' from IDF [75] are two: milk and meat. Manure can be considered as a possible co-product, residue or waste but not analyzed further in the guide. The last PEFCR on dairy products [76], published in February of 2025 refers to this methodology to allocate emissions to products. Additionally the methodology is of interest to analyze because in many studies on dairy farming impact it is the implemented allocation [13]. The methodology is based on equation 3.25.

$$AF_{\text{milk}} = 1 - 6.04 \cdot \frac{M_{\text{meat}}}{M_{\text{milk}}} \tag{3.25}$$

AF_{milk} represents the % of the total emissions that will be associated to the total produced milk. M_{meat} is the sum of the live weights of all culled cows and calves sold from the farm, being considered exiting the system. $M_{m}ilk$ is the mass of total FPCM exported from the farm, excluding then the internal usage. A typical value of 0.02 kg_{meat}/kg_{milk} is expected, generating an allocation of 12% to meat and 88% to milk. For this allocation method as for anyone implemented the emissions allocated through this proportions are the ones not unequivocally attributable to the single products. For example the energy used for milking will not be subdivided but allocated in its entirety to the product milk. The calculation of allocation factors for the standard scenario is proposed in various steps:

1. Definition of fluxes exiting the system.

   Total FPCM produced in one year

$$\text{FPCM}_{\text{tot}} = \text{FPCM}_{\text{COW}} \cdot \text{YEAR} \cdot (\text{PROD. COW}) = 1183.0\,\text{TONN} \tag{3.26}$$

   It is calculated on 120 total producing cows. This is because 100 cows are lactating every day, but in total 120 will undergo the lactating period in the year.

$$\text{MEAT}_{\text{tot}} = (\text{VEIL}_m + \text{VEIL}_{f,\text{exc}}) \cdot \text{KG}_{\text{live}} + \text{COW}_{\text{culled}} \cdot \text{KG}_{\text{live}} = 24.55\,\text{TONN} \tag{3.27}$$

   The total number of calves exciting the system is composed by the totality of the male calves plus the female ones that are not useful in the stabilization of number for the herd.

2. Allocation of separable impacts

In this first approach not many inputs can be associated singularly to one product.

- **Feed**

  The way the feed necessity was calculated opens to the possibility to allocate at least one part of the feed impact directly to the different products. The energy necessary for lactating, for example, represents a defined part of total energy input and can be related to the feed following equation 3.28. In the construction of the herd milk is produced in cows that are assumed as at their final weight, not requiring energy for growth. Equation 3.13 can be then reduced to just the first factor in the sum. It is then possible to obtain the relative weight of the milking energy on the total energy for feed.

$$\%\text{MILK}_{\text{dir,feed}} = \frac{GE_{\text{milk}}}{GE_{\text{tot}}} = \frac{(NE_l \cdot n_l).REM \cdot DE\%}{GE_{\text{tot}}} \tag{3.28}$$

With n_p being the number of productive cows every day.

The same can be calculated for the share of energy directly related to meat production. It is assumable that pregnancy energy is related to the calf formation and energy for growth will be reflected in an increase in final weight, that in this 'static' system can be assumed as live weight that will be sold, at the end of the production years. Equations 3.29 and 3.30 describe the direct share of feed for the various products.

$$\%\text{VEAL}_{\text{dir,feed}} = \frac{GE_{\text{veal}}}{GE_{\text{tot}}} = \frac{\left(\frac{\sum(NE_p \cdot n_p)}{REM \cdot DE\%} \cdot \frac{V_{\text{exit}}}{V_{\text{tot}}}\right)}{GE_{\text{tot}}} \tag{3.29}$$

n_p represents the number of pregnant cows in each category. It is in fact important to differentiate between milking cows, dry cows and growing cows between 1–2 years old, having the three different energy requests to bring on the pregnancy (N_p) (following the 2019 IPCC energy need calculations [12]). V_{exit} and V_{tot} are the Veal exiting and the total born in the year. Not all the energy for pregnancy exits the system with the exiting animals, one part will stay in the system with the females replacing elderly cows. Considering it a stable system, the energy for pregnancy related to calfs staying in the farm can be attributed to the cows exiting the farm. All producing cows are in fact considered as exiting, and with them they will bring also the energy spent to give them birth

$$\%\text{COW}_{\text{dir,feed}} = \frac{GE_{\text{cow}}}{GE_{\text{tot}}} = \frac{\left(\frac{\sum(NE_g \cdot n_g)}{REG \cdot DE\%} + \frac{\sum(NE_p \cdot n_p)}{REM \cdot DE\%} \cdot \frac{V_{\text{tot}} - V_{\text{exit}}}{V_{\text{tot}}}\right)}{GE_{\text{tot}}} \tag{3.30}$$

The same argument has to be made for growth, with different energy requirements for different categories of animals. In the allocation of IDF2015 the two products, cow and veal, are inside the same functional unit MEAT, with no distinction. The final direct allocation of feed to meat will so be:

$$\%\text{MEAT}_{\text{dir,feed}} = \%\text{VEAL}_{\text{dir,feed}} + \%\text{COW}_{\text{dir,feed}} \tag{3.31}$$

- **Energy**

  For energy the subdivision is simple and depends on the goal for which energy will be used.

  Milking and milk cooling energy will be directly allocated to milk.

- Allocation of other impacts

  All the non directly allocated impacts follow the rule imposed in IDF 2015. Having the total flux of products the Allocation Factor for milk will be:

$$AF_{\text{milk}} = 1 - 6.04 \cdot \frac{MEAT_{\text{tot}}}{FPCM_{\text{tot}}} = 87.46\% \tag{3.32}$$

  The result for general allocation to milk is similar to the expected 88% [75].

3.2.2 IDF 2022

In the revision of the guide in 2022, the International Dairy Federation changed the allocation methodology. The main reason that justified the change is the lack in both specificity and range [11]. It was in fact observed that the range of validity for the methodology is between o and 3% in the MEAT/MILK relation. It was also found that, being calves and cull cows different in characteristics and economic value, analyzing them as the same product constituted an incongruence. In the guide an underlying physical relationship is used, based on the animals' utilization of feed net energy in the production of meat and milk. Three products can be defined: milk, veal and culled cows. Reasonable approximations for the net energy requirements for the various stages of growth of the cows can be obtained from figure 3.8 [11].

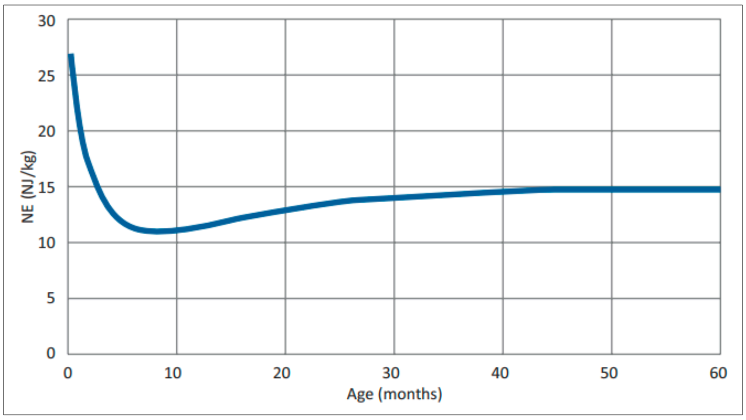


Figure 3.8: Energy requirements for each kg of meat in the various stage of growth [11]

A necessity of 27.5 MJ/kg for calves (E_{veal}) and 15 MJ/kg for mature animals (E_{cow}) can be assumed. One kg of FPCM will request 3.1 MJ (E_{milk}) [11]. It is suggested to consider manure as a residue. In the case manure is exported from the farm the consideration cannot be made, it is advised to implement economic allocation (analyzed in section 3.2.4) or to follow the methodology displayed in Section 9.3.1 of the FAO LEAP guidance [77] (section 3.2.3). The allocation factors are obtainable with equation 3.33.

$$AF_{\text{milk}} = \frac{FPCM_{\text{tot}} \cdot E_{\text{milk}}}{VEAL_{\text{tot}} \cdot E_{\text{veal}} + COW_{\text{tot}} \cdot E_{\text{cow}} + FPCM_{\text{tot}} \cdot E_{\text{milk}}} \tag{3.33}$$

With the same logic allocations to veal and cows are calculable.

In the direct allocation of inputs, the only difference with the IDF2015 methodology is that the two factors calculated in Equation 3.29 and 3.30 are allocated respectively to veal and cow, not summed.

The final allocation factors for the three products are:

$$\begin{cases} AF_{\text{milk}} = 90.28\% \\ AF_{\text{veal}} = 1.89\% \\ AF_{\text{cow}} = 7.83\% \end{cases}$$

3.2.3 FAO

When manure is considered a valuable output of the farm, and its production cannot be separated from the animal production system, the total supply chain emissions up to the farm gate must be allocated among all co-products. The methodology of allocation to apply for FAO LEAP guide [77] is a biophysical approach based on the energy for digestion that the cow expends in order to utilize the nutrients and generate the manure. It is calculated as the heat increase for feeding of the diet [77]. To give a numerical value to this increase in heat the guide refers to calculations by Emmans [78]. The study considers the daily increment in heat in 15 calorimeter experiments on cattle. The quantity of energy associated with fecal organic matter (manure SV) is considered as the remaining heat increment once the increments connected to fermentation, excretion and positive retention of protein and lipids are subtracted from total heat increment. It is quantified in 3.80 kJ/g (3.80 MJ/kg) [78].

The quantity of Volatile Solids of manure produced in the standard scenario is quantified with equation 16.

The reference products in this allocation methodology are 4: milk, veal, cow and manure (dry). In the allocation vs are considered for manure, but being VS/DM a stable value the allocation of impacts is not influenced.

Some additions to process separation need to be made, with electric, methane and petrol consumptions referred to manure treatment directly allocated to the product.

The general allocation factors are then obtainable through Equation 3.34 .

$$AF_{\text{milk}} = \frac{FPCM_{\text{tot}} \cdot E_{\text{milk}}}{VEAL_{\text{tot}} \cdot E_{\text{veal}} + COW_{\text{tot}} \cdot E_{\text{cow}} + FPCM_{\text{tot}} \cdot E_{\text{milk}} + MANURE_{sv} \cdot E_{\text{manure}}} \tag{3.34}$$

The allocation factors for the four products are:

$$\begin{cases} AF_{\text{milk}} = 76.55\% \\ AF_{\text{veal}} = 1.60\% \\ AF_{\text{cow}} = 6.64\% \\ AF_{\text{manure}} = 15.21\% \end{cases}$$

The results are in line with the proposed calculation in FAO LEAP [77].

3.2.4 ECONOMIC

Indicated as the go-to methodology in the case information on feed is not available, it is acceptable in the LCA analysis. To be implemented a complete and satisfactory explanation on why other methods cannot be applied is necessary [10]. The revenue flows associated to the co-products should be calculated based on a market price specific to the characteristics and geography of the products. It is indicated as the methodology to adopt when considering manure as a co-product in the IDF 2022 guide [11]. The methodology is extremely subject to the variable of price of manure. There is no central market for manure and prices can strongly vary based on location and productive situation in which it is produced. To try and solve the problem of price of manure, the 'Borsa Liquami' project has been promoted in Mantova Province. It consists in the creation of an online platform [79] in which exchanges of animal manure can be promoted giving the possibility to whom tries to sell and buy to get in contact. The general price indicated as selling price from the farm for manure is of 1.5€/m^3 [80]. This value brings to the next problem with manure market: the characteristics can be very different between different breeds with different diets, and even in the same conditions can vary strongly. To refer to the FU manure Dry Matter(DM) the price has to be referred to the quantity of solids in the manure. The possible prices are presented in Table 3.9.

Solids (%)	Price ($/kgdm)
4%	0.038
5%	0.030
6%	0.025
8%	0.019

Table 3.9: Price per kg of manure dry substance at different solids percentages

The selected price as standard is 0.019€/kg$_{DM}$, being it the corresponding to the humidity level considered as the standard dry matter of manure sent to Anaerobic Digestion but.

For what concerns milk and meat the evaluation of prices is less problematic, being referred to centralized markets. The values considered for meat are obtained from the ISMEA Mercati [81] platform and considered as 3.90€/kg$_{liveweight}$ for VEAL and 1.54€/kg$_{liveweight}$ for cows. The price of milk at farm gate is referred to the value for Lombardia obtained by CLAL [82] and is considered 0.5204€/kg. The price values can be affected to monthly variations, making the allocation methodology quite unstable or in any case dependent on the market fluctuations.

3.3 Scenarios

In the section, an outlook on the analysed scenarios is presented. The different scenarios have been implemented with two main goals: to study the stability of the various allocation methodologies, how they react to different parameters varying in the analysed system and to observe the effects that different agronomical practices can have on the CF of products. The same methodology presented in the previous paragraphs is implemented in the evaluation of inputs and impacts for all the different situations analysed. In the definition of the scenarios presented in the next paragraphs only the inputs/impacts variable referred to the standard scenario are presented, for any factor non specifically presented the calculations have been performed referred to standard.

3.3.1 High productivity (stnd)

Considered as the standard scenario, it tries to replicate the standard conditions for an Italian dairy farm, excluded farms producing milk for Parmigiano Reggiano, which are separately considered due to specific rules in alimentation and agronomical practices. As already stated it is referred to a high producing reality. Following a recap of the various obtained inputs-impacts that will be implemented in OPENLCA system are presented.

1. The number of animals in the farm is obtained in Table 3.10

Table 3.10: Number of animals farm (stnd)

Category	**Number Tot**	**In Farm**	**Pregnant**	**Exiting**
Milking Cow	100	100	59	36
Dry Cow	20	20	18	0
Heifer (1–2 years)	36	36	33	0
Calfs (0–1 year)	52	36	0	16
Male Calfs	52	0	0	52

2. The productivity is of 9858.4 kg FPCM/year/head. This brings to the exiting fluxes being:

Table 3.11: Annual production (stnd)

Product	**Tonn/year**
FPCM	1183.003
Cow	21.697
Veal	2.856

3. The feed characteristics and necessities are:

Table 3.12: Feed characteristics (stnd)

Characteristic	**Value**
REM	0.537
REG	0.346
DE	73.30%
Ym	5.70%
MY	1.98%
CP	16.10%

Table 3.13: Energy requirements [MJ/day](stnd)

Category	**NEm**	**NEa**	**NEg**	**NEl**	**NEp**	**GE, nopreg**	**GE, preg**
Milking Cow	46.95	0.00	0.00	48.15	4.70	241.59	253.52
Dry Cow	39.17	0.00	0.00	0.00	3.92	99.50	109.45
Heifer (1–2 years)	32.11	0.00	15.98	0.00	3.21	144.62	152.78
Calfs (0–1 year)	15.97	0.00	7.94	0.00	0.00	71.90	0.00

Table 3.14: Total gross energy and total feed (stnd)

GE,tot [MJ/day]	**FEED,tot** [kg_{DM}/day]
35096.55	1902.25

4. Methane from enteric fermentation, with the two analysed methods:

Table 3.15: Methane from enteric fermentation [kg/day] (stnd)

Category	CH4, nopreg	CH4, preg	CH4, tot	CH4, tot (check)
Milking Cow	0.26	0.25	25.49	26.68
Dry Cow	0.11	0.10	2.23	2.33
Heifer (1–2 years)	0.16	0.15	5.62	5.88
Calfs (0–1 year)	0.07	0.00	2.66	2.78
Total			**35.99**	**37.66**

5. Estimation of total manure SV and the methane emitted from its management:

Table 3.16: Manure production and methane emissions from manure management (stnd)

Category	kg_{SV}/day	CH4, manure management (kg/day)
Milking Cow	380.62	0.87
Dry Cow	33.21	0.08
Heifer (1–2 years)	83.82	0.19
Calfs (0–1 year)	39.63	0.09
Total	537.27	1.23

6. Direct and indirect NO2 emissions from manure management:

Table 3.17: Nitrogen direct emissions [kg/day] (stnd)

Category	N,int	N,ret	N,exc	Direct Emission NO_2
Milking Cow	34.714	17.577	17.137	0.016
Dry Cow	3.029	0.000	3.029	0.003
Heifer (1–2 years)	7.645	0.539	7.107	0.007
Calfs (0–1 year)	3.614	0.864	2.750	0.003
Total				**0.028**

Table 3.18: Indirect Nitrogen emissions [kg/day] (stnd)

Category	Volatilization	Leaching	Indirect Emission NO_2
Milking Cow	4.713	0.000	0.074
Dry Cow	0.833	0.000	0.013
Heifer (1–2 years)	1.954	0.000	0.031
Calfs (0–1 year)	0.756	0.000	0.012
Total			**0.130**

7. Energy consumption:

Table 3.19: Energy consumptions [kwh/year] (stnd)

Category	**UBA Factor**	**Electric**	**Methane**	**Petrol**
Milking Cow	1.0	462.10	88.70	535.50
Dry Cow	0.8	369.68	70.96	428.40
Heifer (1–2 years)	0.6	277.26	53.22	321.30
Calfs (0–1 year)	0.4	184.84	35.48	214.20
Total		70239.20	13482.40	81396.00

8. The various allocation methods produce a general allocation factor, obtained following the methodology described. Some of the inputs or impacts are subjected to directly allocated impacts, causing them to have different allocation factors compared to the general.

Table 3.20: Allocation of flows following IDF2015 (stnd)

IDF2015	**Milk (%)**	**Meat (%)**
Feed	80.49	19.22
Electric	91.04	8.96
Methane	95.14	4.86
General	87.46	12.54

Table 3.21: Allocation of flows following IDF2022 (stnd)

IDF 2022	**Milk (%)**	**Veal (%)**	**Cow (%)**
Feed	81.96	4.27	13.77
Electric	93.05	1.35	5.60
Methane	96.23	0.73	3.04
General	90.27	1.89	7.83

Table 3.22: Allocation of flows following FAO LEAP (stnd)

FAO LEAP	**Milk (%)**	**Veal (%)**	**Cow (%)**	**Manure (%)**
Feed	74.80	4.12	13.15	7.94
Electric	62.86	0.72	2.98	33.44
Methane	61.22	0.00	0.00	38.78
Petrol	70.65	1.48	6.13	21.73
CH4 Manure	0.00	0.00	0.00	100.00
N2O, Dir e Ind.	0.00	0.00	0.00	100.00
General	76.54	1.60	6.64	15.21

Table 3.23: Allocation of flows following ECONOMIC (stnd)

ECONOMIC	**Milk (%)**	**Veal (%)**	**Cow (%)**	**Manure (%)**
Feed	83.15	4.16	12.31	0.39
Electric	70.04	0.75	2.26	26.95
Methane	61.22	0.00	0.00	38.78
Petrol	85.43	1.55	4.64	8.38
CH4 Manure	0.00	0.00	0.00	100.00
N2O, Dir e Ind.	0.00	0.00	0.00	100.00
General	92.55	1.67	5.03	0.74

3.3.2 Medium Productivity (med)

In the medium productivity scenario, the milk produced by every lactating cow every year has been assumed as **6750 kg FPCM**. This value corresponds to the median value of the range of medium-producing cows in the IPCC refinements 2019 [12]. The scenario is implemented because many studies highlight how from a reduced production of milk, the environmental footprint increases [13], but usually they do not explicitly consider a variation in feed characteristics in the calculations.

1. **Herd** Standard.

2. Exiting fluxes

Table 3.24: Annual production (med)

Product	Ton/year
FPCM	810
Cow	21.697
Veal	2.856

3. Feed characteristics and necessity

Table 3.25: Feed characteristics (med)

Characteristic	Value
REM	0.514
REG	0.309
DE	65.00%
Ym	6.30%

Table 3.26: Energy requirement [MJ/day] (med)

Category	NEm	NEa	NEg	NEl	NEp	GE, nopreg	GE, preg
Milking Cow	46.95	0.00	0.00	32.97	4.70	239.29	253.35
Dry Cow	39.17	0.00	0.00	0.00	3.92	117.27	129.00
Heifer (1–2 years)	32.11	0.00	15.98	0.00	3.21	175.85	185.47
Calfs (0–1 year)	15.97	0.00	7.94	0.00	0.00	87.43	–

With

Table 3.27: Total gross energy and total feed (med)

Parameter	Value
GE,tot [MJ/day]	37111.0
FEED,tot [kgss/day]	2011.4

4. Methane from enteric fermentation

Table 3.28: Methane from enteric fermentation [kg/day] (med)

Category	CH_4, nopreg	CH_4, preg	CH_4, total
Milking Cow	0.27	0.29	26.57
Dry Cow	0.13	0.15	2.74
Heifer (1–2 Years)	0.20	0.21	7.13
Calfs (0–1 Year)	0.10	0.00	3.38
Total			**39.83**

5. Estimation of total manure sv and the methane emitted from its management

Table 3.29: manure production and methane emissions from manure management (med)

Category	**SV [kg/day]**	**CH_4, manure management [kg/day]**
Milking Cow	481.49	1.10
Dry Cow	49.72	0.11
Heifer (1–2 Years)	129.28	0.30
Calfs (0–1 Year)	61.21	0.14
Total		**1.65**

6. Direct and indirect NO2 emissions from manure management

Table 3.30: Nitrogen direct emissions (med)

Category	**N,int**	**N,ret**	**N,exc**	**Direct Emission NO_2 [kg/day]**
Milking Cow	34.569	17.577	16.991	0.016
Dry Cow	3.570	0.000	3.570	0.003
Heifer (1–2 years)	9.282	0.539	8.743	0.008
Calfs (0–1 year)	4.395	0.864	3.531	0.003
Total				**0.031**

Table 3.31: Nitrogen indirect emissions (med)

Category	**Volatilization**	**Leaching**	**Indirect Emission NO_2 [kg/day]**
Milking Cow	4.673	0.000	0.073
Dry Cow	0.982	0.000	0.015
Heifer (1–2 years)	2.404	0.000	0.038
Calfs (0–1 year)	0.971	0.000	0.015
Total			**0.142**

7. Energy consumptions: standard, the energy for increased feed mixing and increased manure recovery is considered as neglectable, not having in literature representative factors;

8. Allocation

Table 3.32: Allocation of flows following IDF 2015 (med)

Category	**Milk**	**Meat**
Feed	74.12%	25.88%
Electric	86.92%	13.08%
Methane	92.90%	7.10%
General	81.69%	18.31%

Table 3.33: Allocation of flows following IDF 2022 (med)

Category	**Milk**	**Veal**	**Cow**
Feed	76.86%	5.20%	17.95%
Electric	90.29%	1.89%	7.83%
Methane	94.73%	1.03%	4.25%
General	86.41%	2.64%	10.95%

Table 3.34: Allocation of flows following FAO LEAP (med)

Category	Milk	Veal	Cow	Manure
Feed	64.19%	4.81%	16.34%	14.66%
Electric	56.66%	0.86%	3.56%	38.92%
Methane	61.22%	0.00%	0.00%	38.78%
Petrol	57.87%	1.77%	7.34%	33.02%
CH_4 manure	0.00%	0.00%	0.00%	100.00%
N_2O, dir e ind.	0.00%	0.00%	0.00%	100.00%
General	62.70%	1.92%	7.95%	27.44%

Table 3.35: Allocation of flows following Economic (med)

Category	Milk	Veal	Cow	Manure
Feed	78.46%	5.03%	15.69%	0.81%
Electric	68.46%	1.05%	3.17%	27.32%
Methane	61.22%	0.00%	0.00%	38.78%
Petrol	82.16%	2.17%	6.52%	9.14%
CH_4 manure	0.00%	0.00%	0.00%	100.00%
N_2O, dir e ind.	0.00%	0.00%	0.00%	100.00%
General	89.01%	2.35%	7.07%	1.57%

3.3.3 Low Productivity (low)

As for medium productivity, the aim is to study the effects of reduced production and worse feed. The production considered is **5000 kg FPCM/cow/year**, the upper limit for low producing cows in IPCC 2019 Refinements [12].

1. **Herd:** Standard.

2. Exiting fluxes

Table 3.36: Annual production (low)

Product	Ton/year
FPCM	600
Cow	21.697
Veal	2.856

3. Feed characteristics and necessity

Table 3.37: Feed characteristics (low)

Characteristic	Value
REM	0.503
REG	0.291
DE	62.00%
Ym	6.50%

Table 3.38: Energy requirements [MJ/day] (low)

Category	NEm	NEa	NEg	NEl	NEp	GE, nopreg	GE, preg
Milking Cow	46.95	0.00	0.00	24.42	4.70	228.91	243.97
Dry Cow	39.17	0.00	0.00	0.00	3.92	125.62	138.18
Heifer (1–2 years)	32.11	0.00	15.98	0.00	3.21	191.53	201.83
Calfs (0–1 year)	15.97	0.00	7.94	0.00	0.00	95.22	–

Table 3.39: Total gross energy and total feed (low)

Parameter	Value
GE,tot [MJ/day]	37180.9
FEED,tot [kgss/day]	2015.2

4. Methane from enteric fermentation

Table 3.40: Methane from enteric fermentation [kg/day] (low)

Category	CH_4, nopreg	CH_4, preg	CH_4, total
Milking Cow	0.27	0.29	27.80
Dry Cow	0.15	0.16	3.20
Heifer (1–2 Years)	0.22	0.24	8.46
Calfs (0–1 Year)	0.11	0.00	4.01
Total			**43.48**

5. Estimation of total manure sv and the methane emitted from its management

Table 3.41: Manure production and methane emissions from manure management (low)

Category	SV [kg/day]	CH_4, manure management [kg/day]
Milking Cow	498.01	1.14
Dry Cow	57.35	0.13
Heifer (1–2 Years)	151.52	0.35
Calfs (0–1 Year)	71.79	0.16
Total	778.68	**1.78**

6. Direct and indirect NO_2 emissions from manure management

Table 3.42: Nitrogen direct emissions (low)

Category	N,int	N,ret	N,exc	Direct Emission NO_2 [kg/day]
Milking Cow	33.201	17.577	15.624	0.015
Dry Cow	3.824	0.000	3.824	0.004
Heifer (1–2 Years)	10.101	0.539	9.563	0.009
Calfs (0–1 Year)	4.786	0.864	3.922	0.004
Total				**0.031**

Table 3.43: Nitrogen indirect emissions (low)

Category	Volatilization	Leaching	Indirect Emission NO_2 [kg/day]
Milking Cow	4.297	0.000	0.068
Dry Cow	1.051	0.000	0.017
Heifer (1–2 years)	2.630	0.000	0.041
Calfs (0–1 year)	1.079	0.000	0.017
Total			**0.142**

7. Energy consumptions: standard.

8. Allocation

Table 3.44: Allocation of flows following IDF 2015 (low)

Category	Milk	Meat
Feed	67.88%	31.43%
Electric	82.34%	17.66%
Methane	90.41%	9.59%
General	75.28%	24.72%

Category	Milk	Veal	Cow
Feed	72.36%	6.03%	21.61%
Electric	87.48%	2.43%	10.09%
Methane	93.21%	1.32%	5.47%
General	82.48%	3.41%	14.11%

Table 3.45: Allocation of flows following FAO LEAP (low)

Category	Milk	Veal	Cow	Manure
Feed	56.00%	5.35%	18.81%	19.84%
Electric	53.73%	1.04%	4.31%	40.92%
Methane	61.22%	0.00%	0.00%	38.78%
Petrol	51.85%	2.14%	8.87%	37.14%
CH_4 manure	0.00%	0.00%	0.00%	100.00%
N_2O, dir e ind.	0.00%	0.00%	0.00%	100.00%
General	56.17%	2.32%	9.61%	31.90%

Table 3.46: Allocation of flows following ECONOMIC (low)

	MILK	VEAL	COW	MANURE
ECONOMIC	74.41%	5.81%	18.55%	1.22%
ELECTRIC	67.01%	1.37%	4.12%	27.50%
METHANE	61.22%	0.00%	0.00%	38.78%
PETROL	79.18%	2.82%	8.49%	9.50%
CH4 MANURE	0.00%	0.00%	0.00%	100.00%
N2O, DIR E IND.	0.00%	0.00%	0.00%	100.00%
GENERAL	85.78%	3.06%	9.19%	1.96%

3.3.4 PIT

In the PIT scenario, the quantity of inputs and output flows is coherent with the Standard scenario. The difference lies in the treatment of manure: in this case, it is considered as stored on site and consequently spread on fields.

1. **Herd:** Standard.
2. **Exiting Fluxes:** Standard.
3. **Feed characteristics and necessity:** Standard.
4. **Methane from Enteric Fermentation:** Standard.
5. **Total manure SV and methane from its management:**

Table 3.47: Manure production and methane emissions from manure management (pit)

Category	**kg SV/day**	**CH_4, manure management, kg/day**
Milking cow	380.62	17.75
Dry cow	33.21	1.55
Heifer (1-2 years)	83.82	3.91
Calfs (0-1 year)	39.63	1.85
Total	**537.27**	**25.05**

6. **Direct and indirect NO_2 emissions from manure management:**

Table 3.48: Nitrogen direct emissions (pit)

Category	**N,int**	**N,ret**	**N,exc**	**Direct emission N_2O, kg/day**
Milking cow	34.714	17.577	17.137	0.054
Dry cow	3.029	0.000	3.029	0.010
Heifer (1-2 years)	7.645	0.539	7.107	0.022
Calfs (0-1 year)	3.614	0.864	2.750	0.009
Total	–	–	–	**0.094**

Table 3.49: Nitrogen indirect emissions (pit)

Category	**Volatilization**	**Leaching**	**Indirect emission N_2O, kg/day**
Milking cow	4.713	0.000	0.074
Dry cow	0.833	0.000	0.013
Heifer (1-2 years)	1.954	0.000	0.031
Calfs (0-1 year)	0.756	0.000	0.012
Total	–	–	**0.130**

7. Energy consumptions:

Table 3.50: Energy consumption [kWh/year/head] (pit)

Category	**UBA factor**	**Electric**	**Methane**	**Petrol**
Milking cow	1.0	466.60	88.70	787.90
Dry cow	0.8	373.28	70.96	630.32
Heifer (1-2 years)	0.6	279.96	53.22	472.74
Calfs (0-1 year)	0.4	186.64	35.48	315.16
Total	–	70923.20	13482.40	119760.80

8. **Allocation:**

Table 3.51: Allocation of flows following IDF 2015 (pit)

IDF2015	Milk	Meat
Feed	80.49%	19.51%
Electric	91.01%	8.99%
Methane	95.14%	4.86%
General	87.46%	12.54%

Table 3.52: Allocation of flows following IDF 2022 (pit)

IDF 2022	Milk	Veal	Cow
Feed	81.96%	4.27%	13.77%
Electric	93.05%	1.35%	5.60%
Methane	96.23%	0.73%	3.04%
General	90.27%	1.89%	7.83%

3.3.5 Parmigiano Reggiano (pr)

The scenario is composed to respect the Parmigiano Reggiano rules of production [83].

1. **Herd:** Standard.

2. **Exiting Fluxes:** Standard.

3. **Feed characteristics and necessity:**

Table 3.53: Feed characteristics (pr)

CHARACTERISTIC	VALUE
REM	0.512
REG	0.306
DE	64.50%
Ym	6.00%
MY	1.98%
CP	16.10%

captionEnergy requirements [MJ/day] (pr)

Category	NEm	NEa	NEg	NEl	NEp	GE, nopreg	GE, preg
Milking cow	46.95	0.00	0.00	48.15	4.70	287.92	302.13
Dry cow	39.17	0.00	0.00	0.00	3.92	118.58	130.44
Heifer (1-2 years)	32.11	0.00	15.98	0.00	3.21	178.25	187.98
Calfs (0-1 year)	15.97	0.00	7.94	0.00	0.00	88.63	–

GE,tot [MJ/day]	FEED,tot [kgss/day]
42144.01	2284.23

Table 3.54: Total gross energy and total feed (pr)

4. **Methane from Enteric Fermentation:**

Table 3.55: Methane from enteric fermentation [kg/day] (pr)

Category	**CH4, nopreg**	**CH4, preg**	**CH4, tot**
Milking cow	0.31	0.33	31.98
Dry cow	0.13	0.14	2.79
Heifer (1-2 years)	0.19	0.20	7.28
Calfs (0-1 year)	0.10	0.00	3.45
		Total	**45.49**

5. **Total manure SV and methane from its management:**

Table 3.56: Manure production and methane emissions from manure management (pr)

Category	**Kg SV/Day**	**CH4, manure management (kg/day)**
Milking cow	583.62	1.33
Dry cow	50.92	0.12
Heifer (1-2 years)	132.72	0.30
Calfs (0-1 year)	62.84	0.14
Total	830.09	**1.90**

6. **Direct and Indirect NO_2 emissions from manure management:**

Table 3.57: Nitrogen direct emissions (pr)

Category	**N,int**	**N,ret**	**N,exc**	**Direct emission NO2 [kg/day]**	
Milking cow	41.370	17.577	23.793	0.022	
Dry cow	3.609	0.000	3.609	0.003	
Heifer (1-2 years)	9.408	0.539	8.869	0.008	
Calfs (0-1 year)	4.455	0.864	3.591	0.003	
			Total	**0.038**	

Table 3.58: Nitrogen indirect emissions (pr)

Category		**Volatilization**	**Leaching**	**Indirect emission NO2 [kg/day])**
Milking cow		6.543	0.000	0.103
Dry cow		0.993	0.000	0.016
Heifer (1-2 years)		2.439	0.000	0.038
Calfs (0-1 year)		0.987	0.000	0.016
Total				**0.172**

7. **Energy consumptions:** Standard.

8. **Allocation:**

Table 3.59: Allocation of flows following IDF 2015 (pr)

IDF2015	**Milk**	**Meat**
Feed	80.49%	19.22%
Electric	91.04%	8.96%
Methane	95.14%	4.86%
General	87.46%	12.54%

Table 3.60: Allocation of flows following IDF 2022 (pr)

IDF 2022	Milk	Veal	Cow
Feed	81.96%	4.27%	13.77%
Electric	93.05%	1.35%	5.60%
Methane	96.23%	0.73%	3.04%
General	90.27%	1.89%	7.83%

Table 3.61: Allocation of flows following FAO LEAP (pr)

FAO LEAP	Milk	Veal	Cow	Manure
Feed	74.80%	4.12%	13.15%	7.94%
Electric	62.86%	0.72%	2.98%	33.44%
Methane	61.22%	0.00%	0.00%	38.78%
Petrol	70.65%	1.48%	6.13%	21.73%
CH4 Manure	0.00%	0.00%	0.00%	100.00%
N2O, Dir e Ind.	0.00%	0.00%	0.00%	100.00%
General	76.54%	1.60%	6.64%	15.21%

Table 3.62: Allocation of flows following ECONOMIC (pr)

ECONOMIC	Milk	Veal	Cow	Manure
Feed	83.15%	4.16%	12.31%	0.39%
Electric	70.04%	0.75%	2.26%	26.95%
Methane	61.22%	0.00%	0.00%	38.78%
Petrol	85.43%	1.55%	4.64%	8.38%
CH4 Manure	0.00%	0.00%	0.00%	100.00%
N2O, Dir e Ind.	0.00%	0.00%	0.00%	100.00%
General	92.55%	1.67%	5.03%	0.74%

3.3.6 1ANNO

In the 1anno scenario, a different behaviour is supposed in the farm. Newborns are not sold at 42kg but fattened for 1 year before exiting the system. The feed composition has been assumed equivalent to the standard.

1. **Herd:**

Table 3.63: Herd composition (1anno)

Category	Number Tot	In Farm	Pregnant	Exiting
Milking cow	100	100	59	36
Dry cow	20	20	18	0
Heifer (1-2 years)	36	36	33	0
Calfs (0-1 year)	52	36	0	16
Male calfs	52	52	0	52

2. **Exiting Fluxes:**

Table 3.64: Annual production (1anno)

Product	Tonn/Year
FPCM	1183.003
Cow	21.697
Veal (1 year)	21.920

3. **Feed characteristics and necessity:**

Table 3.65: Energy requirements [MJ/day] (1anno)

Category	NEm	NEa	NEg	NEl	NEp	GE, nopreg	GE, preg
Milking cow	46.95	0.00	0.00	48.15	4.70	241.59	253.52
Dry cow	39.17	0.00	0.00	0.00	3.92	99.50	109.45
Heifer (1-2 years)	32.11	0.00	15.98	0.00	3.21	144.62	152.78
Calfs (0-1 year)	15.97	0.00	7.94	0.00	0.00	71.90	0.00
Male calfs	15.97	0.00	6.72	0.00	0.00	67.07	0.00

4. **Methane from Enteric Fermentation:**

Table 3.66: Methane from enteric fermentation [kg/day] (1anno)

Category	CH_4, nopreg	CH_4, preg	CH_4, tot (eq.14)
Milking cow	0.25	0.26	25.49
Dry cow	0.10	0.11	2.23
Heifer (1-2 years)	0.15	0.16	5.62
Calfs (0-1 year)	0.07	0.00	3.84
Male calfs	0.07	0.00	3.58
		Total	**40.75**

5. **Total manure SV and methane from its management:**

Table 3.67: Manure production and methane emissions from manure management (1anno)

CATEGORY	KG SV/DAY	CH4, manure management, kg/day
MILKING COW	380.62	0.87
DRY COW	33.21	0.08
HEIFER (1-2 YEARS)	83.82	0.19
CALFS (0-1 YEAR)	57.24	0.13
MALE CALFS	53.39	0.12
TOTAL	608.28	1.39

6. **Direct and Indirect NO_2 emissions from manure management:**

Table 3.68: Nitrogen direct emissions (1anno)

CATEGORY	N,int	N,ret	N,exc	Direct emission, [kg/day]
Milking cow	34.714	17.577	17.137	0.016
Dry cow	3.029	0.000	3.029	0.003
Heifer (1-2 YEARS)	7.645	0.539	7.107	0.007
Calfs (0-1 YEAR)	5.220	1.248	3.972	0.004
Male calfs	4.870	1.320	3.550	0.003
Total				0.033

Table 3.69: Nitrogen indirect NO2 emissions (1anno)

Category	Volatilization	Leaching	Indirect emissions, [kg/day]
Milking cow	4.713	0.000	0.074
Dry cow	0.833	0.000	0.013
Heifer (1-2 YEARS)	1.954	0.000	0.031
Calfs (0-1 YEAR)	1.092	0.000	0.017
Male calfs	0.976	0.000	0.015
Total			0.150

7. **Energy consumptions:**

Table 3.70: Energy consumption [kWh/year/head] (1anno)

Category	UBA factor	Electric	Methane	Petrol
Milking cow	1	462.10	88.70	535.50
Dry cow	0.8	369.68	70.96	428.40
Heifer (1-2 YEARS)	0.6	277.26	53.22	321.30
Calfs (0-1 YEAR)	0.4	184.84	35.48	214.20
Male calfs		184.84	35.48	214.20
Total		82808.32	15895.04	95961.60

8. **Allocation:**

Table 3.71: Allocation of flows following IDF 2015 (1anno)

IDF2015	Milk	Meat
Feed	72.01%	27.99%
Electric	84.09%	15.91%
Methane	91.36%	8.64%
General	77.73%	22.27%

Table 3.72: Allocation of flows following IDF 2022 (1anno)

Idf 2022	Milk	Veal	Cow
Feed	76.86%	10.59%	12.55%
Electric	90.62%	3.99%	5.39%
Methane	94.91%	2.17%	2.92%
General	86.87%	5.59%	7.54%

Table 3.73: Allocation of flows following FAO LEAP (1anno)

Fao leap	Milk	Veal	Cow	Manure
Feed	69.32%	10.11%	11.90%	8.67%
Electric	61.13%	2.10%	2.83%	33.95%
Methane	61.22%	0.00%	0.00%	38.78%
Petrol	67.08%	4.31%	5.82%	22.79%
Ch4 manure	0.00%	0.00%	0.00%	100.00%
N2o, dir e ind.	0.00%	0.00%	0.00%	100.00%
General	72.67%	4.67%	6.31%	16.35%

Table 3.74: Allocation of flows following ECONOMIC (1anno)

Economic	**Milk**	**Veal**	**Cow**	**Manure**
Feed	75.76%	12.84%	11.00%	0.41%
Electric	66.57%	4.40%	2.07%	26.96%
Methane	61.22%	0.00%	0.00%	38.78%
Petrol	78.28%	9.06%	4.26%	8.40%
Ch4 manure	0.00%	0.00%	0.00%	100.00%
N2o, dir e ind.	0.00%	0.00%	0.00%	100.00%
General	84.81%	9.81%	4.61%	0.77%

Chapter 4

Anaerobic Digestion process

4.1 Description of biomethane production cycle

Biomethane production, as already described, consists in a multi-stage process involving multiple variables and conditions. The main stage of production is the Anaerobic Digestion of organic matter, followed by cleaning and upgrading. In Italian context two different options for the production of biomethane have been strongly implemented, depending on the feedstock utilized: based on agricultural substrates or on the organic fraction of municipal solid waste. The plants treating the two substrates, while executing the same organic processes, have very different dimensions and characteristics. In the definition of the theoretical plant to operate in the study context it is of interest to define the suitable processes and characteristics. Plants for agricultural biomass treatment are usually smaller, with a [84]. The supposed plant is modeled based on agronomical inputs. The substrates undergo a pretreatment phase, with drying, milling and mixing as processes for agronomical inputs. Once the characteristics of the substrate are homogenized it can undergo the actual Anaerobic Digestion. The process consists in the action of different microbial communities in the absence of oxygen. The complex molecules are broken into monomers by hydrolytic bacteria. Then a fermentation occurs, guided by acidogenic bacteria. The fermentation brings to the production of Volatile Fatty Acids, then converted into acetate, H2 and CO2 by acetogenic bacteria. Methanogenic Archaea (also present in the digestive system of cows) produce methane utilizing Acetate or a combination of H2 and CO2 [85]. At the end of the microbiological processes 2 streams are obtained: Biogas and Digestate. For both a post-operation is implemented. The biogas can then have two possible ends: to cover the energy requirement by the reactor one part of the gas is burned in a cogeneration plant, the other part undergoes a cleaning process before the upgrading [86]. The flow is newly divided, with the subdivision of biomethane and CO2. The methane is destined to the entry into the National grid, CO2 is liquefied and available for market. The digestate is divided into solid and liquid fractions. The use and practices connected to digestate are described in paragraph 3.5.

4.2 Mix used in Anaerobic Digestion

The selection of the mix of substrates that enters the Anaerobic digestor is a key factor in the production. The production of biogas with just dairy manure as a substrate is possible, but would incur in some problematic situations, first of all the economic feasibility. Manure is usually associated with poor methane yields, it is then of interest to co-digest it with other substrates to improve process efficiency and economic conditions [87]. Many biomasses can be used in a digester, depending on the availability, usually dependent on geographical allocation and period of the year (some cultures will only be available in some short periods of time). Usually in Europe two models of AD plants for the digestion of manure are implemented: centralized plants, that collect manure and residues from various farms, or on-farm plants [87].

In the present study it is of interest to analyze the first option. The manure is in fact supposed as exiting the farm, while an on-property operation of the digester would indicate that manure did not exit the system at farm gate, compromising the principles of the LCA study. The presence of big plants that collect discarded biomass from several farms highlights how the anaerobic digestion of manure can constitute an economical operation. The main parameters to be respected in the biogas mix are:

- **C/N RATIO,** between 20:1 and 30:1 [88]. A low C/N brings to an excess in ammoniaca formation, which causes inhibition of methanogenic bacteria. Too high relation would bring to low N concentrations and low bacterial growth;
- **Volatile solids content,** >70% [89]. The higher the VS% the more degradable substance is available;
- **Specific Methanogen Potential,** >250-300 Nm^3 CH_4/tonDM [89], the higher the SMP the higher the energetic efficiency of substrate.

A possible composition for the substrate mixture is presented in Table 4.1 (the chemical compositions in the Table are obtained from an elaboration of data in [90] and [91]). It is referred to some of the biomass that can usually be found in anaerobic digestion in Northen Italy. In the zone different types of animal farming are present with relative feed supply chains, originating both animal sewage and residues from cultivation of feed.

Table 4.1: Characteristics of different substrates

Substrate	**% of DM**	**DM(%)**	**VS/DM(%)**	**BMP(Nm^3/kgVS)**	**CH_4(%)**	**C/N**
Cattle manure	22.00%	8	75	0.375	57.5	10.1
Corn stover	8.00%	33	94	0.625	52.5	65
Hen manure	14.14%	49.5	68.2	0.306	55	7.9
Broiler litter	18.17%	62.9	74.7	0.265	55	7.2
Sorghum	18.85%	29	91	0.625	52.5	40.2
Triticale	18.85%	31.5	91.7	0.625	52.5	40.2

The proposed mix optimizes the main parameters for anaerobic digestion: C/N=25, BMP is 0.459 $Nm^3/kgSV$ and VS are over 70%.

4.3 Description of parameters used in Anaerobic Digestion

The process is analyzable in different passages:

- **Transportation,** once recovered from the farms the biomasses are brought to the digestion plant. The medium radium for zootechnical waste is of 9 km [92], the same assumption has been made for the agronomical residues and cover crops. The manures are conferred through 30tonn camions, the agricultural biomass is bailed and dried in the fields, then brought to the plant with a tractor with dumper. The storage for manures is considered as minimum possible, given that the freshness of manures impacts both on the methanogen potential and on the emissions of the cycle [93].
- **Anaerobic digestion,** once the mix composition and characteristics are defined it is possible to estimate the biogas production based on the methanogen potentials of the various biomasses. There is no consideration of the improved operation conditions and productivity that the mix brings with respect to the single substrate [87]. In Table 4.2

Table 4.2: Biogas production

Substrate	**ktonn ss/year**	**ktonn sv/year**	**kNm^3/year**
Cattle manure	250.00	187.50	70.31
Corn stover	90.91	85.45	53.41
Layer hen manure	160.68	109.59	33.53
Broiler litter	206.48	154.24	40.87
Sorghum	214.20	194.93	121.83
Triticale	214.20	196.43	122.77
TOT			**442.72**

the total producible biogas is presented starting from the available cattle manure solids of 250 tonn of SS/year. The biogas is available with a quantity of methane of 53,7%. The number is obtained weighting the expected concentrations from literature from the actual biogas attributable to each biomass.

Once the quantity of biogas is obtained it is possible to derive the quantity of digestate that is available for post treatment. Knowing the composition of biogas its weight can be calculated as:

$$\frac{\mathrm{kg_{biogas}}}{\mathrm{Nm^3}} = \frac{\mathrm{kg_{CO_2}}}{\mathrm{Nm^3}} \cdot 0.467 + \frac{\mathrm{kg_{CH_4}}}{\mathrm{Nm^3}} \cdot 0.537 = 1.3\,\frac{\mathrm{kg}}{\mathrm{Nm^3}} \tag{4.1}$$

With total weight of the entering biomass being 5472 tonn/year the weight of digestate is equal to:

$$\mathrm{DIG_{tot}} = \mathrm{kg_{tot}} - \frac{\mathrm{kg_{biogas}}}{\mathrm{Nm^3}} \cdot \mathrm{Nm}^3_{biogas} = 4896.5\,\mathrm{tonn/year} \tag{4.2}$$

- **Cleaning,** all of the biogas goes through a purification stage, in which it is cleaned. In this stage the losses can be supposed as 1,5% [9]. This part of the biogas is considered as burned in the off gasses.

- **Upgrading,** as already stated not all of the produced biogas will be subject to upgrading, one part is directly burned in a cogeneration plant to obtain heat and electricity necessary for the process. The losses connected to the recovery of biomethane are considerable of 2% [94], number that represents an advanced separation technology. This quote is then lost in the off-gasses.

- **Energy production,** the energy necessary for the operation of the plant can be calculated considering:

  1. El. energy for pretreat-digestion: 0.20kwh/kwh biomethane [95];
  2. Th. energy for digestion: 0.15 kwh/kwh biomethane [95];
  3. El energy for upgrading of biogas to biomethane: 0.2 kwh/Nm^3 biomethane [96];
  4. Th. Energy for upgrading of biogas to biomethane: 0 [96];

Energy is produced through a CHP. The total efficiency of the system is considered of 75%, divided as 40% electric and 35% thermal. Some of the technical characteristics for the CHP system are presented in Table 4.3.

Table 4.3: CHP Characteristics

CHP CHARACTERISTICS	**VALUES**
TOT EFFICIENCY	75%
EL EFFICIENCY	40%
TH EFFICIENCY	35%
KW,el	50
KW,th	43.75
hours of utilization	8000
m^3 biogas/hour	23.35
tot biogas used [m^3]	186780.08

In support of the CHP system the plant is considered connected to the electric Net for eventual electricity necessities and to the national gas network with a high efficiency boiler for thermal needs. Once the flux of biogas to be used for own energy generation is defined the energy recovery from the sector of upgrading can be considered. An outlook on the energy fluxes considered for the plant is in Table 4.4.

Table 4.4: Energy Balances

BALANCES	**EL**	**TH**
NECESSITY [KWH]	474058	355543
CHP GENERATION [KWH]	400000	350000
RECOVERY [KWH]	0	35832
DIFFERENCE [KWH]	74058	-30289
IMPACT OF DIFF. [KGCO2eq]	25180	0

The plant is self sufficient for what concerns heat production. One part of the thermal energy produced in the CHP is in excess and can have other applications. Giving the proportion and general order of magnitude of the excess energy it is probably used in loco, it is difficult to imagine some form of commercialization. Electricity production from the CHP is not sufficient to cover self consumption, that opens to two main options: increase the dimensions of the CHP, not in use in the document because it would bring to an increase in excess of heat and a decrease of the methane production; to import some current from the net, with an associated impact of: 0.340kg CO2eq/kwhel [51].

A general mass balance can now be formed, considering the biogas flux burned in the cogeneration system. It is developed in Table 4.5.

Table 4.5: Mass Balances

FLUX	DRY [tonn/year]	HUMID [tonn/year]
BIOMASS	1136	5472
BIOGAS (PURIFIED)	553	-
BIOGAS CHP	237	-
BIOGAS UPGRADING	316	-
BIOMETHANE	86	-
CO_2	224	-
DIGESTATE	584	4911

4.4 Allocation of impacts

As for the PEF studies, for the RED directives, the total emissions of the system have to be subdivided between the various co-products. The main factors to keep in eye to implement the allocation are that residues and wastes have no allocated emissions and that in the RED directives the only option is energetic subdivision [9]. So, with respect to previous allocation techniques, not only fluxes with no economic value have no allocation but also fluxes with no LHV will be emission free, apart from direct emissions from the cycle. LHV is the only allocation parameter. It is than possible to exclude from the division of emissions the Carbon Dioxide, being it completely oxidated (LHV=0, apart from the directly allocated emissions). The main products interested in the allocation of emissions are: the produced Biomethane and the Digestate. The allocation is based on the LHV. While for biomethane there is a concordance in literature to have an LHV=50 MJ/KG [9], for digestate the values vary strongly. The adopted value is 17.2 MJ/kg DM of digestate, obtained from ENEA [92]. The obtained values are presented in Table 4.6.

Table 4.6: Allocation of impacts biomethane and digestate

Allocazione %	
Biometano	30.02
Digestato	69.98

The results are moved towards the Digestate with respect to the ENEA study [92]. The reason is to attribute to the high quantity of digestate production. One of the main variables imposing the ratio of biomethane to digestate is the composition of the mix. In cases with similar composition the allocation results are comparable [92], consequently the data is considered acceptable.

4.5 Factors in emission calculation

As already described in section 2.4.2 the calculation of the impact connected to the biomethane production has to be developed following the rules described in RED2 [9]. In the case of the production of biomethane or electricity from biogas with a substrate formed by a mix of biomasses, the equation to refer to is Equation 4.3.

$$E = \sum (S_n \cdot (e_{ec,n} + e_{td,n} + e_{l,n} - e_{sca,n})) + e_p + e_{td,prod} - e_{ccs} - e_{ccr} \tag{4.3}$$

Sn accounts for the quote of the n biomass on the total substrate entering the digester. It is calculated based on the Equation 4.4 [9]:

$$S_n = \frac{P_n \cdot W_n}{\sum(P_n \cdot W_n)} \tag{4.4}$$

Where Pn is the energetic efficiency of the humid biomass [MJ/kg humid] and Wn is a ponderation factor specific to the n substrate. Wn is defined through Equation 4.5.

$$W_n = \frac{I_n \cdot \left(\frac{1-AM_n}{1-SM_n}\right)}{\sum I_n} \tag{4.5}$$

The ponderation factor takes into account two main variables: the yearly input to co-digestion of the single biomass (tonns) and the medium humidity of the same (AMn) confronted with the standard humidity for the biomass n. The variability of humidity is not considered in the study. The generation of the mix is based on theoretical parameters and the characteristics of the biomass are obtained through literature analysis, considering the impact of different humidity levels is not in the interest of the study and would not bring to reliable results. An outlook on the calculation of the parameter is in Table 4.7.

Table 4.7: Characteristics of substrates

Substrate	**UM (%)**	**In**	**Wn**	**Pn**	**Sn**
Cattle manure	0.92	3125.0	0.57	0.4	0.134
Corn stover	0.67	275.5	0.05	3.1	0.091
Layer hen manure	0.51	324.6	0.06	2.6	0.090
Broiler litter	0.37	328.3	0.06	4.6	0.161
Sorghum	0.71	738.6	0.13	3.5	0.276
Triticale	0.69	680.0	0.12	3.4	0.247

Once the weighting factors have been calculated the single contributions have to be studied. The theory regarding the single emission factors has already been treated, an analysis of the values the various have in the present study is performed.

1. e_{ec}, representing the impact of the cultivation and harvesting activities for the biomasses.

   One of the main points of interest in the present study, it represents the main numerical connection between the farm and the biofuel facility. It can account for the different agricultural practices, bringing to same products with different associated impacts. In the RED 2 consideration of the situation, a distinction has to be made between the three categories of biomasses entering the digester:

   - **Animal excreta,** the value to be associated with the agricultural activities in RED 2 [9] is zero. This is because they are considered as residues with no economical value, and consequently no associated impact. As already stated in all of the development of the document this consideration does not represent many of the situations on the Italian territory and the different values obtained from the allocations of dairy impacts will be implemented in the consideration of manure. In the RED guides the only impact that can be associated with the residues is the one connected to their collection and storage. The two factors are not considered in the present document because they have been accounted for in the dairy farming analysis and double counting wants to be avoided.

- **Agronomical residues,** as for manure the consideration of corn stover as a residue takes it to have no emissions associated in the agronomical side. In this case the collection and pretreatments are not previously analyzed and have to be accounted for. The operation of bailing and wrapping can be considered to have an impact of 0.010 kg CO2eq/kg dry biomass [92].
- **Cover crops,** are the only input with an associated impact related to the farming side. The cover crops can have different allocated carbon footprints based on the agronomical practices applied. For sorghum ,an impact of 75g CO2eq/kg dry is considered, for triticale 93g CO2eq/kg. The impacts of cultivations, as already analyzed, is strongly dependent on the quantity and characteristics of implemented fertilizers.

For the biomasses under analysis the factors are presented in Table 4.8.

Table 4.8: e_{cc} for each substrate component

	manure	egger	broiler	maize	sorghum	triticale
e_{cc} **[g $\mathbf{CO_2}$eq/kg dry]**	0	0	0	10	75	93

2. e_l, not influential in the present analysis, some considerations on the possibility to store carbon in the ground are addressed in the paragraphs on Digestate. In the study of impact from biomethane, it is considered as zero.

3. e_{td}, accounts for transportation of the different biomasses. The transportation has been hypotized considering the production sites in the zone of the plant, the medium distance between the biomass production facilities and the anaerobic plant as 9 km [92]. The manures are considered to be brought to the plant through 30tonn tankers, the other biomasses are supposed as bailed and transported with a tractor equipped with a dumper. The operational characteristics [92] of the transportation vehicles are presented.

Table 4.9: Transport data

	tanker	**tractor**
distance [km]	9	9
capacity umid. [tonn]	30	20
l/km [full]	0.49	0.66
l/km [empty]	0.25	0.66
kg CO_2/l	3.14	3.14

Once the operational parameters are defined the etd factor can be derived. In Table 4.10 a synthetic outlook on the results is offered.

Table 4.10: Emissions from transportation

	Manure	Pollina	Broiler litter	Corn stover	Sorghum	Triticale
Tonn dry/trip	2.4	14.9	18.9	6.6	5.8	6.3
Tot emiss trip [kg $\mathbf{CO_2}$]	16.3	16.3	16.3	29.0	29.0	29.0
g $\mathbf{CO_2}$/kg dry	6.8	1.1	0.9	4.4	5.0	4.6

4. e_{sca}, represents the emission saving through carbon accumulation via improved agricultural management. The Equation 4.6 should be used to evaluate the factor [97].

$$\text{esca} = (CS_A - CS_R) \cdot 3.664 \cdot 10^6 \cdot \frac{1}{n} \cdot \frac{1}{p} - ef \tag{4.6}$$

The CS factors represent the mass of carbon stock per unit area, where CS_R accounts for the reference agricultural management system, while CS_A quantifies the impacts of the actual practice, evaluated in the minimum span of 10 years after the start of the new methodology [97]. N is the period in years of the crop cultivation, while P is the productivity in biofuel of the crop (MJ/ha/year). Ef accounts for the increased use of herbicides or fertilizers associated with the new technique. To account for emission reductions related to the e_{sca} parameter, voluntary schemes require a long-term commitment from the farmer or economic operator to continue applying the improved management practice for a minimum of 10 years. Additionally, before a claim can be submitted, the improved management practice must have been applied continuously for at least 3 years. The maximum total annual emission reduction claimable is limited to 45 gCO_{2eq}/MJ of biofuel or bioliquid over the entire period of e_{sca} practice application, if biochar (obtainable through pyrolysis of the digestate) is used as a soil organic amendment either alone or in combination with other eligible e_{sca} practices. In all other cases, the maximum limit mentioned above is 25 gCO_{2eq}/MJ of biofuel or bioliquid for the entire period of e_{sca} practice application. Following the methodology of RED 2 a Bonus Manure is obtainable. It consists of '45g of CO2eq/MJ manure' used for anaerobic digestion. This factor quantifies the decrease in emissions brought with the change in operational behavior with respect to manure. The main cause of the diminished impact is given by the fact that even if the digestate is returned to the field, it will have less volatile structures and generate an important decrease in leaching of CH_4 and NO_x [98]. The bonus is calculable considering 18 MJ/kg dry manure as a standard value [99]. The values obtained in the calculation are presented in Table 4.11.

Table 4.11: Calculation of e_{sca} factor

Esca	**Um**	**Pn [MJ/kg humid]**	**kg CO_2/kg humid**	**g CO_2/MJ biomet**
Manure	92%	0.4	64.8	162.0
Layer hen manure	50.50%	2.6	401.0	154.2
Broiler litter	37.10%	4.6	509.5	110.8

5. e_p, relative to the emissions generated during the actual production process. Principally relative to electric extraction from the grid. The expenses depend on the different amounts of current that can be directly associated to each product.

6. $e_{td,p}$, is of interest on the finished product when it arrives to consumer, but not in the present case of a gate to gate study, in which the analyzed life cycle of the product ends with the exiting the gate of the same.

7. e_u, is considered zero for biofuels and bioliquids. (Annex VI [9] (point 13 of annex vi RED2)

8. e_{ccs}, no sistem of co2 capture is considered, so the factor is 0.

9. e_{ccr}, no system of co2 capture is considered, the factor is 0.

4.6 Digestate production and use

Being all of the input characteristics hypotized through literature values, a complex balance to define the characteristics of digestate is not performed. The total characteristics of digestate are gotten from [100] and presented in Table 4.12. The humidity of the digestate in the case under study is slightly lower than the humidity presented in the general analysis in 'manuale digestato' [100]. This is connected to both the simplification of the process and biogas final composition (it has been considered as a mix of Carbon Dioxide and Methane, but in reality 10-15% of the total gas could be composed of water and hydrogen sulfite or other trace gasses [101]), beyond the big variability of input parameters to the system. The value of humidity is so considered as the one obtained in calculations and other values in the analysis can be considered as coincident to the ones in [100], considering that the data is presented as a percentage of the solids, independently from their quantity.

Table 4.12: Chemical composition of as it is Digestate

pH	**ST%**	**SV (%)**	**TOC (%)**	**NTK (%)**	**C/N**	**Nam. (%NTK)**	**P (%)**	**K (%)**
7.84	11.85	74.8	44.1	6.8	7	54	1.3	5.9

Where for SV, TOC, NTK, P and K the % is referred to their share of Total Solids. The Digestate, usually, is not used as it is, but has to undergo various processes before its application. The first operation to perform is the division between the solid digestate and liquid. The solid digestate represents the fraction of digestate with higher total solids and organic components. Its typical chemical composition is presented in Table 4.13 [100]. The liquid part represents the high humidity and low organic components fraction of the digestate and is presented in Table 4.14 [100]. The high presence of solids in the analyzed scenario brings to a balance that is slightly shifted towards the solids component. It has been considered that 20% of total digestate is separated as solid, high for the values in the general literature but acceptable in many analyses [100] [102] [103].

Table 4.13: Chemical composition of solid fraction of Digestate

pH	**ST%**	**SV (%)**	**TOC (%)**	**NTK (%)**	**C/N**	**N am (%NTK)**	**P (%)**	**K (%)**
8.7	30	87	46.7	2.5	19.6	28	0.9	1.5

Table 4.14: Chemical composition of liquid fraction of Digestate

pH	**ST%**	**SV (%)**	**TOC (%)**	**NTK (%)**	**C/N**	**N am. (%NTK)**	**P (%)**	**K (%)**
7.93	7.37	66	38.9	8.3	5.4	57	1.4	7.5

Both the total solids of the solid and liquid part are slightly higher than most literature texts, but still acceptable [102]. The produced quantities are 982 tonns of solid digestate and 3929 of liquid digestate.

The solid fraction is rich in organic matter and phosphorus, making it suitable for three main uses today: composting, biochar production, and soil amendment. In the first two uses, the substrate undergoes a new process, consuming energy but increasing the stability of the Carbon [103]. The use as amendment is particularly effective as it is rich in lignin and cellulose, which enhance soil structure, water retention, and microbial activity.

The liquid fraction of digestate is rich in ammoniacal N, which ensures a ready nutrient effect for agriculture [102]. The use as liquid fertilizer is strongly limited by the risk of Nitrogen leaching and emissions to air [102] [103]. The fertirrigation has to be performed with determined techniques, to reduce the emissions [100]. The use as fertilizer is analyzed in section 4.6.2.

Based on the study by Beghin et al. [104], an analysis of the possibility to use as it is digestate directly on field has been performed. In this case, beyond the effects as fertilizer, it can stabilize the Carbon. The process is described in Section 3.7.

4.6.1 Rules for application of digestate

The use of digestate in the agronomical field is strongly regulated by both the European Union and Italian government. The first normative point of interest regards the possibility of considering the digestate a coproduct of anaerobic digestion. In DM 25/02/2016 [105] 3 conditions are described that the digestate has to ensure:

1. It is produced in an authorized plant, from materials present in the following list:
   - Hay, branches or other non dangerous agricultural or forestal material;
   - Agricultural material from arable crops;
   - Livestock effluents;
   - Waste waters;
   - Residues from agri-food processing activity;
   - Waste waters from oil mills and wet pomace;
   - Animal by-products.
2. It is certain that the digestate will be used for agronomical uses;
3. No treatments outside of dehydration, sedimentation, clarification, centrifugation, drying, filtration, solid-liquid separation, stripping, nitrification-denitrification, and constructed wetland treatment have to be performed.

Particular rules limit the application of solid and liquid digestate. They correspond to the rules for manure and slurry, art 8 and 9 of DM 25/02/2016 [105]. The use of solid digestate is then prohibited in the following situations:

- on surfaces not used for agricultural activities, with the exception of public and private green areas and land designated for environmental recovery and restoration;
- in forests, except for livestock effluents naturally released by animals under extensive or free-range farming systems;
- within 5 meters from the banks of surface water bodies;
- for coastal and lake waters, within 5 meters from the shoreline;
- on frozen or snow-covered soils, on land with a high groundwater table, active landslides, or water-saturated soils, with the exception of areas cultivated with crops that require flooding;
- in any situation where the competent authority issues specific bans to prevent the spread of infectious, parasitic, or contagious diseases in animals or humans.

For the liquid digestate the limitations include:

- on land with an average slope exceeding 10 percent;
- within 10 meters from the banks of watercourses;
- within 10 meters from the shoreline of marine or lake waters;
- near roads and residential areas, at distances defined by regional regulations, unless slurry is applied using techniques that minimize odor emissions or is immediately incorporated into the soil;

- in cases where slurry may come into direct contact with crops intended for human consumption;

- in horticultural cultivation when crops are already present, and on fruit crops, unless the application system ensures complete protection of the aerial parts of the plants;

- after planting in areas used as public parks or gardens, playgrounds, recreational areas, or any land intended for public use;

- on forage crops within three weeks prior to mowing or grazing.

The limits on the quantities that can be deployed depend on the categorization of the terrain: nitrogen vulnerable areas are limited to 170 kg of N for hectare while not at risk areas open to the use of 340kg of N for hectare. This quantity is referred exclusively to the quantity associable with livestock effluents. The fraction derived from the digestion of other non-livestock materials and substances is counted among other nitrogen sources in the nitrogen balance, and have to be added to the used nitrogen after a reduction of 20% to account for atmospheric emissions during storage.

4.6.2 Evaluation of the effects of fertilizers substitution

The substitution of fertilizers with digestate is an important evolution of the agricultural production system. With the nearly absence of losses connected to the anaerobic digestion, the use on fields gives the possibility to close the cycle of nutrients [106]. The study regarding dairy farming is performed on a gate to gate philosophy. This approach does not give the possibility to study in its completeness the cycle of Nitrogen involved in the system. The characteristics and impacts deriving from the agricultural inputs are in fact obtained from the ecoInvent database. The database calculates impacts based on a weighted mean of many studies and analysis, originating an input representative of a compromise between the various techniques of cultivation. The total utilized fertilizer are not obtained through theoretical relations but based on the sum of all the fertilizer inputs of the cultivations presented in the database. The main substances analyzed are N, P and K. The quantities of each fertilizer referred to the kg of dry matter for each cultivation involved is presented in Table 4.15.

Table 4.15: Quantity of Fertilizers for each KG of Digestate

SOSTANZA	MAIZE SILAGE	SOY FEED	BARLEY	HAY	FLOUR	TOT (1KG DF)
AMMONIA ANIDRUS	1.03E-04	5.86E-04	0.00E+00	1.89E-04	1.10E-02	1.41E-03
AMMONIUM NITRATE	1.46E-03	9.72E-04	2.46E-02	2.68E-03	1.82E-02	6.50E-03
AMMONIUM SULFATE	7.15E-05	0.00E+00	8.62E-04	1.31E-04	0.00E+00	1.93E-04
INORGANIC NITROGEN	6.31E-04	0.00E+00	7.87E-03	2.12E-03	0.00E+00	1.94E-03
INORGANIC PHOSPHOR	4.95E-04	8.06E-03	1.07E-02	3.67E-03	7.63E-03	3.75E-03
UREA	2.41E-03	5.29E-04	8.66E-03	4.43E-03	9.92E-03	6.12E-03
PHOSPHATE ROCK	0.00E+00	7.01E-04	0.00E+00	0.00E+00	0.00E+00	5.53E-05
POTASSIUM CHLORIDE	0.00E+00	1.62E-02	1.12E-02	2.42E-02	1.48E-02	9.07E-03
POTASSIUM SULFATE	0.00E+00	0.00E+00	0.00E+00	2.68E-03	0.00E+00	5.96E-04
PACKAGING	1.60E-02	4.98E-02	7.97E-02	1.17E-01	1.58E-01	7.53E-02

To obtain the total amounts of Nitrogen, Potassium and Phosphorous the concentration of the three in the fertilizers is analyzed. Both the 'active principle' concentration and the impact of CO2 are obtained from the EcoInvent database. It is important to notice that in this paragraph the analysis does not include considerations on the use of the fertilizers, but just on the impact allocated to the product fertilizer. In fact much of the impact caused by the use of fertilizers is not connected to their production but to the volatilization and leaching of the compounds. The possible variation of impact related to the emissions to air and water is studied in the next section (4.6.3).

Table 4.16: CF of Fertilizers

SUBSTANCE	% ACTIVE INGREDIENT	KG CO_2eq/kg
AMMONIA ANIDRUS	0.824	3.230
AMMONIUM NITRATE	0.350	2.550
AMMONIUM SULFATE	0.212	0.875
INORGANIC NITROGEN	1.000	6.210
INORGANIC PHOSPHORUS	0.429	3.030
UREA	0.466	1.730
PHOSPHATE ROCK	0.320	0.150
POTASSIUM CHLORIDE	0.632	0.498
POTASSIUM SULFATE	0.541	1.090

The total amount of each compound to be inserted in field is then obtainable considering a total of slightly less than 700 tonn dry feed each year. The quantities are presented in Table

4.17.

Table 4.17: Total elements yearly used

Elemento	**Tot kg/anno**
N	5740.78
K	4202.97
P	1128.17

In the [107] article the ability to release the inorganic Nitrogen by different digestates is studied. It is highlighted how for a digestate generated from the anaerobic digestion of animal slurry and agronomical residues the rate of release is high, with 67% of total immitted Nitrogen available for plants. Potassium can be considered with an 80% availability in one year [106] while phosphorous availability can strongly vary: from the 50% of [106] up to over 70% in all tested digestates for [108]. A value of 75% (coherent with [108]) has been implemented as in real conditions N is the limiting quantity for application. The total liquid digestate necessary for the availability of the different nutrients for the plants is calculated in Table 4.18.

Table 4.18: Element availability in digestate

Element	**Tonn/year dig**	**Availability**
N	1401	0.67
K	950	0.80
P	1367	0.75

75% for phosphorous availability has been chosen because of the great variability of data from literature: it is unwanted to have the P as the limiting quantity of the analysis being the values so dependent on situations and methods.

It is then possible to substitute the whole nutrient requirements for the feed of the herd with nutrients coming from digestate. It is not advised, as it does not constitute a good agronomical practice and it could compromise crops yield and quality [100]. The interest of the study relies on the positive normative effects that the various practices could have and not on the quality of agronomical production, the advise is not taken count of and all of the fertilizers are substituted with liquid digestate. With the missed purchase of the fertilizers, apart from the economical benefits, not under study, a decrease in the emissions from the feed can be calculated.

4.6.3 Evaluation of emissions to air/water from digestate use

The emissions deriving from fertilizers do not depend only on their production, but are strongly influenced by leaching, volatilization and run-off of the various polluting compounds. The way the fertilizers interact with the environment is then a fundamental parameter conditioning the emissivity of the whole system. The analysis of the environmental impact caused by the digestate/fertilizers has to be performed following the IPCC VOL 4 CHAP. 11 [109] guide. The main emissions to consider, generated by soil management are N2O direct and indirect emissions.

- **Direct emissions,** are mainly caused by enhanced microbial activity, that causes nitrification and denitrification bringing to an increase in N_2O production [109]. Many factors can influence the biological processes in act and the subsequent emissions, varying from the obvious N concentration to soil moisture, temperature and agronomical practices [110]. The goal of the study in this context is to compare the effects related to the change in fertilizers, the soil and environment conditions are then considered as stable and not influent for the emissions of the system. The Equation 4.7 proposes the calculation to obtain the direct N_2O emissions.

$$\mathrm{N_2O_{Direct\text{-}N}} = \sum_i ((FS_i + FAM_i) \cdot EF_{1i} + (FCR_i + FSOM_i) \cdot EF_{2i}) + N_2\mathrm{O_{NCs}} + N_2\mathrm{O_{NPRP}} \tag{4.7}$$

Where:

- $\mathrm{N_2O_{Direct\text{-}N}}$: emissions from urine to grazed soils, kg N_2O–N yr^{-1}
- FS: amount of synthetic fertiliser N applied to soils, kg N yr^{-1}
- F_{AM}: amount of organic N additions applied to soils, kg N yr^{-1}
- F_{CR}: annual amount of N in crop residues, kg N yr^{-1}
- F_{SOM}: annual amount of N in mineral soils that is mineralised, kg N yr^{-1}
- EF_{1i}: emission factor for N applied to soils, ha^{-1}
- F_{PRP}: annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr^{-1}
- EF_{PRP}:emission factor accounting for N_2O emissions related to the N input, kg N_2O–N (kg N input)$^{-1}$
- $\mathrm{N_2O_{NCs}}$: annual emission factor for N_2O emissions from flooded rice, kg N_2O–N (kg N input)$^{-1}$

EFi represents the emission factor related to addition of N in the i conditions. From the observation of the equation it is possible to state that, for direct emissions, as they are evaluated in IPCC guide, there is no difference between organic or synthetic fertilizers. The sum Fsn+Fon does not change if the proportion between the two moves. The quantity of N inserted in the field is though important. In the scenario with digestate addition the quantity of N in the field is higher than the one with only synthetic fertilizers because of the not total availability of the Nitrogen. The increase is not simple to quantify, considering the behaviour of digestate is strongly dependent on the spreading methodology [100]. A technique generating a reduced EFi is supposed, balancing the higher quantity of Nitrogen. Direct emissions are considered stable.

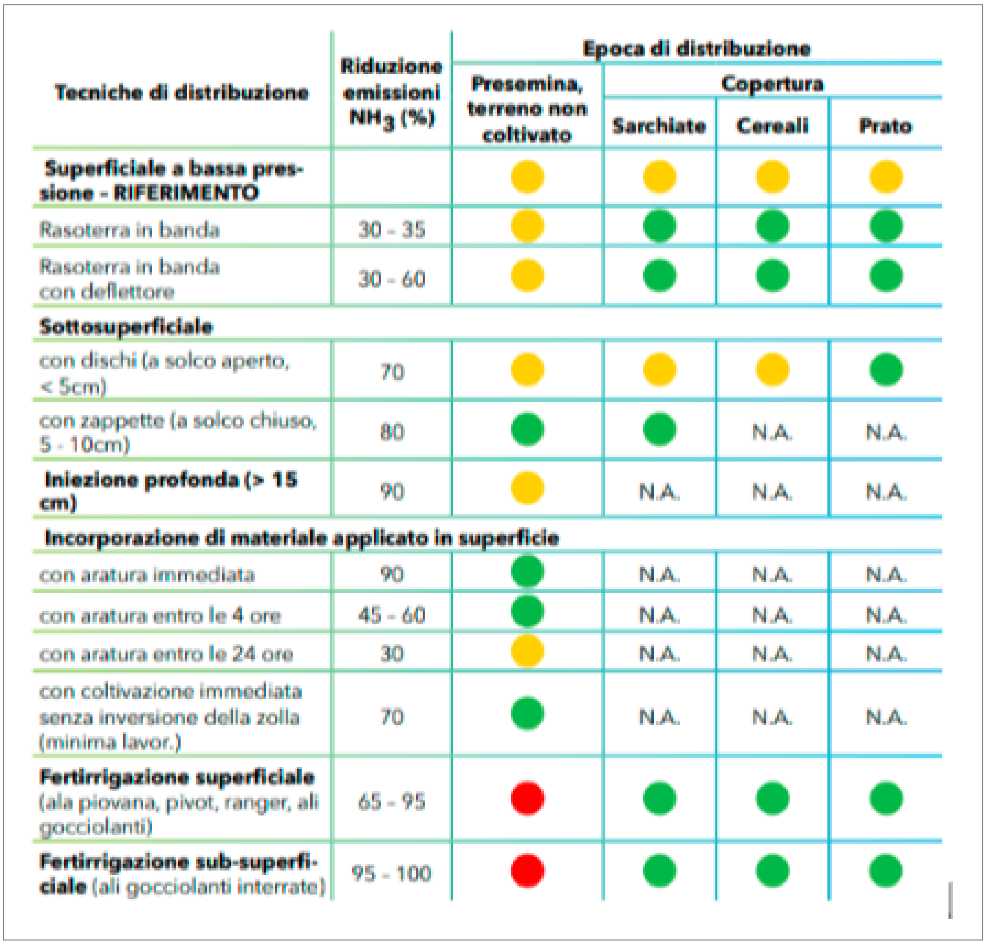
- **Indirect emissions,**the emissions from soil management take place on two indirect pathways: N volatilization/deposition and N leaching. Those emissions are considered indirect because they occur off-site from where the N addition is performed [109]. The N gets volatilized under the form of NH3 or NOx and subsequently redeposits on soils or surfaces of lakes and other water sources [109]. The leaching is caused by the missed retention of N sources in the soil, and the consequent run off in the water flows. The methodology adopted to evaluate the leaching/run off from managed soils is presented in Equation4.8

$$\mathrm{N_2O_{(L)}} - \mathrm{N} = (FSN + FAM + FPRP + FCR + FSOM) \cdot \mathrm{Frac_{LEACH\text{-}(H)}} \cdot EF_5 \tag{4.8}$$

EF5 is the emission factor from leaching and runoff, Frac leach is the fraction of N that is lost to leaching-runoff. As for direct emissions in this equation only the quantity of N added to the soils has an impact, without an evaluation of the origins and form of the Nitrogen. An increase in leaching emissions can be supposed following the growth of the Nitrogen inserted in field connected to the digestate use.

$$\mathrm{N_2O_{(ATD)}} - \mathrm{N} = \left\{ \sum_i (FSN_i \cdot \mathrm{Frac_{GASF_i}}) + [(FAM + FPRP) \cdot \mathrm{Frac_{GASM}}] \right\} \cdot EF_4 \tag{4.9}$$

Where FracGASF represents the fraction of synthetic fertilizer N that volatilizes as NH3 and NOx and FracGASM considers the organic N application. In this case the inputs of synthetic and organic fertilizers are differentiated in the effect. In the IPCC guide [109] the default values for the two are indicated. They present an important difference in value, with GASF being 0.11 and GASM 0.21. The standard emissions from digestate use in this field are then supposable as over double the emissions from synthetic fertilizers (increased N introduction and a nearly double multiplicative factor). This is one of the main critical points in the use of liquid digestate as fertilizer [111] The techniques with which the digestate is distributed in the field is fundamental to reduce the emissions and increase the availability for plants [100]. The ammonium losses usually occur in the period just after the digestate distribution, they can arrive to 80% of the inserted N if wrongly executed [100]. In figure 4.1 an outlook on some of the distribution techniques and on the effect they could have on the ammonium emissions is presented. Given this incredible variability in the possible entity of the volatilization emissions and considered that the fertilizing techniques are not under analysis in this paper, for the future calculations it has been considered that a reduction of around 50% of vol. emissions is obtainable with decent agronomical techniques. This plausible reduction gives the possibility to consider the variation of NOx emissions between digestate and synthetic fertilizers as negligible for the present analysis.



Tecniche di distribuzione	Riduzione emissioni NH_3 (%)	Epoca di distribuzione: Presemina, terreno non coltivato	Copertura: Sarchiate	Copertura: Cereali	Copertura: Prato
Superficiale a bassa pressione - RIFERIMENTO					
Rasoterra in banda	30 - 35				
Rasoterra in banda con deflettore	30 - 60				
Sottosuperficiale					
con dischi (a solco aperto, < 5cm)	70				
con zappette (a solco chiuso, 5 - 10cm)	80			N.A.	N.A.
Iniezione profonda (> 15 cm)	90		N.A.	N.A.	N.A.
Incorporazione di materiale applicato in superficie					
con aratura immediata	90		N.A.	N.A.	N.A.
con aratura entro le 4 ore	45 - 60		N.A.	N.A.	N.A.
con aratura entro le 24 ore	30		N.A.	N.A.	N.A.
con coltivazione immediata senza inversione della zolla (minima lavor.)	70		N.A.	N.A.	N.A.
Fertirrigazione superficiale (ala piovana, pivot, ranger, ali gocciolanti)	65 - 95				
Fertirrigazione sub-superficiale (ali gocciolanti interrate)	95 - 100				

Figure 4.1: Effects of different spreading techniques on Digestate NH_3 emissions [100]

4.7 Evaluation of Carbon Sink

Soils represent a major carbon sink in terrestrial ecosystems, capable of removing CO_2 from the atmosphere and storing it as organic matter for decades to centuries. An increase at a global level of the agricultural soil organic stock by 0.4% per year has the potential to compensate for the global emissions of greenhouse gases from anthropogenic sources [104]. A sink, as defined by the IPCC, is *"any process, activity or mechanism which removes a greenhouse gas... from the atmosphere"* ([112], p. 19). In agricultural systems, carbon inputs from crop residues, manures, or organic fertilizers such as digestate can contribute to the accumulation of soil organic carbon (SOC), provided that the carbon is stabilized within the soil matrix. Management techniques can strongly influence the quantity of organic carbon constantly in the soil. To estimate changes in SOC, the IPCC endorses the gain–loss method, whereby the net change is calculated as the difference between annual carbon inputs and outputs (losses from mineralization, erosion, etc.). Specifically, *"net change in soil carbon is estimated as the sum of inputs multiplied by a stabilization factor minus carbon losses"* ([113], pp. 2.20–2.22). This approach is particularly suitable for evaluating the carbon impact of organic amendments, as it allows for the use of empirical or literature-derived values for both total carbon input (C_{input}) and the stabilized fraction (f_{stable}). In [114] the variation of carbon stock for different substrates which have undergone anaerobic digestion is studied. Of particular interest is the study extracted from [104], in which a comparison is made between a situation in which dairy slurry is mixed with maize fibers and applied on field, and one in which the mix undergoes anaerobic digestion before being distributed on the field. Even if the starting mix from digestion is different in this context, it can be considered as comparable, at least from what could be expected in digestate characteristics and behavior. In the study, the factor relative to the carbon immobilized in the soil, represents the general carbon variation due to the fertilizer use, being obtained considering the soil before and after the cultivation of maize. The study considers the total Carbon cycle, starting from the total carbon of the mix and analyzing how much of that is stable after the cultivation period, but gives disaggregated values on the losses in the various phases. The factor referred to how much of the carbon exiting the digester will be in the field after the crop cycle is 0.58 [114].

Chapter 5

Results elaboration

5.1 OpenLCA

To give consistency and coherence to calculations, openLCA software was employed in the calculations of Carbon Footprints. It is a free, professional Life Cycle Assessment and footprint software, presenting numerous features and many available databases. OpenLCA is developed by GreenDelta, designed to support comprehensive LCA modelling and analysis. The interface allows for the modelling of complex product systems, impact assessment calculations, and scenario analyses. It allows users to build detailed process-based models, import and modify datasets, and analyse environmental impacts in line with international standards. Furthermore, OpenLCA is compatible with various commercial and open-access life cycle inventory (LCI) databases, such as ecoInvent, Agribalyse, and the Social Hotspots Database, which makes it suitable for a wide range of applications, including product design, waste management, energy systems, and environmental policy analysis. A comprehensive evaluation of environmental burdens across different categories including global warming potential, eutrophication, and resource depletion, is possible. OpenLCA constitutes the calculator, but its utilization without a proper database is strongly limited. EcoInvent 3.10 database was implemented in the calculations of impacts. EcoInvent represents one of the most comprehensive and widely recognised LCI datasets, continuously developed and evolved by the ecoInvent centre with base in Switzerland. The database provides datasets differentiated for geographical and technological choices, opening to an accurate representation of the location based scenario. It is structured based on a process-based modelling approach, with datasets that include detailed information on inputs, outputs, emissions, and by-products associated with various unit processes. The integration between the ecoInvent dataset and OpenLCA software permitted a coherent representation of the product system and processes under investigation, ensuring a robust and consistent basis for the calculation of environmental impacts.

5.2 Reduction of emissions from anaerobic digestion implementation

Once the standard scenario is fully defined, a first comparison can be made considering the PIT scenario. While the number and composition of the herd, and all characteristics related to feed are constant, the main difference between the two is given by the final use of Manure. In the STND case it is sent to anaerobic digestion, in PIT it is collected on site and successively spread on the fields. It is a very interesting comparison because it is formally acknowledged by the European Directives that anaerobic digestion of manure improves the agricultural practices [9] and a Bonus is issued for its implementation (Cap 4.5). In no part of RED2 an explanation on the entity of the bonus is presented. It was then of interest to analyze the actual reduction in emissions brought by the use Anaerobic Digestion. Firstly, in Figure 5.1, the total CO2eq emissions by the two systems are presented.

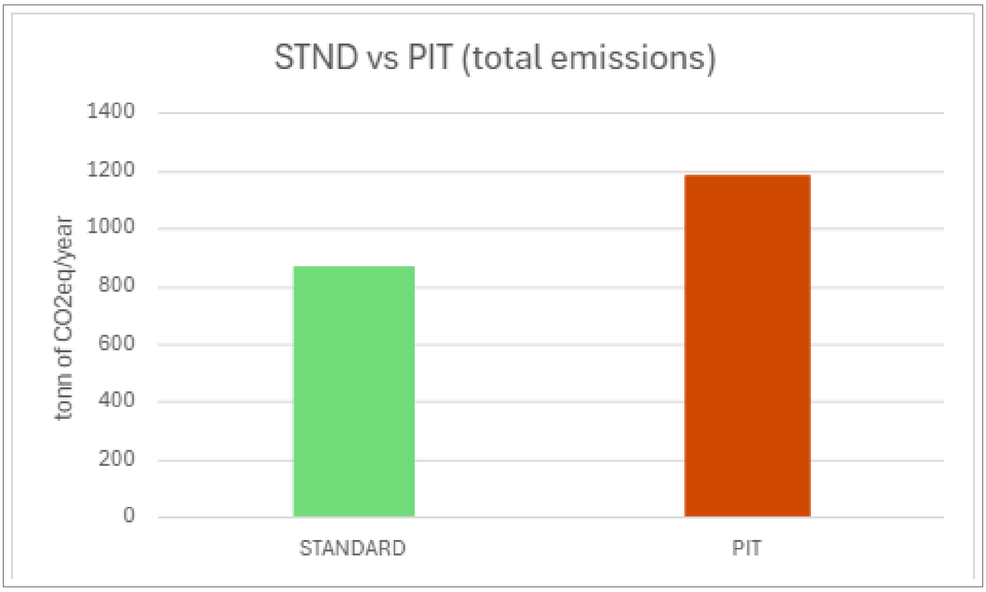


Figure 5.1: STND vs PIT, total cycle emissions

A reduction of 26.9% is obtained. Symbolizing the high impact of the technique on the final Footprint of the involved products. The results are dependent on the feed characteristics, with an increase in Manure production and of the emissions associated with its management growing with the decrease of digestibility of feed. In the PIT scenario, various of the allocation techniques are not applicable, with manure that is not a co-product when directly spread on fields, with no economic value assigned. For this reason, only the IDF 2015 and IDF 2022 methods were analyzed for the scenario. A comparison between the Footprints of Milk is presented in Figure 5.2.

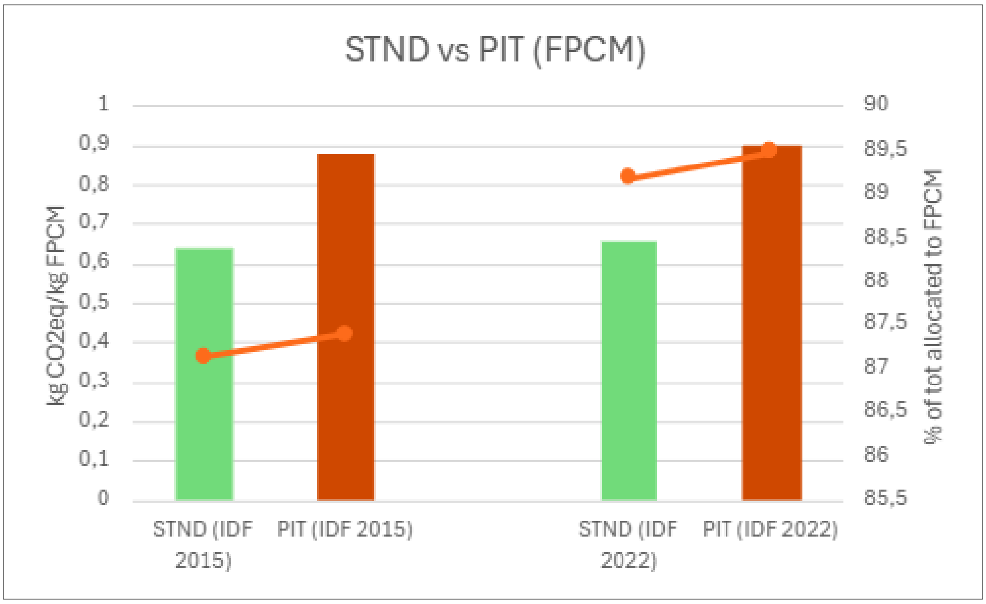


Figure 5.2: STND vs PIT, FPCM footprint

As expected, the reduction in total emissions by the system reflects on the Footprint of Milk. The extent of the reduction is though dependent on the allocation methodology implemented.

In IDF2015, the quantity of emissions associated with the total milk produced is between 87 and 87.6%, with an increase in the PIT scenario. For IDF2022, the total share appears slightly higher, between 89 and 89.5% of total emissions. The tendency to have an increase in the share of total emissions assigned to milk for the PIT scenario is confirmed. To better understand this dynamic, the Meat Footprint for the two scenarios was analyzed in Figure 5.3. An approximation was performed to make the results from the two allocation methodologies comparable: Veal and Cow, which are considered different products in IDF2022, are combined under the Meat denomination, proper to IDF2015.

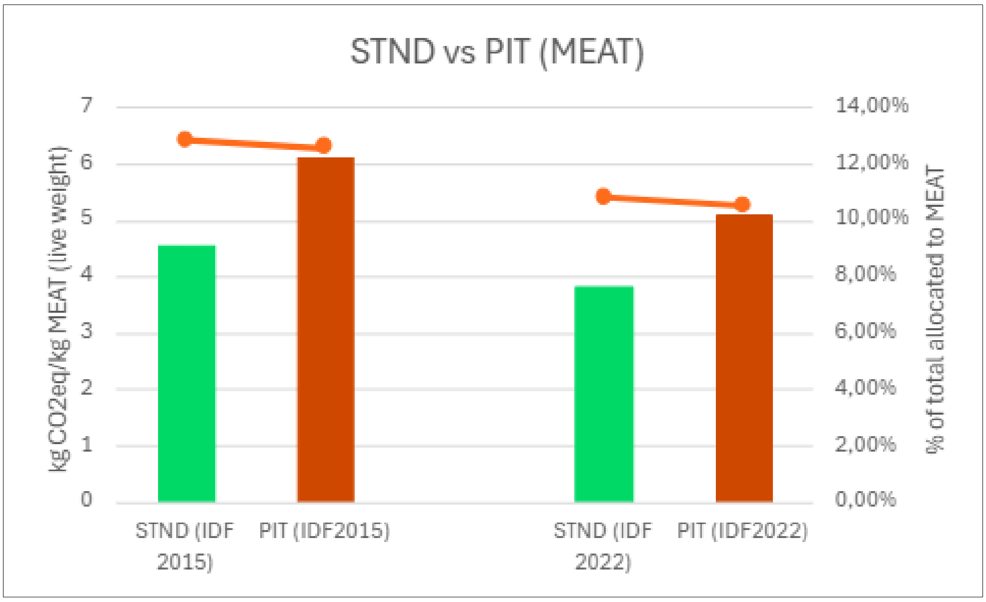


Figure 5.3: STND vs PIT, meat footprint

A reduction in the share of total emissions allocated to Meat is found when passing from the IDF2015 to the IDF2022, confirming the inverse trend for Milk. Between STND and PIT, a reduction of the share can be observed. This confirms again the trend noted in the analysis in Figure 5.2. The phenomenon is attributable to the reduction of the relative weight of the emissions directly allocated to Meat in the PIT scenario, in which non directly allocable impacts are importantly higher.

5.3 Emissions generated in the different scenarios

One of the main goals of the thesis is the study of the different impacts associated with the various agronomical techniques analysed. The total CO2eq emissions generated by the agronomical part of the cycle in the various scenarios are presented in Figure 5.4. In the Figure, apart from the actual quantity of CO2eq yearly generated by the system operation, the variation with respect to the STND scenario is highlighted. The PIT scenario is not considered of interest from now on in the study: the analysed allocation methodologies cannot be applied and Anaerobic Digestion is not implemented, making it not comparable with the others.

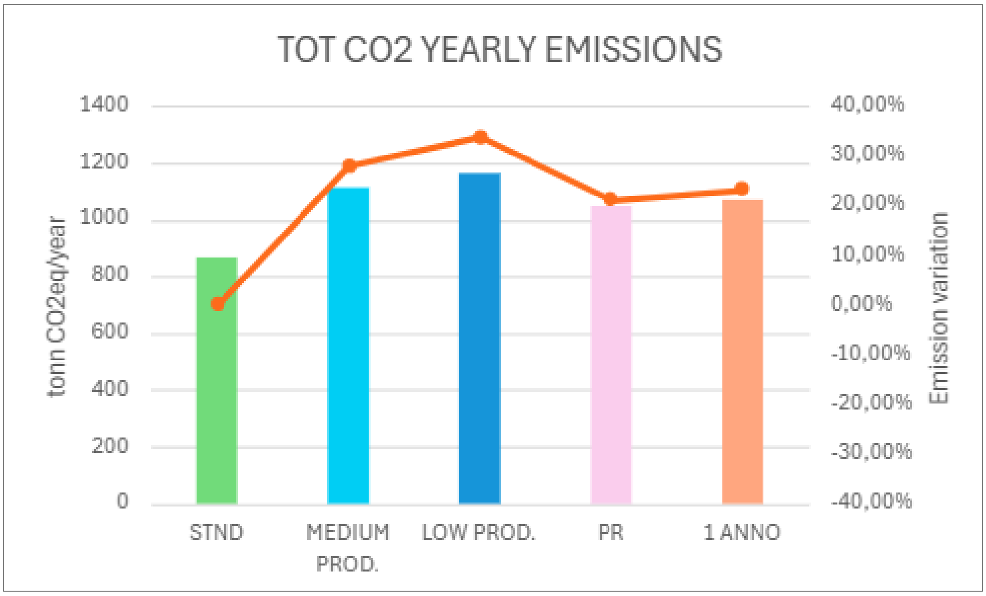


Figure 5.4: Total carbon footprint of the various scenarios

An increase in the total Footprint of systems with respect to the STND scenario is noticeable in all of the other analysed cases. In MEDIUM and LOW the effect is linked to the decreased digestibility of feed and consequent increase in Enteric Methane emission and Feed necessity. In particular, the Enteric Fermentation emissions have been identified as strongly dependent on the kind of feed implemented, not only related to digestibility, but to many more complex biophysical parameters [13]. In this sense, the analysis results not sufficiently thorough, with only the main factors used in IPCC calculations considered as varying in the scenarios. It is reasonable to assume that improved feeding techniques could bring to the same production levels as STND, while decreasing the Enteric methane generated. In PR, a similar motivation leads to an increase, slightly less influential. This is because the DE in PR is considered as slightly improved, and the methane conversion factor Ym is lower in the PR case, as specified in [51]. Besides the feed characteristics, its own impact is different in the PR diet, with a different base feed mix, with a lower impact/kg. In the 1ANNO scenario, the number of animals living on the farm changes, bringing increased inputs and consequent increased impact of the system. The quantities of products and their proportions are though different, generating the possibility to have reduced impacts for some specific products exiting the farm.

5.3.1 The effect of the different allocation methods to milk in the various scenarios

In the previous paragraph, it has been shown how the various choices implemented in dairy farming strongly influence the possible total Footprint of the systems. The footprints of the various generated products are not only dependent on the total impact of the systems, but also vary with the choice of allocation methodology. The various methodological choices try to describe different relations connecting the products and their inputs, generating though conflicting results. In Table 5.1, the resulting footprints for Milk in all of the scenarios and with all of the allocations are presented. It is important to underline, as already stated, that the results refer to a 'gate-to-gate' analysis, in which product LCA is brought on from the moment the inputs get in the farm to the moment the products exit the farm gate, non considering various processes that would be proper of a total 'cradle-to-grave' analysis.

Table 5.1: Carbon Footprint of Milk in the different scenarios and allocation techniques [kg CO2eq/kg FPCM]

	NO ALLOC.	**IDF 2015**	**IDF 2022**	**ECONOMIC**	**FAO**
STND	0,73	0,64	0,65	0,66	0,43
MEDIUM PROD.	1,37	1,13	1,18	1,18	0,70
LOW PROD.	1,94	1,48	1,60	1,60	0,94
PR	0,89	0,78	0,80	0,79	0,45
1 ANNO	0,90	0,71	0,78	0,74	0,48

It is immediately evident how the relation between the increase in emissivity of systems and the increase in Footprint of Milk is not linear. The main factor influencing the impact of Milk can then be highlighted: production level. It is simply demonstrable when comparing the results obtained in the PR and 1ANNO scenarios with the Low and Medium productivity scenarios: in the first two an increase of total emissions of over 20% is translated in an increase of milk emissivity, varying based on the various allocation methodologies, of the same order of magnitude; in the scenarios in which the production levels were lowered, the Footprint of Milk showed an increase of even more than double, despite the increase in the Footprint of the system by less than 35%. The results can be considered consistent with expectations, as the influence of milk productivity on its overall environmental impact is widely recognised in the literature [13]. This brings to one of the first important considerations on the CF of milk, with the selection of herd characteristics and genetics highly influential on the final Footprint of the produced Milk. When observing the PR scenario with respect to STND another factor is demonstrated as influential on the Footprint of milk: Feed characteristics. The Digestibility of Feed has an impact on the total emissions by the system, more than influencing the emissions from the product Milk, not generating a not linear increase in Footprint. It is though expected that the decrease of Digestibility, causing an increase in Manure production, will prove to be more influential in scenarios that consider Manure as a co-product of the process.

The study aims not only at the individuation of the factors influencing the systems' Footprints, but also to the observation of the effects of different allocation methodologies on the final Footprints of involved products. It is then of interest to singularly analyse the relation between each couple of allocation techniques, trying to identify the most influential factors for each and the inconsistencies generated.

Building on the concept, in Figure 5.5 the first comparison is presented, between those that can be considered the slightly more traditional allocation methodologies for the Dairy sector, IDF 2015 and IDF 2022, both not considering Manure as a co-product of the cycle.

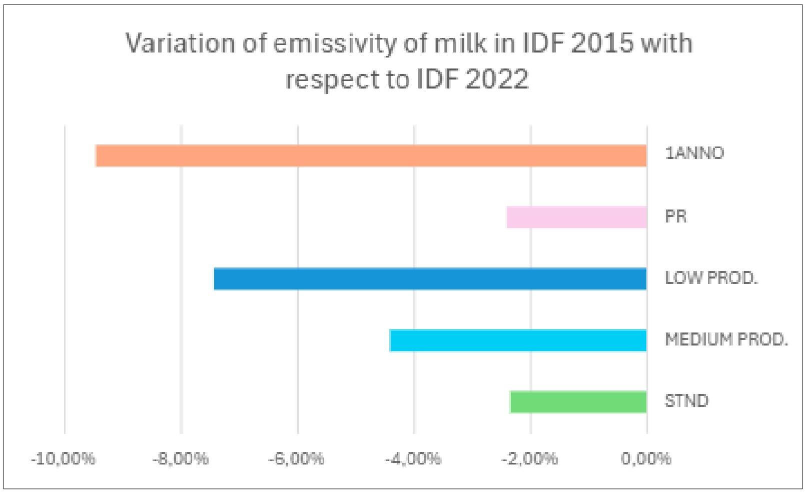


Figure 5.5: Variation of Footprint of FPCM in IDF 2015 allocation with respect to the IDF 2022

The Footprint of Milk in IDF2015 is lower than the one calculated following IDF 2022 procedure. The trend is confirmed in all of the scenarios, but in different proportions. In 1ANNO the differences between the two are accentuated, with a decrease of 9.5%. To try and understand the reasons of the shift in impacts, the parameters with which the calculations are performed can be analysed. The two methodologies differ in a fundamental concept: in IDF 2015, no 'Energy' is considered as associated to the various products, only the weight of the final outputs influences the allocations, with the 'Energetic' relation between products superimposed. The product Meat includes both Cow and Veal live weights, without posing a difference between the energetic expenditure connected to the generation of the single kg of product. IDF 2022 has an 'Energetic' approach and differentiates between Cow and Veal. The increased impact of Milk in IDF 2022 is a symbol of the difference between the methodologies, with IDF 2015 placing at a disadvantage the product Meat, in favour of reduced emissions allocated to Milk. The effect is in fact more influential when Meat quantities are higher or when milk quantities are lower, both conditions reducing the share of Milk in the final products.

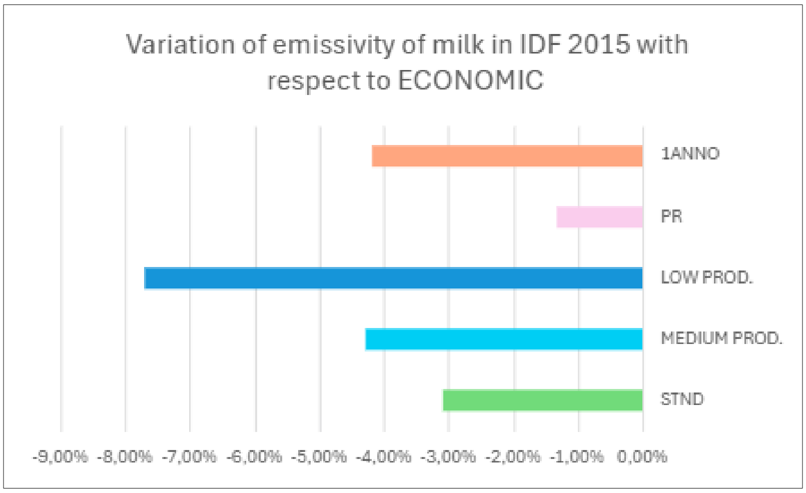


Figure 5.6: Variation of Footprint of FPCM in IDF 2015 allocation with respect to the ECONOMIC

In Figure 5.6 the results show again a reduced impact associated to Milk for the IDF 2015, when compared to the ECONOMIC allocation technique. The two are strongly different in both considered products and concept of allocation. The ECONOMIC allocation assigns some

Footprint to Manure, when considered as a co-product that exits the farm with an economic value. The lower producing scenarios are the most affected, with Milk CF reduced of nearly 8% in IDF 2015 with respect to ECONOMIC. This again highlights how in IDF 2015 there is a higher stability of allocation, with lower variations of Footprint connected to a lower production of Milk. The higher stability is not always a good factor, with the risk of non-actual representation of the real cycle balances. Economic allocation is though presented as the last option for the allocation of impacts, being it both very dependent on the socio-economic situations and not representative of a physical relation but of an imposed society one. Being the relations in Figure 5.5 and 5.6 similar, it is of particular interest to analyse the relation between IDF 2022 and ECONOMIC, in Figure 5.7, for which a higher stability and correlation are expected.

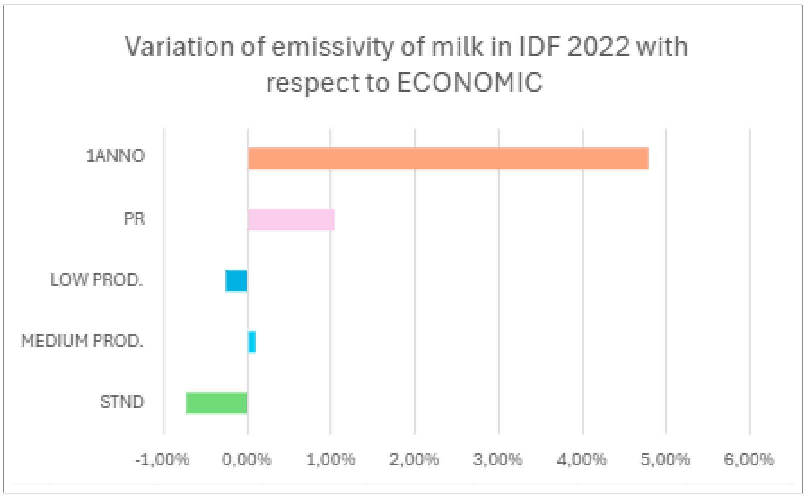
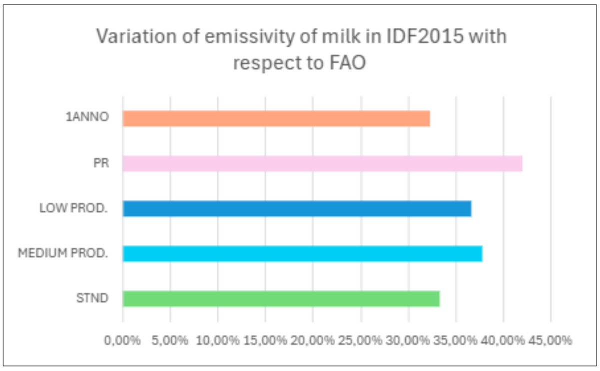
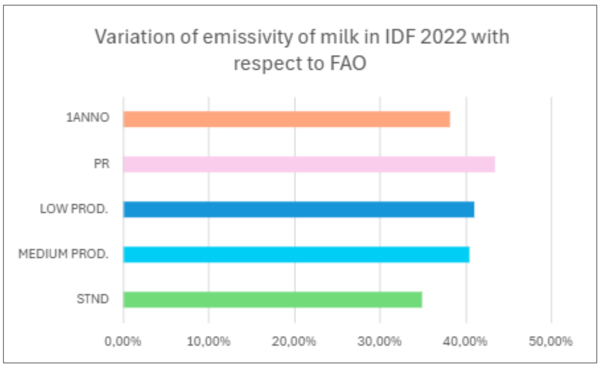


Figure 5.7: Variation of Footprint of FPCM in IDF 2022 allocation with respect to the ECONOMIC

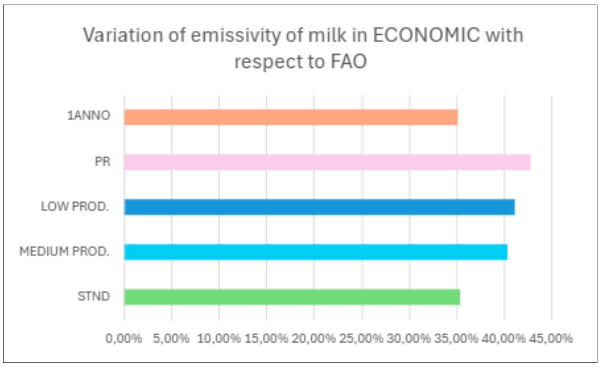
As expected, the relation between the two allocation methodologies is close, showing similar results in the various scenarios. The main difference can be detected in the 1 ANNO scenario, in which a 4.8% difference in Footprint can be noted, with Economic slightly less emissive. This shows that the main difference in the methods is found in the consideration of Veal, in proportion more costly than energetic, for how they were defined. A deeper analysis of the effects of the various allocation methodologies on the other products of the agronomical cycle is brought on in section 5.5. The FAO allocation methodology diverges strongly from the other analysed, with a significant decrease in Milk Footprint. It presents an important drift in the Milk emissivity in all of the scenarios for all allocations, making it more interesting to analyse it in relation to the other three together.



(a) IDF 2015 allocation vs FAO



(b) IDF 2022 allocation vs FAO



(c) ECONOMIC allocation vs FAO

Figure 5.8: Comparison between IDF 2015, IDF 2022, and ECONOMIC allocations with respect to FAO

The three other methods present over 35% more Footprint associated with Milk with respect to FAO. IDF 2015 is the one with the lowest drift, but in any case very important. The difference in this regard, when compared to IDF 2022 and ECONOMIC, is due to the already demonstrated tendency of the method to assign a smaller share of emissions to Milk. FAO shows to reduce the 'internal' variation between the scenarios, smoothing the differences in CF. The strong difference between this methodology and the others has to be appointed on the much higher influence of manure in the balance. While also ECONOMIC considers Manure as a product, the share of emissions attributed to it is significantly lower with respect to the corresponding in FAO. This brings to the consideration that, with such a big bias, the allocation of energy to Manure following the [78] consideration is probably an overstatement of the energy that should be attributed to the kg of DM. It is derived from some biophysical considerations, but the comparison with the single kg of FPCM makes it not fully representative of the actual energy balances in the system. Another factor to be considered (not that influential in ECONOMIC, because the relative value of manure is very low) is that for the other products the quantities considered are referred to live weight or to collected milk, defined and stable products, while in manure collection, storage and exportation from the farm many variables could highly influence the actual delivered quantities, reducing the relative weight of the product in the allocation balances. The fact that FAO methodology is presented as an option in the various sectorial guides opens the doors to the possibility of very different impacts associated to Milk, inside the same scenario.

5.4 What about the other products of the cycle

The relations used to define allocation methodologies are defined IDF, EDA and PEFCR dairy, all realities specific to Milk production. Being the present a study on the cycles involved, and not only on the specific production of milk, it results of extreme interest, to better understand the behaviour of allocation methodologies, to analyse the variation of the Footprints of the other products exiting the farm. The analysis of the co-products leads to the possibility of, theoretically, of connecting what happens on the agronomical side, the farm, to the production of the biomethane with Manure as a substrate, the main goal of the study.

5.4.1 Meat

Meat as a product is only represented in IDF 2015, with the other methodologies differentiating between Cow and Veal. The CF in the different scenarios is presented in Figure 5.9, while in Table 5.2 the total share of emissions to Meat and the relative to every kg of live weight are presented.

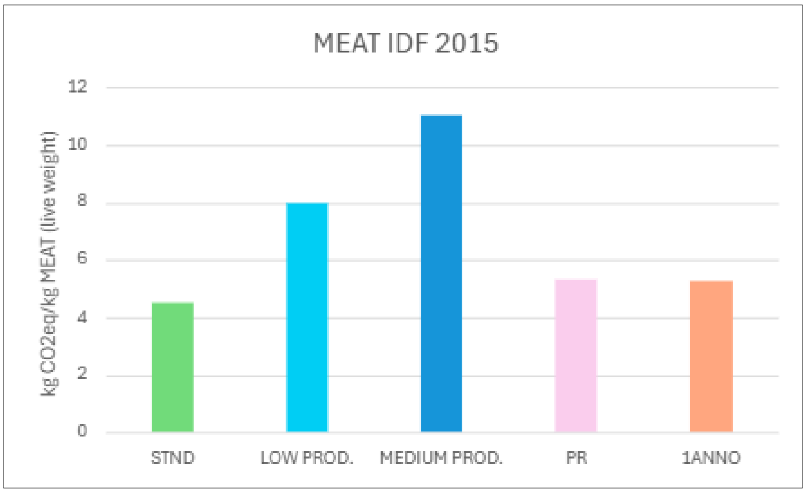


Figure 5.9: Variation of Footprint of Meat in IDF 2015

Table 5.2: Percentage of total Footprint associated to Meat

MEAT	%	%/KG
STND	12,9%	$5{,}2 \times 10^{-6}$
MEDIUM PROD.	17,6%	$7{,}2 \times 10^{-6}$
LOW PROD.	23,3%	$9{,}5 \times 10^{-6}$
PR	12,5%	$5{,}1 \times 10^{-6}$
1 ANNO	21,5%	$4{,}9 \times 10^{-6}$

The CF of Meat follows a similar trend to the Milk CF. Again, the variation between the scenarios is strong, with the impact in Low over double the one in STND scenario. This underlines again how the productivity levels influence the total emissions of the system. In the Medium and Low cases, the increase in Footprint of Meat is enhanced by the reduced presence of Milk in the balance, with a bigger total share of emissions allocated to Meat. This brings, in the extreme case of Low, to an increase in CF of over 140%, against the 130% in Milk. Total shares assigned to Meat show, as expected, a linear trend with Milk production when analysing the scenarios in which that is the main variable. In PR the total share is slightly reduced in relation to STND, indicating a lower impact on the balance of the directly allocated inputs. This is because, especially when considered as a singular product, Meat has an influential part of the feed directly allocated and, increasing the total emissions from the system (Enteric Fermentation emissions, not directly allocated), its weight on the equilibrium decreases. In any case, the lower total and specific allocations do not result in a lower final CF of Meat, indicating the STND as the best agronomical practice also for Meat. 1 ANNO presents a high share of impact associated with Meat, a consequence of the increased quantity of the product exiting the system. This leads to the scenario having the lowest share of emissions for kg of live weight. The increase in the total Footprint of the scenario is again stronger than the variation, causing a higher CF. The consideration of Meat as the sum of young and old animals exiting the system does not accurately represent the balances in the cycle, putting in the same category very different products from Energetic and Economic points of view. The two products are treated separately in the following paragraphs. It is also important to underline how the product Meat (and Veil and Cow) is considered as live weight. This means that before the actual consumption by the consumer, the product will not only undergo various processes, storage and transportation stages that should be considered in the LCA, but will also highly reduce its weight when considering Retail Product Weight [115]. The results should so be interpreted considering the gate-to-gate approach.

5.4.2 Veal

Veal is considered a separate product in three of the four allocation methods. Its quantities are constant throughout the scenarios, with the exception of 1ANNO, in which 21920 kg of Veal exit the system against the 2850 of the others. This is expected to be reflected in a substantially higher share of emissions allocated to it in 1ANNO. As for Meat, in Figure 5.10 the CFs of Veal for the different scenarios and allocation methodologies are presented, while in Table 5.3 the total shares allocated to Veal and to the single kg are displayed.

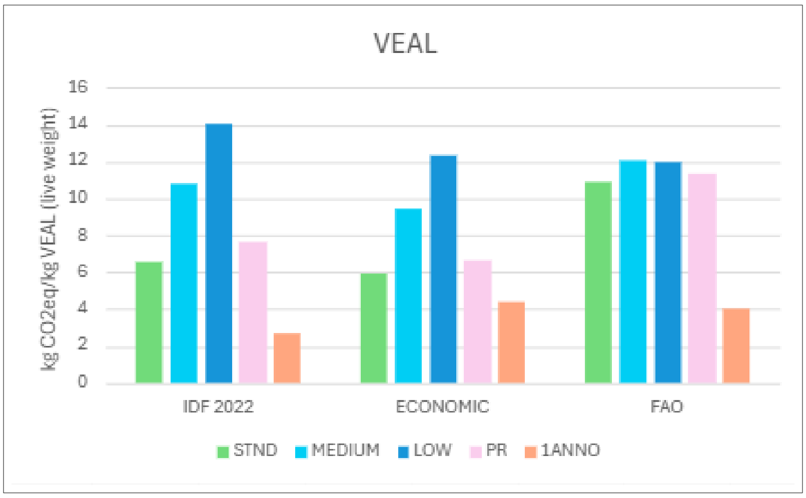


Figure 5.10: Variation of Footprint of VEAL with the various allocation methods

Table 5.3: Percentage of total Footprint associated to VEAL

VEAL	IDF 2022	ECON	FAO	%/KG 2022	%/KG ECON	%/KG FAO
STND	2,17%	1,94%	3,57%	$7{,}6 \times 10^{-6}$	$6{,}8 \times 10^{-6}$	$1{,}3 \times 10^{-5}$
LOW PROD.	2,77%	2,44%	3,23%	$9{,}7 \times 10^{-6}$	$8{,}6 \times 10^{-6}$	$1{,}1 \times 10^{-5}$
MEDIUM PROD.	3,46%	3,06%	3,15%	$1{,}2 \times 10^{-5}$	$1{,}1 \times 10^{-5}$	$1{,}1 \times 10^{-5}$
PR	2,07%	1,81%	3,08%	$7{,}2 \times 10^{-6}$	$6{,}3 \times 10^{-6}$	$1{,}1 \times 10^{-5}$
1 ANNO	5,44%	9,02%	8,35%	$2{,}5 \times 10^{-6}$	$4{,}1 \times 10^{-6}$	$3{,}8 \times 10^{-6}$

In the comparison between the three analysed allocation methods, a difference in trends is evident: while for Economic and IDF 2022 the CF evolves in a similar way to the previous when changing scenario, in FAO the CF are very close, apart from 1ANNO. The 1ANNO scenario is obviously the most affected by change, with a reduction of over 100% in CF with respect to STND in IDF 2022 and FAO. This highlights a problem in the methodologies: the allocation techniques are developed referring to Dairy farms, in which the main objective is Milk production, and the proportions between productive and non-productive animals on the farm are usually similar. The change of this proportion leads to errors in the description of the system, with a CF reduced because the quantity of one single product out of the total varies. A farm could produce Veal with very low impact just increasing the number of animals on the farm and their weight, without actually reducing the emissions associated with the production of the weight. The rules should be applied only to Dairy farms, but in a social environment as the Italian, with many medium-little activities, the definition of what is a dairy farm and what is a meat production farm could be closer than what could be thought. The rules for the calculation of impact from the IDF underline how, if possible, the fattening and dairy facilities should be considered as two separate cycles, not posing though a strong delimitation on how to separate the two or on what specific parameters define the different objective of the farm, in fact opening to the possibility to different interpretation. Low production scenario not only has the biggest CF for all of the allocation techniques, but also presents the highest share of emissions allocated, confirming the dependence of the other products of the cycle on the Milk productivity of the animals. In general, when compared to Meat, the CF of Veal results higher, symbolizing the increased value (Energetic and Economical) associated with Veal. Given the consideration, it is expected that the CF of Cow will be lower than both Meat and Veal.

5.4.3 Cow

Cow is the representative product of the live weight of culled cows exiting the system. Some techniques could be implemented to modify the weight of the animals before the exit from the system, but are not considered in the analysis. No scenario was composed varying the quantity of exiting Cow weight, considered nearly 21700 kg.

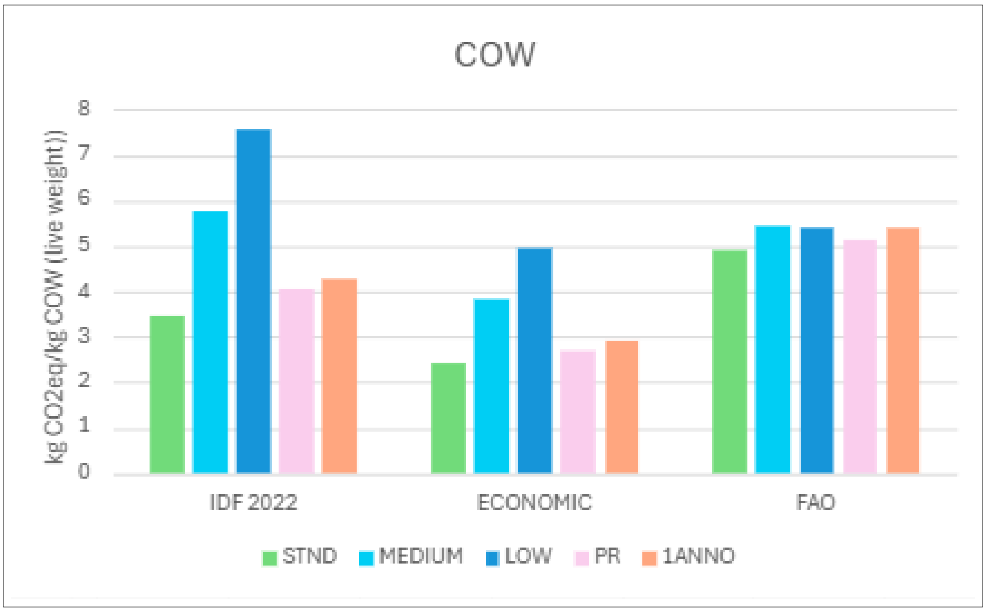


Figure 5.11: Variation of Footprint of COW with the various allocation methods

COW	% IDF 2022	% ECON	% FAO	%/kg 2022	%/kg ECON	%/kg FAO
STND	8.65%	6.03%	12.27%	4.0E-06	2.8E-06	5.7E-06
MEDIUM	11.24%	7.48%	11.08%	5.2E-06	3.4E-06	5.1E-06
LOW	14.14%	9.32%	10.80%	6.5E-06	4.3E-06	5.0E-06
PR	8.34%	5.57%	10.56%	3.8E-06	2.6E-06	4.9E-06
1ANNO	8.69%	5.91%	11.00%	4.0E-06	2.7E-06	5.1E-06

Table 5.4: Comparison of cow footprint percentages and emissions per kg under IDF 2022, ECONOMIC, and FAO allocations.

The general trends (if the 1ANNO scenario is excluded) are similar to the Veal ones. The biggest difference in impact (119%) is found again in the IDF 2022 methodology when considering the Low scenario with respect to STND. Fao presents a nearly constant share of impact associated with the single kg of product, highlighting the high stability of the allocation methodology when treating Meat products. It is an interesting effect because it reduces the volatility of CF associated to the single product, but in the meantime it reduces the accuracy of the representation of the energy and carbon cycles, in fact nearly detaching the product from the agronomical techniques implemented to obtain it. Economic allocation generates particularly low results, both in total shares allocated and in actual Footprint. This is attributable to the much lower economic value of Cow if compared to Veal. The gap in economic value generates a big difference in how Veal and Cow CF evolve, with Cow's reducing of over 30% between IDF 2022 and Economic, while Veal's only reduces its of about 10% (with the exclusion of 1ANNO scenario). In general, as expected, a CF lower with respect to Meat and Veal can be detected for Cow, representing the lower Economic value and Energetical expenses for the production of the kg of liveweight. It could be of interest to analyse how the allocation techniques react to different herd replacement rates, factor that is quite constant in literature (indicating an optimized farming technique) but could be used to change the balances, as seen for Veal in 1ANNO scenario.

5.4.4 Manure

The last product of the agronomical cycle to singularly be analysed is Manure. It represents the product that connects the two cycles, Dairy farming and Biomethane production. As previously underlined, following the current regulatory framework, the allocation of impacts to Manure has to be considered as zero. In the study this limit has been removed to observe the influence on the Biomethane cycle by the CF of Manure. Two of the four allocation methodologies consider the product, while for IDF 2015 and IDF 2022 the allocation has been imposed following the RED constrains.

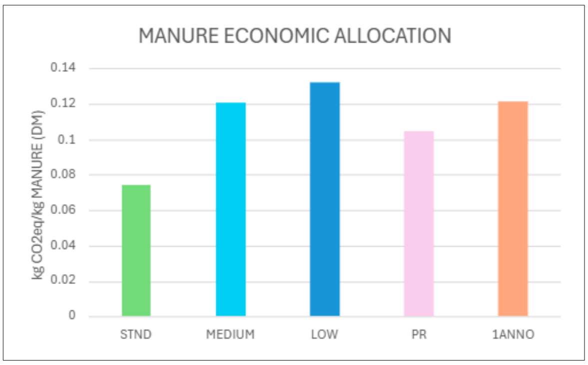


Figure 5.12: Variation of Footprint of MANURE in ECONOMIC

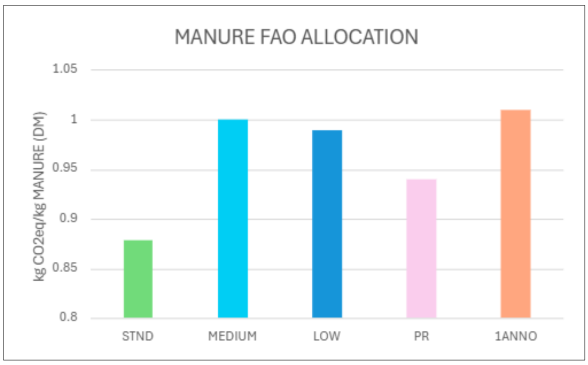


Figure 5.13: Variation of Footprint of MANURE in FAO

MANURE	% ECONOMIC	% FAO	%/kg ECON.	%/kg FAO
STND	2.20%	26.14%	8.5E-08	1.0E-06
MEDIUM	3.78%	32.44%	1.1E-07	9.4E-07
LOW	4.29%	34.06%	1.1E-07	9.1E-07
PR	3.96%	35.65%	9.9E-08	8.9E-07
1ANNO	3.32%	27.61%	1.1E-07	9.5E-07

Table 5.5: Comparison of manure footprint percentages and emissions per kg under ECONOMIC and FAO allocations.

The two considered methodologies generate strongly different results. Nearly one order of magnitude is present between the results of the two, for both total share and actual Footprint. The low price of manure limits the Footprint and the share of emissions allocated to it. The increased production of manure in all scenarios with respect to STND is reflected by the increased shares of total impact allocated to the product. The growth is not linear, with PR producing the biggest quantity of manure (nearly 400000 kg), but not having the most shares assigned. This is to be interpreted considering that in PR the production of milk is strongly higher than Low and Medium, with an important economic value assigned to it if confronted with Manure. 1ANNO on the other side has an increased production of Veal, high value product, making the total economic value of the system higher, reducing the shares assigned to Manure with respect to all scenarios excluded STND. The final footprint is though higher than both Medium and PR, because the emissions have to be divided in a lower quantity of product. An important aspect of the study can be highlighted: the feed characteristics have a lower effect on manure Footprint then the number of animals in the herd. Observing the PR and 1ANNO scenarios it is noticeable how, with the same production of Milk, and even with an additional product quantity in 1ANNO, the Manure impact is lower in PR. When considering that the total Footprint of the system is very close between the two, the difference in feed characteristics, connected to manure production, would suggest an allocation methodology that better represents the cycle of nutrients and better connects the increase in enteric fermentation with the digestion processes. The difference in digestive processes by cows feeding with PR mix against the STND mix leads to such an important increase in Manure production that it compensates the increase in shares of total CF. A similar dynamic is noticeable when comparing Medium and Low in FAO allocation technique, in which the increase of production brings to a reversal of the usual trend of CF, detaching it from the total emissions of the system. This occurrence opens to one possibility: if one of the main objectives of the farm is Biomethane production, a worse feeding mix from the Digestibility point of view, can lead to an increased possibility of production of gas, coupled with a lower CF associated to the input manure. A negative technique from the optimal agronomical practices point of view becomes then a good method to reduce the CF of a specific product.

5.5 Footprints of Biomethane and Digestate

In the previous sections, one aspect has been put in light: Agronomical choices impact on total emissions by systems producing similar goods and, with them, on the Manure produced in these systems. This is the main reason for which a study observing the effects of different input CFs associated to Manure has been brought on. The current consideration of Manure as a process residue, not bringing emissions as inputs in the system, leads to the consideration of different inputs, produced in sensibly different situations, with highly different environmental characteristics as the same. It is understandable under the assumption that European regulations are written with the main objective of incentivizing determined techniques and practices, but they do not represent the actual Carbon cycle involved. The calculation of the Footprint of

Biomethane and Digestate was brought on following the procedures described in Chapter 4. The base most influential factors in Equation 4.3 are presented in Table 5.6. These values are referred to the STND allocation considerations, with 0 as input for cattle Manure. In Table 5.7, the STND CFs of Biomethane and Digestate are presented. It is important to underline again how, for current techniques, those would represent the CFs of the products in any case, totally ignoring the origin of biomass.

Table 5.6: Main factors in emission equation calculation

	Cattle manure	**Hen manure**	**Bro. litter**	**Corn stover**	**Sorghum**	**Triticale**
$\mathbf{e}_{cc}$, **MJ**	0.00	0.00	0.00	0.43	3.31	4.08
$\mathbf{e}_{td}$, **MJ**	0.78	0.17	0.14	0.24	0.28	0.26
$\mathbf{e}_{sca}$, **MJ**	-162.00	-154.21	-110.76	0.00	0.00	0.00
Sn	0.13	0.09	0.16	0.09	0.28	0.25

Table 5.7: CF of Biomethane and Digestate standard

	Value	**Unit**
Biometano STND	-13.98	g CO_2eq/MJ
Digestate STND (before separation)	-32.58	g CO_2eq/MJ
Digestate STND (before separation)	-554.54	g CO_2eq/kg DM

The value obtained for Biomethane results coherent with the standard and typical values presented in the Annexes of RED 2 [9]. The negative value results from the entity of bonuses from implemented biomass, higher than the impact of the whole process. Again this symbolizes how European regulations do not give a complete outlook on the actual Carbon and Energy cycles involved, but generate a stable environment for investments, with the goal of decarbonizing the energy sector, even if through methodologies that do not correctly represent reality. The Digestate impact as presented in Table 5.7, was calculated for the product as it is when the process of Anaerobic Digestion concludes. The various processes the digestate undergoes, first of all the separation of liquid and solid parts, are not included in the previous table calculations, but are considered in the following passages. The choice to present the Digestate as it is has been made because its use has been analysed in both, the case of Fertilization with only the liquid fraction and the case of Carbon sink, in which the whole digestate has been considered as entering the field. Before considering the different possible characteristics of the implemented Digestates it is though important to evaluate what impact the Economic or Fao allocations to Manure would bring in the cycle. The different input value is not expected to highly influence the CFs, but it could give a contribution towards a more coherent representation of involved streams.

5.6 Variation in Footprints considering the different manure allocations

In the considered mix, Manure constitutes 22% of the substrate Dry Matter and has a ponderation factor (S_n) in the mix of 13,4%. The impact of the addition of the Manure CF has to be viewed considering its relative weight in the mix. It is important to underline how similar studies should be performed on the two other inputs subject to the manure bonus in the mix (Layer hen manure and Broiler litter) to give a more complete representation of the effects of the methodology on Biomethane CF. The results connected to the RED [9] consideration of Manure are displayed with the ones generated by the Economic and Fao allocations to highlight the total independence of the RED methodology (presented under the denomination STND from now on in the document) from the agronomical techniques.

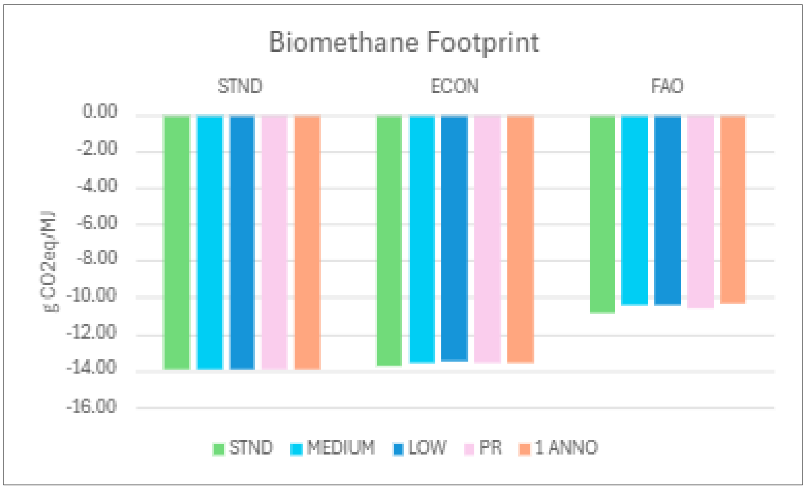


Figure 5.14: Biomethane Footprint with the different allocation methods to MANURE

Table 5.8: Increase in Biomethane Footprint

	STND	**MEDIUM**	**LOW**	**PR**	**1 ANNO**
STND	0.00%	0.00%	0.00%	0.00%	0.00%
ECONOMIC	1.90%	3.09%	3.39%	2.68%	3.12%
FAO	22.53%	25.65%	25.36%	24.10%	25.90%

The STND allocation, as anticipated, generates a univocal result, independently from the scenario in which Manure is produced. With the implementation of Economic, a slight difference is noticeable with the STND. Depending on the scenario, the different CFs of Manure generate an increase between 1.90% and 3.39% of the Biomethane Footprint (intending as increase the reduction of the negative Carbon Footprint). Inside the Economic allocation, the variation between CFs of Biomethane in the various scenarios is less marked than the ones in the agronomical side. The maximum internal variation is 1,5%. The value has to be analysed considering the low actual variability of the CF of Manure in the Economic allocation methodology and the relative weight of dairy Manure in the substrate mix. The effects are more observable with FAO allocation. An increase between 22.53% and 25.90% of the Footprint is generated. Variations between scenarios are more marked in this case, with a maximum difference in Biomethane Footprint of 4.4% between STND and 1ANNO. The increased influence of the agricultural practices on the Anaerobic Digestion cycle internal to the allocation is to consider a positive effect of the FAO methodology. The effect is connected to the increased differences in Manure CFs using the FAO methods. A similar methodology applied to Leyer hen manure and Broiler litter would bring to an enhanced influence of the agricultural side of the cycle on the emissivity by Biomethane. The effect in the present study is still limited and has to be weighed against the inconsistencies highlighted in the FAO allocation results, but can be considered an important result on the possibility of a connection between the cycles. The last consideration about the correlation between Biomethane and Milk CFs can be made by comparing the results. With the Economic allocation, the minimum increase of Biomethane CF of 1.90% in STND scenario corresponds to a decrease in Milk Footprint when compared to IDF 2015 of 3,1%. The maximum of 3.4% in LOW is associated to a decrease for Milk of 7.7%. With the FAO allocation the minimum increase of 22.5% for Biomethane corresponds to a reduction in Milk Footprint of 33.4% when compared with IDF 2015 (used as the comparison meter, being the most used methodology in literature, as previously described). The maximum variation of 25.9% for the 1ANNO scenario translates in a decrease of Milk CF of 32.4%. The relation between the cycles can be enhanced with the consideration of use of Digestate in the fields producing the feeds for the herd. Figure 5.15 compares the CFs of the various scenarios with the three considered allocations. The product the Figure refers to is still as it is Digestate, with the characteristics presented in Table 4.12. The results are then expected to be very similar in trend to the results displayed in Figure 5.14 for Biomethane.

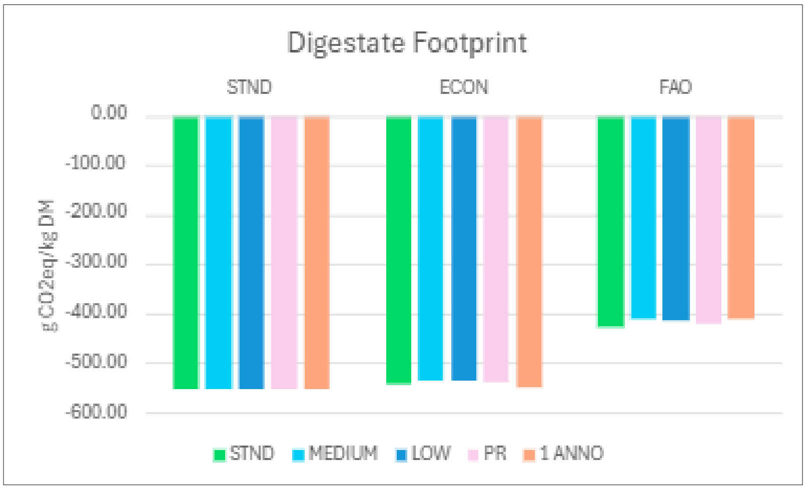


Figure 5.15: Digestate Footprint with the different allocation methods to MANURE

The CF of Digestate was similarly impacted by the allocations to Manure. The correlation is explainable with the low directly associated input-processes considered in this phase. In the next paragraphs, in which additional processes and transportation are included, the results are expected to vary differently. Using the Economic allocation, the best CF is found in 1ANNO scenario, with a value very close to -550 gCO_{2eq}. The highest impact is observed in LOW scenario, with -536 gCO_{2eq}. The variations, as for the Biomethane case, are minimal. FAO allocation leads to higher influence by the agronomical part, with a minimum Footprint of -430 gCO_{2eq} in STND and a maximum of -411 gCO_{2eq} in 1ANNO.

5.7 Agricultural use of Digestate

Two processes were analysed when treating the utilization of Digestate in the cultivation of the crops composing the feed: the use as Fertilizer and the ability to stabilize Carbon in the ground. It is important to underline that many other possibilities for agronomical utilization of Digestate are possible, and how extremely dependent on techniques and climate the actual impacts of the practices can be. The analysis on the agricultural use of digestate has been performed only regarding the STND scenario.

5.7.1 Fertilizer

In the application of Digestate as fertilizer, only the Liquid part has been considered. The characteristics of the implemented Digestate are presented in Table 4.13. The CF of the implemented Digestate is different from the previously presented because the various treatments the digestate undergoes, first of all the separation between solid and liquid, are considered. Additionally, transportation is considered and has a different impact depending on the DM of the substrate. In Table 5.9, the effects of the various allocation methodologies on the CF of the standard feed mix are calculated.

Table 5.9: Feed CF in Fertilizer substitution case

FEED	STND	ECONOMIC	FAO
DIGESTATE [g CO_2/kg UM]	-39.943	-39.167	-30.734
STND FEED [kg CO_2/kg DM]	0.666	0.666	0.666
NEW FEED [kg CO_2/kg DM]	0.524	0.526	0.543

The different impact brought in by the Digestate applied on the fields, for the various allocations, is translated into different final CFs of the feed mixture. In NEW FEED two main effects are considered: the negative emissive input connected to Digestate and the substitution of Fertilizers. The decrease of input impact by feed affects the whole Dairy Farm system. The resulting influence is studied only for the product Milk, being it the principal product of the Dairy farm system. A similar effect is presumable for the other products of the system, weighted on the shares of feed directly allocated to each product and of the general shares of the emissions allocated to each.

Table 5.10: Milk CF in fertilizer substitution case

	IDF 2015	IDF 2022	ECONOMIC	FAO
STND MILK [kg CO_2eq/kg FPCM]	0.639	0.654	0.659	0.425
NEW FPCM [kg CO_2eq/kg FPCM]	0.550	0.565	0.571	0.348
REDUCTION	13.86%	13.54%	13.30%	18.09%

The allocations IDF 2015 and IDF 2022 are considered in calculations because of the different CF of milk they generate. For both, the new feed considered is the one indicated as STND in Table 5.10, newly highlighting the dissociation between the farm-side allocation of impacts and the Anaerobic digestion. The maximum absolute decrease in Milk CF is found in the IDF methodologies, but in FAO the decrease has more relative weight, introducing a reduction of 18.09% of the Milk CF. This despite the higher input CF of Digestate in the FAO case, confirming the methodology the most convenient for the Footprint of Milk. The reduction in total impact by the system would obviously positively impact the CF of Manure in the considered methodologies, giving the possibility to obtain a new reduction in Biomethane CF. The iterative calculation has not been performed.

5.7.2 Carbon sink

The last analysed aspect regards the ability of Digestate to immobilize Carbon in the soil when spread on fields. The input CF referred to the implemented Digestate is different from the previous, being it considered as non-separated but treated and transported to the fields. The characteristics of the Digestate introduced into the fields are the ones presented in Table 4.12. The fertilization effects are considered combined with the Sink effects, but result slightly different from the previously calculated, being the characteristics of implemented Digestate different. As analysed in the methodology chapter about Digestate, the positive effects on the CO_{2eq} emissions of the system are constrained to the application of the best agronomical techniques in Digestate spreading. The different methodologies could highly influence the Sink effects by Digestate.

Table 5.11: Feed CF in Carbon Sink case

	STND	**ECONOMIC**	**FAO**
DIGESTATE [g CO_2/kg UM]	-65.0	-63.8	-50.2
STND FEED [kg CO_2eq/kg DM]	0.666	0.666	0.666
NEW FEED [kg CO_2eq/kg DM]	0.505	0.507	0.528
SINK FEED [kg CO_2eq/kg DM]	0.334	0.336	0.357

A reduced Footprint for the implemented Digestate is observed. It can be attributed to both the increased % DM and consequent reduced impact of transportation and the missed passage of separation of the fractions of Digestate. New Feed has a reduced impact with respect to the one calculated in Table 5.9, it is important to underline how the two effects as Fertilizer have been considered equivalent, but different characteristics of Digestate are expected to interact in different ways with the soil. Sink Feed represents the new possible CF of the standard feed mix, considering the Carbon stored in the ground. Priming effects have not been considered in the present study, being them dependent on the specific soil characteristics [114]. A more specific biophysical and biochemical analysis on the effects of the Digestate on the specific terrain it is applied to could be of interest to find the actual quote of Carbon fixed in the Soil. In Table 5.12, the effects of the reduction of CF of feed have been brought to the products of the cycle, in particular Milk.

Table 5.12: Milk CF in Carbon Sink case

	IDF 2015	**IDF 2022**	**ECONOMIC**	**FAO**
STND MILK [kg CO_2eq/kg FPCM]	0.639	0.654	0.659	0.425
NEW MILK [kg CO_2eq/kg FPCM]	0.538	0.553	0.559	0.339
SINK MILK [kg CO_2eq/kg FPCM]	0.432	0.447	0.453	0.232
REDUCTION	32.44%	31.70%	31.29%	45.40%

With all of the allocation methodologies apart from FAO, the reduction results in a relatively constant effect, with values between 31.3% and 32.4% deducted by the initial Milk Footprint. In FAO the relative weight of reduction is higher, being the CF of Milk lower to begin with. The final CF of milk can be considered quite constant throughout the IDF 2015 and 2022 and the Economic allocation methodologies for the STND scenario. the difference between the allocation to milk of the three and the one by FAO is confirmed, indicating the relative weight that emissions allocated to Manure have on the output of the Anaerobic digestion system. In the production of Carbon Neutral or Carbon Negative food sources, the concept of biological immobilization of Carbon can assume a very important role. The evaluation of the actual quote of the incorporated Carbon that is immobilized requires studies and measurements to be confirmed to have access to the negative CO_{2eq} credits. The possibility of bringing the effects to all of the combined cycle gives the idea of the weight that similar methodologies can have on the assessed impact of systems. This highlights the importance of unified and consistent methodologies to evaluate the impact of the techniques

Chapter 6

Conclusions

In the thesis, an analysis of the carbon footprints associated with the dairy and biomethane production cycles has been performed. The main objective was to highlight the most influential factors in the definition of their impacts and to interpret how the two combined cycles influence each other's emissions. A scenario-based analysis has been implemented to evaluate the effects that different agronomical choices and techniques have on the combined emissions. To fully understand the most impactful factors an analysis of how the calculations are defined and of the allocation of impacts internal to the various products of the cycle has been performed. Four allocation methodologies have been studied for the agronomical side, all of which are acceptable in the voluntary declarations: IDF 2015 (supported by European PEFCR), IDF 2022, Economic and FAO. The calculations of Carbon Footprints have been implemented with the use of OpenLCA software with the EcoInvent database.

The frameworks regulating the definition of impacts for the two productive cycles are not coherent when treating dairy manure, with the PEF recommendations giving different possibilities for allocation of impacts to manure, while the Renewable Energy Directives open to the only option to consider it a residue, not bringing emissions into the system. This assumption brings with it a detachment between the two systems. It has been disrupted, to explore the possibilities of connection and try to better exploit the energy cycles involved between dairy farming and biomethane produced with dairy manure as a substrate.

As a first step of the investigation, the positive effects of anaerobic digestion on emissions from the agronomical cycle have been confirmed. A reduction of total emissions up to 27% was obtained by confronting the Standard scenario for anaerobic digestion with the Pit scenario, with the same product flows, but in which manure is stored at the facility and then spread on fields rather than undergoing Anaerobic Digestion. While the definition of the total emissions from the cycles is coherent throughout the various available methodologies, they strongly differ in the internal subdivision of impacts between the various products. A difference of 33.4% of impact allocated to milk is obtainable by simply choosing to use the FAO allocation method in place of the IDF2015 one, with IDF 2022 and Economic allocations in a +-5% range from IDF 2015. Different scenarios present strongly different total and allocated Footprints, with the Low Producing farm increasing yearly emissions from the same number of animals by nearly 34% while producing 49.3% less milk with an allocated impact increased by 131% with IDF2015 with respect to Standard. The various allocation methodologies result as not stable, with a strong variations of allocated impact referring to the same scenario depending on what the methodology weighs more with respect to the others. In Economic Veal allocation increases with respect to the others, in IDF 2022 Beef has more weight, while for Fao the balance is moved towards manure. This generates the possibility to adopt the method most convenient for the farming choice, not generating an actual reduction of emissions, but just reducing the allocated Footprint of the interested product. In the IDF2015 and IDF2022 the manure is not considered as a product, for Economic the allocated impacts vary between 70gCO2eq/kgDM in

Standard and 130g for Low while Fao allocations increase the associated emissions by nearly one order of magnitude between 880g for Standard and 1,01 kg for 1anno.

The evaluation of the impact associated with manure leads to the second part of the study, in which the biomethane cycle equivalent CO2 emissions were evaluated. A mix of substrates has been formed, in which manure constitutes 22% of the total dry matter but is 13,4% of the weighted contribution in the Emissivity Equation. Following the Renewable Energy Directives methodology the impact of 1 MJ of biomethane produced from the selected mix is –13.98gCO2eq. While in line with the expected value, the calculation shows one big flaw: for all of the treated scenarios the biomethane produced has the same emissivity, in fact detaching the production of biomethane from the origin of the biomasses. Manure with highly different associable emissivity in the PEF reasoning becomes totally the same at the entry of the Digester in RED, generating the possibility of a miscount of emissions and influencing the description of the nutrients and Carbon cycles. The Economic and FAO manure allocations have been implemented, generating an increase in biomethane emissivity. For the Economic allocation the effect was smaller, with an increase between 1.90% in Standard and 3,40% in Low, which corresponds to a 3.80% and 7.70% reduction in milk Footprint. It was more important in FAO, with an increase between 22.4% in Standard and 25.9% in 1anno which decreased milk emissivity by 33.4% and 32.4%. The digestate, a coproduct of the digestion, is also affected by the change in input emissions, modifying the emissivity from –560.4gCO2eq/kgdry in the RED calculations for the Standard scenario to –549.8g in Economic allocation and –434.13g in FAO.

As a last step, in the closing of the cycle, the digestate has been supposed to substitute the Fertilizers in the cultivation of the biomasses constituting the feed of the cows. The negative emissivity from the digestate is therefore brought into the system as an input generating a reduction in feed emissivity and, subsequentially, in the total emissions from the systems. The use of the Digestate, added to the missed purchase of Fertilizers strongly reduces the emissions allocated to the single kg of milk, with a reduction in Standard scenario between 13.5% for Economic allocation and 18.5% for FAO. It is important to underline that the digestate considered in FAO allocation has a lower positive impact on the system (22.5% more emissivity), but higher on milk because FAO allocation to milk is much lower when confronted with the others. Another exploitable effect of the use of digestate on fields is the possibility of obtaining a carbon sink, with Carbon immobilized in the soil after the harvest of the plants. A reduction of the impact of the kg of dry feed of over 150gCO2eq as Carbon Stock is obtainable with the correct agricultural practices. This brings to the possibility of ulteriorly reducing the emissions allocated to milk and manure, consequently leading to the possibility to reduce again the emissions from produced biomethane if FAO or Economic allocations are employed.

The project has brought to light two main factors in the dairy-biomethane LCA analysis:

- Agricultural choices have considerable importance in the emissions by the cycle. The choice of the farm structure and 'philosophy' is fundamental for the reduction of emissions of Milk, with the productivity of the cows and feed characteristics first drivers of the reduction. A decreased activity from the animals can also be beneficial for the emissivity of the produced milk and, if connected, biomethane. The number of nonproductive animals in the farm represents a factor in emissivity, with a reduced presence leading to a reduced emissivity of the system. Outside the composition of the herd and feed the actual agronomical practices can have fundamental importance, with one non-allocated kg of FPCM in the Standard scenario passing from 1kg of CO2eq in the Pit case to 0.733kg in case of anaerobic digestion of manure, to then potentially decrease down to 0.530kg with the use of digestate on field and the declaration of Carbon Stock. The biomethane is not so affected by practices for the current interpretations but could be if the manure input rules were changed. Agronomical use of Digestate strongly influences the Biomethane emissivity giving the possibility, that other ways would not be applicable, to subdivide the emissions between the two products. If the practice is not applied, and digestate becomes a residue, all the emissions are allocated to biomethane.

- The Carbon Footprint of Products is totally dependent on the different methodologies chosen to allocate emissions within the system. The potential of the change of technique is incredible, with milk footprint in the same conditions in the standard scenario passing from 0.659kg of CO2eq in the Economic allocation to 0.425kg for FAO. The single possibility of allocation for the biomethane cycle limits this effect to the different possible agronomical inputs. The fact that the allocation of emissions is so powerful, should lead to considerations on a way to define a univocal methodology to account for the Footprint, that prevents the generation of fictitious decreases in emissions of a single product.

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