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APPLICATION OF ENVIRONMENTAL SUSTAINABILITY ASSESSMENT METHODOLOGIES TO WASTE MANAGEMENT SYSTEMS AND TO ENERGY AND MATERIAL RECOVERY PROCESSES

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Coordinatore Dottorato	**Relatore**
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Canditate Presentation

During the three years of her PhD, Esmeralda Neri focused her research project on the study of the application of the Life Cycle Assessment methodology (LCA) to industrial chemical processes, and to processes of energy and material recovery and waste management, in collaboration with many companies of the sector.

She studied the topic of the transformation of residual biomass to renewable energy; the main applications related to this issue were the process of gasification of wood chips with the production of thermal energy and electricity, and the recovery of branches arising from the operation of management of public and private green on local scale for the production of thermal energy.

The candidate focused the work also on the study of the evolution over time of the impact of an organic waste treatment plant (integrating composting and anaerobic digestion) with the aim to assess whether and how the introduction of the energy recovery system lead to a real improvement of the process with an overall decrease of the environmental impacts.

In 2014 she has participated in the Pioneers into Practice program, with a national placement at the company I.R.C.I. S.p.A. based on a feasibility study for the generation of energy from agro-industrial residues by anaerobic fermentation plant (biogas) and an international placement at the University of Valencia with the study of the energy content associated with the different use of water. From 2015 she is one of the Local representative Climate-KIC Alumni Association.

In addition, Esmeralda Neri spent a period of research at the Universitat Autònoma de Barcelona under the supervision of Prof. Xavier Gabarrell Durany, where she has approached to the integration of green metrics (CO_2ZW) and methodologies of environmental impacts (LCA, Material Flow Analysis) for the assessment of the carbon footprint of a waste management system, focusing the study also on the avoided impact due to the process of recycling of paper.

During the last year she also approached to the study of the management of the end of life of tires, with the assessment of different scenarios of material and energy recovery, with a particular attention to the pyrolysis process.

Moreover, she was also involved in works related to the application of the LCA methodology to chemical processes, focused mostly on maleic anhydride and terephthalic acid production.

She has been the co-supervisor of four 2nd level degrees thesis in Industrial Chemistry proving a great ability in coordination of the activities of the students.

During the PhD, the candidate attended the School Green Skills for boosting transitions in water management (Valencia, 2014), the National School of Chemistry of the Environmental and Cultural Heritage (2015) and Course of Life Cycle Costing and Social Life Cycle Assessment (2016), several scientific seminaries, three national congresses and two international congresses with oral communication. Furthermore the research activity carried out in this three years is reflected in one article.

In my opinion Esmeralda Neri has carried out a very good work for the thesis.

The Board expresses a very good score on the activity carried out by the candidate during the whole cycle of doctorate and considers her worthy to attain the PhD in Chemistry.

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Abbreviations

CED	Cumulative Energy Demand
CF	Characterization Factor
CML	Centrum Milieukunde Leiden
COD	Chemical Oxygen Demand
COP	Conference of Parties
DALY	Disability Adjusted Life Year
DfE	Design for Environment
EA	Environmental Assessment
ED	Ecosystem Diversity
ELT	End of Life Tires
EPA	Environmental Protection Agency
EU	European Union
EWC	European Waste Catalogue
GHGs	Green House Gases
GWP	Global Warming Potential
HH	Human Health
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Integrated Product Policy
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
MBT	Mechanical-biological treatment
MCI	Marginal Increase in the Cost
MFA	Material Flows Analysis
MSW	Municipal Solid Waste
MUD	Model of Environmental Declaration
NG	Natural Gas
OFMSW	Organic Fraction Municipal Solid Waste

ORC	Organic Rankine Cycle
PAH	Polycyclic aromatic hydrocarbons
PDF	Potential Disappeared Fraction of species
PMF	Particulate Matter Formation
RA	Resource Availability
RDF	Refuse Derived Fuel
REPA	Resource and Environmental Profile Analysis
SD	Density of the Species
SETAC	Society of Environmental Toxicology and Chemistry
sLCA	Social Life Cycle Assessment
SNCR	Selective Non-Catalytic Reduction
SWOT	Strengths Weaknesses Opportunities Threats
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
YLD	Years of Life Lived with a Disability
YLL	Years of Life Lost

Abstract

During the PhD program in chemistry, curriculum in environmental chemistry, at the University of Bologna the sustainability of waste management systems and of energy and material recovery processes was investigated through the application of the LCA (Life Cyle Assesment) methodology, which allows a systematic approach that supports the detection of environmental-oriented strategies to obtain industrial improvements.

The study is intended to help analyses aimed at understanding the global effects of the waste management sector and the efforts were focused on the integrated waste management system and on systems of recovery of energy and materials in order to investigate the best way to manage waste taking into account the technologies available on the market and the features of each situation at local scale, evaluating their sustainability in comparison with traditional systems, from a life cycle perspective.

The environmental benefits associated with changes and improvements of the adopted solutions were assessed through a global approach.

Results emerged from the analysis confirms that the sustainability in the waste management sector should be evaluated considering all the stages and flows involved in each system in order to avoid the shifting of the environmental burdens from a step to another. Only a deeper knowledge may help to address successfully the challenge towards a transition to a more sustainable use of resources and to guide future national industrial policy toward a low-carbon economy.

In the future, LCA analysis should be increasingly supported even by other tools able to investigate the other two dimension of sustainability, represented by the social and the economic spheres.

1. Introduction

1.1 Circular Economy Background

The energy and environmental crisis, linked to the availability and use of resources of the planet, have been at the center of a global debate from nearly half a century; despite that, for too long it has been faced in a non-systematic way.

The continuous growth of the world population and the rise of living standards have increased the demand of energy, raw materials and goods. This increase of demand is correlated, due to the use of linear model of production – consumption – waste generation, to the reduction of resources availability and to the increase of greenhouse gases production. The central aspect had always been the productivity, with the need to maintain a high standard of consumption in order to guarantee it. For these reasons it is essential to apply and spread more sustainable development models.

The Sustainable Development theory, introduced in the 80ies, made possible to tackle the problem at scientific and institutional level. Secondly, the Green Economy model has been developed, which plans to realize the improvement of welfare and social equity reducing environmental risks, mentioned for the first time in 1992 during the Rio Conference, and it is achieved through an increasing sustainability assessment of production processes and of resources efficiency.

Therefore, the first time the Sustainable Development was mentioned dates back to 1987, in the Brundtland Report, which states that the "sustainable development is a process of change in which the exploitation of resources is consistent with the future needs as well as with the current ones" [1], tying in a interdependent relationship the protection and valorization of natural resources with the economic, social and institutional spheres.

This kind of approach leads to the Circular Economy model, in which the residues arising from production processes can assume a value for other production processes, in a perspective of Industrial Symbiosis. The Circular Economy is now promoted by numerous official documents of the European Commission, such as the Europe strategy to 2020 [2] and the Circular Economy Package of 2015 [3] and in the same year, the climate conference in Paris COP 21 has also reinforced this approach to this issue, by imposing restrictions to the exploitation of resources of the Planet and to global warming.

Later, in 1991 Herman Daly defined the Sustainable Development as “the development that remains within the carrying capacity of ecosystems” [4], introducing the conditions to guarantee it:

- the human burden must not exceed the carrying capacity of the nature;
- the use rate of renewable resources should not exceed their regeneration rate;
- the release of pollutants and slag should not exceed the absorption capacity of the environment;
- the extraction of non-renewable resources must be compensated by the production of an equal amount of renewable resources.

In 2001 The United Nations Educational, Scientific and Cultural Organization (UNESCO) expanded the concept of Sustainable Development by inserting another parameter to consider the cultural diversity [5], which must be guarantee by the Institutions. So the four pillars become (Figure 1.1.):

- Environmental Sustainability, the ability to preserve over time the environmental functions, to maintain the quality and the reproducibility of natural resources. This goal is achieved through the efficiency improvement of processes and the application of the Life Cycle Assessment (LCA) methodology;
- Economic Sustainability, the capacity of an economic system to generate a lasting growth, meant as income and work;
- Social Sustainability, the ability to ensure the welfare conditions to human beings, promoting health and safety of workers, education and solidarity;
- Institutional Sustainability, the ability to ensure stability, democracy, participation and justice, ensuring the respect for diversity and human rights.

Indeed, in recent years, in addition to the Life Cycle Assessment (LCA) methodology, other methods have been developed, whose purpose is to assess the impacts related to also the other spheres: the Life Cycle Costing (LCC), to evaluate the economic impact of a process/system, and the Social Life Cycle Assessment (sLCA), able to investigate the social sustainability.

These four dimensions should be analyzed in a systematic vision to achieve a common goal.

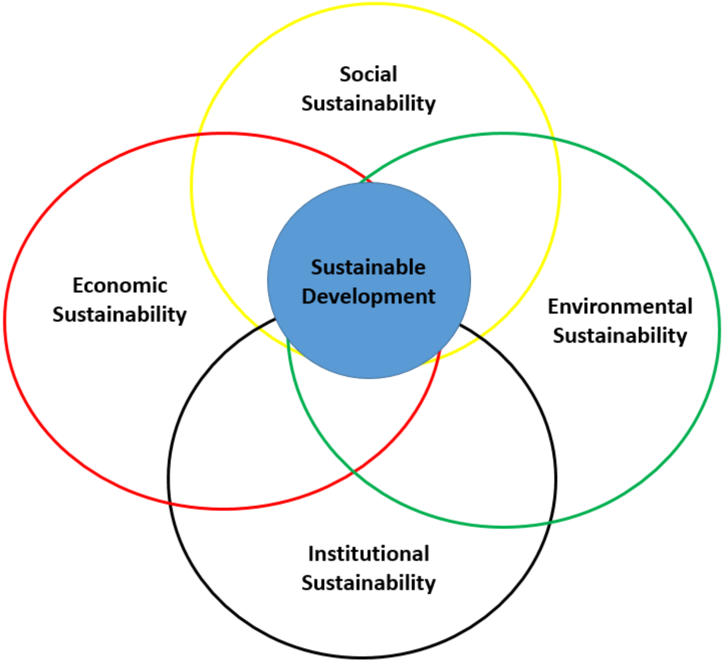

Figure 1.1. The four spheres of Sustainable Development [5].

The implementation of the maintenance of the four spheres is possible through the Green Economy approach. The definition globally and institutionally recognized is the one given by the United Nations Environment Program (UNEP) in 2011, that defined it as “an instrument that is able to realize the improvement of the welfare and of the social equity reducing environmental risks” [6].

The Green Economy is therefore a model that could be applied through the Industrial Ecology, the discipline that deals with the design and management of industrial systems, taking the natural systems as a model and his goal is to understand the interactions between economic activities and the environment. Then Industrial Ecology gives to companies a tool to achieve a sustainable and competitive economy. The principle on which it is based is the closure of the production cycles, starting from the assumption that, as in natural systems, there are no waste but only by-products to be reused. In this way, Industrial Ecology principles are linked to validation tools such as the Life Cycle Assessment, the integrated environmental monitoring and Risk Analysis and can be applied to integrated systems of waste management, in such a way to minimize the impacts and valorize the waste.

This thesis is inserted in this context and will deal with the application of the Life Cycle Assessment methodology to integrated waste management systems.

In addition to the analogy with natural systems and the introduction of a closed cycle economic model, there are others key concepts, that characterize the Industrial Ecology [7]:

- analysis of the system which allows a broad view of the relationships between human activities and the environment;
- study of the flows and transformation of matter and energy, in order to establish how the various products, by-products and waste can be used, reused and converted into others goods and services;
- a multidisciplinary approach to study a problem.

Industrial Ecology is based on eleven principles, formulated by Allenby in 1995 [8]:

1. products, processes, services and activities can produce residues, but not waste;
2. each process must be designed to be easily adapted to innovations preferable from the environmental point of view;
3. each molecule that enters a process, it must leave it as part of a commercial product;
4. each erg of energy used must produce a transformation of matter;
5. industries must minimize the use of materials and energy;
6. materials used must be the least toxic available;
7. industries must use most of the necessary materials obtained from recycling;
8. each product must be designed to preserve the inherent utility of the materials used;
9. each product must be designed in order to be able to be used to create, at the end of his life, others useful products;
10. every industrial property must be developed taking care to maintain or improve the local habitat;
11. it must be promoted the interaction between material suppliers and users in order to develop cooperation to minimize packaging and to promote the recycling and reuse of materials.

The eleven principle are actuated through the application of tools [9], such as:

- Material Flows Analysis (MFA), to follow and quantify the flows of materials in the production chain;
- Ecodesign, defined as the integration of environmental aspects into the product design;

- Life Cycle Assessment (LCA), which considers all the environmental impacts associated with each step of the industrial development;
- Green Policies, i.e. European Directives, national legislations, environmental certifications, extended producer responsibility;
- Industrial Symbiosis, which considers waste and by-products of a process as resources for other processes.

By aggregating the contributions of these disciplines and themes the definition of Circular Economy was provided by Ellen MacArthur Foundation, intended as "an economy that regenerates and reconstructs, through the design, and whose objective is to maintain products and materials to their maximum utility value at any time. It reproduces the nature in the way to improve and optimize the systems through which operates" [10].

The Circular Economy results in a continuous development cycle that optimizes the availability of resources and minimizes the risks, using renewable resources. The Circular Economy is also mentioned in the documents of the European Commission [11] and is based on three fundamental principles:

- preserve and increase the natural capital;
- optimize the availability of resources;
- increase the efficiency of systems.

1.2 Normative Background

In Europe, the management of municipal solid waste has undergone significant changes over the paste twenty years.

For many decades, Europe has witnessed a growth of prosperity and welfare based on an intensive use of resources. Today, however, it is faced with a double challenge: to promote the growth needed to create jobs and prosperity for citizens and at the same time to ensure a sustainable future.

The World Business Council for Sustainable Development estimates that by 2050, it will be necessary to multiply the resources efficiency from 4 to 10 times, with important improvements to be achieved already by 2020 [12]. This transformation requires a policy framework that rewards innovation and resource efficiency and able to create the conditions for new economic opportunities for a greater security of supply through product redesign, sustainable management of environmental resources, the promotion of recycling and reuse, the replacement of materials and the saving of resources.

The EU economy currently loses a significant amount of potential secondary materials present in the waste stream. In 2013 in the EU in total about 2.5 billion tons of waste were generated; of these 1.6 billion have been neither reused nor recycled, going completely lost. It is estimated that it would be possible to recycle or reuse further 600 million tons of waste and that a more efficient use of resources along the entire value chain could reduce the need for the 17-24% of material inputs by 2030, with savings for the European industry of the order of 630 billion euro/year, that is the 8% of the annual turnover, while reducing the total annual emissions of greenhouse gases for the 2-4% [13].

In a perspective of a greater resource efficiency, the transformation of waste into resources is a crucial element as well as the missing link to achieve a circular economy. Thanks to a more ambitious waste policy it could be possible to obtain major advantages: a sustainable growth and the creation of job, the reduction of greenhouse gas emissions, savings related to the improvements of the waste management practices and a better environment.

Ensuring continuity to a more efficient use of resources can bring significant economic benefits. In an ideal circular economy systems products maintain their added values as long as possible and there is no waste. When a product reaches the end of its life cycle, the resource remains within the economic system, so that it can be reused several times, thus creating new value, even if also in a highly developed circular economy some elements of linearity remain, because the demand of virgin resources could hardly be completely stopped and the residual waste generated must be disposed.

Therefore, the European environmental policy aims at taking also into account the diverse situations in various regions and is founded on the principles of precaution, of preventing environmental damages at source, and of “polluter pays”.

Waste management must follow policies based on the “3R” concept of reduction, reuse and recycling. As for the European context, the framework Directive on Waste 2008/98/EC [14] identifies the so-called waste hierarchy:

1. prevention: the top priority for all stages of circular economy is to ensure to produce less waste.
2. preparation for reuse;
3. recycling;
4. recovery (including energy recovery);
5. disposal.

In November 2013, the 7th Environment Action Plan of the European Union for Environment [15] was adopted and will guide until 2020 the Community policy. It sets out that it is necessary to intensify the efforts to protect the natural capital, stimulate growth and innovation in a low-carbon and resource-efficient economy and safeguard health and welfare of population, respecting the limits of the Earth.

In detail, the Seventh European Action program identifies specific actions to give full implementation to EU legislation on waste, which primarily require the application of the waste hierarchy and the effective use of instruments and other market measures to ensure that:

- landfills are restricted to the residual waste (non-recoverable and non-recyclable);
- energy recovery should be limited to non-recyclable materials;
- recycled waste are used as the main and reliable source of raw materials for the European Union, through the development of non-toxic materials cycles;
- hazardous waste must be managed responsibly and its generation must be reduced;
- there will not be an illegal transportation of waste, with a rigorous monitoring support;
- food waste must be reduced.

For this purpose at European level a review of the legislation in force about products and waste is ongoing, including a review of the objectives of the main directive on waste, in line with the Roadmap to a Resource Efficient Europe [12].

For a reduction of the consumption of fossil fuel, the European Commission planned this objectives:

- greater energy efficiency (20% by 2020);
- replacement with renewable resources (20% by 2020, 10% in transport);
- 20% reduction of greenhouse gas emissions by 2020;
- use of recyclable/biodegradable packaging;
- enhancement of biodegradable waste composting.

The waste management policy must necessarily take into account the priorities identified at European level, first and foremost the stop of landfill disposal and the activation of useful actions to realize the decoupling between economic indicators and the generation of waste.

In 2015, during COP 21, a new Circular economy package was created [3, 11], submitting a review of legislative proposals on waste management with the aim to increase the recycling rate and reduce landfilling:

- to increase to 65% by 2030 the target for preparation for reuse and recycling of municipal waste;
- to increase the percentage of municipal waste reused and recycled, reaching at least 70% by 2030;
- to increase the percentage of recycled packaging waste, until 80% by 2030;
- to reduce the landfilling of all waste to a maximum value of 10% by 2030;
- to ban the landfilling of waste from separate collection;
- to promote the Industrial Symbiosis.
- to promote the development of the market of secondary raw materials of quality.

In six Countries landfilling of municipal solid waste has already been abolished, with percentage over the last twenty years from 90% to less than 5% and a recycling rate up to 85% in some Regions, while in other Countries more than 90% of the waste is still disposed in landfills and less than 5% recycled [13].

The landfilling of all recyclable waste will be prohibited by 2025 and the Member States should endeavor to eliminate this practice by 2030. Moreover, energy recovery, even by waste to energy plants and bio-fuels, will offer a solution only for non-reusable and non-recyclable waste and the landfilling or incineration should not be eligible for subsidies in the future.

1.3 Motivation and structure of the work

The sustainability in the waste management sector represents one of the primary target of our society mainly because its environmental footprint is not limited to a defined area but it has serious repercussions all over the world.

This is the reason why a great effort at legislative level and of organization was devoted to applied researches with the aim to mitigate these aspect and provide new solutions; among many, it is worth noting the EIT (European Institute of Innovation & Technology), an independent body of the European Union set up in 2008, that spurs innovation and entrepreneurship across Europe to overcome some of its greatest challenges.

Each of us should try to be an active part of change and an industrial chemist with an environmental background could be a perfect figure to connect chemists and engineers, with a contribution of transversal knowledge on various sectors.

For this reason, the research conducted during this doctoral thesis at the Department of Industrial Chemistry "Toso Montanari" of the University of Bologna, under the supervision of the Prof. Fabrizio Passarini, aims at applying the LCA methodology to waste management systems, to processes of recovery of energy and of materials.

The main goal was to investigate in depth the LCA methodology, understanding the strengths and gaps of its application in the waste management sector, using it as a screening tool in order to support the procedure of decision making. This approach was applied to several case studies taking into account the features of the various areas investigated and choosing those witch represent the most developed technologies. In every case study, a comparison with alternative systems was carried out verifying the preferred solution from the environmental point of view: only a holistic approach is able to assess sustainability along the whole system and evaluate the effective gain associated with system changes.

Thus, in order to provide an overview of the work carried out during the three years program, the work has been structured as follows:

- in Chapter 1, there is an introduction to the circular economy theme and to the reference legislation;
- in Chapter 2, the Life Cycle Assessment methodology has been studied;
- then, with the Chapter 3 starts the experimental sections, first analyzing waste management systems, taking into account two different cases study;
- secondly, in Chapter 4 the energy recovery processes have been investigated through three different systems;
- finally material recovery processes have been analyzed in Chapter 5;
- lastly, Chapter 6 outlines the main conclusions and personal considerations that should be given to the study.

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2. Methodology

2.1 LCA Methodology

Life Cycle Assessment (LCA) is a tool that allows the assessment, in view of a minimization, of the potential environmental impacts associated with production and use of a product, system or an industrial process.

For this purpose energy and material flows are identified and quantified in input and output.

An LCA study may consider the entire life of a product ("from cradle to grave" approach), i.e. from the extraction and acquisition of raw materials, through the production and processing, the use and the end of life and disposal or recovery.

2.2 History of the LCA

The LCA methodology now ranks in the broader context of Sustainable Development and Industrial Ecology.

The basic idea, which is the consideration of environmental issue related to a product, dates back to the late '60s, thanks to the initiative of some researchers who began to deal with the consumption of resources, especially non-renewable ones, and the generation of waste in industrial processes [1].

The only effective and complete way to study production systems from an environmental point of view is to examine the performance by following step by step the path taken by raw materials, from their extraction, through all the processing and transformation processes, up on their return to earth in the form of waste. The philosophy followed can be summarized in the phrase "from cradle to grave". Before taking the name "Life Cycle Assessment", other terms were used, such as life cycle analysis, cradle to grave analysis, resource and environmental profile analysis, eco balance, energy and environmental analysis, etc.

This approach was a novelty, as previously there was a tendency to view the individual processes and any improvements made to them, without assessing whether such improvements were actually effective or only apparent when placed in a global view.

The first example of Life Cycle Thinking dates back to the early 70s, used as a decision support, especially in big American companies, for example by EPA (U.S. Environmental Protection Agency) and by some British producers of PET bottles.

In the United States such research took the name of REPA, Resource and Environmental Profile Analysis. Among the first companies that used this method there is the Coca Cola Company, which commissioned studies to determine the environmental consequences of the production of different type of beverage containers, in order to identify which material (plastic, glass, steel or aluminum) and which strategy at the end of life of the containers, was energetically most advantageous.

At the end of the crisis in the mid-70s, the knowledge that limited energy resources were consumed at high rate, gave impetus to the study, by experts and researchers, of the issues concerning the exploitation of resources and the resulting effects on the environment.

This led, in the ‘80s, to the statement of the concept of “Sustainable Development”.

At the same time in Europe the energy analysis textbook by Boustead and Hancock was released, considered one of the milestones in the history of the LCA methodology.

The term was coined during the SETAC (Society of Environmental Toxicology and Chemistry) LCA conference at Smuggler’s Notch (Vermont, USA) in 1990, enclosing within itself all previous approaches to this type of assessment (REPA, EA), defining LCA as:

“the process to identify the environmental burdens associated with a product, process or system by identifying and quantifying energy and materials used and emissions released into the environment, in order to assess their impact and identify opportunities for improvement. The assessment includes the entire life cycle of the product, process or activity, through the extraction and processing of raw materials, product manufacturing, transportation and distribution, use, reuse, storage, recycling, until the disposal”.

At around the same time, International Standard Organization (ISO) drew up the regulations of reference for the methodology, later published in 1996. These standards are part of the 14040 series [2-3]:

- ISO 14040: principles and framework;
- ISO 14041: goal and scope definition and inventory analysis;
- ISO 14042: life cycle impact assessment;
- ISO 14043: interpretation.

Later, this series has been updated, merged and then replaced by only two standards: ISO 14040:2006-Principles and framework, and ISO 14044:2006-Requirements and guidelines, representing the internationally recognized reference for the implementation of a LCA.

2.3 Goal and scope definition

The first phase of an LCA is that in which it is explained the purpose and the aim of the study.

According to ISO 14040, the aim of LCA indicates:

- the intended application;
- the reason why is made the study;
- the type of audience;

In the scope is defined the functional unit, the system boundaries, the data required to perform the modelling and their reliability, assumptions and limitations.

In general, it is possible to relate the scope of an LCA study to the following purpose:

- research and development;
- green marketing;
- supporting environmental management systems;
- eco-design.

The goal and scope definition can be constantly reviewed and update, as new information becomes available [4].

2.3.1 System boundaries definition

The system boundaries determine which unit processes should be included in the LCA and must be consistent with the purpose of the study. The criteria used in the selection must be explicitly stated and explained, as well as any omission related to phases of the cycle, processes, inputs and outputs. The boundaries may be initially established on the basis of geographical and technological criteria, and then be refined as the study proceeds, excluding non-relevant components and by including other not previously considered. In any case, the criteria used must be justified in the field of application [3]. Classically, all stages from raw material extraction to disposal or recovery of the product are considered (from cradle to grave approach); however, in some cases, the peculiarity of the study may require a different approach in which it is not possible to consider all stages of the life cycle. For example, for the production of materials that have different possible uses, it is not possible to follow all of their destinies once outside the production chain. For this reason, the purpose of these studies is defined “from cradle to gate”. Other limitations to be taken into account are the temporal boundaries, indicating the period of reference for the study in which the data collection is done. These can refer to the Best Available Techniques or an average operating situation. In an LCA study several exclusion criteria may be used, to decide which information should be included in the assessment, based on:

- mass: when using the mass as a criterion, prompted the inclusion in the study of all inputs and outputs that cumulatively contribute more than a certain defined percentage;
- energy: similarly, when using energy as a criterion, all input and output streams should be considered, that cumulatively contribute more than a certain percentage of the total energy produced;
- environmental significance: all flows that contribute to the environmental load more than a certain defined amount have to be included.

2.3.2 Functional unit definition

The functional unit is one of the key element of the study, as it is the quantitative measure of the production of products or services that the system provides. The whole study is based on the functional unit. This is even more important when performing comparative studies: in this case, the considered systems must have the same functional unit. The system boundaries are very important to understand which steps consider in the life cycle.

2.3.3 Allocation criteria

Generally, in most industrial processes, in addition to the main product, also by- or co-products are generated; therefore it is necessary to perform an allocation in order to properly assign the incoming and outgoing flows only to the desired product (i.e. the functional unit taken into consideration). The allocation consists in partitioning to the various by- and co-products the environmental loads and energy, on the basis of a distribution parameter, often physical, such as volume, mass or energy. ISO 14044 shows the following procedure for allocations:

- when possible, avoid allocation by breaking the process into separate sub-processes, each with its own output or expanding the boundaries of the system;
- if it is impossible to avoid the allocation, the inputs and outputs of the system should be allocated to the different products according to basic physical relations, such as mass, volume or energy content;
- if it is not possible to use physical relationships, then the allocation might be made on the basis of the economic value of the various co-products.

2.4 Life Cycle Inventory (LCI)

The inventory analysis is the stage dedicated to the inventory of all input and output streams for all stages of the process considered. In this phase the mass and energy flows crossing the process that allow the operation of the production system in question are then explicated, through all the transformation and transport processes.

It is the most “hard-working phase”, as it represents a quantitative and detailed description of the system.

A system is defined as a set of unit operations, connected through flows of mass and energy, which perform a defined function and is separated by the system boundaries from the surrounding environment.

At this level the part concerning the evaluation of environmental impacts associated with the input and output stream of the system is not tackled [1].

The data coming from the inventory are processed to obtain different information divided into categories:

- raw materials;
- energy;
- products, co-products and waste;
- air, water and soil emissions.

2.4.1 Quality and reliability of data

The assessment of reliability of data collected during the inventory is of crucial importance, since the results will be considered as representative as greater is the accuracy of the input data.

To ensure this, first of all it is necessary to build a detailed flow diagram in which all the operations that make up the system considered are indicated.

For the more developed processes it is possible to use literature references to obtain detailed information, but it is still preferable to use primary data from real processes.

The quality of the data must be described and evaluated in a systematic way, to allow the reproducibility.

Some parameters should be considered in the quality requirements of the initial data:

- temporal coverage, that concerns a representative time when data are collected;
- geographic area in which data are collected;
- technology used;
- precision;
- completeness;
- consistency;
- reproducibility;
- sources from which the data are taken;
- uncertainty, that considers which assumptions were made.

It is not always possible to guarantee compliance with all the previous features, especially as it regards the temporal or geographical features.

At this stage it is appropriate to distinguish between foreground and background system. The first indicates the sequence of processes that are needed to get directly the functional unit; the second indicates the materials and energy.

From here it is possible to define (Figure 2.1.):

- foreground data, specific data that are needed to the system description;
- background data, generic data about the materials used, energy, transport and waste management. These data can be found in literature or in some specific database (such as Ecoinvent [5], which is one of the major present in SimaPro database).

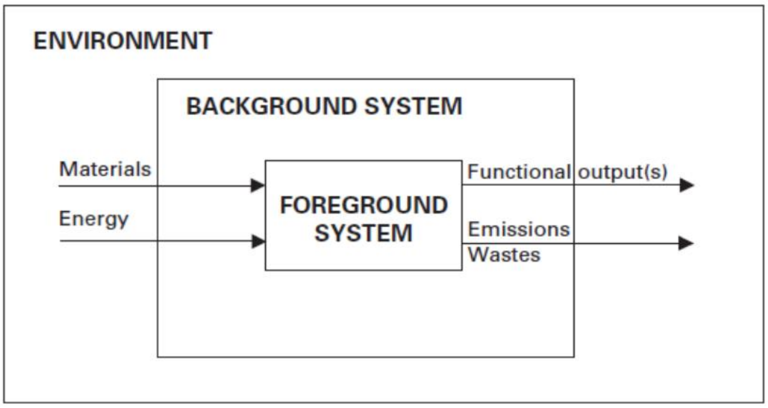


Figure 2.1. Foreground and background systems [4].

2.5 Life Cycle Impact Assessment (LCIA)

This is the interpretation stage of LCA methodology, which evaluates the importance of the potential environmental impacts identified in the inventory analysis.

Impact assessment method consists of four phases:

- classification;
- characterization;
- normalization;
- weighing.

Of these, two are considered obligatory in every LCA (classification and characterization), while the other two are considered optional (normalization and weighing).

2.5.1 Classification

Classification includes the organization of the inventory data. Once defined the considered impact categories, the results of the inventory must be allocated to the respective categories. To implement this, the problem-oriented strategy is used, in which the impact assessment methods are divided into:

- midpoint oriented: data are converted using intermediate impact categories (e.g.: Climate change or fossil fuels production);

- endpoint oriented: data are converted using final impact categories (i.e.: damage to the ecosystem, human health and consumption of resources).

2.5.2 Characterization

After the step of classification of the different impacts caused by the processes, the characterization methods are applied, in order to quantitatively determine (with the appropriate units) the contribution of individual emissions.

At this purpose, equivalent factors are used, called indicators, for different impact categories, which indicate how much a substance contributes to the category when compared to a reference substance. In this way, impact is then represented by numeric values obtained by processing LCI data, after their grouping and classification. To each impact is connected a damage (to human health, to the quality of the ecosystems or to resources depletion) due to the effect that causes it and the relationship is to consider a potential cause. For this reason it is important not to confuse the impact generated with the effect that it can cause.

2.5.3 Normalization

It is the calculation of the magnitude of the results of the category indicators relative to some reference information.

It is useful to understand how much an impact category gives a significant contribution to the overall environmental problem. It is obtained by dividing the indicators of the impact categories to the value of normalization.

Through the normalization it can be concluded that:

- the impact categories that contribute little in comparison with the other categories, may not be considered, thereby reducing the number of issues considered;
- the normalization results show the order of importance of environmental problems generated by the life cycle, compared with the total environmental load.

2.5.4 Weighing

The weighing step is quite complicated, but nevertheless very used.

Weighing sets the life cycle assessment on social, policies or economic bases.

There are several solution that can be adopted:

- Use a list to evaluate the impact categories and propose standard weights;
- Set a goal for each impact category and use it to obtain a weighting factor;
- Express all the data with the same monetary unit (monetization).

2.5.5 ReCiPe 2008 method

The ReCiPe 2008 method is one of the methods used in the impact assessment in the LCIA phase and provides results both at midpoint and endpoint level.

About the midpoint approach, the model refers to the CML method (Centrum Milieukunde Leiden), proposed in the Handbook of LCA [7], developed in the Netherlands in 1992.

Instead for the endpoint approach Eco-indicator method is considered [8].

In 2000, as a result of a SETAC conference, a commission has been convened in Brighton, formed by fifty experts of LCA, to study and understand weaknesses and strengths of the midpoint and endpoint methods. It was concluded that it has been useful to develop a model that considers both methods, founding the ReCiPe 2008.

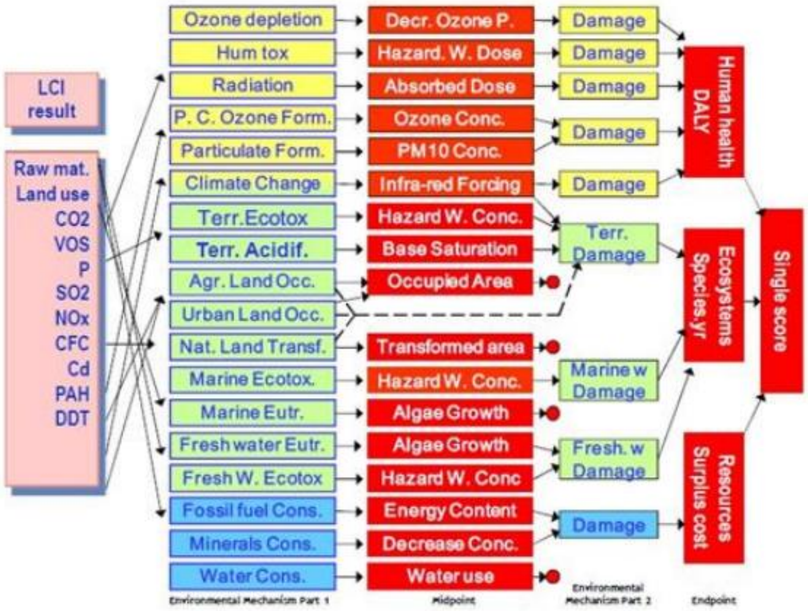


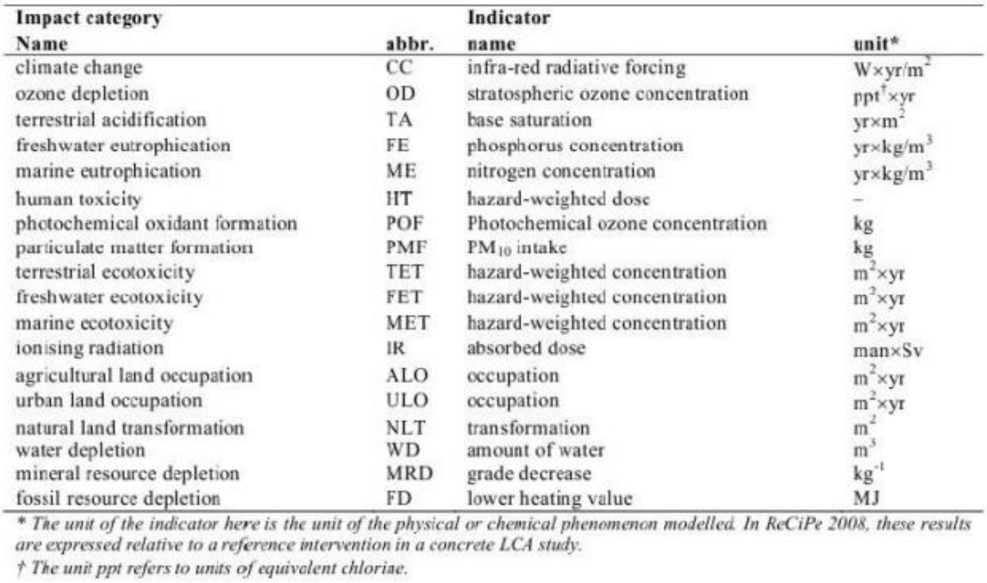
Figure 2.2. Midpoint and endpoint categories in the ReCiPe 2008 model [6]

ReCiPe 2008 includes two groups of impact categories with characterization factors appropriately associated. At midpoint level the methods involves eighteen impact categories, which are (Figure 2.2):

- Climate change;
- Ozone layer depletion;
- Terrestrial acidification;
- Fresh water eutrophication;
- Marine eutrophication;
- Human toxicity;
- Photochemical oxidation;

- Particulate matter formation;
- Terrestrial ecotossicity;
- Fresh water ecotossicity;
- Marine ecotossicity;
- Ionizing radiation;
- Agricultural land occupation;
- Urban land occupation;
- Natural land transformation;
- Water resources depletion;
- Fossil fuel depletion.

For each of the above categories a characterization factor (indicator) is associated. In Table 2.1 the indicators associated to the individual categories are shown.



Impact category		**Indicator**	
Name	**abbr.**	**name**	**unit***
climate change	CC	infra-red radiative forcing	$W \times yr/m^2$
ozone depletion	OD	stratospheric ozone concentration	$ppt^{\dagger} \times yr$
terrestrial acidification	TA	base saturation	$yr \times m^2$
freshwater eutrophication	FE	phosphorus concentration	$yr \times kg/m^3$
marine eutrophication	ME	nitrogen concentration	$yr \times kg/m^3$
human toxicity	HT	hazard-weighted dose	–
photochemical oxidant formation	POF	Photochemical ozone concentration	kg
particulate matter formation	PMF	PM_{10} intake	kg
terrestrial ecotoxicity	TET	hazard-weighted concentration	$m^2 \times yr$
freshwater ecotoxicity	FET	hazard-weighted concentration	$m^2 \times yr$
marine ecotoxicity	MET	hazard-weighted concentration	$m^2 \times yr$
ionising radiation	IR	absorbed dose	man×Sv
agricultural land occupation	ALO	occupation	$m^2 \times yr$
urban land occupation	ULO	occupation	$m^2 \times yr$
natural land transformation	NLT	transformation	m^2
water depletion	WD	amount of water	m^3
mineral resource depletion	MRD	grade decrease	kg^{-1}
fossil resource depletion	FD	lower heating value	MJ

** The unit of the indicator here is the unit of the physical or chemical phenomenon modelled. In ReCiPe 2008, these results are expressed relative to a reference intervention in a concrete LCA study.*

† The unit ppt refers to units of equivalent chlorine.

Table 2.1. Midpoint categories and their associated indicators [6].

At endpoint level, midpoint categories are grouped into three macro categories of damage:

- Human Health (HH);
- Ecosystem Diversity (ED);
- Resource Availability (RA).

2.5.5.1 Human Health

The damage to human health is assessed through the concept of “disability-adjusted life years”, DALYs, introduced in LCA studies by Hofstetter in 1998 [9].

For each disease, DALY derives from human health statistics, as the sum of years of life lost (YLL) and the years of life lived with a disability (YLD). It gives the same importance for a year of life lost at any age and does not consider any change for future generations.

$DALY=YLL+YLD$ Equation 2.1

$YLD=w*D$ Equation 2.2

Where w is a severity factor between 0 and 1 (0 means completely in health and 1 means death); D is the illness duration.

DALY depends on subjective assumptions:

- it is referred to a specific region in a certain period of time and applying a world average in the calculation of the characterization factors it is assumed that it is acceptable;
- it does not consider age differences and changes for future generations;
- it gives a subjective weight to the scale of disease.

2.5.5.2 Ecosystem Diversity

The way to described the quality of ecosystems (biodiversity, ecological function, aesthetic and cultural values and generic information) considers the mass and energy flows. So it can be said that a high-quality of an ecosystem is when the flows take place, while interruptions are due to human activities.

ReCiPe 2008 method provides information on flows at species level and considers that the diversity of living species represents the quality of the ecosystems.

It must be chosen which groups of species can be used to be representatives of the global system quality; moreover it must be chosen to consider the definitive extinction or the reversible disappearance of a species in a particular region in a certain period of time. It can be assumed that the extinction depends on multiple factors and that a single product can’t cause it.

For this purpose, the Potential Disappear Fraction of species (PDF), which is the fraction of species disappeared in a certain period in a certain area, is used as a basis for determining the quality of the ecosystem.

Both the loss of terrestrial species and aquatic ones are taken into consideration and all species have the same importance.

The equation for the calculation of the endpoint characterization factor for the damage to the ecosystem (CF_{ED}) is given by:

$$CF_{ED}=PDF_{ter}*SD_{ter}+PDF_{fw}*SD_{fw}+PDF_{mw}*SD_{mw} \quad \text{Equation 2.3}$$

Where SD is the density of the species.

The subscripts represent:

- terr: terrestrial systems;
- fw: freshwater systems;
- mw: marine systems.

It must be estimated approximately the total number of species on Earth, divided into terrestrial, freshwater and marine species. In addition, the terrestrial area (excluding desert, glaciers and agricultural areas), the volume of fresh and salt water should be estimated.

In this way it is possible to calculate the density of the species.

2.5.5.3 Resource Availability

One of the risks feared by scientists in recent decades is the resources depletion. The resources depletion and the demand for others have a big impact on the price market. The ReCiPe 2008 method assesses how the depletion of a resource affects the future availability of the same resource; for this purpose a function has been developed, that estimates the increase of the extraction costs considering a continuous consumption.

This fraction is expressed by the MCI factor (in $/kg^2), marginal increase in the cost, which is the increase in the cost of a product ($/kg) due to the extraction (kg) of a resource r.

$$MCI_r = \frac{\Delta Cost_r}{\Delta Yeld_r} \quad \text{Equation 2.4}$$

The rising cost in \$/kg must be multiplied by a factor that express the amount consumed.

2.5.6 The "Cultural Theory"

The ReCiPe method uses the concept of "Cultural Theory", a theory developed by Thompson [10] that considers the behavior of people with regard to two fundamental dimensions of human life: the attachment to the group and the compliance with the rules of the group. Different combination of the values of the two dimensions considered identify a lifestyle that affects the choices and the values of each person and of the group to which it belongs. Five types of people (archetypes) are so identified, which are (Figure 2.3.):

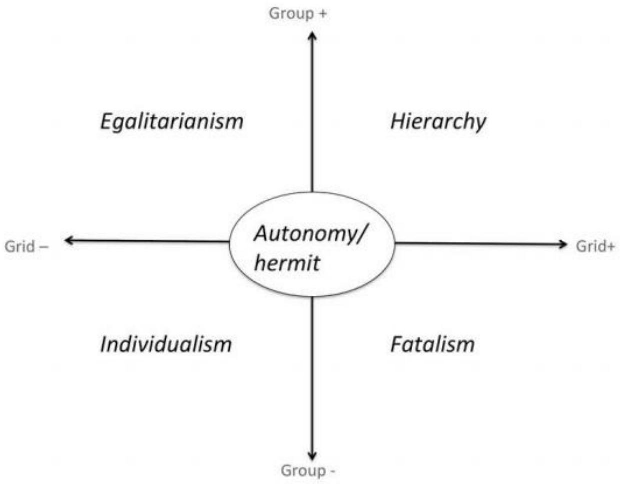


Figure 2.3. The five archetypes of Cultural Theory [10].

- Individualist. The individualist is a person free from any bond and, for that reason, every vision and decision is temporary and negotiable;
- Egalitarian. The egalitarian is a person who has a strong attachment to the group but not to its laws and this therefore leads him to not accept the division into roles and to question the relationships within the group: this creates conflict;
- Hierarchist. The hierarchist has a strong link with the group and its rules, creates a strong stability, ensuring control over himself and other;
- Fatalist. The fatalist is subjected to the rules of the group but at the same time does not feel himself part of it and therefore tends to act independently;
- Autonomist. The autonomist refuses to belong to the group and to all its impositions.

It seems clear that the first three archetypes base their decisions on solid prospects, while the last two acting independently are difficult to predict and are not considered in the model.

2.5.7 Cumulative Energy Demand

The Cumulative Energy Demand (CED) is a characterization method used for the energy assessment. The purpose of this method is to investigate the use of energy throughout the life cycle of a good, service or process. This includes the direct uses or the indirect consumption of energy due to the employment of, for example, materials from construction or raw materials.

This method was developed in the early seventies, after the first oil price crisis [11].

The Cumulative Energy Demand by itself is not an exhaustive method for the environmental load assessment, since it is limited only to energy loads related to various operations involved in a production system. For this reason it is suitable to join it to other assessment methods which includes impact categories relating to other effects with the corresponding characterization factors.

In any case it is considered a good method to implement a preliminary analysis, to identify the most energy-intensive steps in a process or to build a basis to realize an environmental balance.

CED is an assessment system that uses a midpoint approach. It focuses on the use of energy resources, which are divided into eight categories, in the Ecoinvent database, distinguished between renewable and non-renewable (Table 2.2):

	subcategory	**includes**
non-renewable resources	fossil	fossil carbon, lignite, crude, natural gas, peat
	nuclear	uranium
	from forest	wood and biomass from forest
Renewable resources	biomass	wood, food waste, biomass from agriculture
	wind	wind energy
	solar	solar energy (to produce thermal energy or electricity)
	geothermal	geothermal energy (shallow, 100-300m)
	water	hydroelectric energy

Table 2.2. categories used in the CED method [12].

Each category corresponds to a characterization factor described below:

- non-renewable fossil resources: gross calorific values is used as characterization factor. Among the fossil fuel resources there is also the peat, despite resulting from biomass, as it is not renewable in the short-term;
- uranium: the characterization factor used in Ecoinvent is quantified considering the “energy content” of the fossil isotope in natural uranium extracted from mines;
- forest: for wood and biomass from forest not used for human activities, the characterization factor is calculated using the same principles used for the renewable biomass. The CED value is classified non-renewable;
- renewable biomass: the characterization factor is based on the gross calorific value of the biomass produced at the collection point (considering the residues);
- water: for the characterization factor for the energy produced by the use of water the potential energy used for the generation of hydroelectric power is considered.

For the other renewable energy sources (solar, wind and geothermal) the energy input is given by the converted energy:

- for solar, the energy considered is that converted by photovoltaic modules and transmitted to the inverter, or the thermal energy converted by a solar collector provided for the hot water storage. The panel efficiency and the collector to convert solar energy into electricity and heat, respectively, is not taken into account;
- for wind power, the kinetic energy converted from a wind power plant equal to the rotation energy of the turbine blades is considered. The efficiency of the blades to convert the kinetic energy of wind into rotational energy is not taken into account;
- for geothermal energy the converted energy from salt-water heat exchangers equal to the amount of energy supplied to heat pump is considered. Only the energy from shallow plants is considered, because for deep ones (>1000m) energy cannot be considered renewable because after 30 years the site is no longer usable.

The CED method has not a normalization step and to obtain a total (cumulative) energy consumed to each impact category, a weight factor equal to 1 is considered.

2.5.8 Global Warming Potential

The Global Warming Potential (GWP) is a characterization factor which expresses the contribution to the greenhouse effect of a gas compared to the effect due to CO_2, which has a value of 1 by definition [12].

The GWP model was developed by IPCC (Intergovernmental Panel on Climate Change) and assess the global warming potential of greenhouse gases (such as CO, NOx, hydrofluorocarbons, chlorofluorocarbons, CH_4, N_2O, etc.), expressed in kg CO_2 equivalent ($kgCO_{2\ eq}$).

GWP takes into account the absorption capacity of the infrared radiation of a given species and its residence time in atmosphere. It is measured as the ratio of the contribution to the absorption of radiation that provides the release of 1kg of substance and the contribution of 1kg of CO_2 [13].

Both contribution are assessed for the same period of time of permanence: periods of 20, 100 or 500 years may be considered..

In table 2.3 GWP values of some substances are presented.

Gas	Life time (years)	GWP_{20}	GWP_{100}	GWP_{500}
CO_2		1	1	1
CH_4	12.0	62	23	7
N_2O	114	275	296	156

Table 2.3. GWP of some gases [13].

2.6 Interpretation

At this stage the results obtained in the steps of inventory analysis and impact assessment are taken into account; for this reason, it is possible to make a review of the scope and an assessment of data quality, in order to improve the system.

The ISO 14040 includes especially three elements to consider:
- identification of significant issues based in the results previously obtained;
- assessment which considers completeness, sensitivity and consistency;
- conclusions, limitations and recommendations.

2.7 Analysis of data quality

In the uncertainties analysis three factors linked to the collected data are considered:
- Technosphere, that is the modelling of the technical system, such as production process, transport and infrastructure;
- Ecosphere, modelling of environmental mechanisms, that is what happens to an emissions into the atmosphere;
- Valuesphere, that refers to subjective choices, which includes the Cultural Theory.

The uncertainties related to “ecosphere” are frequently very big (from one to three orders of magnitude) and difficult to assess, while for the “value sphere” it is difficult to talk of real uncertainties because, being subjective choices, it is difficult to identify a single scale of values unanimously recognized [6].

There are primarily three types of uncertainty:

- data uncertainty;
- uncertainty of model representation;
- uncertainty due to the incompleteness of the model.

Data uncertainties are expressed by the standard deviation. For this purpose a statistical method is used, such as the Monte Carlo method.

The uncertainty of the model is due to the fact that it is impossible to create a model that accurately reconstructs the reality, because to create a system should imply the implementation of subjective choices. The uncertainties on the model include:

- representativeness: it is often necessary to use indirect literature data;
- allocation;
- future events;
- functional unit choice.

To deal with all these uncertainties there are several ways to assess them:

- uncertainty analysis;
- sensitivity analysis;
- contribution analysis.

The analysis of data quality can be performed using the values pedigree matrix, developed by Weidema [14].

This matrix takes into account different characteristics inherent to data: the acquisition method, the independence of data sources, the representativeness, temporal, technological and geographical correlation. To each indicator is then correlated a score regarding the quality of the data considered. Scores vary in a range from 1, which represents an excellent data quality, to 5, which indicates a very bad quality (Table 2.4.).

	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumption OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert): data derived from theoretical information (stoichiometry, enthalpy, etc)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuation	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuation	Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter period	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
Temporal correlation	Less than 3 years of difference to our reference year	Less than 6 years of difference to our reference year	Less than 10 years of difference to our reference year	Less than 15 years of difference to our reference year	Age of data unknown or more than 15 years of difference to our reference year
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area	Data from area with slightly similar production conditions	Data from unknown OR distinctly different area (north America instead if Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study (i.e. identical technology)	Data from processes and materials under study (i.e. identical technology) but form different enterprises	Data in related processes or materials but same technology, OR data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but in laboratory scale of different technology

Table 2.4. Quality pedigree matrix [14].

Scores are used to assess the uncertainty associated with the data used in the model, expressed within a range (or standard deviation).

2.7.1 Uncertainty analysis

It is described in ISO 14044 and is a procedure used to determine data uncertainty and how this reflects on the calculations. Uncertainty could be assessed through the Monte

Carlo approach, a statistical numerical method, based on the distribution probability of random variables.

The uncertainty analysis is performed to confirm data obtained from the assessment step.

The Monte Carlo method uses a series of simulations in order to obtain several estimates, by applying an algorithm that is able to generate a series of unrelated numbers, which follow a probability distribution: in the case of LCA studies the distribution is a lognormal trend, with a 95% of confidence interval [6].

The simulation requires that the parameters of each process (the inventory analysis data) are made varying within their uncertainty range. The simulation answers are then saved and the method proceeds with a new simulation. The procedure is repeated several times: usually 1000 or 10000 iterations. From each simulation different results are obtained, which together determine the uncertainties distribution.

The Monte Carlo method has the possibility to compare only two scenarios at a time, showing the categories (of damage or impact) and the frequency for which one of the two scenarios has greater impact of the other.

The results of the uncertainty analysis are shown in the form of histogram bars representing the number of times (for the various categories considered) in which the scenario A results in a greater impact compared to scenario B, and vice versa.

2.8 Sensitivity analysis

Sensitivity analysis is described in ISO 14044 and is able to assess how the changes in data and the methodological choices may affect the results of the inventory step.

This type of analysis must be performed during a study and at the end of it, so as to verify the influence of the most important choices. Therefore it could change the assumptions and calculations. In this way is possible to understand the importance of hypotheses and assumptions in order to assess the reliability of final results and conclusions.

2.9 Contribution analysis

The purpose of this statistical analysis is to identify processes which make a significant contribution in the determination of the final results. Often a LCA contains hundreds of different processes, but the results are determined by just a dozen of these. With the information obtained from the analysis it is possible to focus the attention on the determinant processes and analyze whether these are sufficiently representative and if the assumption made are important for the process.

2.10 Software SimaPro

In this work, Life Cycle Analysis has been performed with the aid of SimaPro software, a program, developed by Pré Consultants, accordant to the ISO requirements and among the most used for this type of study [15]. Within the program it is possible to find a section dedicated to processes and another to products:

1. Process. It is possible to choose between different processes, already equipped with a documentation specifying their construction (author, source of data, technical specification), environmental, social and economic information relating to input and output streams (e.g.: use of raw materials, emissions, economic impacts and avoided ones). Each process can be single (unit process) or may contain other processes (system process);
2. Product stage. It divides the system into various life cycle steps:

- production, which considers all the steps of transportation of raw materials, semi-finished and finished products;
- life cycle, related to the assembly and use steps;
- end of life, within which all steps of the end of life of a products are presents, as disassembly, treatment, recovery, recycling and disposal with the related environmental burdens that result;
- disassembly, that defines the flows and addresses them to their end of life scenarios;
- reuse, which considers all stages, environmental impact and avoided ones.

2.11 Ecoinvent database

The Ecoinvent database [5], of Swiss origin, covers nearly 3000 processes, related to:

- energy;
- transport;
- building materials;
- chemical products;
- agriculture;
- pollutants treatment.

The first database was published in 2003 by the Swiss Center for Life Cycle Inventories and subsequently updated and integrated with other database. Due to the large amount of data present, this database is also used for other types of studies, such as Integrated Product Policy (IPP) or Design for Environment (DfE).

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3 Waste management

3.1 Background

The sustainable development process indicates a multidisciplinary approach comprising (Figure 3.1):

- economic sustainability: the possibility to guarantee the livelihood of all the inhabitants of the Earth;

- social sustainability: the opportunity to ensure safety, health and education to every human being;

- environmental sustainability: the maintenance of the quality of natural resources and of the environment.

These three concepts are inseparable from each other and typically represented in the diagram of Figure 3.1.

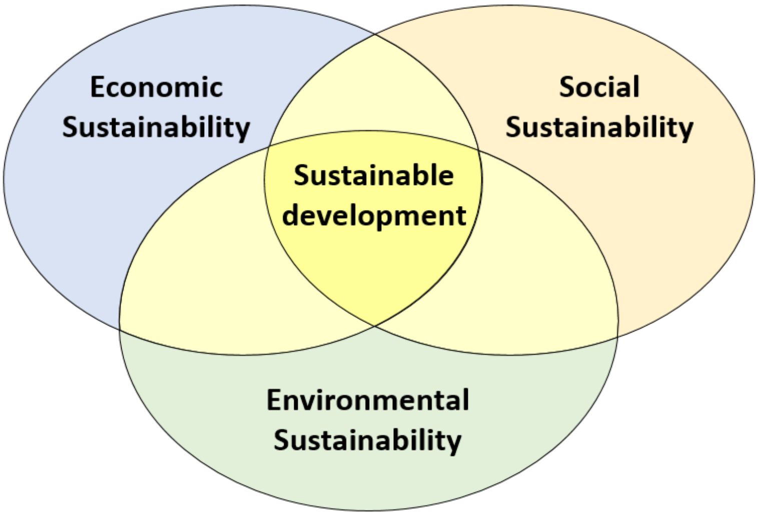

Figure. 3.1. Representation of the concept of sustainable development.

The most widely accepted definition of sustainable development is that contained in the Brundtland report, written in 1987 by the World Commission on Environment and Development, where it is defined as a process of change that aims to meet the basic needs of all individuals without compromising the ability of future generation to meet their own. On December 28, 2013 the Decision 1386/2013/EU [1] was published, containing the general program of the European Union's action on the environment by 2020, "Living well within the limits of our planet", that has the following priorities:

- protecting, preserving ad improving the EU's natural capital;

- transform the Union into a low carbon, efficient in the use of resources, green and competitive economy;
- protect Union citizens from environmental risks for health;
- to maximize the benefits of EU legislation on the environment improving implementation;
- improve cognitive and scientific basis of EU environmental policy;
- provide for policy support investments on environment and climate taking into account environmental externalities;
- improving environmental integration and policy coherence;
- improve the sustainability of Union cities;
- increase the effectiveness of EU action in tackling environmental and climate challenges at international level;

The Union’s environmental policy aims, therefore, at a high level of protection to take into account the diversity of situations in various regions, and is founded on the principles of precaution and preventive action, of correction of environmental damage and on the principle of “polluter pays”.

In detail, the Seventh European Action program identifies specific actions to give full implementation to the EU legislation on waste, which primarily require the application of waste hierarchy and the effective use of instrument and other market measures to ensure that:

- landfill must be limited to the residual waste (i.e. non-recoverable and non-recyclable);
- energy recovery must be limited to non-recyclable materials;
- recycled waste must be used as the main and reliable source of raw materials for the Union, through the development of non-toxic materials cycle;
- hazardous waste must be managed responsibly and their producing must be limited;
- the illegal waste transport is banned, with the support of a strict monitoring;
- food waste must be reduced.

For this purpose at European level a revision of the legislation on product and waste is in progress, including a review of the objectives of the main directives on waste, relying on the Roadmap for a Resource Efficient Europe.

Waste management policy must necessarily take into account the priorities identified at European level, foremost the abandonment of the use of landfill, the activation of useful actions to realize the decoupling of economic indicators and waste generation.

3.2 The case study of the evolution over time of a bio-waste treatment plant

3.2.1 Background and motivation

Humanity still strongly depends on non-renewable resources. In particular, energy from fossil fuels seems to play a crucial role in our day life. Worldwide oil production and consumption data confirm a still increasing trend from 1965 [2], with evident socio-economic implications and dramatic environmental consequences due to the increasing CO_2 concentration in the atmosphere (406 ppm in February 2017 [3]).

Therefore, in order to reduce our dependence on traditional sources and try to mitigate the effects on ecosystems, a fast and smarter transition to a more sustainable source of materials and energy is required.

Among the most critical aspects, waste from agricultural activities and food supply chain constitutes a valuable and renewable material and energy source, which can be valorized through several techniques. Among these, anaerobic fermentation has increased its importance within the scientific community: over than 20000 documents include the term “anaerobic digestion” within their title, abstract and keywords, the majority of these (77.6%) are peer-review articles and conference papers (14.2%) [4].

In general, the management of organic residues as well as the other classes of waste in EU is driven by the Directive 2008/98/EC [5] which suggest the "3R" approach: *reduction, reuse* and *recycling*. In fact, the generation rate in Europe decreased significantly during recent years and the amount of municipal waste disposed in landfill was reduced as a consequence of the directive application [6]. Bio-waste disposal into landfill is strongly discouraged in order to prevent environmental consequences due to methane releases and substances leaching into groundwater. Therefore, the organic fraction is usually collected separately and then sent to further treatments, such as: *i)* composting plant to produce a mixed soil amendment; *ii)* anaerobic digestion, to produce biogas from an enhanced degradation; *iii)* more structured systems in which both anaerobic digestion technology and composting procedures are combined in order to generate renewable energy together with the bio-based fertilizer.

The organic transformation into compost has some potential benefits. First, it minimizes the amount of waste dumped with a sensible contribution to the reduction of the landfill volume dedicated to biodegradables. Second, the use of compost can help mitigating greenhouse gases (GHGs) emissions by decreasing the need of synthetic fertilizers and sequestering carbon in soil that has received compost application [7].

Despite these advantages, the compost manufacturing chain is characterized by intense energy requirements and gas emissions generated during the whole procedure [8]. Therefore, to maximize process efficiency and reduce resource needs, companies are looking for a more integrated systems which combine benefits from the renewable energy production using anaerobic digestion technologies, as GHGs mitigation [9-10] and the avoided use of synthetic fertilizer [11].

All this considered, the object of the study is the activity of "Romagna Compost" plant, located in Cesena district (Northern-central Italy), operating since 2001 and made up by the company leader in Italy for the recovery of materials and waste management (HERA s.p.a.) and other companies operating in the agricultural and food sector of the territory.

"Romagna Compost" plant carries out an industrial process treating the organic fraction from municipal solid waste (MSW), together with biodegradable garden/park and agricultural waste; in this study it has been analyzed from a life cycle perspective, considering its conversion from the sole production of compost to an integrated system of anaerobic digestion and subsequent oxidation. This operation, started in 2007 (year1) and ended in 2013 (year 7), required a large number of interventions obtaining an integrated technology comprising two cogeneration units for the production of electrical and thermal energy, subsequent production of compost from digestate and waste water treatment system within the plant.

For this purpose, thanks to the use of mainly primary data, the temporal evolution of the plant is evaluated step-by-step, considering the period in which it worked as a traditional composting system to the current combined production of energy and compost, allowing the exchange of electricity, heat and conventional fertilizers [12].

3.2.2 Plant description

The production of renewable energy in the Romagna Composting plant began in December 2009 (year 3), following an enlargement process that transformed the simple aerobic composting process (Fig. 3.2) in an integrated anaerobic-aerobic treatment with annexed cogeneration plant to produce electricity and heat (Fig. 3.3). This new configuration is able to treat around 45000 tons/year of organic fraction and 15000 tons/years of lignocellulosic fraction both coming from separate collection.

Three main classes of waste are managed by the plant:

- the organic fraction of the MSW (OFMSW), collected separately;
- the residues resulting from agro-industrial activities;

- the lignocellulosic scraps from maintenance of public and private green spaces.

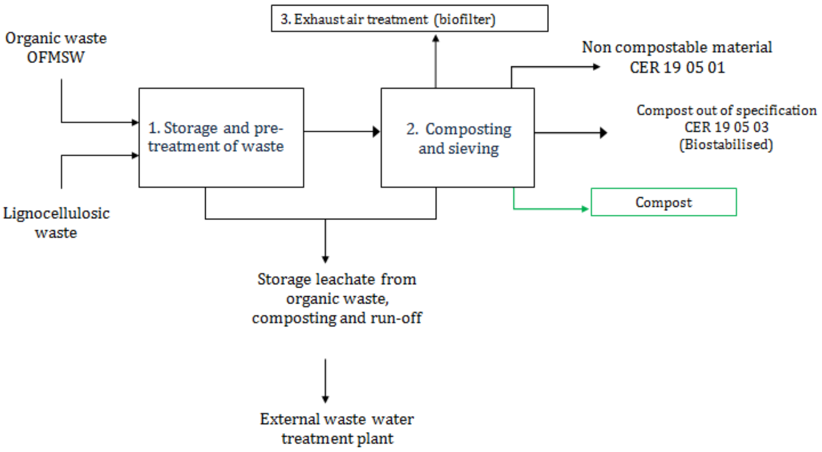

Figure 3.2. Lay-out of the traditional composting plant (year 1).

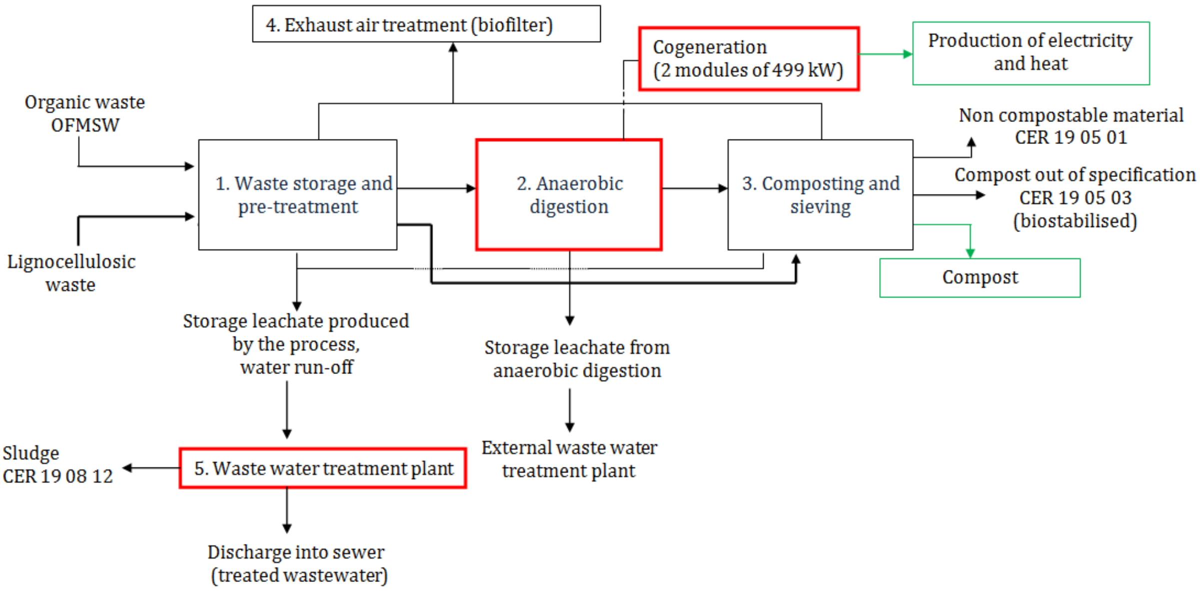

Figure 3.3. Plant lay-out with the integrated anaerobic-aerobic system (year 7).

The whole plant is divided into the following steps, which could be collected into seven main stages:

1. reception and storage of the organic and lignocellulosic waste;
2. pre-treatment of the wet fraction;
3. anaerobic digestion with energy recovery (electricity and heat);
4. mixing;
5. aerobic step;
6. sieving;
7. production of mixed composted soil (compost).

In addition, treatments of the waste water flow and exhaust air are present. Below, a detailed description of the entire plant is reported.

The process starts with the waste storage and pre-treatment, which includes the transfer of the lignocellulosic and bio-waste in the appropriate box and their shredding. While bio-waste is stored inside closed boxes of about 800 m^3 kept in depression through two aspirators that capture the exhausted air (Fig. 3.4), the wood residues from cuttings, prunings and maintenance of the green are stocked outdoors in the square storage area.

Figure 3.4. Wet organic waste conferring step and Open fermenter with sealing grill

The waste is then shredded and homogenized. The product thus obtained is mixed with an equal amount of digestate material coming out from the fermenters, which constitutes the inoculum (Fig. 3.5).

Figure 3.5. Digestate material to the opening of the fermenter

The plant of dry anaerobic digestion (Fig. 3.6) allows the treatment of materials with a high content of dry matter (up to 50%) without the need to convert them into a liquid substrate.

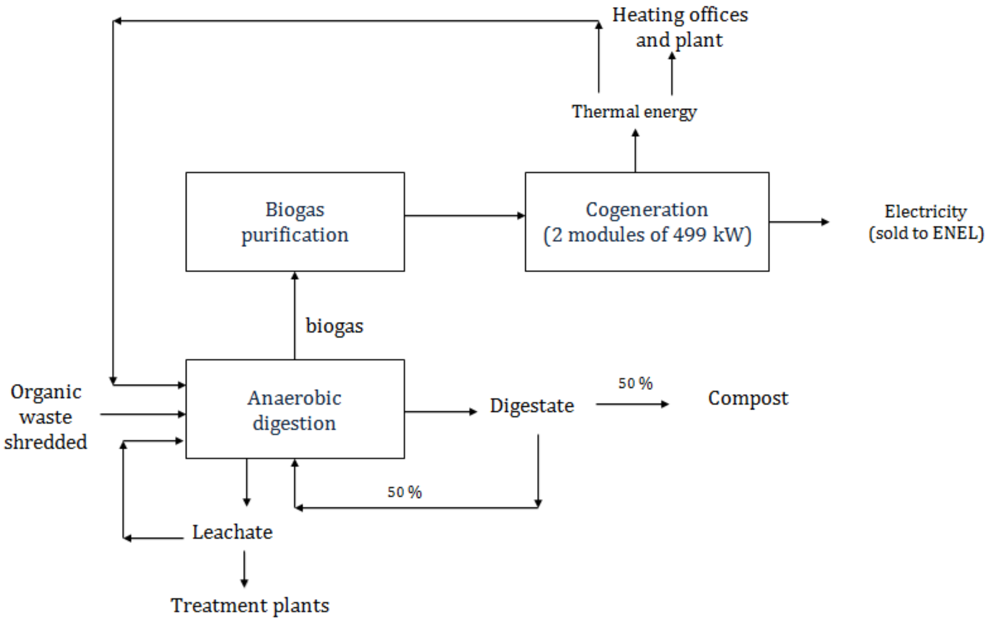

Figure 3.6. Flows of matter and energy from the anaerobic fermentation process.

It is a batch fermentation phase, since the different reactions of anaerobic biodegradation take place inside one fermenter, without the addition or removal of material along the period of fermentation. The plant consists of 11 fermenters in the form of reinforced concrete gas-tight chambers and resistant to acids (Fig. 3.4). Such reactors are drained and filled every 25-30 days, in an alternating manner to ensure a constant production of biogas (Fig. 3.5). The gas produced within the anaerobic digestion plant before being sent to the cogeneration unit is dehumidified, compressed (from about 14 mbar to 104 mbar) and purified by an activated carbon filter (Table 3.1, process control parameters).

Temperature	37 °C
pH	6,5-7,5
Pressure	25 mbar
Period	25 days
Biogas composition[1]	60% CH_4 40 % CO_2 100 ppm NH_3 50 ppm H_2S
Factor of production	80 m^3 biogas/t

[1] concentrations of the components present in greater quantity have been reported. Other substances such as H_2, CO, N_2, H_2O and silanes are contained in low concentrations and irrelevant.

Table 3.1. Control parameters of the process

The cogeneration plant consists of two four-stroke internal combustion engines, with the following features:

- electric power: 499 kW for each engine, 100% recovered;
- thermal power: 530 kW for each engine, currently recovered only in part (Table 3.2).

Thermal power recovered	u.d.m	Cogenerator power	
		Full load (100 %)	Half load (50 %)
First stage intercooler	kW	55	1
Oil	kW	57	45
Engine cooling water	kW	185	150
Thermal power currently available	kW	**297**	**196**
Exhaust gas cooled at 180°C	kW	233	128
Total thermal power	kW	**530**	**324**

Table 3.2. Detail of thermal power recovered

At the end of the anaerobic fermentation cycle about 50% of the digestate is sent to a mixing step with an amount of lignocellulosic material, taking into account different factors, as porosity, C/N ratio, moisture and bulk density.

The processed material is then sent to the aerobic step.

The former plant was constituted only by the current shed, within which the entire process of biological oxidation took place.

Now the aerobic process (Fig. 3.7) follows the anaerobic digestion and is constituted by a first intensive refinement phase in six lanes with forced aeration and subsequent aerobic stabilization in the ventilated area, through a system of aerated and turned cumuli.

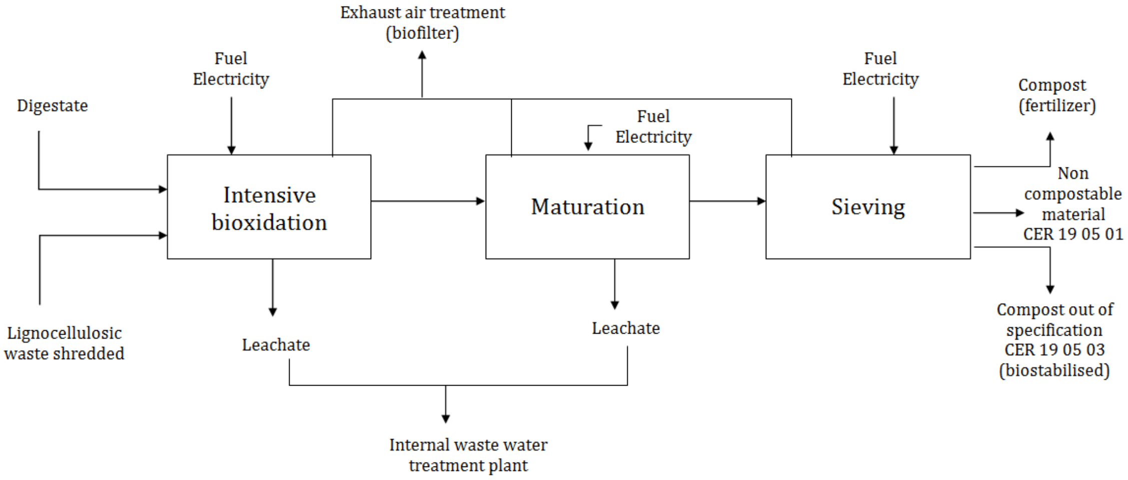

Figure 3.7. Flows of matter and energy of the composting phase (years 6-7)

The sieving allows the removal of coarse materials and the obtainment of a clean compost with homogeneous size. This operation results in three fractions: over size material (EWC, European Waste Catalogue, 19 05 01 [5], non-compostable material) (Fig. 3.8); bio-stabilized (EWC 19 05 03, compost out of specification), consisting of heterogeneous compounds (Fig. 3.9) used as covering material of landfill [13] and compost.

Figure 3.8. Product fraction over screening: screening material such as, woody fraction, plastic fraction.

Figure 3.9. Biostabilised (EWC 190503).

All the odor treatment steps are performed below atmospheric pressure through a vacuum system that picks up and sends the exhausted air to a treatment system consisting of a scrubber and a bio-filter made up lignocellulosic material with a potential for 60000 m^3/h (Fig. 3.10).

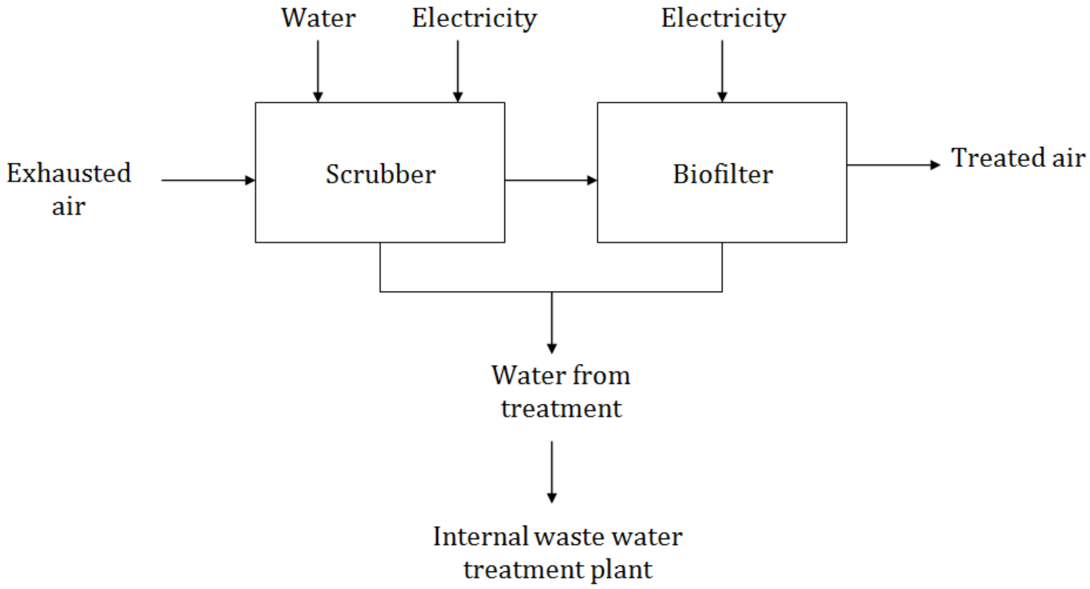

Figure 3.10. Scheme of flows of matter and energy to the phase of exhausted air treatment, years 4-7.

The types of emissions from the plant are summarized in Table 3.3. The waste water treatment plant (Fig. 3.11) is constituted by an activated sludge sewage treatment plant with final ultrafiltration using synthetic membranes.

Emission denomination	**Biofilter**	**Flue cogenerator 1 (removal system: afterburner)**	**Flue cogenerator 2 (removal system: afterburner)**
Authorized capacity (Nmc/h)	60000	2377	2377
Minimun height (m)	1.2	6	6
Section (m^2)	600	0.049	0.049
Period (h/g)	24	24	24
Maximun permissible concentration of pollutants (from current Aut.)	300 UO/mc	Oxides of sulfur (expressed as SO$_2$) 500 mg/Nm^3 Oxides of nitrogen (expressed as NO$_2$) 450 mg/Nm^3 Particulate matter10 mg/Nm^3 CO 300 mg/Nm^3 HCl 10 mg/Nm^3 COT 150 mg/Nm^3 HF 2 mg/Nm^3	(ascogenerator1)

Table 3.3. Main plant emissions

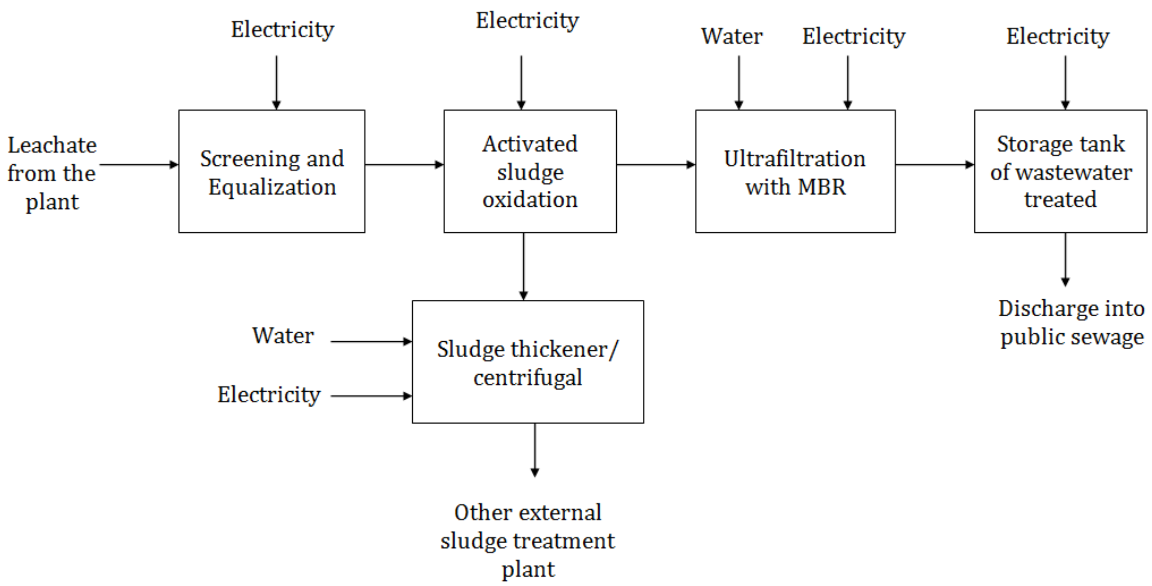

Figure 3.11. Schematic flows of matter and energy of the waste water treatment plant, years 6-7

3.2.3 Goal and scope definition

The aim of the study is to assess, in a systematic and comprehensive way, the extent of different types of environmental impact relative to the treatment of bio-waste in the plant investigated, in a well-defined timeframe of seven years: from 2007 (year 1) up to 2013 (year 7). During this period significant changes occurred in the process configuration:

- years 1-2: traditional composting plant;
- year 3: traditional composting plant and start of the waste water treatment plant and anaerobic fermentation process. The expansion of the plant ended and in the same year the process of composting and the first fillings of the anaerobic digester were conducted, which is why the data of this period do not express the real potentiality of the plant;
- year 4: the plant was definitely set up;
- year 5: the plant became fully operational, reaching the maximum capacity of treatment authorized;
- years 6-7: integrated anaerobic-aerobic system.

According to these changes in the process configuration, the amount of the bio-waste recovered increased following the plant expansion, from 12575 ton/year in years 1-2 to 37950 ton/year for the period years 6-7.

This comparison allows a good understanding of how the impacts of the plant varied going from a traditional composting process to an integrated anaerobic-aerobic system. The main reasons that led to this study are the following: first, it was required to assess the environmental effects coming from the introduction of innovative and cleaner technologies; in addition, it was interesting to test the application of LCA methodology to this waste treatment plant, which has not been widely investigated, to date.

One ton of bio-waste entering the plant was selected as functional unit, since it represents the system in terms of energy produced and consumed by the process, input of raw materials and emissions: the main function of the studied system is linked to the operation of biological treatment of bio-waste, combined with energy recovery, when existing. For this reason, in relation to the processes of anaerobic fermentation and composting, input and output related to the use of fuels, lubricants, transportation of solid and liquid waste, treatment and disposal of them, as well as environmental emissions of different nature were considered within the boundary of the system, according to the principles of Burgess and Brennan 2001 [14], with a *cradle-to-gate* approach.

The study consists essentially of three phases (Fig. 3.12):

Phase 1: analysis of the system before and after enlargement, considering as system boundaries the input of bio-waste into the system until the final fate of waste streams products; in the years following the expansion the energy recovery from biogas was also considered.

Phase 2: extension of the boundaries of the system, including the transport of bio-waste from the place of collection to the recovery in the plant under investigation.

Phase 3: extension of the boundaries of the system, considering the possibility of disposing bio-waste in other ways, according to the plants present in the Region in which it is generated.

The boundaries of the system do not include flows of material, energy and waste associated with the phases of extension of the plant.

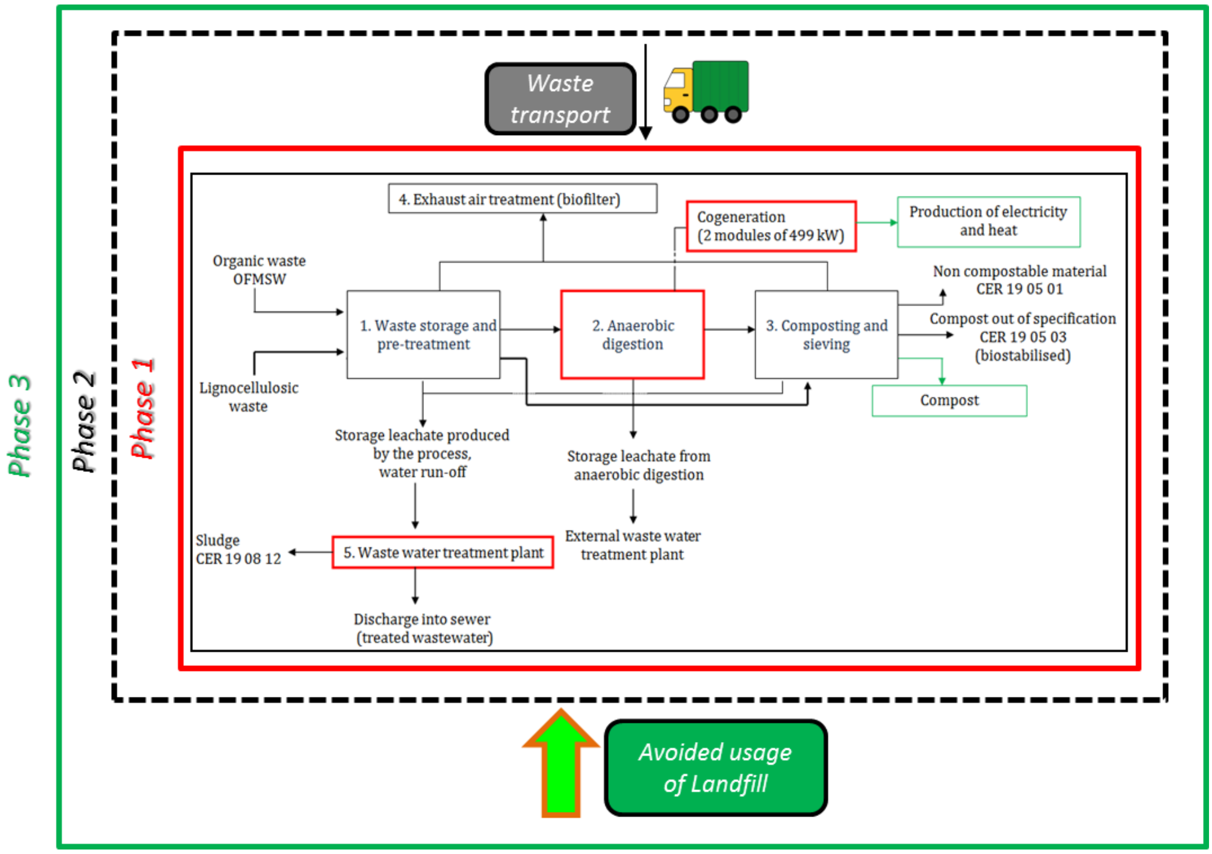

Figure 3.12. Boundaries of the system.

3.2.4 Life Cycle Inventory (LCI)

Most of the information used were directly furnished by the company (primary data) or extrapolated from technical reports of public bodies (e.g. Province, Regional division of the Environmental Protection Agency, etc.). Other information, not directly provided by the plant, as fugitive emissions or impacts associated to infrastructure, were derived from the dedicated database (e.g. Ecoinvent [15]) or from bibliographic references. Information concerning resources consumption (such as water and fuel) for the years 1-7, are approximations based on the data of the subsequent years were performed. Table 3.4 collects all the LCI.

	Process lines/parameters		Classic composting plant		Integrated anaerobic-aerobic system				
					Start new plant	1° year of operation	Operational plant		
			Year		Year				
1	Storage and pre-treatment of waste	u.d.m	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
INPUT	Quantity of organic waste (OW)	t/year	13194	11955	17193	29706	39551	39795	38453
	Quantity of lignocellulosic waste	t/anno	1534	2455	4696	5598	6691	7317	9008
	Transport of organic waste	tkm/t $_{ow}$	40	40	40	79	63	72	109
	Transport of lignocellulosic waste	tkm/t $_{ow}$	35	35	35	35	35	35	35
	Use of fuel for shredding of waste	MJ/t $_{ow}$	15.79	15.79	15.79	14.41	14.41	14.41	14.41
	Fuel consumption for movement of shovels	t/year	3.68	3.60	5.47	8.82	11.50	11.78	11.86
	Consumption of electricity	kWh/year			10000	19272	19008	23366	27348
	Lubrificants	t/year	0.20	0.20	0.20	0.4	0.5	0.5	0.5
OUTPUT	Leachate untreated in the internal sewage plant	t/year	850	1721	901	3313	2237	1836	1730
	Transport of the leachate produced	km/t	0.69	0.69	2.41	2.41	2.41	2.41	2.41
2	Anaerobic fermentation	u.d.m	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
INPUT	Quantity of OFMSW to digestion	t/year	-	-	1270-	26735	35596	35816	34608
	Digestate (inoculum)	t/year	-	-	-	28951	30331	29494	28929
	Fuel consumption for movement of shovels	t/year	-	-	9	10	14.58	14.58	14.58
	Energy consumption of the fermentation plant	kWh/year	-	-	11200	180374	221702	234439	251200

	Lubrificants	t/year	-	-	-	3.3	3.3	3.3	3.3
OUTPUT	Biogas production	Nm^3/year	-	-	88618	3175147	3781487	4090939	4198117
	Eletricity production	kWh/year	-	-	141789	5251617	6345389	6989286	7182523
	Thermal energy production	kWh/year	-	-	93580	2276849	2751057	3063365	3080853
	Leachate	t/year	-	-	-	2434	2694	4534	5176
	Transport of leachate to the disposal plant	tkm/year	-	-	-	2.41	2.41	2.41	2.41
	Mineral oil exhausted	t/year	-	-	-	1.9	1.9	1.9	2.9
	Emissions from cogenerators								
	Fumes temperature	°C	-	-	-	450	450	450	450
	Average flow of dry steam	Nm^3/h	-	-	2147	2147	2147	2147	2147
	Oxides of nitrogen expressed as NO_x	mg/Nm^3	-	-	450	450	450	450	450
	Carbon monoxide– CO	mg/Nm^3	-	-	300	300	300	300	300
	Particulate matter PM	mg/Nm^3	-	-	10	10	10	10	10
	Oxsides of sulfur expressed as SO_2	mg/Nm^3	-	-	500	500	500	500	500
3	Composting and Sieving	u.d.m	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
INPUT	Digestate	t/year	-	-		14858	26503	28000	24593
	Organic waste	t/year	12798	11596	15940		-		
	Lignocellulosic waste (structuring)	t/year	1534	2455	4696	5598	6691	7317	9008
	Electricity consumed from biossidation step	kWh/year	-	-	69420	215548	305617	380132	432209
	Electricity consumed from maturation step	kWh/year	65019	60092	60092	38747	99966	101095	93913
	Fuel consumption for movement of shovels	t/year	7.85	7.10	9	12	18	16.4	16.4
	Fuel consumption for sieving	t/year	7.4	6.6	6.6	5.96	5.66	7.34	5.75
	Electricity consumption for sieving	kWh	-	-		2745	14538	6815	5338
OUTPUT	Biostabilized produced	t/year	5360	3447	3670	6507	6467	6697	7737

	(CER 19 05 03)								
	Transport of biostabilised to disposal plant	km/t	0.25	0.25	0.25	0.12	0.13	1.11	3.64
	Screening material (EWC 19 05 01)	t/year	1555	1420	1192	1510	4812	6713	7075
	Transport of screening material to disposal plant	km/t	0.25	0.25	3.83	3.83	3.37	3.50	3.15
	Compost	t/year	1846	936	340	2377	3591	2930	2370
4	Treatment process air	u.d.m	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
INPUT	Water used in scrubber	t/year	3480	3480	3480	3480	3480	3480	3480
	Energy consumption from scrubber pumps	kWh/year	334098	334098	334098	334098	334098	334098	334098
	Energy consumption by liofile aspirator	kWh/year	602910	602910	602910	602910	602910	602910	602910
	Woodchip for biofilter	m³/year	200	200	200	200	200	200	200
OUTPUT	Biofilter emissions – odorimetric units	Odorimetric units	300	300	300	300	300	300	300
	Exhaust biofilter woodchips (CER 15 02 03)	t/year	169	169	169	169	169	169	169
5	Leachate and waste water from process treatment								
INPUT	Waste water in input to waste water treatment plant	t/year	-	-	7150	25206	15979	20009	26167
	% leachate from landfill	%	-	-	48	70	62	74	77
	Average of COD in input	mg/l	-	-	18720	18457	19829	19800	19143
	Average of COD in output	mg/l	-	-	2000	2000	2000	2000	2000
	Wastewater discharged into sewer (net of the leachate)	t/year	3000	3000	3000	11850	5748	9528	17898
	Shoveled sludge (net of the leachate)	t/year	-	-	303	1151	488	272	144

	Sludge transport	km/t	-	-	2.41	2.41	2.41	6.36	6.35
	Electricity consumption for wastewater treatment plant	kWh/year	-	-	227659	227659	231780	324409	324642
	Consumption of fresh water	t/year	-	-	3200	3374	3806	6897	7243
	Hydrochloric acid	t/year	-	-	35	33	36	51	37
	Sodium hypochlorite	t/year	-	-	2	1	2	2	5
	Citric acid solution	t/year	-	-	11	13	7	10	18
	Defoamers	t/year	-	-	6	6	4	1.75	2.75
6	Utilities (offices, equipment room, lockers room, etc)								
	Electricity consumption	kWh/year	-	-	-	18466	137957	116024	159549
	Fresh water	t/year	180	180	180	1380	1380	1380	1400

Table 3.4. Flows of material and energy in and out of the plant

All the information were reorganized into process steps in order to evaluate the more impacting stages, from an environmental point of view, and estimate potential benefits as a consequence of the improvement. In particular, seven scenarios were created, one for every year of functioning (from year 1 to year 7).

Among the scenarios, the following process steps were considered:

1. Storage and pre-treatment of waste (Fig. 3.13);

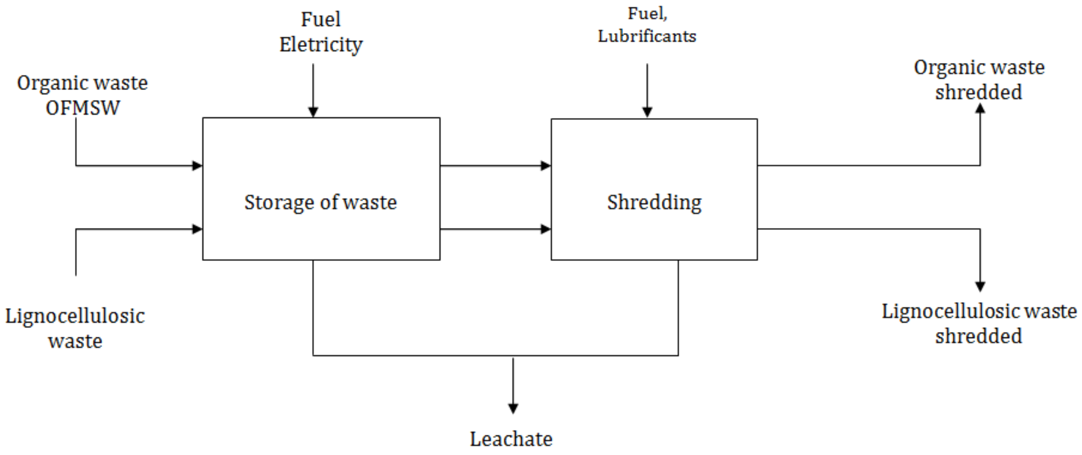

Figure 3.13. Flows of matter and energy to the phase of storage and pre-treatment of waste.

2. Anaerobic fermentation (Fig. 3.6);
3. Composting and screening plants (Fig. 3.7);
4. Treatment of process air (Fig. 3.10);
5. Leachate and waste water treatment process (Fig. 3.11);
6. Energy and other utilities.

Steps 2 and 5 were excluded from years 1-2 scenarios, since they were not present in the plant (Figs. 3.2-3.3-3.14-3.15). Below a detailed description of each step is reported.

Figure 3.14. Rendering of the system (year 1).

Figure 3.15. Rendering of the system (year 7).

Storage and pre-treatment of waste

This stage includes all the input and output flows for the collection and pre-treatment of the bio-waste and of the lignocellulosic fraction (wood residues with LHV=9.5 MJ/kg), such as:

- fuel consumption for shredding and handling procedures, together with the usage of lubricants for machineries;
- electricity requirement to maintain a depression condition within the storage box, to avoid the dispersion of malodorous substances. This solution was introduced in year 3, since previous configurations implied an open space waste discharge.

The amount of leachate produced in the storage, was expressed as outflow of COD (Chemical Oxygen Demand) and ammonia nitrogen (the main pollutants present). This residues are sent to dedicated treatment plants, therefore their transportation was included within the boundaries.

Anaerobic fermentation

The stage of anaerobic fermentation was introduced in year 3, therefore it is only present in the inventories of the scenarios which refer to years 3-7 period. Electricity and heat are co-produced by biogas combustion using two cogeneration modules (499 kW each). For this reason a system boundaries expansion was performed, in order to consider the avoided impacts associated with these recoveries. Currently, only 20% of the heat can be recovered for heating fermenters and offices, while the remaining 80% is dissipated. On the other hand, electric energy is used to feed pumps, compressors and other devices within the whole plant.

The modeling of anaerobic fermentation is based on the processes belonging to Ecoinvent database, appropriately replacing the data with those of the plant under study.

Moreover, this stage includes fuel consumption to perform waste movement, and the use of lubricants in the cogeneration modules. In addition, the infrastructure were considered.

Waste streams output from this stage, are mainly exhausted mineral oil, leachate produced by the plant (expressed as above) and emissions from biogas combustion, considered through the use of primary data coming from the plant.

Composting and Sieving

These stages take into account all the impacts related to infrastructure, consumption of the electricity (to move fans) and fuel (e.g. waste movement), and the sieving processes. The modeling is based on the processes belonging to Ecoinvent database, appropriately replacing the data with those of the plant under study.

Output streams are constituted by three main fractions, with different particle size and functions:

- *compost*, $d_p < 8$ mm;
- *off-specification compost*, also called “bio-stabilised”, 8 mm$<d_p<$28 mm (Figure 3.5);
- *non-compostable material*, $d_p>$28mm (Fig. 3.8);

where d_p indicates the diameter of the particles.

The finer fraction, i.e. the compost, is a fertilizer that can replace conventional nitrogen fertilizers used in agriculture, parks and gardens. Therefore, the model assumes an avoided production of a synthetic fertilizer, considering a conversion based on the content of nitrogen.

The bio-stabilised residue is not classified as hazardous special waste (EWC 190503), since it contains parts of plastic, glass and other inert materials (Table 3.4): for this reason, it can be used as engineering material for the daily cover in landfills [16]. Although such use of waste is considered an operation of recovery, impacts associated to glass, plastic and inert in landfill were taken into account, while the organic fraction, simply replacing the soil, was not accounted.

Product fraction	**u.d.m**	**Values**
Glass	% ss	4.3
Plastic	% ss	1.1
Inert	% ss	9.8
Humidity	%	27.7

Table 3.5. Product composition of biostabilised

Transportation of the off-specification compost within the landfill site was also included. The non-compostable and oversize material (EWC 190501) for the years 1-4 consisted exclusively of plastics, so it was considered a 100% disposal in nearby landfill. On the other hand, now it is mainly composed by a plastic (45%) and woody waste (55%) mixture. Therefore, the remaining scenarios assume the 85% of whole amount dumped, while the remaining 15% was transferred to the incinerator of Coriano (Rimini district) and to RDF (Refuse Derived Fuel) treatment plant in Ravenna.

Model takes into account both impacts of dumping and incineration. In the latter case, data from Coriano incinerator were taken into account to complete the inventory [17].

In addition, leachate from bio-oxidation and maturation step was considered in a different way depending on years. For the year 1 the outgoing flow has been included in terms of COD and ammonia nitrogen, in the case of year 7 it was assumed to be treated in the sewage treatment plant.

Process air treatment

The treatment of the process air has not changed during the expansion, thus it presents the same impacts for all scenarios considered (years 1-7).

Input of water is required to humidify air inlet in the scrubber. In addition, electricity is consumed to force the water recirculation (by pumps) and aspirator (estimate flow rate of 60000 m^3/h), which conveys the exhaust air to the bio-filtering bed. In addition, the model includes the amount of wood chips (wood chips, softwood, u = 140%) used to constitute the filter thanks to its double function: first, as a filling material, then as a substrate for the microorganisms of the biofilter. This substrate is in general replaced every three years, therefore 169 t were considered for regeneration each year. The waste water collected are conveyed to the treatment plant and then not present as output flows. The purified air coming out from the biofilter is emitted into the atmosphere (limit of 300 odor units).

Leachate and waste water treatment process

The treatment of leachate is active since year 3, thanks to the construction of a biological sewage plant.

At this stage it is necessary to consider the energy consumed by the operation of the blowers that allow the insufflation of air into the activated sludge tank, pumps and other components and the consumption of water for the washing of biological membranes for ultrafiltration. Data were directly furnished by the company.

In addition, the impact of the production of the reagents used for cleaning membranes (hydrochloric acid, hypochlorite, citric acid, antifoaming agents, etc) and the impact associated to the infrastructure (waste water treatment plant) have been inserted. Finally, the treated waste water discharged in public sewer has been considered as a stream in output of COD and ammonia nitrogen. The sludge, extracted from the oxidation tanks, is centrifuged to reduce the moisture content and destined to other disposal processes. For this reason, transportation was also considered.

Utilities

This group includes the consumption of electricity and drinking water not associated to the phases of the system, such as from offices, changing rooms, general lighting and other components.

Fugitive emissions

Fugitive emissions are present both during the anaerobic fermentation and composting. Due to the lack of primary information, secondary data have been used. In the process of composting the direct emissions caused by degradation and mineralization of the organic matter that may contribute to the greenhouse effect, mainly consist of CO_2 and for a small fraction of CH_4 and N_2O. However, carbon dioxide is considered *biogenic CO_2* and not generally counted as GHG [18], since it is part of the natural cycle of the carbon. The release of CH_4 and N_2O depends on the technology, the type of waste storage and management of the process. The presence of a bio-filter downstream of the process, as in the plant studied, allows the removal of trace pollutants, with good efficiencies of abatement. In general, fugitive emissions of methane are difficult to determine and vary depending on the technology and the system configuration. Some researchers estimated losses amounting to 3% of the whole CH_4 production [19]. On the other hand, the Intergovernmental Panel on Climate Change [18] considers for the fermentation process a fugitive emissions between 0-10% of methane production, but it also states that the losses may be avoided where the technical standards for biogas plants ensure the combustion of any unintentional emissions of CH_4 [18]. Therefore, to be more conservative a methane loss of 1% compared to its total production has been considered for the years 4-7 with an integrated anaerobic-aerobic plant, because the system is equipped with an emergency torch.

Instead, for the traditional composting process (years 1-3), based on the data of Table 6, fugitive emissions of methane equal to 0.91 $kgCH_4/t_{ww}$ have been considered, considering the presence of a biofilter downstream.

Emissions	**Plant Technology**	**Waste typology**	**Degradation**	**Emissions**
CO_2	open	biowaste	**50-60 % input of C org**	47-173 kg CO_2/t ww
	close (in depression)			**250-390 kg CO_2/t ww**
CH_4	open	biowaste	0.8-2.5 % C degraded	0.03-1.5 kg CH_4/t ww
	close (in depression)		**2.4-3 % C degraded**	**0.02-1.80 kg CH_4/t ww**
N_2O	open	biowaste	0.1-0.7 % input of N	7.5-252 kg N_2O/t ww
	close (in depression)		**1.8 % input of N**	**10-120 kg N_2O/t ww**

Table 3.6. Gaseous emissions during the composting process of organic waste [24].

Second phase: system boundaries extension to the bio-waste transportation

In order to have a wider perspective of the environmental burdens, a system boundaries expansion was performed including transportation of the bio-waste from the collection sites to the plant. The data of transportation have been included in the model process. Table SA6 shows the drastic increase of this value by the years, due mainly to the transport of waste from other Regions to exploit the full productive capacity of the plant considered (40000 t/year). Transportation in LCA studies is in general expressed as tkm by multiplying the tons of waste transported per distance in kilometers. Then, the values of Table 4 have been added to those of Table 3.7 to obtain the system boundaries extension.

Year	Potentialities plant	Fraction of waste from out of the region	Transport of organic waste
1-3	15000 t/year	0 %	40 tkm/t
4	30000 t/year	18 %	79 tkm/t
5	40000 t/year	17 %	63 tkm/t
6	40000 t/year	20 %	72 tkm/t
7	40000 t/year	29 %	109 tkm/t

Table 3.7. Flows of waste from out of the region and distances of transport.

The share of waste from outside Emilia Romagna region, especially from Marche, Abruzzo and Campania, can vary yearly and it does not depend on the process, but only on logistical and economic factors.

The report on municipal waste [6] highlights the lack of anaerobic digestion plants in central Italy. In fact, according with 2014 survey only 29 plants were identified in Italy, 90% of them are located in Northern and the rest in the South.

At first, for each year of the study, in terms of single score (Fig. 3.16), the impact due to the transport only was considered, therefore considering the quantities carried and kilometers traveled.

Then, the contribution of the transportation was added to the overall impact, thus extending the system boundaries.

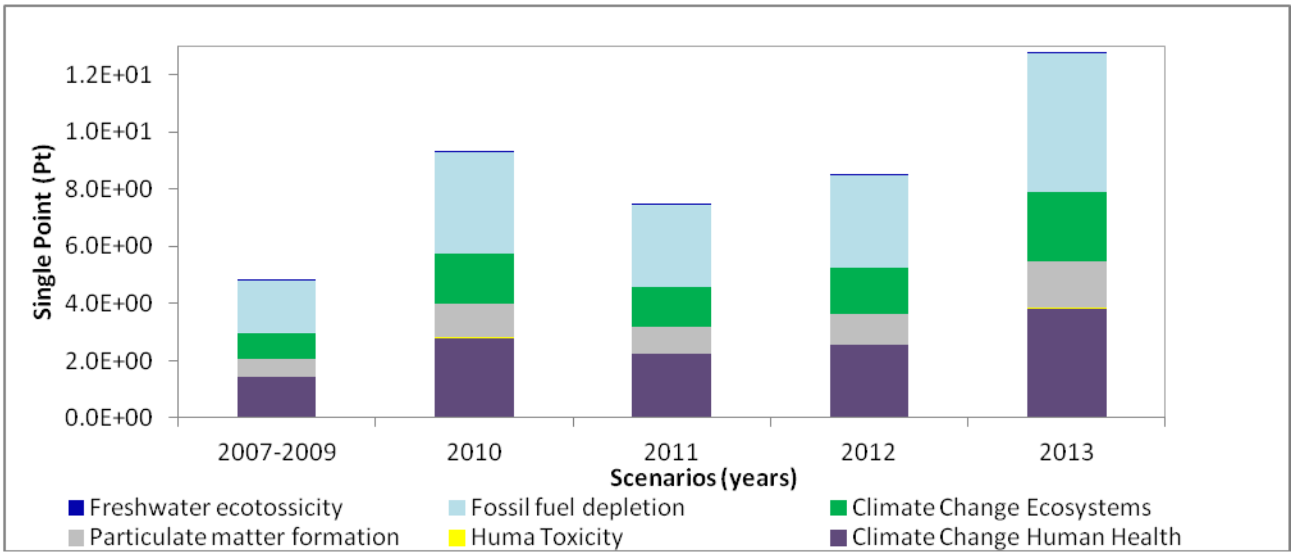

Figure 3.16. Single point: midpoint impact categories for the process of transport of organic waste, scenarios years 1-7.

Third Phase: system boundaries extension to the waste management in Italy

In the last phase of the study the boundaries of the system were further extended, considering the avoided disposal in landfill of the lignocellulosic fraction and bio-waste outside the Emilia Romagna Region. This scenario represents the case in which the organic residues are landfilled, due to the lack of an appropriate composting plant in the nearest Regions. Transportation was simulated assuming average distances from the place of collecting to the municipal landfill. The avoided impacts were estimated using the default process "Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CHU", already contained in Ecoinvent database, due to the lack of a process related to the disposal of bio waste in landfill in the reference database.

3.2.5 Impact assessment and results interpretation

ReCiPe [20] method was adopted to carry out the LCIA stage. Both *midpoint* and *endpoint* levels were used to perform the analysis, selecting a *Hierarchist (H)* perspective.

In the first assessment phase the comparison was performed among the different years (from 1 to 7), in terms of single points. Fig. 3.18 shows the single score trend associated with the treatment of 1 ton of bio-waste. Results, in terms of damage categories, are shown in Figure 3.17. In this first stage of the analysis the transportation of bio-waste was not considered.

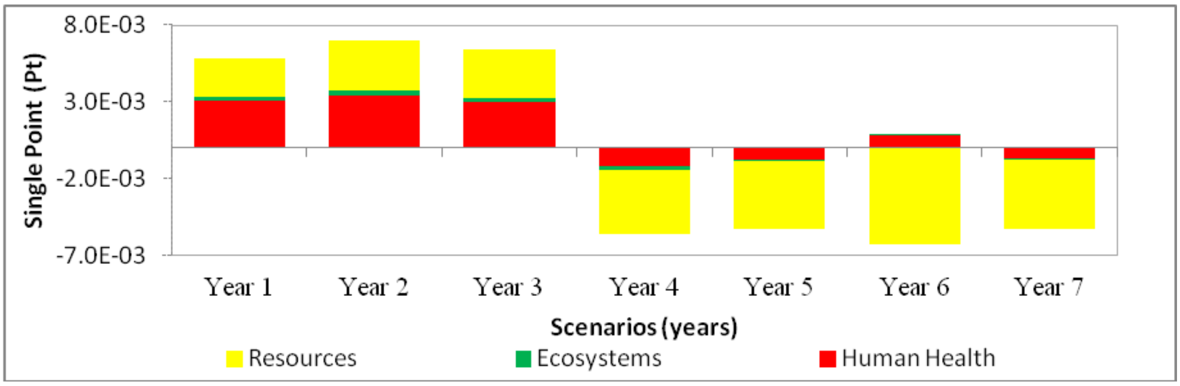

Figure 3.17. Single Point: impact of the process scenarios for years 1-7, impact categories endpoint

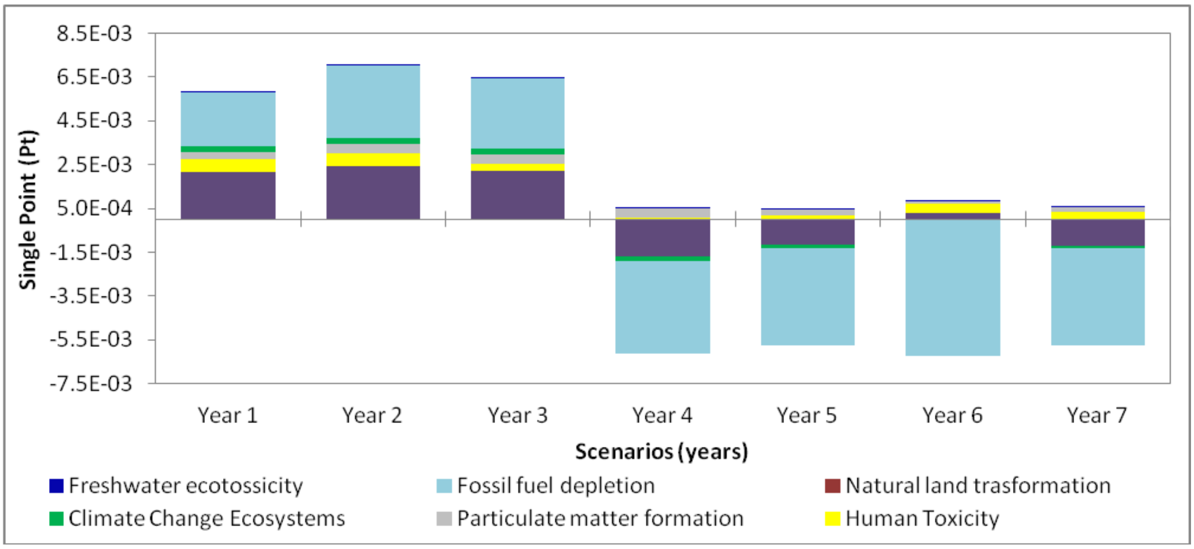

Figure 3.18. Single Point: impact of the process scenarios for years 1-7, midpoint impact categories.

In the second phase of the study, expanding the boundaries of the system, the avoided impact related to the collection of waste outside Emilia Romagna Region, which otherwise would have been disposed of in landfills due to the lack of adequate recovery plants in the areas of generation and collection, was included. The comparison of the various scenarios was performed in terms of single score for endpoint (Table 3.8 and 3.19) and midpoint (Fig. 3.20) categories.

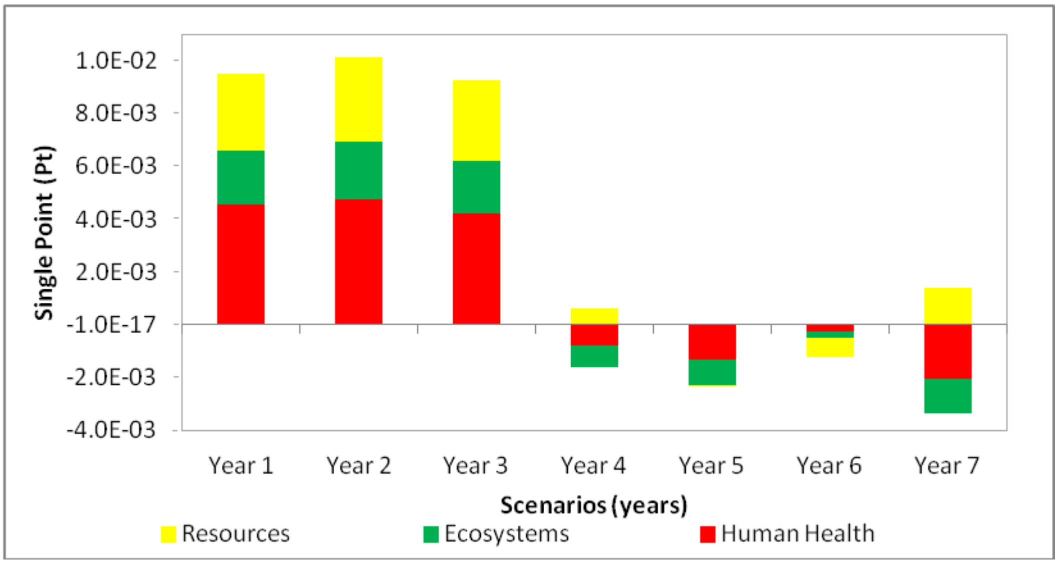

Figure 3.19. Single Point: impact of the process with the extension of the boundaries to the organic waste management in Italy for the scenarios years 1-7, impact categories endpoint.

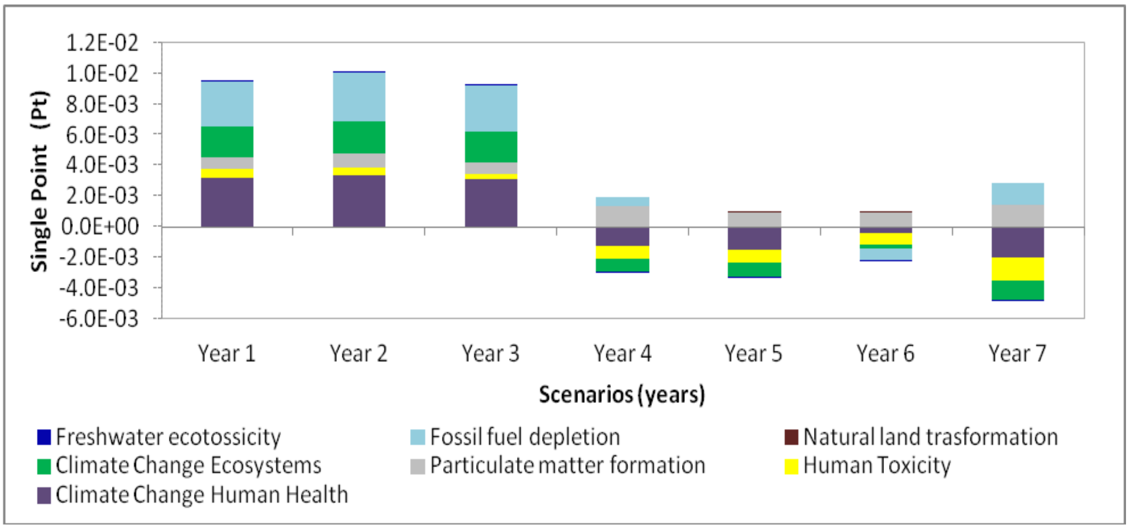

Figure 3.20. Single Point impact of the process with the extension of the boundaries to the bio-waste management in Italy for the scenarios from year 1 to year 7, midpoint categories.

Impact Categories	***Unit***	***Year 1***	***Year 2***	***Year 3***	***Year 4***	***Year 5***	***Year 6***	***Year 7***
Human Health	DALYs	2.30E-07	2.40E-04	2.13E-04	-4.02E-05	-6.74E-05	-1.26E-05	-1.03E-04
Ecosystems	species·yr	9.34E-10	9.86E-07	8.98E-07	-3.71E-07	-4.30E-07	-1.13E-07	-5.97E-07
Resources	$	4.44E-03	4.92E+00	4.75E+00	9.32E-01	-7.96E-02	-1.11E+00	2.18E+00

Table 3.8. Characterization table considering the endpoint damage category

It is important to take into account that the two configurations (year 1 of traditional composting and year 7 with an integrated anaerobic-aerobic system) consist of different phases that contribute to the overall impact of the system under study. Considering year 1, the process consisted of three main phases: storage and pretreatment of the bio-waste, composting and treatment of the exhausted air (biofilter) (Fig. 3.21).

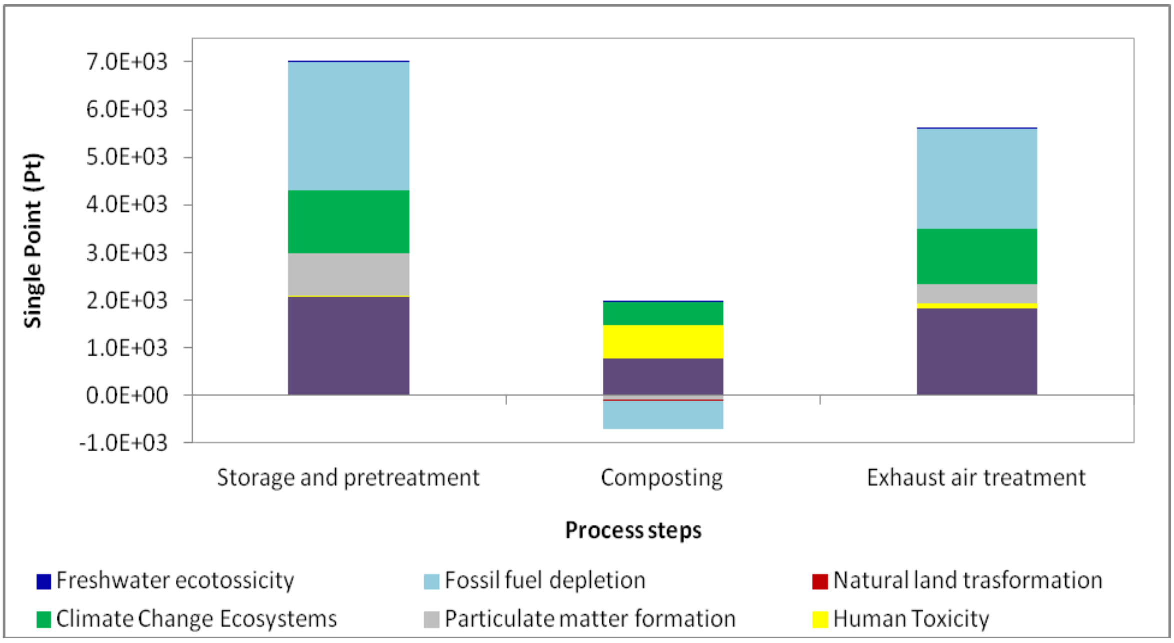

Figure 3.21. Single Point impact of the different phases of the process for year 1, midpoint categories

The year 7 scenario, instead, is the current configuration and consists of seven sub processes (Fig. 3.22).

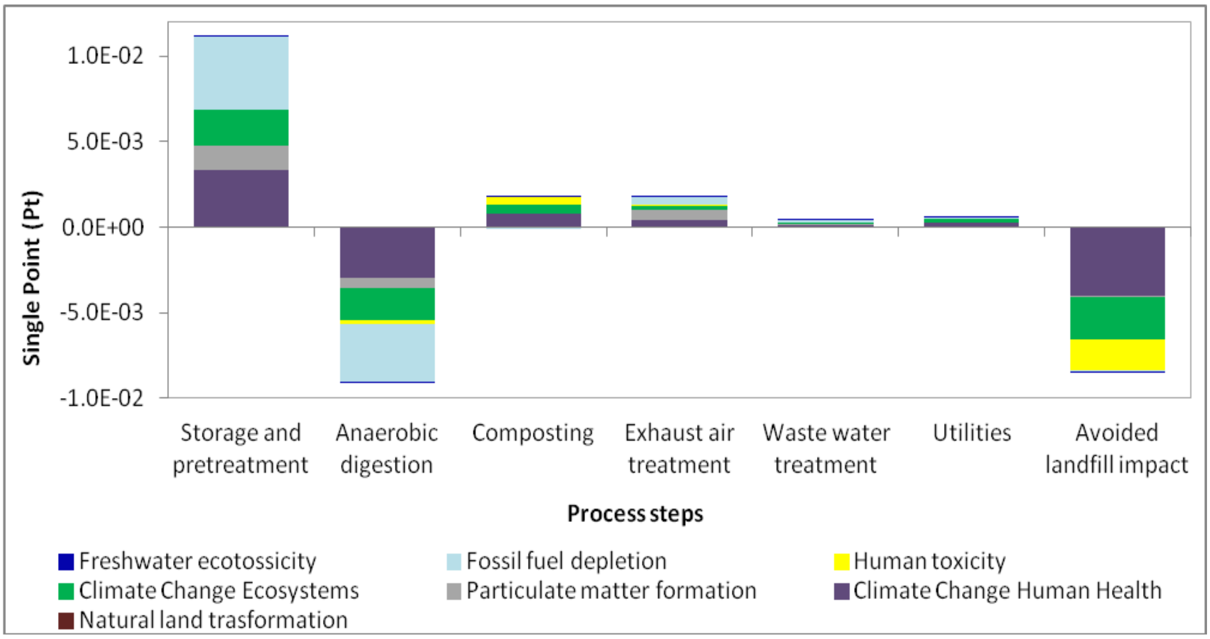

Figure 3.22. Single Point impact of the different phases of the process for year 7, midpoint categories.

Finally, to assess which of the processes present within the model contribute most to the total impact, an analysis of contribution for the two extreme scenarios, year 1 (Fig. 3.23) and year 7 (Fig. 3.24), has been performed.

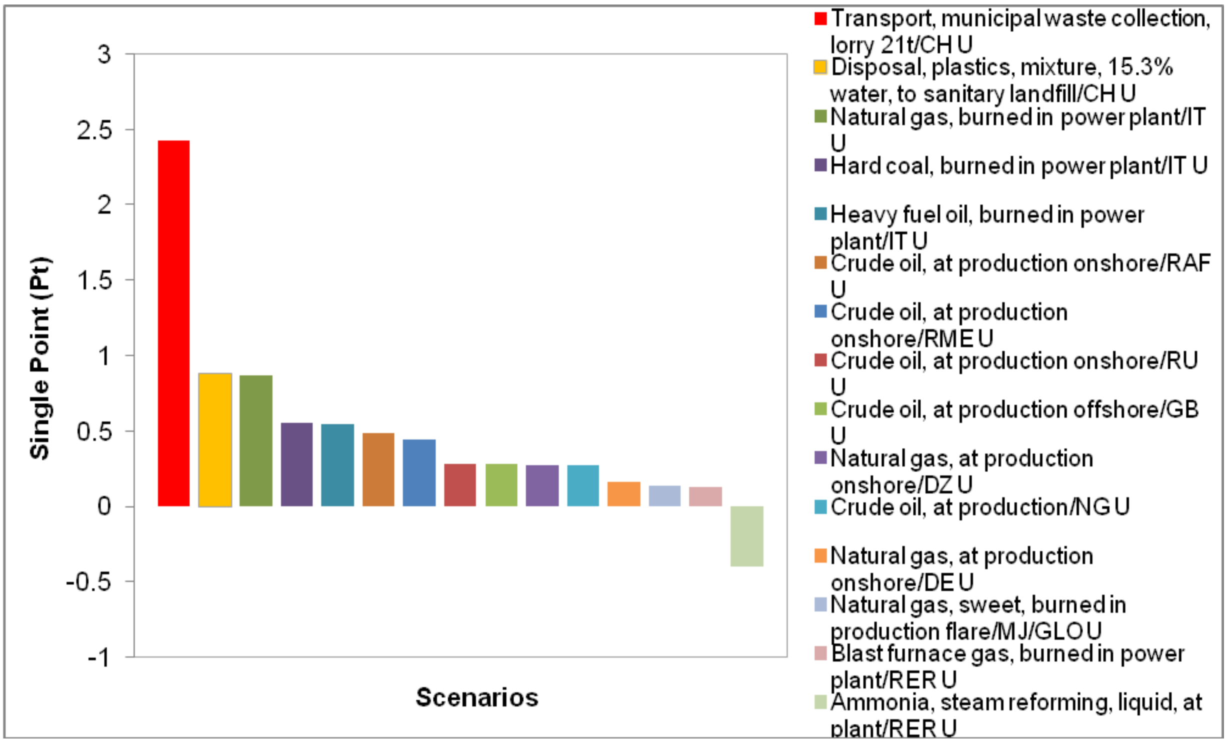

Figure 3.23. Contribution analysis of year 1.

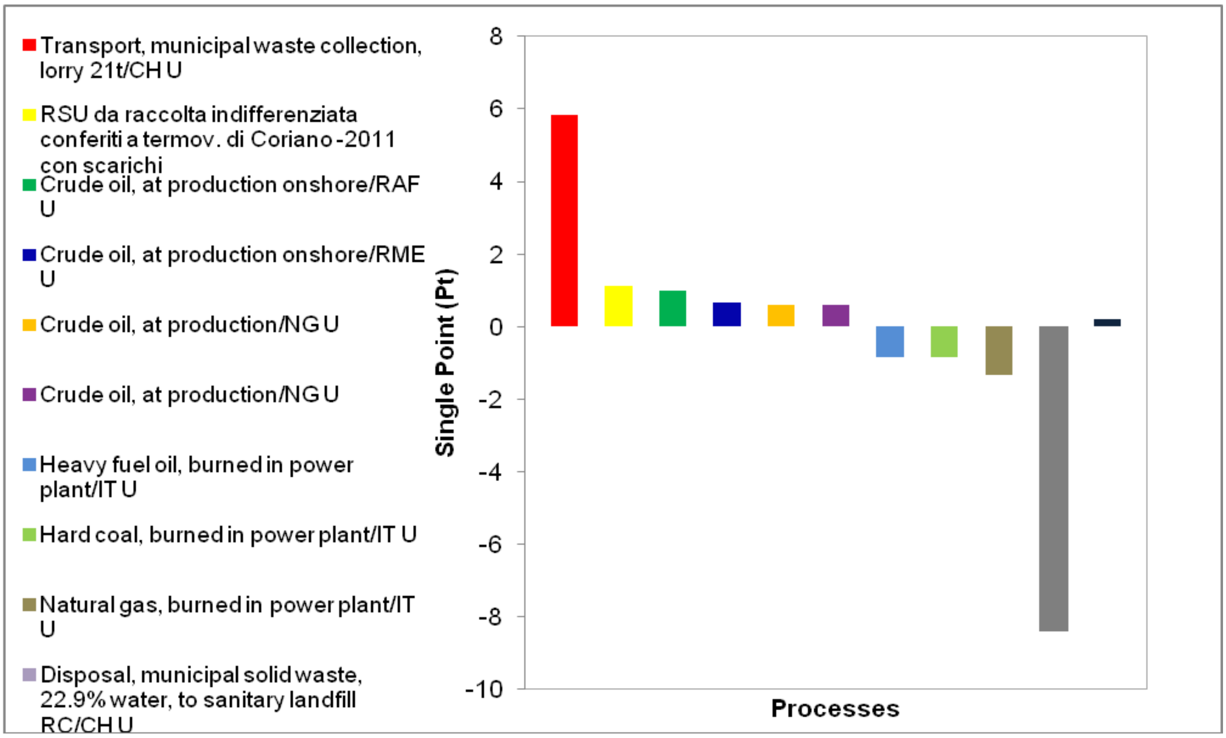

Figure 3.24. Contribution analysis of year 7.

A noticeable change of impacts can be observed between year 3 and year 4, when the installation of eleven anaerobic fermenters was implemented. The traditional composting process is an energy-intensive process, as it requires energy for the operation of oxygen supply. The only avoided impact is due to the production of mixed composted fertilizer, which may replace some conventional fertilizers, such as urea.

From year 4, thanks to the implementation of the integrated process of anaerobic fermentation and composting, it was possible to obtain a positive energy balance, since the electricity generated from biogas is greater than the total consumptions. In addition, the energy produced and sold to the national grid prevents the production of the same amount from conventional sources. This saving results in an avoided impact in terms of climate change, consumption of fossil fuels and transformation of natural territory. The impacts related to the formation of particulate matter and human toxicity are present in all scenarios and are attributable to the process of waste transportation and disposal of not compostable residues (Table 3.9).

Years	CER 19 05 01 disposed (t)	% disposed at WTE plant	% disposed at landfill
1	1555	0	100
2	1420	0	100
3	1192	0	100
4	1510	18	82
5	4812	28	72
6	6713	79	21
7	7075	16	84

Table 3.9. Quantity of non-compostable material produced (CER 19 05 01) and type of final disposal.

In Fig. 3.20, slight variations during the last years are due to different percentages of non-compostable material sent to incinerator (from year 4) or landfill, depending on the availability of these facilities.

Considering waste transportation (Fig. 3.16), the main impact categories appear to be the formation of particulate material and fuel consumption, attributable to the greater distances for the transport of bio-waste from the place of collection to recovery.

By comparing the results obtained in the years 6-7, there is a noticeable difference attributable particularly to the greatest amount of waste from other regions (20% in year 6 and 29% in year 7). However, there is a global avoided impact in terms of climate change (with effects both on human health and ecosystem), human toxicity and water ecotoxicity (related to landfill leachate).

In the year 1 scenario (Fig. 3.21) the storage and pre-treatment phase is that with the higher impacts, followed by biofiltration and composting. This is mainly due to the fossil fuel consumption for transportation of the bio-waste and the consumption of electricity for the aspiration of exhausted air conveyed to the bio-filter to be purified.

The impact associated to human toxicity is greater for the phase of composting because, at the end of this phase, a fraction of not compostable material is sent to other disposal facilities, such as landfill or incinerator. At the same time, it is possible to note an avoided impact for the transformation of the natural land, due to the use of the mixed composted product in replacing of the conventional fertilizers.

For the scenario year 7 (Fig. 3.22), the most impacting step is that of storage and pre-treatment of bio-waste in terms of climate change and fossil fuel consumption, associated to the transport of bio-waste. The anaerobic fermentation with the production of renewable electric energy and waste treated from outside the Region (in which otherwise it would have been disposed of in landfill) help reducing the impacts of the global process.

As for the contribution analysis (Figs. 3.23-3.24), for both scenarios, although with different individual scores, the process that contributes most to the impact of the plant is the transport of bio-waste from the place of collection to the treatment plant. The subsequent processes differ considerably for the two configurations.

Fig. 3.16 shows the impacts variation increasing the transport distance of 1ton of bio-waste. From Table 3.7 it is possible to note significant impacts in the years 4 and 7, where transport distances are respectively 79 tkm/t and 109 tkm/t. The different sources of bio-waste can vary from year to year, based on logistic and economic factors, independently from the management of the system. In addition to different distances, there may be differences in the quantities of waste from outside the Region, until the full capacity of the plant is reached.

3.2.6 Uncertainty analysis

In order to verify the robustness of our model a sensitivity analysis was performed. Quality pedigree matrix [21] was adopted to evaluate the uncertainty values. According to previous studies [22-23], Monte Carlo analysis was selected as statistical method. This method makes use of an algorithm able to producing a series of random numbers for which it assumes a lognormal distribution, with a confidence interval of 95%. For the purposes of the study, year 1 and year 7 scenarios were selected, being representative of the two different plant configurations (traditional composting vs integrated anaerobic-aerobic system). The comparison between them was repeated for a high number of iterations (around 10000).

A bar charts visualization was used to show the percentage of times the scenario A (red for year 1) has a greater impact than B (blue, year 7) and vice versa.

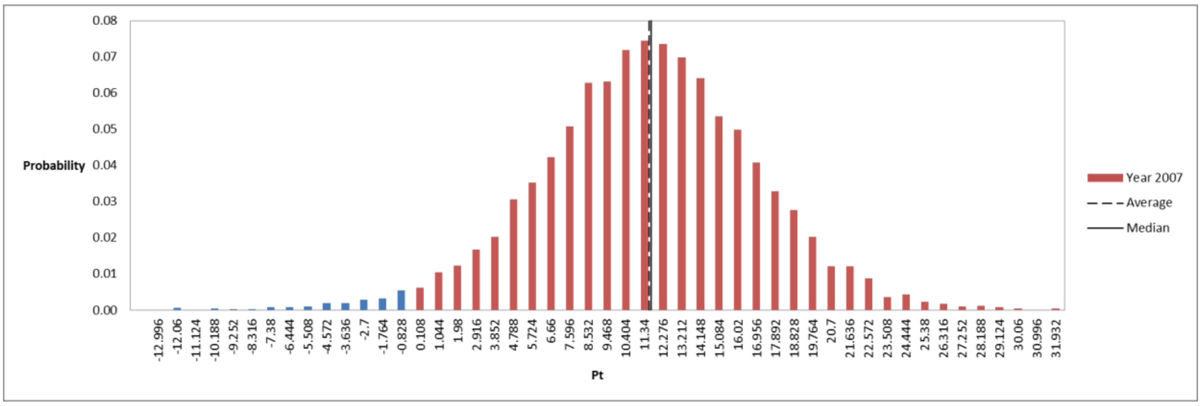

Figure 3.25. Monte Carlo Analysis: process year 1 (A) vs process year 7 (B), single point.

The results of the analysis are depicted using the Gaussian curve (Fig. 3.25), which shows the probability in which scenario A has a greater impact than B. The maximum of probability is obtained for the single score of 11.5, corresponding to the statistical average. This value equals the difference of the total impact in terms of single score between the scenarios related to year 1 and year 7. In addition, Figure 3.26 reports the comparison in terms of single score of the total impact, showing that, for the 97.7% of iterations, the scenario year 1 is the configuration with a higher impact, mostly due to its energy requirements.

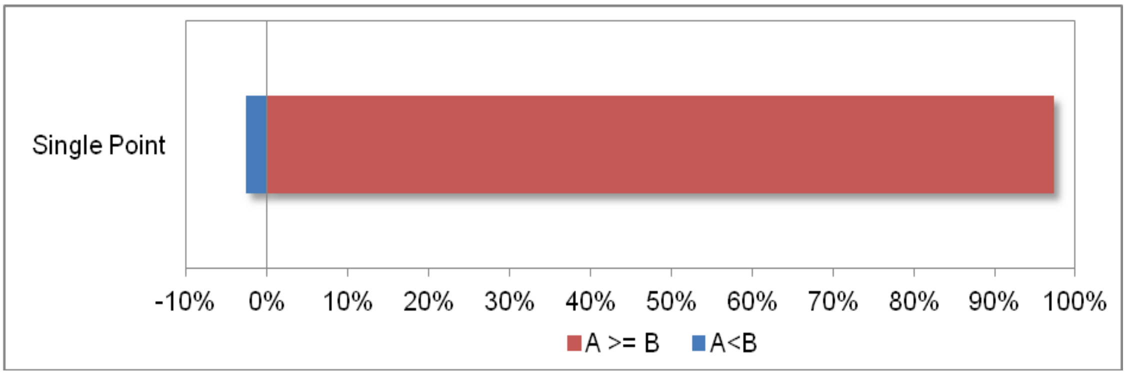

Figure 3.26. Monte Carlo Analysis: process year 1 (A) vs process year 7 (B), single point.

The same analysis can be carried out at midpoint (Fig. 3.27) and endpoint (Fig. 3.28) levels.

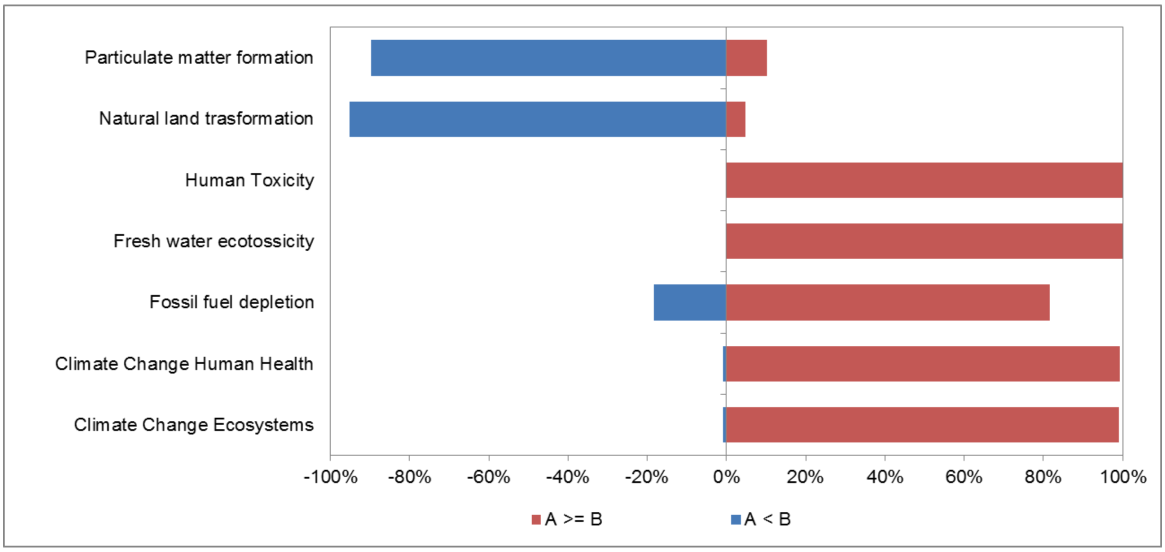

Figure 3.27. Monte Carlo Analysis: process year 1 (A) vs process year 7 (B), midpoint categories.

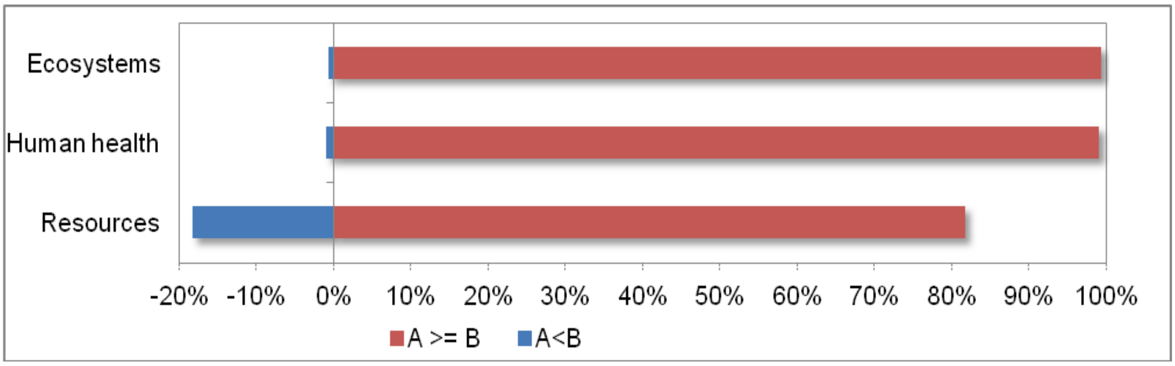

Figure 3.28. Monte Carlo Analysis: process year 1 (A) vs process year 7 (B), characterization endpoint.

The former shows that scenario A is worse than B for most of the midpoint categories. Only considering *particulate matter formation* and *natural land transformation* the scenario related to year 7 seems less convenient. This trend is mainly due to the greater distance of transportation and to the abundance of over screening material (EWC 190501) disposed of in landfill or sent to the incinerator. Results at the endpoint level (Fig. 3.28) confirm the scores achieved previously: scenario A is always the most unfavorable for all three categories of damages.

3.2.7 Personal conclusions and recommendation

Considering the European targets that tend to reduce the use of fossil fuel and the greenhouse gases emissions, the interest in the production of energy from renewable resources and in particular from bio-waste is growing.

In this study, LCA methodology was applied to evaluate how the impact of a treatment plant for the biodegradable fraction of MSW changed over time after the conversion of a traditional composting process to an integrated anaerobic-aerobic system.

LCA results show a considerable decrease of the environmental impacts over the years, thanks to the recovery of energy through the biogas production during anaerobic fermentation, which made it possible to avoid impacts from conventional sources (considering Italian energy mix). This results particularly in an impact decrease for the categories “fossil fuels depletion”, “climate change - human health”, “climate change – ecosystems”.

Categories “human toxicity” and “particulate matter formation” are related to the transport of waste and disposal process of non-compostable material (EWC 190501), a residue composed mainly of plastics and inert, which can be disposed of in landfills or in an incineration plant, according to the availability of disposal facilities or other economic considerations. The process of transport of bio-waste plays a key role in the impact assessment, especially in the years after the improvement. The greater capacity of the plant, in fact, allowed the treatment of further waste, coming from other Italian Regions.

Therefore, system boundaries were extended to the transport of bio-waste and to the avoided disposal of this waste in landfills (which is its present fate), due to the lack of recovery plants in the other Regions. This scenario shows a greater impact for the categories of “particulate matter formation” and “fossil fuels depletion”, due to the long distance of transport; but there is also a greater avoided impact for category “Human toxicity”, thanks to the avoided impacts for landfilling.

Monte Carlo analysis, applied to the comparison between year 1 and year 7 scenarios, confirmed the results obtained from the assessment of the damage, i.e. in 97.7% of the runs the traditional composting plant is most impacting than the new plant, equipped with an integrated anaerobic-aerobic system. The scenarios created represent a good simulation of real processes, since mainly site-specific primary data were used. It is expected that future changes in the composition of the incoming waste, resulting from an increase in separate collection of waste, could affect positively the results in the damage categories. A better quality of bio-waste, in fact, implies a reduction in the flow of compostable material to other disposal plants and therefore a reduction of the environmental impacts. The presence of adequate recovery plants near the areas of waste generation, moreover, would significantly reduce transport distances with less fuel consumption and emission reductions resulting from this operation.

In conclusion, the life cycle assessment of this plant, during recent years, allows the identification of the most critical aspects in the production phase, underlining processes with the highest impact, which could suggest possible improvements in terms of environmental benefits, company image and economic revenues.

3.3 The case study of the integration of different methodologies for the assessment of waste management systems environmental impact.

This work, which is ongoing, is a collaboration between the University of Bologna and the Institute of Environmental Science and Technology (ICTA) of the Autonomous University of Barcelona (UAB) and ARPA Marche.

The Life Cycle Assessment methodology could be applied not only to processes but also to a whole system of management of a service.

The goal of the study is to apply a specific approach to assess the impact caused by human activities both at local level and on a global scale, considering the whole cycle of processes or systems relating to the management of waste, through the integrated application of the Material Flow Analysis (MFA), the Life Cycle Assessment (LCA) methodologies and the CO_2ZW® tool [25]. These three instruments have been combined and adapted in order to better assess the carbon footprint resulting from the operation of waste management in a Region in Italy.

This work deals with the assessment of the carbon footprint resulting from the management of municipal waste in the Macerata Province, which is composed of 57 Municipalities with a total of about 322000 inhabitants, in the Marche Region, in Italy, using the inventory data provided by the regional section of the cadaster of ARPA Marche [26-27].

Main sources of primary data were derived from:

- O.R.So. (Waste Supra regional Observatory), for mixed waste and for those belonging to the separate collection too;
- Public inventory of waste based at ARPAM Pesaro;
- Unique Model of Environmental Declaration (MUD), that contains data on waste generation, mandatory from the enter into force of Law no. 70 of January 25, 1994 [28].

Macerata Province, in the middle of Italy, has been chosen also because it offers a good example of management of different types of waste collected, thanks to the presence of 11 “eco areas” and different waste management systems for the same fractions. COSMARI (Obligatory Consortium for waste disposal) is the first consortium active in the Marche Region in the context of planning and improvement, born after the Legislative Decree no. 22 of February 5, 1997 (Ronchi Decree) [29].

In each Municipality different parameters have been identified:

- waste collection type (doorstep collection, ecological areas – community depot, road bins);
- quality and type of waste collected (taking into account the numbers of inhabitants in each municipality).

Type of waste collected:

- paper and cardboard;
- organic and green waste;
- glass;
- metals;
- plastic;
- multi materials;
- mixed waste.

Therefore waste streams arising from the collection of individual Municipalities within the Province, were analyzed according to the Material Flow Analysis (MFA) method, considering the type of collection, the type of waste collected and the final fate and/or the recovery of the waste considering transport distances and types of treatment.

Material Flow Analysis (MFA) is an analytical method that quantifies the flows and the storage of materials or substances in a defined system.

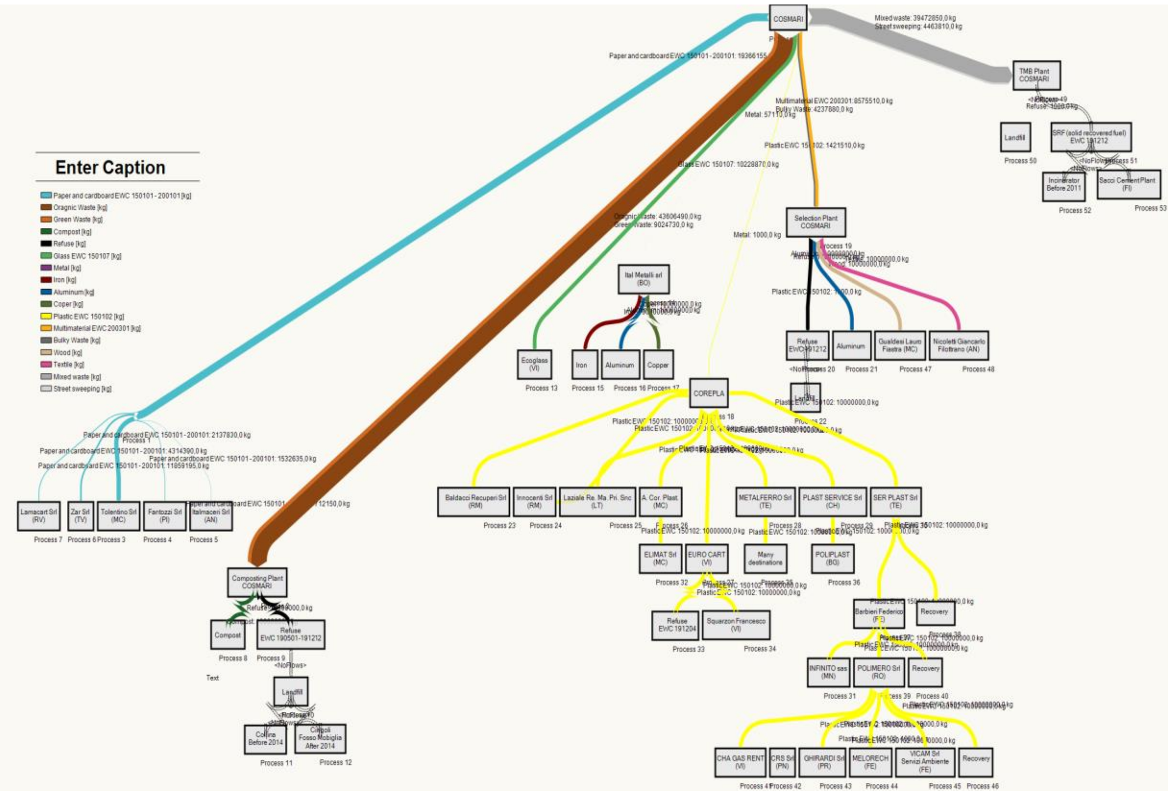

Figure 3.29. Fate of the different waste fraction collected by COSMARI

Secondly, the CO_2ZW® tool was used to calculate the carbon footprint of waste management in the studied area. This tool takes into account the number of inhabitants, the amount of waste treated and the type of treatment. Primary data have been integrated with national reports on municipal waste management drawn up by ISPRA (Institute for Environmental Protection and Research) [30].

3.3.1 Green metrics

The growing awareness of the importance of environmental protection increased the interest in the development of methods of analysis of the evaluation of the burdens on environment and human health [31]. In this context, the environmental problems are no longer perceived as relevant solely to the production site, but they affect the entire life cycle.

However, the sustainability of a process or system can be assessed by different routes that can allow the analysis of different parameters.

Among these, it is possible the use of indicators of environmental sustainability, but the greater problem of these indicators is that they consider just some aspects of a system (usually without considering the consumption of water or energy). These limitations affect their use, making them anyway useful for screening analysis but not for more detailed investigations, for which it is necessary to apply a standardized and internationally accepted methodology as the Life Cycle Assessment.

3.3.1.1 CO_2ZW®

CO_2ZW® tool could be inserted in the context of Green metrics instruments.

CO_2ZW® provides the means to calculate greenhouse gases (GHG) emissions, expressed as carbon equivalent, emitted by the waste management operations in Europe’s Municipalities.

The tool is a calculator based on Excel®, with specific data on waste from Municipalities (or by using default national data) and delivers a carbon footprint index resulting from the treatment of waste management in Municipalities.

The tool is useful to support the monitoring of GHG and to provide an estimation for potential reductions (or increases) of GHG associated with the management and changes in the technology of the local waste management operations.

Many data are required by this instrument:

- total quantity of waste generated in the area under investigation;
- composition of municipal solid waste (MSW) generated;
- fractions of separate collection of glass, plastic, metal, paper and cardboard collected separately and processed in specific plants;
- percentage of impurities generally found in the separate collection of organic waste;
- amount biogas collected from landfills;
- greenhouse gas emission factors for the local energy mix;

In addition, local data are needed to:

- treatment of mixed waste;
- treatment of the organic fraction of the separate collection;
- characteristic of waste treatment plants: recycling efficiency for paper and cardboard, glass, plastic and metals; of composting plants; of the mechanical-biological treatment plants (MBT); fate of the residues resulting from MBT.

Some typologies of preliminary results are shown in Figure 30-31-32.

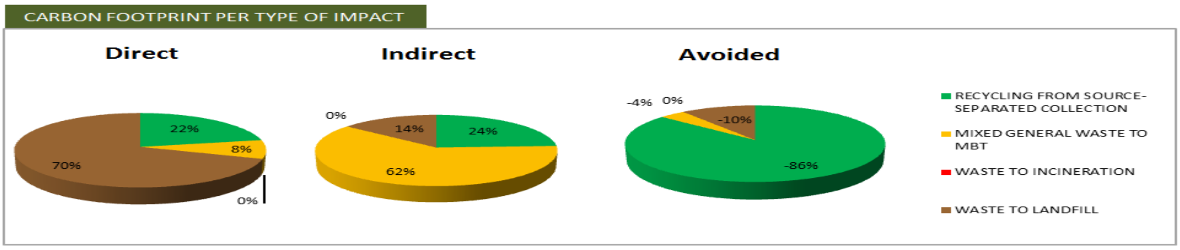

Figure 3.30. Carbon footprint for type of impact.

In Figure 3.30 the results are shown in terms of carbon footprint direct, due mainly to the disposal into landfill, indirect, due to the operations of management of general waste in through a mechanical-biological treatment, and avoided thanks to the recovery of material through recycling.

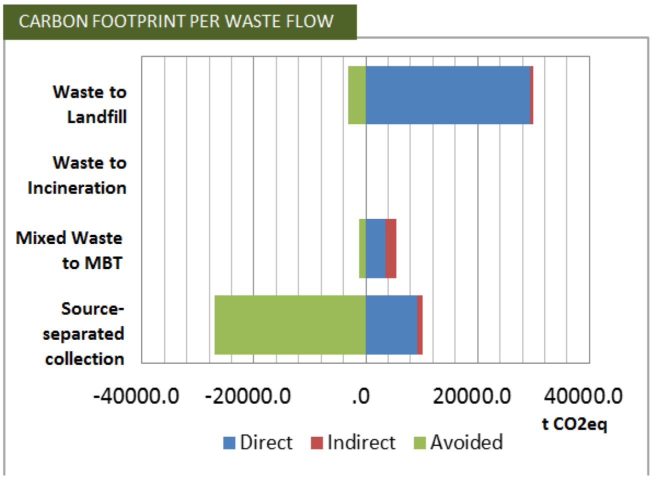

Figure 3.31. Carbon footprint per waste flows.

Instead, Figure 3.31 shows the carbon footprint of the different waste treatments: higher direct impact are due to the disposal of waste in landfill and the principal environmental gain is obtained from the source-separate collection.

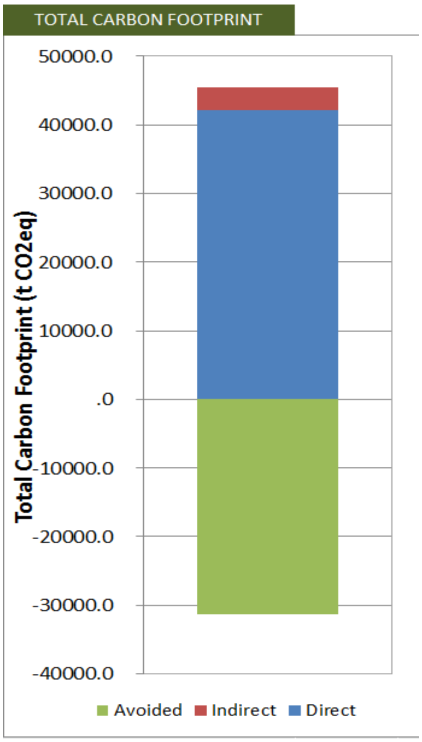

Figure 3.32. Total carbon footprint.

Finally, in Figure 3.32 is shown the total carbon footprint obtained from the sum of all the contributions direct, indirect and avoided for all the typology of waste and treatments taking into account.

3.3.2 Future developments

The next steps of the study will be:

- to continue the evaluation through the Material Flow Analysis (MFA) methodology of different material flows involved in waste management in the Macerata Province;

- to assess, through the CO_2ZW® tool, the greenhouse gas emissions (expressed as equivalent CO_2), GHGs, emitted by the waste management operation in Italy in the same year (2014) and the comparison between the emissions in Italy and those in the Macerata Province;

- in addition, in order to estimate the avoided impact due to the processes of recycling of paper in Italy, to use an attributional LCA (that tries to establish the environmental burdens in a certain period of time, usually present/past) to assess the environmental impact related to the paper and cardboard recycling process in Italy and of the consequential LCA (that seeks to identify the environmental consequence of a decision taking into account the market and the economic implication of a decision) to understand the relation between the recycling operation and import and export and the local market.

3.3.4 Conclusions

The preliminary results show the advantage of using local data of the case study and how they can vary based on the use of specific factors for avoided emissions and its relevance at the national level.

Furthermore, the joint use of three assessment tools for environmental impact (MFA, LCA and CO_2ZW®) provides an additional advantage thanks to the simultaneous assessment of flows of matter involved in the system under study and of the impact that the system could generate on the environment in the period of time under consideration and in the future, thanks to the application of the consequential LCA methodology.

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4 Energy recovery processes

4.1 Background

One of the most complex challenges of the twenty-first century is energy. According to O.N.U. estimates, which provide for a population of 9 billion people already in 2050 [1], determined especially by developing countries, it will be necessary to deal with a proportional increase in demand for energy, essential to guarantee the civil and industrial activities. The energy demand depends on an economic growth hardly containable, but the industrially more developed countries should help to promote technologically and culturally more sustainable choices, covering the transport sector, industrial production and housing infrastructure.

According to the International Energy Agency (IEA) [2], Italian final energy consumption reached 117 million tons oil equivalent (Mtoe) in 2014, about 69% of which is still based on fossil resources. However, Italy has limited traditional energy source reserves and this results in a high impact on the trade balance (around 115 Mtoe were imported in 2014 [2]). Moreover, the present energy system is responsible for the emission of a large amounts of greenhouse gases (GHGs) and other pollutants: in 2014 CO_2 emissions from fossil fuels combustion only were estimated around 320 Mt [2]. This means that Italian energy system has to be deeply rethought, to take steps towards both a higher independence and environmental sustainability, promoting lower energy consumption, increasing efficiency, developing renewable and clean sources.

The “Climate-Energy Package” [3], launched by the European Union, plans to reach by 2020 some objectives to meet the increasingly stringent issues related to climate change and to the consumption of fossil energy resources:

- Reducing greenhouse gas emissions by 20%;
- Raising to 20% the share of energy from renewable sources;
- Reaching the share of 20% of energy savings.

These goals require to find new solutions to the growing demand of energy, which could be compatible with the reduction of carbon dioxide (CO_2) and other greenhouse gases emissions.

Nevertheless, the energy transition is a complex task: according also to the scenarios described by the Energy Roadmap 2050 [4], it will take 40–50 years to reduce the greenhouse gases emissions by 80% compared to 1990 and a reduction over 95% is expected for the electricity sector by 2050. However, in the last years, an increased percentage of renewables in the Italian energy mix is helping to switch from a centralized to a more distributed energy system, facilitating the transition. In fact, renewable energy sources are naturally spread throughout the entire territory, but this wide distribution requires strict regulations to promote a rational exploitation and to meet shared targets.

Italy adopted the European regulatory framework on renewables implementing European Union (EU) Directive 2009/28 [3], which commits the Country to produce 17% of its primary energy from renewables by 2020, including a 10% target for biofuels. The renewable energy share of the European gross final energy consumption was 15.9% in 2014, compared to 15% in 2013, while the target towards 2020 is 20% [5]. Italian Action Plan indicates the way to meet these goals. An exchange mechanism among the Member States is permitted in the calculation of national energy budget (checked every two years). In addition, a burden sharing mechanism is defined: it implies an apportionment of the mandatory quotas among local authorities, which would allow the States to achieve their renewable targets by 2020. In the case of Italy, this distribution is carried out among the Regions, which should arrange a further partition among their Municipalities. Therefore, it looks evident that each Municipality has to develop its own energy strategy, based on a regional plan. In Emilia-Romagna (ER), one of the twenty Italian Regions, the strategy to meet 2020 targets includes the reduction of energy consumption and GHGs emissions by 14.7% and 20% respectively (compared to 2005). Furthermore, an implementation of renewables up to the 8.9% of the 2005 gross final consumption is required. In addition, Municipal Action Plans for Sustainable Energy highlight how the local production, through the implementation of small and medium cogeneration plants, represents the right choice to improve urban energy system [6]. The ER region identified the following mix of renewables to meet 2020 targets: photovoltaic, solar thermal, wood biomass and biogas. Among these, biomass represents an interesting and affordable solution, considering that solid biomass provides the largest contribution to renewable thermal energy both in Europe and in Italy (Figure 4.1).

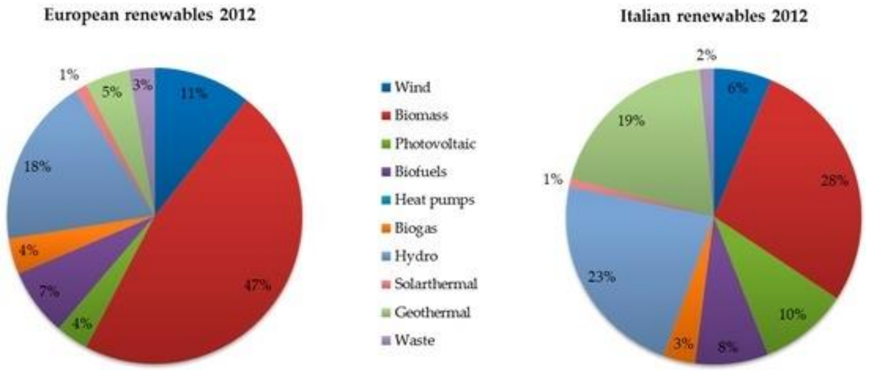


Figure 4.1. European and Italian renewables in 2012 [5].

In addition to renewable sources of solar energy (thermal and photovoltaic), geothermal, wind, hydro, are taking more consideration the use of biomass. Actually, biomass have always represented for humanity an extremely versatile and renewable resource. The ease of finding and usage has placed them first in many applications (cooking, heating, steam generating, etc.), although with the advent of fossil fuels, have been gradually replaced. But while fossil fuel is a finite, polluting and uncertain available source, as not uniformly distributed on earth, wood biomass represent an abundant food source for energy recovery systems that contribute to home heating and electricity production.

In general, biomass is considered a renewable source of energy if two main conditions are satisfied: (i) the biomass regeneration cycle must be respected and (ii) no alterations of natural areas are made to promote the cultivation. Moreover, the use of biomasses differs from other renewable sources since its sustainability is strictly influenced by an advantageous cost/benefit ratio, which can be achieved if the exploitation is performed at a short distance from its end use. Together with these limitations, further problems are related to the use of biomass in cogeneration systems, such as:

- low social acceptability, as well as for combustion processes in general;
- difficult employment of excess thermal energy during warm seasons;
- increase of particulate emissions.

Viable solutions to overcome these problems may include:

- a development of local supply chains for the pruning management of public/private green areas;
- an implementation of small district heating systems;
- a production of pellets or wood chips to feed small domestic boilers.

It may be important to increase the exploitation of this source of energy, reducing the fossil fuels consumption, that are not renewable. Moreover it should be noted as early as

2005 the European Commission considered the importance of using biomass through the enactment of the “Biomass Action Plan” [7]. This program expects an increase in the use these resources from 289000TJ produced in 2003 to 628000TJ in 2010, with lower costs and energy dependencies.

Moreover, biomasses are able to fix carbon, in the form of CO_2 absorbed and converted, by using solar energy, into organic matter at higher energy. They represent a carbon stock that once combusted releases a quantity of CO_2 into the atmosphere equal to that absorbed during its growth. This means that the use of biofuels for energy purpose does not contribute to increase the natural greenhouse effect (if not during transport and pre-treatment), since combustion closes the carbon cycle putting it back into the atmosphere; it remains to consider how this source of energy is more sustainable than the others, given that the CO_2 emission is not the only environmental impact to be verified, although lately have assumed a higher priority.

4.2 The case study of Biomass Residues to Renewable Energy applied at Local Scale

The work resulted in a publication on the journal energies edited by MDPI [8].

4.2.1 Background and motivation

In the context of the energy recovery processes, an interesting example of a “smart” valorization of the residues for biomass to energy purposes is represented by Castello D’Argile, a small Municipality in the province of Bologna (Central-Northern Italy). The main goal is to integrate the current domestic heating system by using centralized wood boilers, fed with biomass residues resulting from local pruning practices. This action, together with the reduction of consumptions and the implementation of green energy procurement for industries, will contribute to reach the territorial targets by 2020 (and those related to the period 2030–2050).

Therefore, the purpose of the present study is to assess the impacts to the environment and human health associated with the energy production using wood chips from pruning residues and to compare it with a traditional and widespread decentralized system of gas boilers. Life Cycle Assessment (LCA) methodology was adopted as a predictive tool to estimate potential environmental burdens. The application of LCA in this field is reported also in previous studies, which investigated renewable energy production from biomass. Cespi et al. [9] assessed an Italian case study, comparing the impacts of logs and pellets stoves. Wolf et al. [10] focused the attention on the Bavarian situation, stressing that it is necessary to focus on regional aspects when assessing the environmental impacts of heat provision. The use of different logging residues to produce bioenergy was also investigated by Hammar et al. [11], taking into account Swedish conditions. Another work outlines the importance of an integrative resources management aimed to close the loop of the production systems, to implement a suitable strategy in line with the regulatory framework [12]. Moreover, Thornely et al. [13] emphasized that medium scale district heating boilers, fed by wood chips, lead to the highest GHGs reduction per unit of harvested biomass.

The recovery of inert green residues and street furniture in the investigated Municipality is carried out by a cooperative Society, named “Città Verde” (“Green City”). Around 4000 t of wood residues are collected each year, and recovered by the cooperative, according to the Italian Legislative Decree 152/2006 [14].

This company collects also wood-based packaging and materials, which, together with the previous residues, are chipped and stored in a plant of the cooperative. The two final destinations of wood residues presently considered are: (i) a biomass combustion plant (located about 70 km away from the place of collection) or (ii) a composting plant (about 14 km away). For comparison purposes, only this second destination has been taken into account. On the other hand, alternative purpose is to use these residues as fuel to meet the energy needs of some public buildings located in Castello d’Argile, currently fueled by natural gas (NG): a nursery, a junior high school and a gym, with a total installed power of 660 kW (60, 350 and 250 kW, respectively).

4.2.2 System boundaries and functional unit

In this framework, LCA was applied to verify the overall impacts of a wood-based centralized appliance and to identify potential benefits if compared with traditional gas boilers. For this purpose, the production of 1 MWh of thermal energy was selected as functional unit in order to complete the models which simulate the cradle-to-gate boundaries: from the raw materials extraction up to the thermal valorization of residues. System boundaries for the traditional and alternative scenarios are depicted in Figures 4.2 A,B.

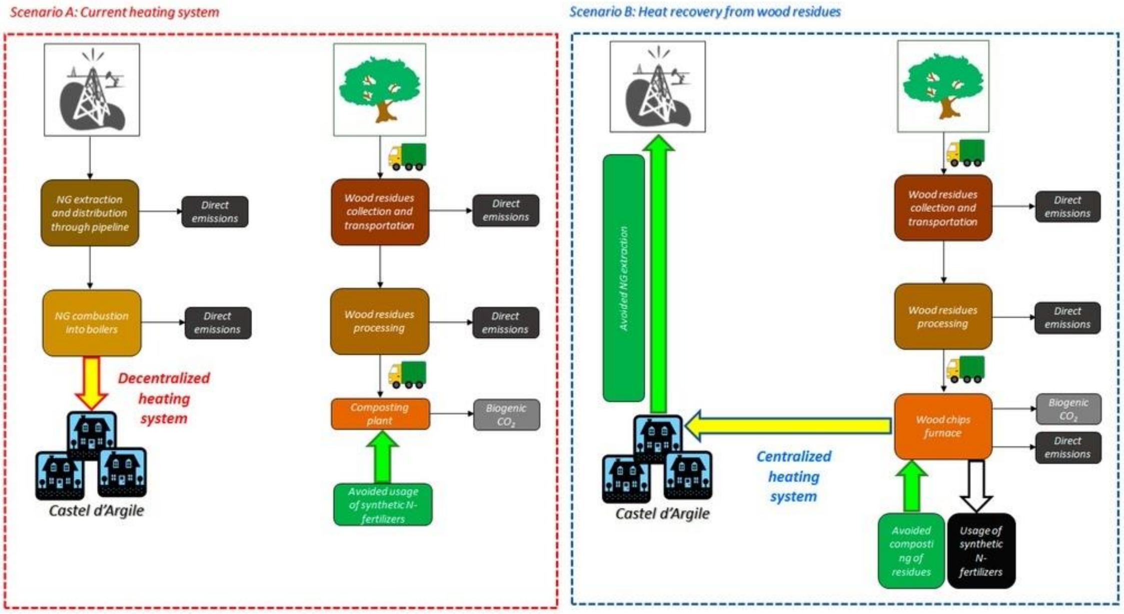


Figure 4.2. System boundaries LCA for (**A**) the current heating system and (**B**) the alternative bio-based system.

4.2.3 LCI of Current Heating System

The current situation is depicted in Figure 4.2A, which describes all the stages involved. Among these are:

- Timber collection, transportation and processing. These stages are common to both scenarios and describe all the treatment procedures necessary to collect wood and reduce their volume.
- The extraction of all the resources (renewables and fossil fuel) to feed the entire supply chain, among which: fuels, electricity, other auxiliaries, infrastructure, etc.

Natural gas (NG) is the fuel used in decentralized appliances to cover the thermal requirements of three public buildings (e.g., nursery, junior high school and gym), presently equipped by individual heating systems. Primary data concerning the decentralized system are not available. Therefore, in order to simulate the production of 1 MWh of thermal energy by NG, which corresponds to around 95 m^3 of NG burned in dedicated appliances, secondary data from the Ecoinvent database have been used to create the model. The default process *Heat, NG, at industrial furnace >100 kW* [15] was selected as a good approximation of the actual situation, for two main reasons: (1) it was developed using average European data (including Italy); (2) methane represents the most widespread fuel in Italian heating appliances [9]. This default process simulates the European production of thermal energy through NG burned in an average >100 kW industrial module. The process includes the upstream stages involved in the fuel extraction and transportation through high pressure pipelines, and all input and output flows to simulate the boiler construction (usually called infrastructure requirements) and the electricity needed for the operation. In this case, being unavailable data concerning the local energy mix used in the Municipality, Italian mix was assumed as a suitable approximation in order to simulate the electricity production. The Ecoinvent database provides also a full list of substances emitted during the NG burning procedure within the appliance. In addition to the emissions from combustion, system boundaries include all the direct and embodied environmental releases for each stage considered. Direct emissions concern all the substances released during the wood processing (e.g., NO_x and Particulate Matter (PM), see Table 1) and transportation. On the other hand, the term *embodied* refers to all the other chemicals emitted during the other stages which characterize the whole cradle-to-gate chain, such as: infrastructures construction (e.g., boiler and truck), electricity and fuel production, resources extraction, etc.

LCI Stage	Process	Unit	Amount
Input Wood Chips Chain	Transportation 2.5 t lorry	tkm	9537.9
	Electricity—chipper	kWh	10.6
	Electricity—bucket	kWh	4.5
	Electricity—shredder	kWh	2.1
Input NG Chain	NG	MWh	1.1
	Electricity, at grid/UCTE U	kWh	3.1×10^{-7}
	Industrial furnace NG	p	7.9×10^{-13}
Output Wood Chips Chain	Particulates—chipper	kg	3.2×10^{-3}
	NO_x—chipper	kg	1.8×10^{-2}
	Particulates—bucket	kg	1.3×10^{-3}
	NO_x—bucket	kg	1.8×10^{-2}
	Particulates—shredder	kg	5.2×10^{-3}
	NO_x—shredder	kg	8.5×10^{-3}
Output NG Combustion	Heat, waste	MJ	3.1×10^{-4}
	Acetaldehyde	kg	2.8×10^{-13}
	Benzo(a)pyrene	kg	2.8×10^{-15}
	Benzene	kg	1.1×10^{-10}
	Butane	kg	2.0×10^{-10}
	Methane, fossil	kg	5.7×10^{-10}
	Carbon monoxide, fossil	kg	6.0×10^{-10}
	Carbon dioxide, fossil	kg	1.6×10^{-5}
	Acetic acid	kg	4.3×10^{-11}
	Formaldehyde	kg	2.8×10^{-11}
	Mercury	kg	8.5×10^{-15}
	Dinitrogen monoxide	kg	2.8×10^{-11}
	Nitrogen oxides	kg	5.1×10^{-9}
	Polycyclic aromatic hydrocarbons	kg	2.8×10^{-12}
	Particulates, <2.5 μm	kg	5.7×10^{-11}
	Pentane	kg	3.4×10^{-10}
	Propane	kg	5.7×10^{-11}
	Propionic acid	kg	5.7×10^{-12}
	Sulfur dioxide	kg	1.6×10^{-10}
	Dioxin	kg	8.5×10^{-21}
	Toluene	kg	5.7×10^{-11}
Input Composting Step	Residues sent to composting plant	kg	294.1
	Compost produced (35% efficiency)	kg	102.9
	Transportation 2.5 t lorry	tkm	2.5

Table 4.1. Life Cycle Inventory (LCI) for the current heating system scenario. NG: natural gas

As depicted by the figure 4.3B and described above, timber residues are now collected and treated at the cooperative plant. Then, they are sent to the nearest composting plant (14 km) in order to obtain fertilizer with 35 wt% efficiency with respect to the input material (wood residues). Distances are assumed to be covered by diesel-based lorry, with an average capacity of 2.5 t. In general, the production of compost leads to the saving of synthetic fertilizers. Therefore, in agreement with literature [15], the model assumes an avoided production of 0.6 kg of *N*-fertilizer per kg of compost produced.

Figure 4.2B represents the alternative scenario in which wood chips residues are used as renewable fuel to cover the heating requirements of public buildings. As in the previous scenario, boundaries include the wood residues collection, transportation and processing, together with all the direct and indirect emissions, considering the whole supply chain.

However, in this case the scenario simulates the thermal recovery of wood residues to produce the described centralized district heating.

4.2.4 LCI of Wood Residues Chain

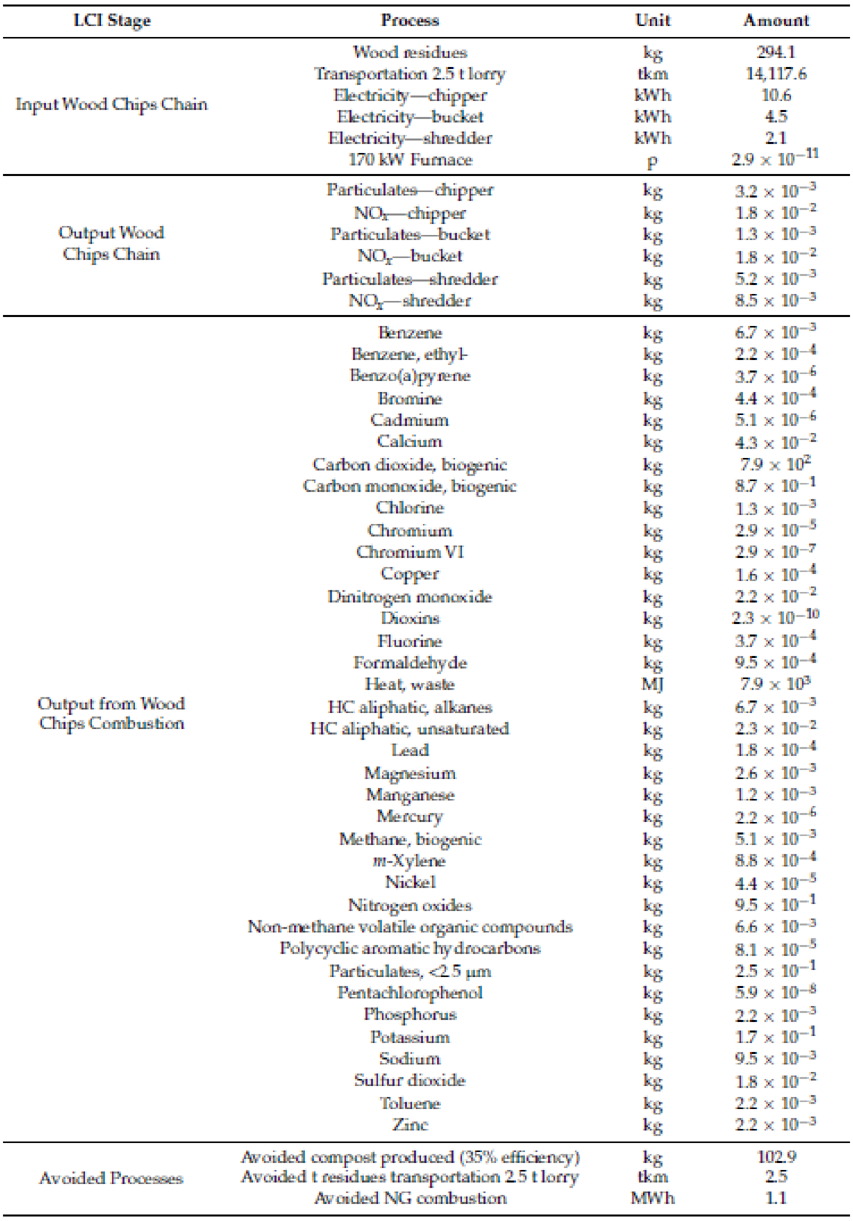
According to the National Inventory of Forests and Forest Carbon Tanks (INFC) [16], the majority of residues collected within the Emilia Romagna region belongs to the hardwood family. Therefore, average value for the Lower Heating Value (LHV) and density (18.12 MJ/kg and 640 kg/m^3 respectively) were estimated based on literature data [17]. In general, the selection of input materials is crucial, since the separation after treatment would require more time and energy. The removal of leaves, wider logs and other residual materials (e.g., plastic and metals) is an example of pre-treatment procedures.

Chips are produced using a wood chipper and a shredder. The model includes all the energy requirements for the machinery used in the chip manufacture and the related emissions in terms of particulates and NO$_x$. The wood chips production phase was modeled using annual data per appliance, reported in Table 4.2.

Italian mix was assumed to cover the electricity needs. According to the Italian Energy Services Operator (GSE) data from 2013 [18], renewables cover only the 30% of the entire production, while fossils fuels are still predominant (59%, of which NG represents 54%).

In addition, a distance of 30 km (round trip) was considered for supplying the wood, assuming an average truck capacity of 2.5 t. This results in around 1600 journeys/year, to cover an overall distance of 4800 km. By the use of the reference process listed in Ecoinvent database (*Transport, lorry 3.5–7.5 t, EURO5/RER U*), a new model to simulate an average 2.5 t lorry capacity was created. In addition, the wood-based scenario includes all the inputs and outputs for the construction of a 170 kW chips furnace (e.g., steel, aluminum, concrete, etc.). Further facilities needed to distribute the heat among the three buildings have not been considered, since primary data were not available; however, according to previous studies, it is known that infrastructure has a very low environmental impact in heating systems [9].

As in the case of methane-based appliance, without primary data available for the emissions, average air releases from wood chips combustion were collected from Ecoinvent library (*Wood chips, from forest, hardwood, burned in furnace/CH U*) [13] and then recalculated on the basis of new values for density, LHV and combustion efficiency (95%). The usage of wood residues as a source of thermal energy implies the avoided extraction of NG to produce 1 MWh. In addition, it prevents the transportation to the composting plant and the subsequent transformation. Therefore, system boundaries include both processes as avoided flows. Detailed inventories for both scenarios are depicted in Table 4.1 and Table 4.2, respectively.



LCI Stage	Process	Unit	Amount
Input Wood Chips Chain	Wood residues	kg	294.1
	Transportation 2.5 t lorry	tkm	14,117.6
	Electricity—chipper	kWh	10.6
	Electricity—bucket	kWh	4.5
	Electricity—shredder	kWh	2.1
	170 kW Furnace	p	2.9×10^{-11}
Output Wood Chips Chain	Particulates—chipper	kg	3.2×10^{-3}
	NO_x—chipper	kg	1.8×10^{-2}
	Particulates—bucket	kg	1.3×10^{-3}
	NO_x—bucket	kg	1.8×10^{-2}
	Particulates—shredder	kg	5.2×10^{-3}
	NO_x—shredder	kg	8.5×10^{-3}
Output from Wood Chips Combustion	Benzene	kg	6.7×10^{-3}
	Benzene, ethyl-	kg	2.2×10^{-4}
	Benzo(a)pyrene	kg	3.7×10^{-6}
	Bromine	kg	4.4×10^{-4}
	Cadmium	kg	5.1×10^{-6}
	Calcium	kg	4.3×10^{-2}
	Carbon dioxide, biogenic	kg	7.9×10^{2}
	Carbon monoxide, biogenic	kg	8.7×10^{-1}
	Chlorine	kg	1.3×10^{-3}
	Chromium	kg	2.9×10^{-5}
	Chromium VI	kg	2.9×10^{-7}
	Copper	kg	1.6×10^{-4}
	Dinitrogen monoxide	kg	2.2×10^{-2}
	Dioxins	kg	2.3×10^{-10}
	Fluorine	kg	3.7×10^{-4}
	Formaldehyde	kg	9.5×10^{-4}
	Heat, waste	MJ	7.9×10^{3}
	HC aliphatic, alkanes	kg	6.7×10^{-3}
	HC aliphatic, unsaturated	kg	2.3×10^{-2}
	Lead	kg	1.8×10^{-4}
	Magnesium	kg	2.6×10^{-3}
	Manganese	kg	1.2×10^{-3}
	Mercury	kg	2.2×10^{-6}
	Methane, biogenic	kg	5.1×10^{-3}
	m-Xylene	kg	8.8×10^{-4}
	Nickel	kg	4.4×10^{-5}
	Nitrogen oxides	kg	9.5×10^{-1}
	Non-methane volatile organic compounds	kg	6.6×10^{-3}
	Polycyclic aromatic hydrocarbons	kg	8.1×10^{-5}
	Particulates, <2.5 µm	kg	2.5×10^{-1}
	Pentachlorophenol	kg	5.9×10^{-8}
	Phosphorus	kg	2.2×10^{-3}
	Potassium	kg	1.7×10^{-1}
	Sodium	kg	9.5×10^{-3}
	Sulfur dioxide	kg	1.8×10^{-2}
	Toluene	kg	2.2×10^{-3}
	Zinc	kg	2.2×10^{-3}
Avoided Processes	Avoided compost produced (35% efficiency)	kg	102.9
	Avoided t residues transportation 2.5 t lorry	tkm	2.5
	Avoided NG combustion	MWh	1.1

Table 4.2. LCI for the wood-residues scenario.

4.2.5 Impact assessment and results interpretation

The Life Cycle Impact Assessment (LCIA) stage was carried out using the ReCiPe analysis method [19], considering four impact categories at a midpoint level, such as: climate change, human toxicity, particulate matter formation (PMF) and fossil fuels depletion. Table 4.3 collects the results for each category selected. Single score results are shown in Figure 4.3.

Impact category	Unit	Current heating system	Heat recovery from wood residues
Climate change	kg CO_2eq.	3980	2398
Human toxicity	kg 1,4-DB eq.	76.9	69.4
Particulate matter formation	kg PM10 eq.	4.3	3.2
Fossil fuels depletion	kg oileq.	1237	752

Table 4.3. Comparison between the current heating system and the wood-based scenario for the production of 1 MWh of thermal energy, at midpoint level. The expression eq. stands for equivalent; and PMF: particulate matter formation.

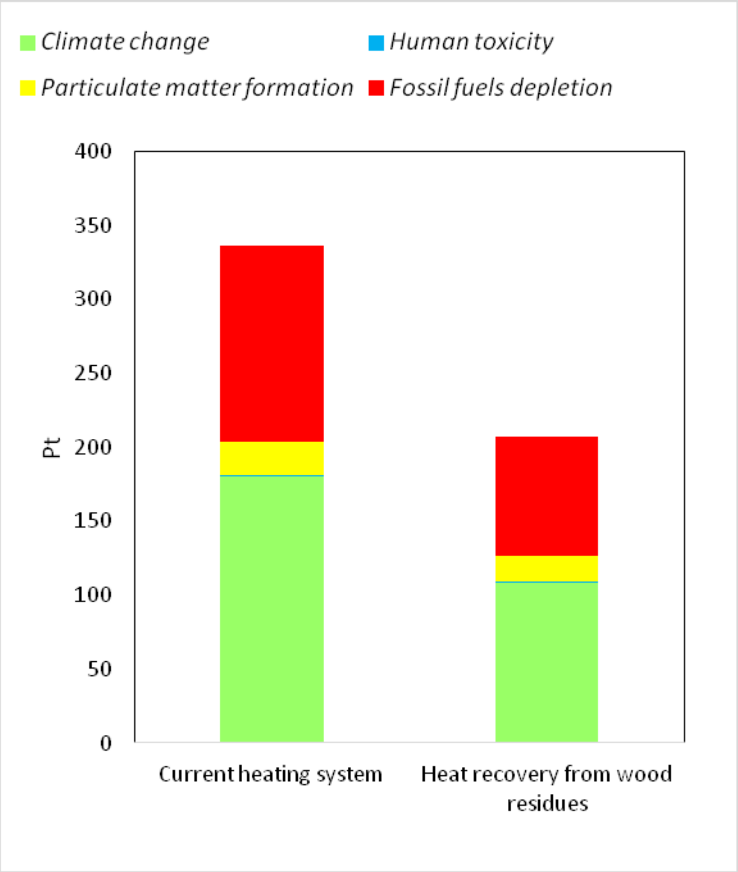


Figure 4.3. Single score assessment: comparison between the current heating system and the wood-based scenario for the production of 1MWh of thermal energy.

As depicted, the use of wood residues leads to considerable benefits in terms of climate change (considering a 100-years perspective) and of fossil fuels depletion, 41% and 40%, respectively. Similar GHGs mitigation trend was already outlined by previous works [10-11], which suggested the importance of using wood-based appliances to reduce climate change effects. Furthermore, Paredes-Sánchez et al. [20] studied the valorization of residues in Asturias and Spain, where the use of biomass offers the opportunity to create a new path to economic development with a reduction of CO_2 emissions. A similar topic has been discussed, regarding the wood residues in British Columbia (Canada) [21]: for small scale community cogenerating plant the use of wood residues generated the cheapest electricity. Wolf et al. [10], studying the energetic use of wood in a German region, outlined that the magnitude of mitigation can vary greatly depending on the current thermal energy mix. Despite the reductions, all the flows involved within the entire biomass chain lead to a non-neutral emission of GHGs. The greatest contribution to GHGs emissions for both scenarios is due to transport, but the difference in GHGs emission is due to the production of NG, which is greater in the traditional scenario. However, it must be reminded that the energy use of biomass requires primary energy both for transportation and fuel production stages, nowadays still covered by fossil resources. Table 4.1 and 4.2 report all the emissions deriving from combustion: substances such as benzene, toluene, PAH, dioxins, mercury and formaldehyde reach significantly higher values than the releases resulting from gas burning. These results could be improved, because they represent average emissions of a wood chip furnace not equipped with innovative pollution abatement technologies [22]. More accurate and primary data concerning the combustion phase are expected in the near future, resulting from dedicated monitoring campaigns. The same revision is desirable for the NG-based scenario, which is modelled considering average data from EU appliances, not primary values. Nevertheless, it is expected that these limitations do not affect significantly the final scores. Interesting results are achieved in terms of PMF, where no significant differences between the scenarios are detected. According to a contribution analysis run for the PMF category, wood chips combustion affects the release of PM only for 15%. This is due to the characteristic of fuel: combustion of chips releases around 0.47 kg PM10 eq. per MWh, lower than the average 0.52 kg PM10 eq. for the wood logs [22]. A detailed inventory analysis was also run to determine which substances contribute most to PM for the whole scenario: primary particulate (e.g., PM > 2.5 and <2.5 μm) affects the category for 32% (mainly fine particulate, 19%); on the other hand 67% is due to secondary particles, which form starting from gases as NOx (59%) and SO_2 (14%). Even if considerations on each category are important, single score is useful to show which scenario is more sustainable if compared globally. As can be seen from Figure 4.3B, the centralized system using wood-based appliances seems more competitive. This trend is depicted by the performance pie chart (Figure 4.4): it shows the overall impacts reduction of the alternative scenario if compared with the traditional decentralized system. The cumulative score is reduced by 38%, with considerable benefits for the community. However, it is interesting to notice that the potential benefits coming from possible future implementations (grey), could prevail.

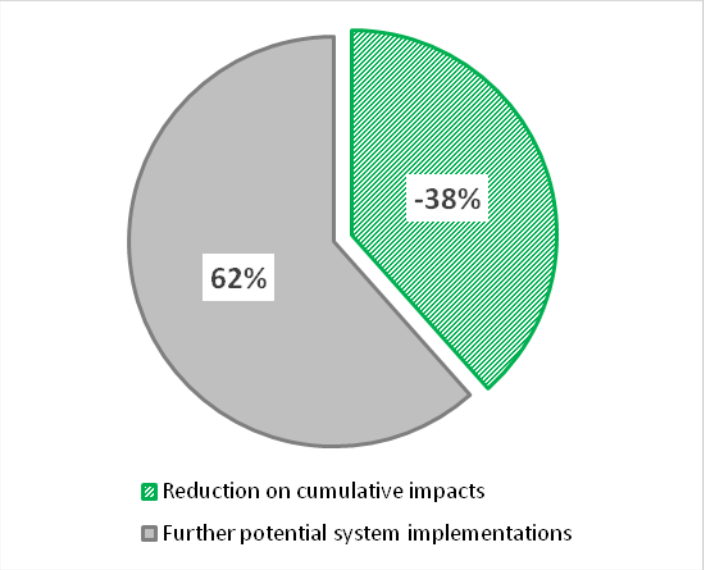


Figure 4.4. Contribution on cumulative score and potentialities of improvement.

A contribution analysis using the SimaPro network tool (Figure 4.5) illustrates where these potentialities are concentrated.

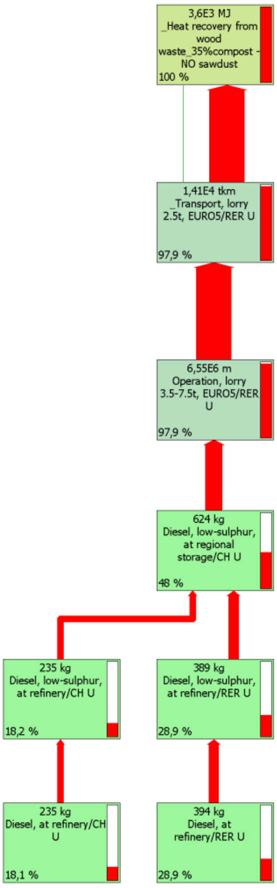


Figure 4.5. Network tool on cumulative score.

The Sankey-based diagram shows that transportation of the biomass residues contributes for 97.9% to the single score. However, the network tool helps to understand the reasons for this high contribution, which is related to the embodied processes in the transportation step. Among these, the diesel chain seems to have the highest contribution, as a consequence of the greater amount of resources and energy requirements for extraction and refinery procedures. According to a personal communication from the working company, an average EURO 5 lorry with 2.5 t capacity is assumed to cover the entire distances and collect all the prunes. In line with the Italian case study, a diesel-fueled truck has been considered in the model. This great usage of fossil-based transportation seems to affect all the impact categories considered. Although the higher contribution (near to 91%) is due to the cumulative effects on climate change and depletion of fossil fuels, it is worth noting the harmful consequences due to the human-related categories: 83% contribution for the release of toxic substances and 84% for the PM. Therefore, a fossil-based transportation still represents a strong limitation for the biomass to energy systems, even if local (e.g., 30 km) prunings are considered. In fact, as reported [23–25] the replacement of diesel with NG in vehicles such as trucks and tractor trailers seems to contribute greatly to CO_2 emission mitigation, reducing the potential impact on climate change. Differently from the CO_2 reduction, which is detected within the whole life cycle of a vehicle (and in particular during its operation procedures), SOx and PM decrease is achieved if the total amount is taken into account [25]. In addition, further reduction is obtained if hybrid trucks are considered: this technology seems to contribute to the climate change mitigation, reducing the operation emissions of around 25% if compared with a traditional diesel truck [26]. Moreover, according to Tong et al. [24], the use of the full electric MHDVs (medium and heavy-duty vehicles) leads to a greater overall GHGs reduction, estimated around 31%–40%. Therefore, given the large contribution of transportation, a sensitivity analysis has been run, showing how the overall impacts may vary if a smaller collection distance is taken into account. In particular, 10 km roundtrip have been assumed. As depicted in Figure 4.6, results are strictly affected by the provision distance: alternative scenario (10 km) achieved around 1/3 of the overall impact evaluated for the 30 km scenario.

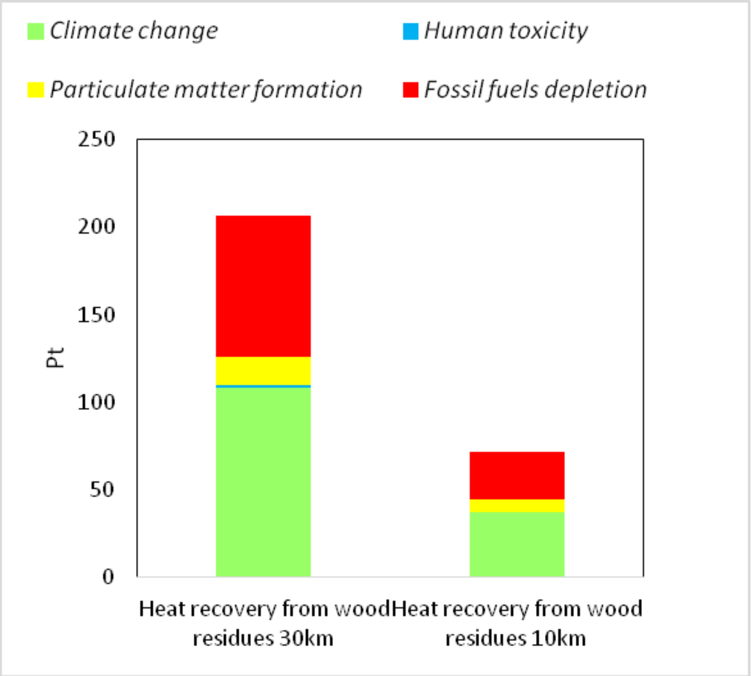


Figure 4.6. Single score assessment: comparison between the traditional wood-based scenario with the scenario with less km, for the production of 1 MWh of thermal energy.

In addition to the use of cumulative score, ReCiPe method makes it possible to convert the results at midpoint level to potential impacts on different receptors. LCA methodology usually refers to three macro-categories of damage: human health, ecosystem quality and resources depletion. Figure 4.7 collects these results, showing that the adoption of a centralized heating system based on the use of biomass residues (locally collected and burned) contributes to a considerable reduction on each damage indicator, estimated around 38%.

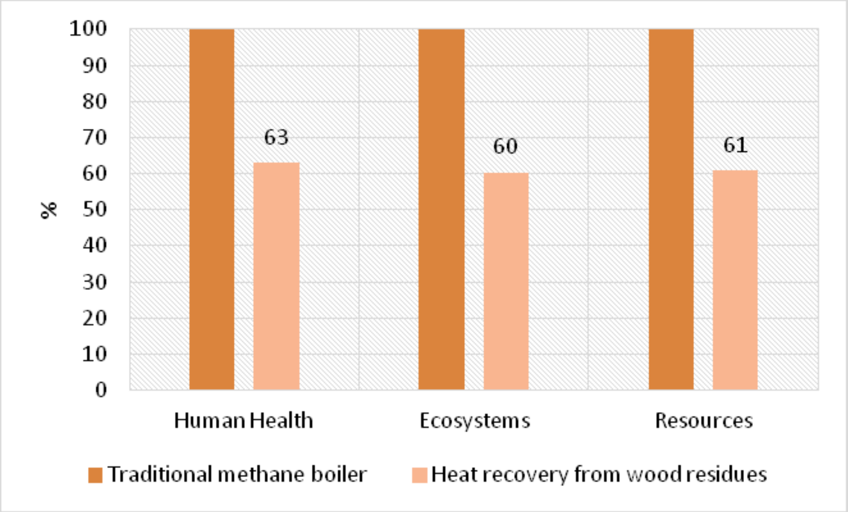


Figure 4.7. Damage assessment distribution among the two scenarios.

4.2.6 Personal conclusions and recommendation

The exploitation of wood residues to produce renewable energy for a small Italian municipality was investigated by the use of LCA methodology. Burdens were evaluated considering all the negative effects on environment, resources depletion and human health within the entire biomass handling chain: from wood handling, up to its transportation and utilization to produce chips, and the burning in a dedicated appliance, to satisfy the heat requirements of some public buildings.

Moving from a decentralized system based on fossil resources (e.g., NG) to a district heating system which implies the usage of local biomass residues, some global environmental impacts appear reduced, such as the GHGs emissions and the depletion of non-renewable fuels. Therefore, this approach based on the collection of the wood scraps deriving from pruning activities could help small communities in achieving the targets fixed by European guidelines for 2020: 15% energy reduction and 20% GHGs mitigation. In addition, the consumption of local resources contributes to increase the energetic independence of these small territories, avoiding to be influenced by socio-economic fluctuations to which all feedstocks are subjected. However, as expected, biomass combustion results in the worst effects in terms of toxic substances emitted. This aspect should be investigated in depth by the use of dedicated monitoring campaigns, to collect primary and updated data to fill in the LCA models. Moreover, all the movements still represent a critical issue, in particular when diesel vehicles are used to cover the distances. Transportation contributes to the global impact by 98%, even if distances are restricted to a 30 km roundtrip. Thus, to meet EU targets for pollution mitigation, an implementation of more sustainable engines (e.g., NG, hybrid and full electric) is certainly recommended. The literature has already shown that the usage of NG-fueled or hybrid trucks, replacing traditional diesel-based vehicles, contributes significantly to GHGs reduction [25, 26]. Nevertheless, emissions from electric vehicles greatly vary depending on the electricity mix: when low-carbon energy grids are implemented, vehicles are close to neutral CO_2 emissions, while if carbon-intensive electricity mix is used, biofuels usage leads to a lower carbon footprint than hybrid [27]. This is the reason why the sustainability should be evaluated case by case, taking into account all the variables and limitations (e.g., economic, geographical, social and political) which affect the system under investigation.

4.3 The case study of Gasification of wood chips arising from virgin biomass

4.3.1 Background: use of woody biomass for energy production through the gasification technology

In all combustion processes, so even in the case of biomass use, many substances are emitted into the air, that can be a source of damage to human health and to the ecosystem.

Different is the case of thermal processes that do not perform a direct biomass combustion, but that exploit the carbon content by operating the partial oxidation under controlled conditions, as the gasification process.

The gasification process consists in the conversion of carbon containing organic material to a fuel gas; it is realized by a partial oxidation through an oxidizing reagent which may be air, or air enriched with oxygen, or pure oxygen. The gas obtained can be used as fuel in a steam generator, or in a high efficiency equipment, such as internal combustion engines or gas turbines.

The two most common methods of energy utilization of syngas involve respectively:

- direct combustion of the gas generated by the gasification process, or after purification treatment, in conventional combustion systems (e.g.: steam generator) that rely on a thermal cycle for the production of electricity, such as that commonly adopted in processes of direct combustion of waste;

- use of syngas on direct conversion systems with high efficiency (piston engines, gas turbines, combined cycles), after purification.

4.3.2 Comparison with direct combustion of biomass

The developed technologies for thermally converting the biomass to obtain energy are essentially three: direct combustion, gasification and pyrolysis.

The main characteristic of the two treatment systems are the following:

- during combustion, due to the supply of oxygen, all the biomass is converted to CO_2, water and other minor products (especially sulfur and nitrogen oxides). In order to produce energy through combustion a steam turbine or an Organic Rankine Cycle (ORC) could be used. In gasification, instead, the gas produces by the process (syngas) is a mixture that contains several substances, including carbon dioxide, hydrogen, methane and other hydrocarbons. Therefore, syngas may be fed in gas engines, or turbines, after adequate cleaning of possible contaminants.
- In addition to syngas, during gasification other by-products are produced, such as the char: unlike the combustion plants, in which the objective is to minimize the formation of ash (light and heavy), in the gasification process the char is considered a product having a commercial value, for example for the production of cement or as a soil amendment.
- However, the quality and the amount of char and syngas products are significantly influenced by the type of gasifier and by the operating conditions. This possibility is absent in the option of direct combustion.
- In biomass combustion, the exhaust gases can only be exploited in steam turbines, using their energy content. The syngas, instead, could be used as fuel in gas engines, but also as raw material for the production of other fuels or of other chemical compounds.
- On a small scale, however, the technological consolidation and the cost-benefit ratio is in favor of the combustion processes. Only in the last two decades gasification plants have being developed, although on a small scale, considered as an alternative to the combustion plants technology.

4.3.3 Life Cycle Inventory (LCI)

In this work the G.M.P. Bioenergy gasification plant (Figure 4.8) was studied, located in Correggio (RE), with a capacity of virgin wood chips of 11500 ton/year (with RH 45%) and a production of electricity of 10.12 MWh/year.

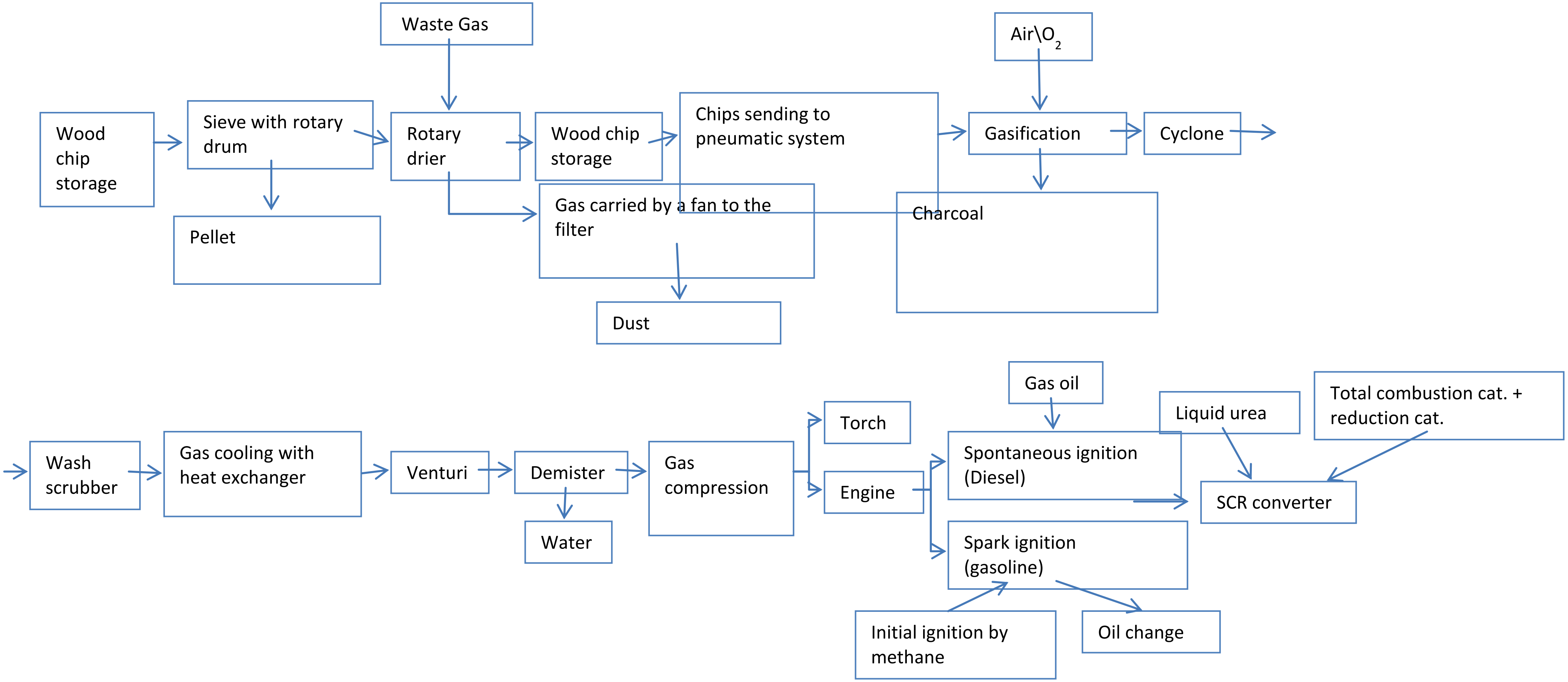


Figure 4.8. Diagram gasification plant.

For the scenarios modelling the software SimaPro 8 (v. 8.0.4.30) [28] and the database Ecoinvent 3.1. [22] were used.

As functional unit, the production of 1MWh of electricity was chosen: all data were calculated in relation to this functional unit.

The inventory analysis was carried through the collection of data provided directly by the company [29], or found in the literature [16,30,31], or in the reference database [22].

Table 4.4 shows the considered % of timber in input to the system:

Poplar	40	%
Black Pine	50	%
Chestnut	10	%

Table 4.4. % of timber in input to the plant

On the basis of these percentages two scenarios were modeled for the timber in input: one for the softwood timber category (poplar and pine) and one for the hardwood category (chestnut).

The wood used in the plant comes from different “waste cuts”, none of which constitutes the most prized part of the biomass: cuts from the removal of diseased plants, pruning made to avoid clutter on the powerline cables or part of the tree that are not used in the building industry because are too small. In the process investigated a lower impact is then computed, as regards this category, through an allocation (that is a distribution of impacts on the different processes that use wood of trees), in order to give a more suitable weight to the function of not simple exploitation of the biomass, but the exploitation of waste material, relative to the gasification process investigated.

In the processes considered the burdens related to the occupation of the territory have been removed, considering only a 30% of the energy needed for “chipping” the plant (as the “top” part that is waste is assumed to be around the 30% of the same plant).

Then four reference scenarios have been created, on the basis of the kind of recovery of energy and/or matter. In all scenarios input related to the functional unit were included, considering the data plant (Table 4.5).

Power	**998**	**kW$_e$**
Hours/year operation	**7500**	
		Input Wood Chips
Moisture	45	%
INPUT Wood Chips	0.00154	t/kWh$_e$
	8000	t/year, < 6% RH
	11500	t/year, 45% RH
	36.8	t/day 45%
	1533	kg/h in input to the pant 45% U
Input power as biomass 45%	3849	MW$_t$
Thermal power output by co-generators	1.7	MW$_t$
Output power as syngas	3014	kW$_t$
Thermal power from pistons	900	kW$_t$
Thermal power from flue gas	800	kW$_t$
Output power as syngas + diesel	3014	kW$_t$
Internal consumption	12	%
Electrical power net of internal consumption	878	kW$_e$
Output power as syngas + diesel	3062	kW$_t$
Thermal power output by co-generators	1700	kW$_t$
Overall electrical efficiency		
Thermal power INPUT to co-generators	3062	kW$_t$
Electrical power OUTPUT from co-generators	998	kW$_e$
Overall thermal efficiency		
Thermal power input to the plant	3849	kW$_t$
Thermal power output from co-generators	1700	kW$_t$

Table 4.5. Summary data relating to the system of gasification, used in LCA modelling [1,2]

For all scenario some common input have been considered (Table 4.6):

Oxygen	84698 kg	Assessed on data plant and through the calculation of the allocation
Softwood	5799 m^3	Assessed on data plant and through the calculation of the allocation
Hardwood	428 m^3	Assessed on data plant and through the calculation of the allocation
Oil	790 liters	Assessed on data plant and through the calculation of the allocation
Diesel	3,6 ton	Assessed on data plant and through the calculation of the allocation
Transport	263559 tkm	Calculated considering the average distance of transport of timber and the number of travel necessary to transport it, considering the quantity needed on the basis of the functional unit chosen for the study.

Table 4.6. Common input.

Air emissions of the plant have been obtained from Company reports and on the basis of the allocation calculation, considering:

- nitrogen oxides;
- carbon monoxide;

- particulate matter;
- hydrocarbons.

Importantly, emissions are always lower than the limits required by law:

- 50ppm for NOx, versus the limit of 200ppm;
- 100ppm for CO, versus the limit of 200ppm.

With regard to air emissions, the particulate matter formation should be then considered (not yet measured at the time of the study), but which is believed to be below the limits of law, given the presence of a filter.

Emissions to water were evaluated on the basis of data plant obtained from the reports relating to the condensation water and considering the allocation calculation, taking into account the values in particular of:

- lead;
- zinc;
- COD (chemical oxygen demand);
- chlorides;
- sulphates;
- ammonia nitrogen;
- nitric oxide;
- surfactants.

The condensed water has a disposal cost for the company of about 50 €/t and it is a non-hazardous waste that is then sent to a waste water treatment plant, because it is rich in COD.

Scenario A. Gasification of virgin wood chips with electricity generation (Figure 4.9);

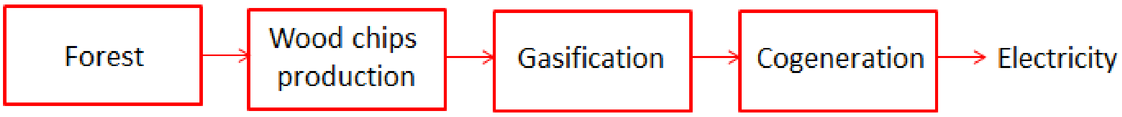


Figure 4.9. Boundaries of the scenario A.

The avoided impact due to the recovery of electricity was considered, as well as the impacts resulting from the emissions into the air of the thermal energy not recovered and from the disposal of pellet (derived from the under-screen) to landfill and char.

Scenario B. Gasification of virgin wood chips with recovery of electricity and thermal energy (Figure 4.10).

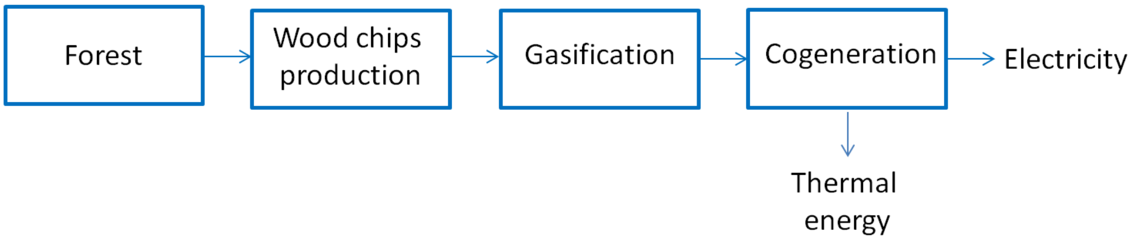


Figure 4.10. Boundaries of the scenario B.

The avoided impact due to the production of electricity and thermal energy, as well as and the impacts generated by the disposal to landfill of pellet and char.

Scenario C. Gasification of virgin wood chips with electricity production and recovery of materials (pellet and char), Figure 4.11.

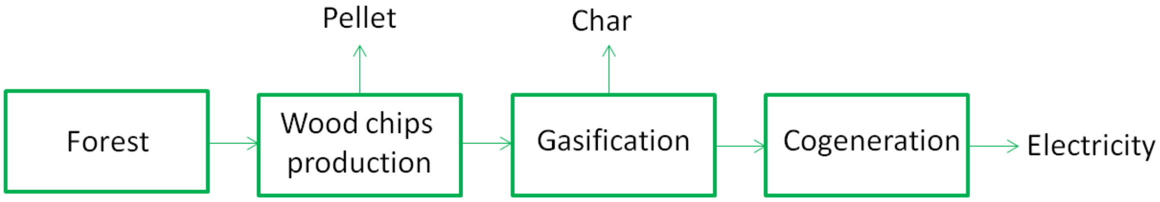


Figure 4.11. Boundaries of the scenario C.

The avoided impacts due to the production of electricity and the recovery of wood pellets and char were considered, as well as the impact generated by the dissipation of thermal energy in the air. Pellets (derived from the under-screen) and char are collected from the plant because they have a commercial value around 20-30 €/t for the pellets and 50 €/t for the char (even if for the char the real prize is estimated to be even higher, around 100-150 €/t).

Scenario D. Gasification of virgin wood chips with production of electricity, and recovery of thermal energy and materials (pellet and char), Figure 4.12.

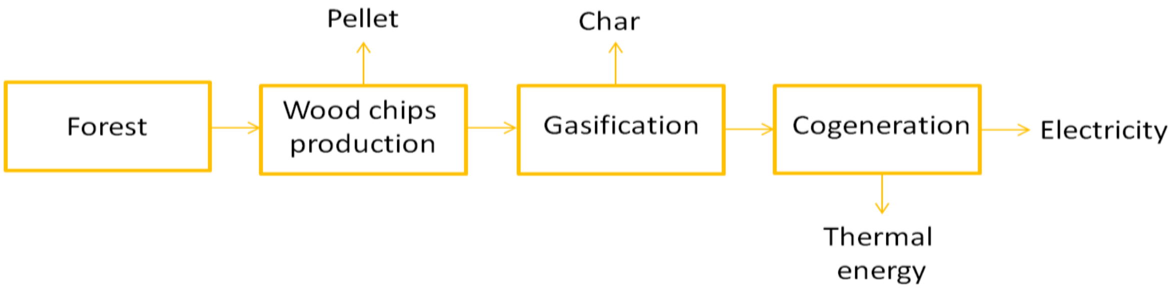


Figure 4.12. Boundaries of the scenario D.

This is the optimal scenario: the recovery of electricity, thermal energy and materials have been considered.

4.3.4 Life Cycle Impact Assessment (LCIA)

For the analysis of the available data and of the scenarios modelled the method of analysis ReCiPe2008 (version update at 2014) has been used [19].

LCA analysis regarded the categories of climate change, ozone layer reduction, terrestrial acidification, human toxicity, photochemical oxidant formation, particulate matter formation, transformation of the natural territory.

The results of the modelling of the gasification scenarios are shown in the Figure 4.13:

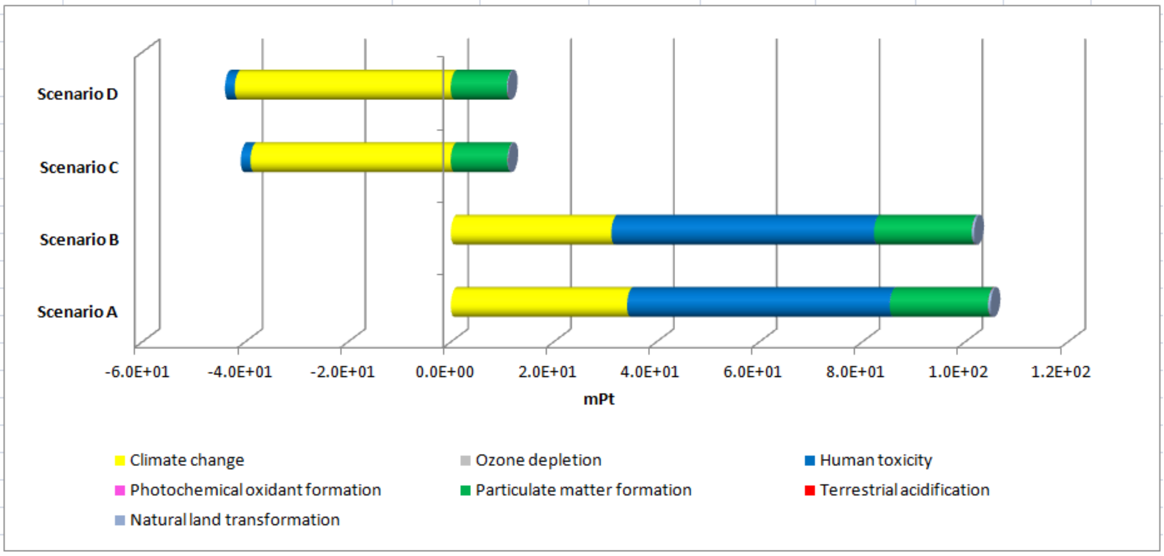


Figure 4.13. Comparison between wood chips gasification scenarios, Single score, midpoint impact categories

Figure 11 shows the results in terms of single score [mPt] in order to compare the four different scenarios in terms of global impact.

Scenario A shows the major impact compared to the scenarios studied, considering only the electricity production, in terms of:

- climate change: this is due to greenhouse gas emissions, such as CO_2, from the entire process, including energy consumption; however, considering the life cycle of the system, these emission are greatly limited by the biomass growth cycle (process upstream to the gasification plant), that during photosynthesis fixes atmospheric carbon into organic matter;
- human toxicity: mainly due to the impact of wood chips combustion;
- particulate matter formation: this aspect is one of the major problems of the use of biomass for energy purposes; however, a direct combustion would have a much greater impact. Instead, in the plant investigated, most of the non-oxidized material is recovered

as char, while the gas produced burns with much greater efficiency than the original wood.

It should be emphasized an absolutely relevant aspect in the examination of the results obtained: the “Electricity, production mix”. A negative output is associated to it, in different quantity but for all the impact categories: this outcome is due to an avoided impact. It means that the energy recovery resulting from the gasification “avoids” that a similar amount of electricity is produced from conventional sources (i.e., the mix of energy sources present in Italy, such as coal fired power station, fuel oil, natural gas, each with an impact). In addition, there is a component related to the nuclear energy acquired from abroad. Lastly, there is a share of renewable energy, increasing in recent years, that have not yet achieved a major proportion, lowering the overall environmental impact.

Scenario B shows lower impacts compared to Scenario A thanks to the recovery of thermal energy downstream to the gasification step in addition to the production of electricity. The avoided impact is greater in case the system also distributes thermal energy, in the form of steam or heated water, or to the surrounding buildings (for heating), or to nearby industries performing processes with high operating temperatures.

The greatest gain from the environmental point of view, however, is for Scenario C and D, thanks to the recovery of material: pellet (obtained from the over-screen fraction of the incoming wood chip) and char (in output from the gasification step) that have a commercial value, thus obtaining a further valorization of the system and reducing the overall impact of the process.

The impacts of these improvements do not appear technically complex but may be difficult to achieve in terms of authorization.

Table 7 shows the results in terms of damage categories (endpoint) expressing them as damage to human health [DALY, disability-adjusted-life-year, years of life lost due to disability] and damage to the diversity of ecosystems [number of species lost per year, species*year].

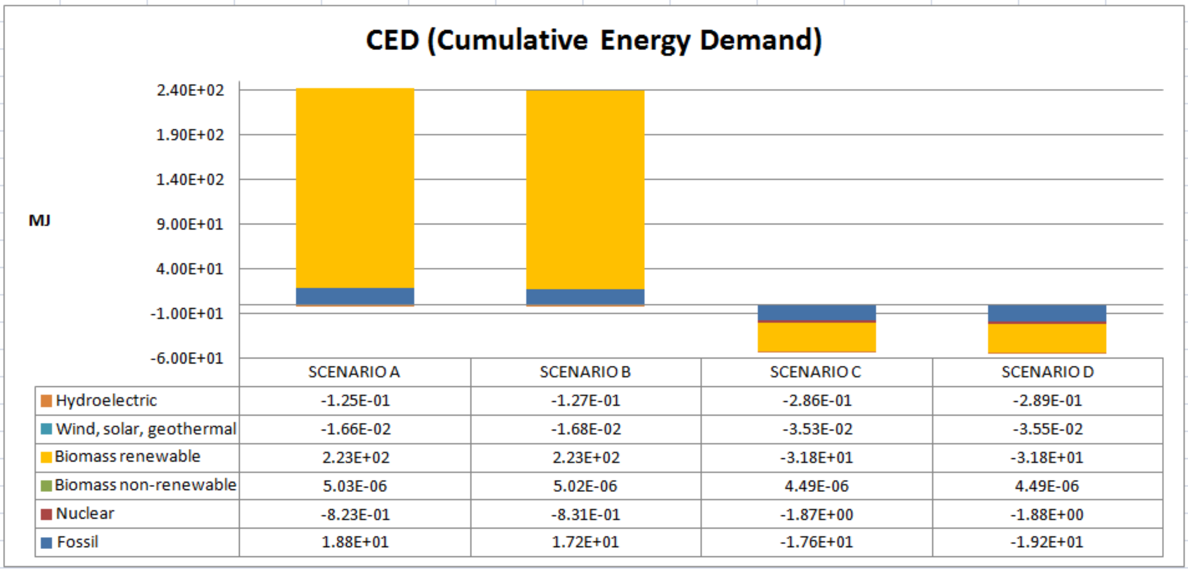
Impact category	Unit	Scenario A	Scenario B	Scenario C	Scenario D
Climate change human health	DALY	1,40E-06	1,28E-06	-1,59E-06	-1,72E-06
Ozone layer depletion	DALY	5,32E-10	4,98E-10	-2,60E-10	-2,94E-10
Human toxicity	DALY	2,32E-06	2,32E-06	-8,58E-08	-8,62E-08
Photochemical oxidant formation	DALY	6,50E-10	6,47E-10	4,02E-10	3,99E-10
Particulate matter formation	DALY	8,68E-07	8,64E-07	5,00E-07	4,95E-07
Climate change ecosystems	species·yr	7,94E-09	7,23E-09	-9,01E-09	-9,72E-09
Terrestrial acidification	species·yr	4,79E-11	4,75E-11	2,67E-11	2,63E-11
Natural land transformation	species·yr	1,08E-09	1,08E-09	3,67E-10	1.44E-02

Table 4.7. Comparison between wood chips gasification scenarios, Single score, midpoint impact categories.

Below, charts regarding the same functional unit used for the study are reported, but related to the energy required (in MJ) in terms of:

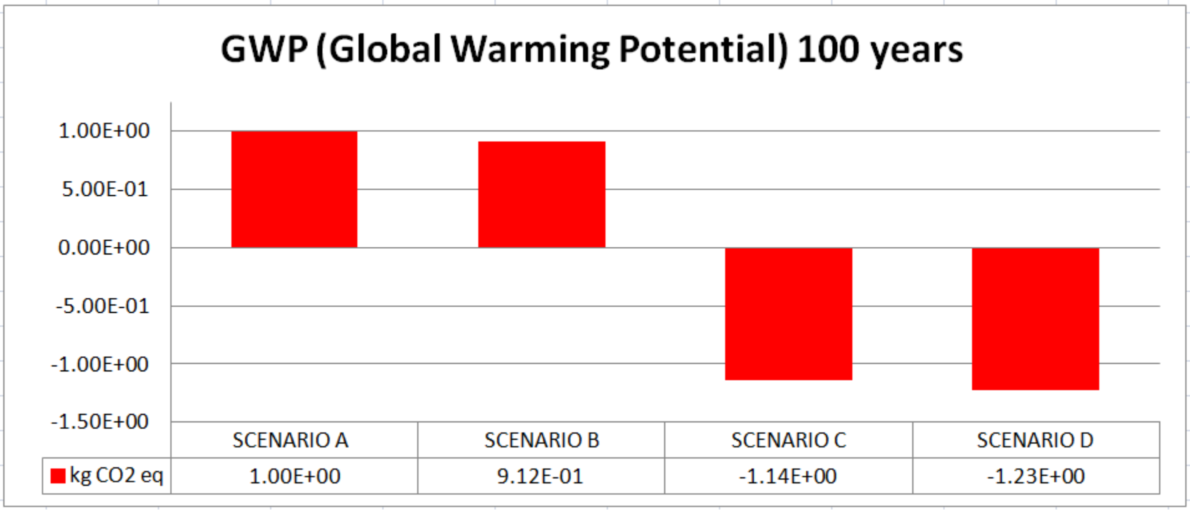
- Cumulative Energy Demand (CED) in Figure 14, representing the direct and “embodied” consumption of renewable resources, expressed in terms of equivalent energy (MJ);
- emissions of CO_{2eq} in terms of Global Warming Potential considering a time horizon of 100 years (Figure 4.15), expressing the contribution to the greenhouse effect of a greenhouse gas in relation to the effect of the CO_2, whose reference potential is equal to 1;
- Water Footprint expressed in m^3 of water consumed (Figure 4.16), representing the volume of water needed to produce a product or a service.

From the results the advantages related to the recovery of material (char and pellet) obtained for Scenario C and D, are greater compared to the only recovery of energy (electrical and thermal).



	SCENARIO A	SCENARIO B	SCENARIO C	SCENARIO D
🟧 Hydroelectric	-1.25E-01	-1.27E-01	-2.86E-01	-2.89E-01
🟦 Wind, solar, geothermal	-1.66E-02	-1.68E-02	-3.53E-02	-3.55E-02
🟨 Biomass renewable	2.23E+02	2.23E+02	-3.18E+01	-3.18E+01
🟩 Biomass non-renewable	5.03E-06	5.02E-06	4.49E-06	4.49E-06
🟥 Nuclear	-8.23E-01	-8.31E-01	-1.87E+00	-1.88E+00
🟦 Fossil	1.88E+01	1.72E+01	-1.76E+01	-1.92E+01

Figure 4.14. Comparison between the wood chips gasification scenarios, in terms of Cumulative Energy Demand (CED), relative to 1MWh of electricity as functional unit



	SCENARIO A	SCENARIO B	SCENARIO C	SCENARIO D
🟥 kg CO2 eq	1.00E+00	9.12E-01	-1.14E+00	-1.23E+00

Figure 4.15. Comparison between the wood chips gasification scenarios, in terms of Global Warming Potential (GWP), relative to 1MWh of electricity as functional unit

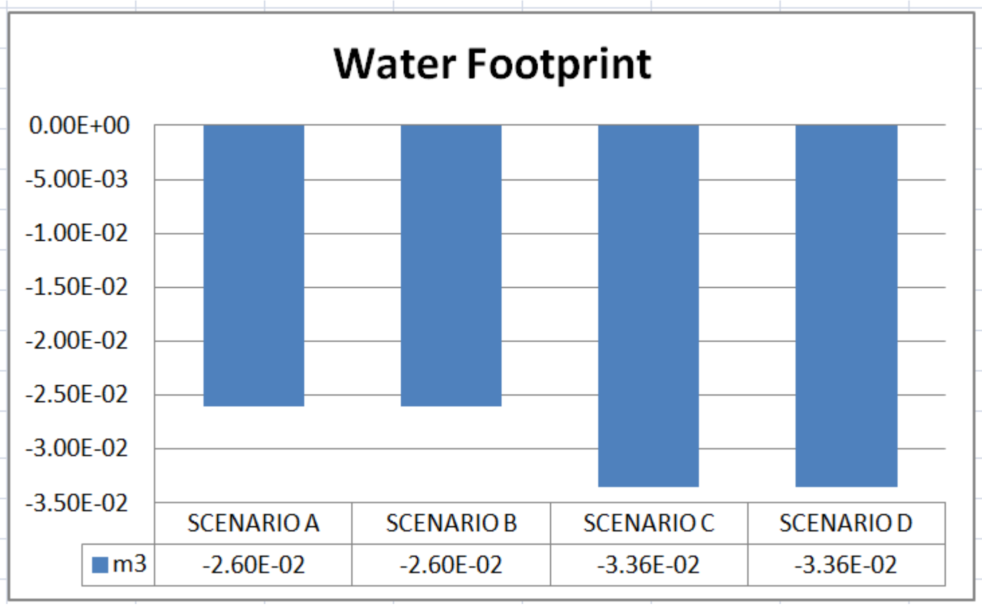


Figure 4.16. Comparison between the wood chips gasification scenarios, in terms of Water Footprint, relative to 1MWh of electricity as functional unit

4.3.5 Personal conclusions and recommendation

In this study the approach and the results obtained by applying the Life Cycle Analysis method (LCA) to the GMP Bioenergy gasification system have been reported.

The plant was studied considering the characteristic of the plant, the electricity production and the hypothetical recovery of thermal energy and materials (pellet and char).

From the analysis of the results it emerged that thermal energy recovery in addition the production of electricity provide a better environmental performance than the only electricity production. With the hypothesis of further implementing the plant with the recovery of pellet and char and their sale, it is possible to obtain greater environmental avoided impacts, improving the overall environmental performance.

The scenarios that consider in addition to the production of electricity the recovery of pellet and char (Scenario C) or the recovery of pellet, char and thermal energy (Scenario D), show a higher avoided total impact for the same amount of electricity produced considering the indicators “carbon footprint” (>1 ton CO_{2eq}/GWh_{el}), “water footprint” (>30 m^3/GWh_{el}) and “cumulative energy demand” (>15 MWh/GWh_{el}).

Finally, another comparison among this technology and alternative systems (direct combustion, pyrolysis, etc.), for the same quantity of energy produced, could provide other relevant criteria for the assessment of the technology environmentally preferable to apply at local scale and offer a support to decision-makers in the process of territorial planning.

4.4 The concept of Industrial symbiosis

The goal of increasing the efficiency in the use of resources, related to the reduction of their availability, is linked to the transition process from the current linear model of production to a circular one.

Industrial symbiosis means the exchange of resources between two or more different industries, considering as “resources” not only the materials (by-products or waste), but also energy waste, services and expertise.

Therefore Industrial Symbiosis has two objectives: the creation of competitive advantages for companies and the improvement of the environmental performance of a territory or of an industrial area.

It is necessary to spread a culture of industrial symbiosis involving industries also of traditionally separated sectors, through an integrated approach, aimed at promoting competitive advantages through the exchange of matter, energy, water and\or by-products.

It is necessary to switch from the traditional management system to a circular one (Figure 4.17) through the involvement of “upstream-companies”, producing flows of by-products that need to be reprocessed and valued, of “transformation-companies”, equipped with the technology to achieve the transformation and the upgrading of by-products, and of “downstream-companies”, which should reuse the product, reprocess and valued them. Outgoing flows from upstream companies thus become input of secondary raw materials, assuming a value.

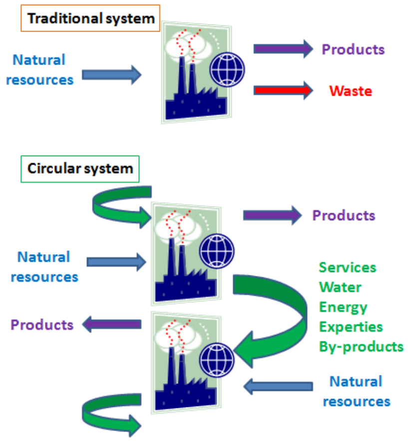


Figure 4.17. Objectives of industrial symbiosis

To achieve a high degree of cooperation between the industries of the same area some conditions are required: easiness in the exchange of utilities and by-products, good capacity of collaboration and communication.

It is also important to point out that the European Commission declared its intention to focus investments to promote the development and the adoption of innovative technologies in a variety of sectors, including that of industrial symbiosis, as a sustainable business model for the recovery of materials, heat and dissipated energy [32]. This approach is not only a potential factor of competitiveness for industrial activities, but also a factor of enrichment for the territory, that could valorize all its resources locally without a dispersion. It must be emphasized that the advantage of industrial symbiosis is, first of all, an economic advantage generated by a saving due to the avoided disposal. If the revenues from the sale of by-products are added to the savings, the economic benefits then become even more appreciable.

Therefore the industrial symbiosis is identified as one of the policy tools to achieving the objectives of the efficient use of resources, especially in the phase of recovery of residues and by-products, and their subsequent valorization into new production processes.

4.5 The case of the feasibility study of the energetic valorization of agro-industrial residues through an anaerobic fermentation plant (biogas)

This work was realized in collaboration with the company I.R.C.I. S.p.A., within the project “Green-Industrial Symbiosis” [33], with the support of the international program “Pioneers into Practice” of the Climate-KIC. The latter is one of the Knowledge Innovation Communities (KICs), and it was born in 2010 within the European Institute of Innovation and Technology (EIT), the body of the European Union committed to create a sustainable growth in Europe dealing with the global challenges of the present [34].

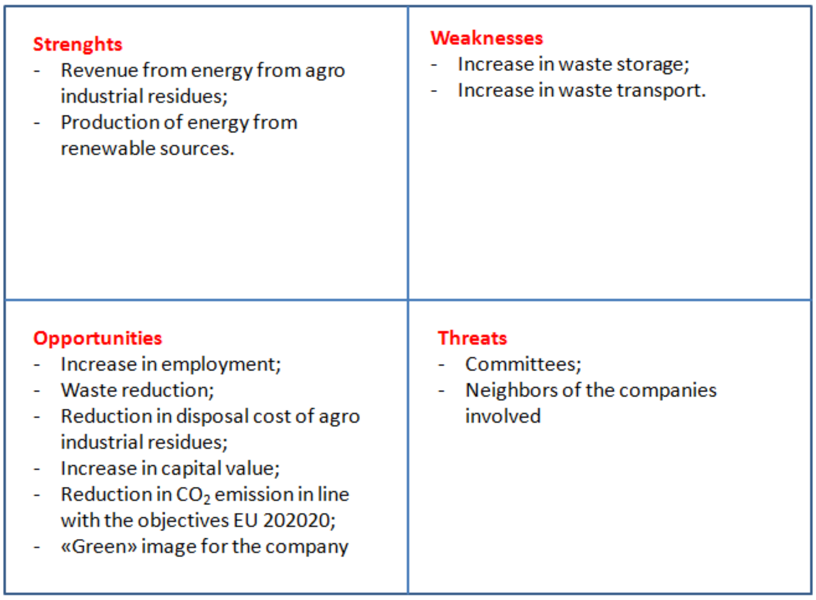
4.5.1 Background: agriculture and renewable sources

It is interesting to outline a leading role for the Emilia Romagna region in the field of renewables, especially those arising from agricultural and agro-industrial sources. This is an important consideration because, if Italy will be able to meet the targets sets by the Directive 28/2009 of the European Union [3], the “climate-energy package”, the development of renewable energy in agriculture in 2020 will reach 8% of the total, equal to 15.5 million tons of oil equivalent [35]. The agricultural sector is therefore called to promote the use of energy from biomass using the most advanced processes, to adopt sustainable farming techniques and to develop research and experimentation on energy from agro-industrial residues and the best technologies applicable to livestock farms.

Moreover the objectives set by the European Union for the use of renewable energy sources in member countries are to be taken into account: 20% for renewable energy sources, -20% energy saving and -20% reduction of CO_2 emissions in 2020 [3].

Then the goal, for environmental purpose, is to reduce the carbon footprint of the chain along the entire life cycle of processes and products.

At first, a SWOT analysis was performed in order to carry out a strategic planning and assess Strengths, Weaknesses, Opportunities and Threats of the energy valorization of residues from agro-food chain (Table 4.8).



Strenghts - Revenue from energy from agro industrial residues; - Production of energy from renewable sources.	**Weaknesses** - Increase in waste storage; - Increase in waste transport.
Opportunities - Increase in employment; - Waste reduction; - Reduction in disposal cost of agro industrial residues; - Increase in capital value; - Reduction in CO_2 emission in line with the objectives EU 202020; - «Green» image for the company	**Threats** - Committees; - Neighbors of the companies involved

Table 4.8. SWOT table about valorization of agro-industrial residues

Considering the regulations on waste legislation [36], it sets out four conditions that a substance must have to be identified as a by-product and not as a waste:

- the substance is produced by a production process, of which it constitutes an integral part, and whose primary purpose is not the production of such substance;

- it is certain that the substance will be used, in the course of the same or a subsequent production process or use, by the producer or others;

- the substance can be used directly without any further processing different than normal industrial practice;

- the use is lawful: the substance, for the specific use, has all the requirements relating to products and health and environment protection and will not lead to impacts on environment or human health.

The list of biomass and by-products that could be used in biogas (anaerobic fermentation) and biomass (pyrolysis, pyro-gasification, combustion) systems is:

- biological origin products;
- organic by-products;
- waste for which the biodegradable fraction is determined at a flat rate;
- waste not deriving from separate collection.

Moreover, by-products used in biomass and biogas plants which could be eligible for incentives are listed below:

- animal by-products not for human consumption;
- by-products from agricultural activity, breeding and green and forestry management;
- by-products from food and agro-industrial activities;
- by-products from industrial activities.

It can be seen a political will to reward the use of by-products for energy use also analyzing the current legislation. For example, the DM 6 July 2012 [37], that promote the production of electricity from renewable sources different from photovoltaics, provides incentives differentiated for the production of electricity from biomass and biogas plants depending on whether the raw materials are products, by-products or waste. The greater incentive is given in the case of by-products use.

4.5.2 Study of the system

The company A.R.P. Tomato is an Agricultural Cooperative Society founded in 1958 by a group of 15 local farmer and it is part of the consortium “Piacenza Food”, created in 1980 by the local Chamber of Commerce. Today the consortium brings together 75 companies, acknowledged for their tradition in the production and quality of products, including sausages, cheese, wine, fruit, tomato preserves, vegetables, milk, honey, pasta and jam.

The company object of study deals with the production of tomatoes, peas and beans.

The main residues arising from this type of production processes are tomato waste (peel/seeds and sieve waste), the sieve waste resulting from the cleaning of vegetables (peas and beans) and sewage sludge, which have a management and disposal cost for the company.

It is also important to point out that these residues are subject to strong seasonality, focused in the period of the tomato campaign, lasting about 70 days, approximately from 20 July to 1 October.

For this reason, it is indispensable the involvement of other partners of the consortium for the implementation of an anaerobic fermentation plant (biogas), especially those dealing with dairy cows breeding, considering the manure and slurry production in ACU (adult cattle units).

First of all every types and quantities of waste arising from A.R.P. Tomato processes have been taken into account, through the use of the "master data sheet INPUT-OUTPUT" (Table 4.9) realized by ENEA for the project "Green-industrial symbiosis".

Resource			**Quantity**
sludge	From waste water treatment	waste	5000 ton
Vegetable residue	Tomato sieve waste	By-products	5000 ton
Vegetable residue	Peas sieve waste	By-products	150 ton
Vegetable residue	Beans sieve waste	By-products	25 ton
Vegetable residue	Tomato peel and seeds	By-products	2000 ton

Table 4.9. master data sheet INPUT-OUTPUT realized by ENEA

It was then investigated whether these residues constitute a cost or a revenue for the A.R.P. company, obtaining the information shown in Table 4.10.

Residue typology	**Destiny**	**€/ton**
Skins and seeds	Animal feed	11 return
Sieve from waste water treatment plant	Biomass for bio-digester	0.516 return
sludge	Spread on the members fields	30 cost

Table 4.10. Revenues\costs resulting from the management of waste resulting from the processes of the company A.R.P. Tomato

The following step was then the definition of types and quantities of waste from the companies members of the consortium that could be used for the feasibility study (Table 4.11).

Farms	Province	Distance (km) from the plant	U.B.A.	Manure	Slurry
1	PC	32	162	X	
2	PC	28	128	X	
3	PC	16	500	X	
4	PC	24	292	X	
5	PC	23	203	X	
6	PC	27	219	X	
7	PC	18	148	X	
8	PC	36	106		X
9	PC	23	163	X	
10	PC	28	252	X	
11	PC	15	136	X	

Table 4.11. Residues data of the members of the consortium

On the basis of these information it has been possible to hypothesize the construction of an anaerobic fermentation plant (biogas) for energy recovery from waste through the collaboration with the company Schmack Biogas s.r.l. for the definition of the plant size and of the possible inputs to the system.

The company n. 3 has been chosen as the ideal site for the “Simulation B: plant located at one of the other partner involved”.

4.5.3 Feasibility study

For the development of the feasibility study for the construction of the anaerobic fermentation plant (biogas) two different scenarios have been considered:

- Simulation A: biogas plant built at the SOC. COP. AGR. A.R.P. TOMATO where also residues from other members would be placed;
- simulation B: biogas plant built at one of the other partner involved, where also residues from other members (including A.R.P.) would be placed.

4.5.3.1 Simulation A

First it was necessary to define which other partners could be involved in the simulation on the basis of the type of residues and the distance from A.R.P. plant, taking into account the Table 4.8. It was decided to consider all companies that:

- produce manure and are at a distance less than 30 km from A.R.P. plant;
- produce slurry at a distance less than 15km (because slurry is less easily stored and more putrescible compared to manure).

For this solution the Schmack Biogas s.r.l. company suggested the construction of a 600kW plant.

The following parameters have been considered:

- type and amount of residues [t/year];
- cost/return resulting from waste management [€/ton];
- seasonality, assuming that when waste resulting from vegetables are not present, these could be replaced by manure/slurry.

In this case biomass from farms have a transport cost. A cost of 2 €/ton for a storage bag of 3000m^3 has been considered (with an occupation of about 6000m^2) for the skins.

In figures 4.18 and 4.19 the two diagrams represent the % by mass and energy of residues from A.R.P. Tomato (red) and from the other partners (green) for the production of electricity.

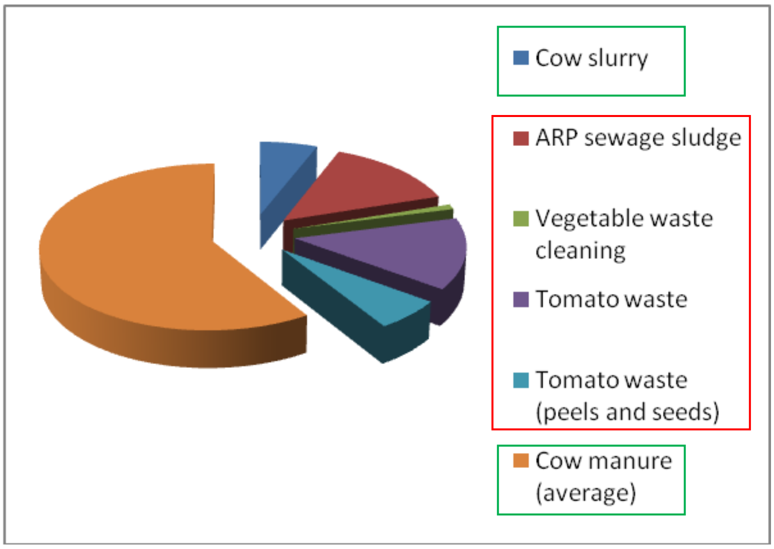


Figure 4.18. % of mass of residues of A.R.P. and of the other members of the total of the production of electricity

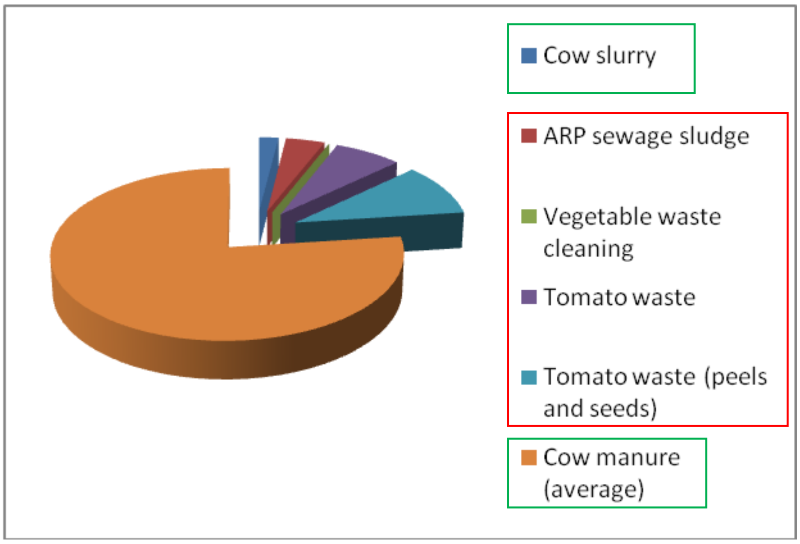


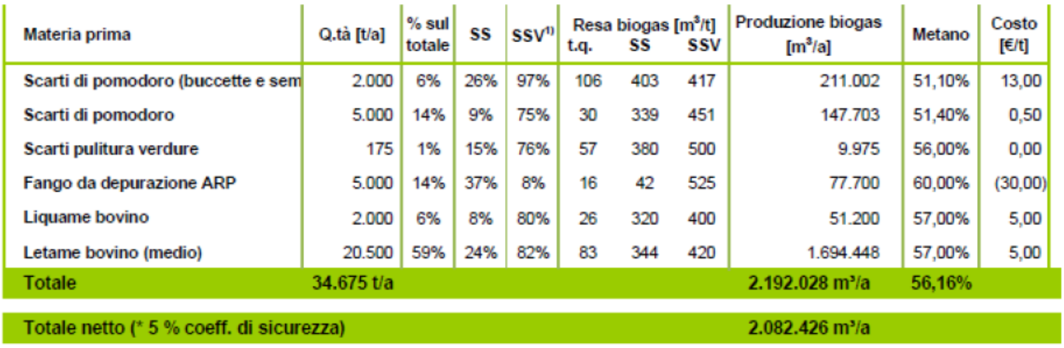
Figure 4.19. % of energy of residues of A.R.P. and of the other members of the total of the production of electricity

The electricity consumed cannot be self-consumed, unless a future change of type of incentive, because would be lost the all-inclusive tariff, reserved for qualified plants powered by renewable resources with an annual average of nominal power not exceeding 1MW [38].

Realizing the plant at A.R.P. it is possible to obtain a thermal recovery, that could be used in two forms: hot water for boilers thermal consumption and steam for the partial compensation of thermal consumption of steam boilers .

All the details of costs, revenues and recovery of Simulation A are in tables 4.12-4.20.

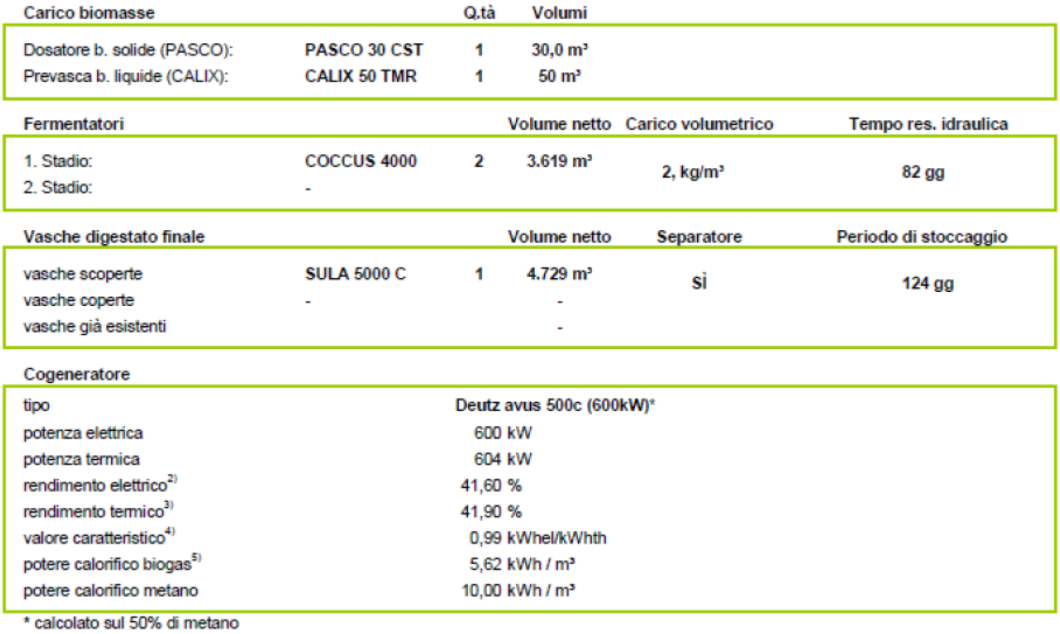
In Table 4.12 it can be seen to see the feed table suggested by Schmack:



Materia prima	Q.tà [t/a]	% sul totale	SS	SSV1)	Resa biogas [m^3/t]			Produzione biogas [m^3/a]	Metano	Costo [€/t]
					t.q.	SS	SSV			
Scarti di pomodoro (buccette e sem	2.000	6%	26%	97%	106	403	417	211.002	51,10%	13,00
Scarti di pomodoro	5.000	14%	9%	75%	30	339	451	147.703	51,40%	0,50
Scarti pulitura verdure	175	1%	15%	76%	57	380	500	9.975	56,00%	0,00
Fango da depurazione ARP	5.000	14%	37%	8%	16	42	525	77.700	60,00%	(30,00)
Liquame bovino	2.000	6%	8%	80%	26	320	400	51.200	57,00%	5,00
Letame bovino (medio)	20.500	59%	24%	82%	83	344	420	1.694.448	57,00%	5,00
Totale	**34.675 t/a**							**2.192.028 m³/a**	**56,16%**	
Totale netto (* 5 % coeff. di sicurezza)								**2.082.426 m³/a**		

Table 4.12. Input plant built at A.R.P.

The plant data (Table 4.13-4.15):



Carico biomasse		Q.tà	Volumi
Dosatore b. solide (PASCO):	PASCO 30 CST	1	30,0 m³
Prevasca b. liquide (CALIX):	CALIX 50 TMR	1	50 m³

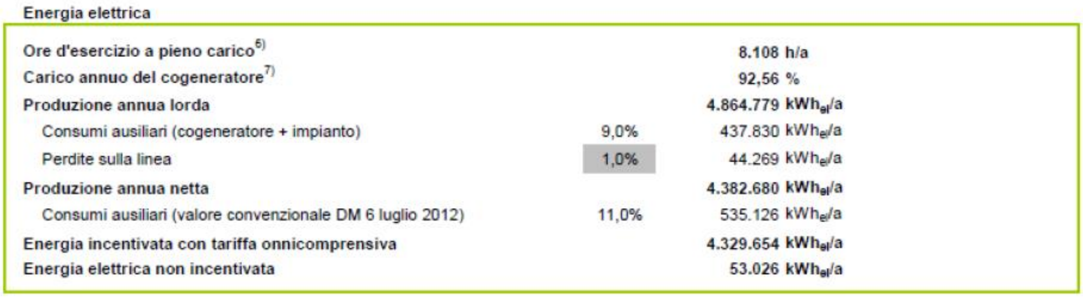
Fermentatori			Volume netto	Carico volumetrico	Tempo res. idraulica
1. Stadio:	COCCUS 4000	2	3.619 m³	2, kg/m³	82 gg
2. Stadio:	-				

Vasche digestato finale			Volume netto	Separatore	Periodo di stoccaggio
vasche scoperte	SULA 5000 C	1	4.729 m³	sì	124 gg
vasche coperte	-		-		
vasche già esistenti			-		

Cogeneratore	
tipo	Deutz avus 500c (600kW)*
potenza elettrica	600 kW
potenza termica	604 kW
rendimento elettrico2)	41,60 %
rendimento termico3)	41,90 %
valore caratteristico4)	0,99 kWhel/kWhth
potere calorifico biogas5)	5,62 kWh / m³
potere calorifico metano	10,00 kWh / m³

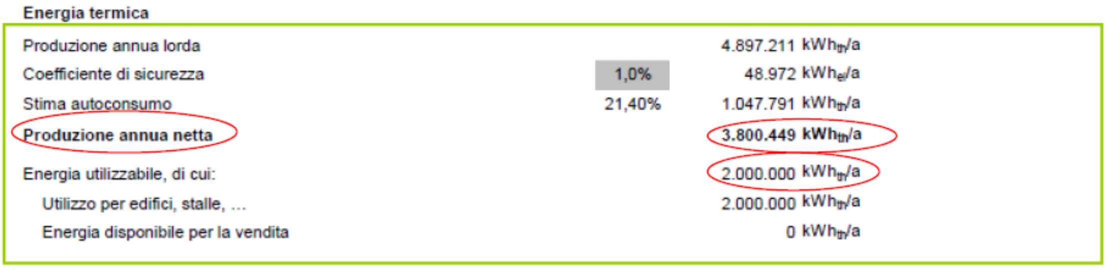
* calcolato sul 50% di metano

Table 4.13. Main components Simulation A



Energia elettrica		
Ore d'esercizio a pieno carico6)		**8.108 h/a**
Carico annuo del cogeneratore7)		**92,56 %**
Produzione annua lorda		**4.864.779 kWh$_{el}$/a**
Consumi ausiliari (cogeneratore + impianto)	9,0%	437.830 kWh$_{el}$/a
Perdite sulla linea	1,0%	44.269 kWh$_{el}$/a
Produzione annua netta		**4.382.680 kWh$_{el}$/a**
Consumi ausiliari (valore convenzionale DM 6 luglio 2012)	11,0%	535.126 kWh$_{el}$/a
Energia incentivata con tariffa onnicomprensiva		**4.329.654 kWh$_{el}$/a**
Energia elettrica non incentivata		**53.026 kWh$_{el}$/a**

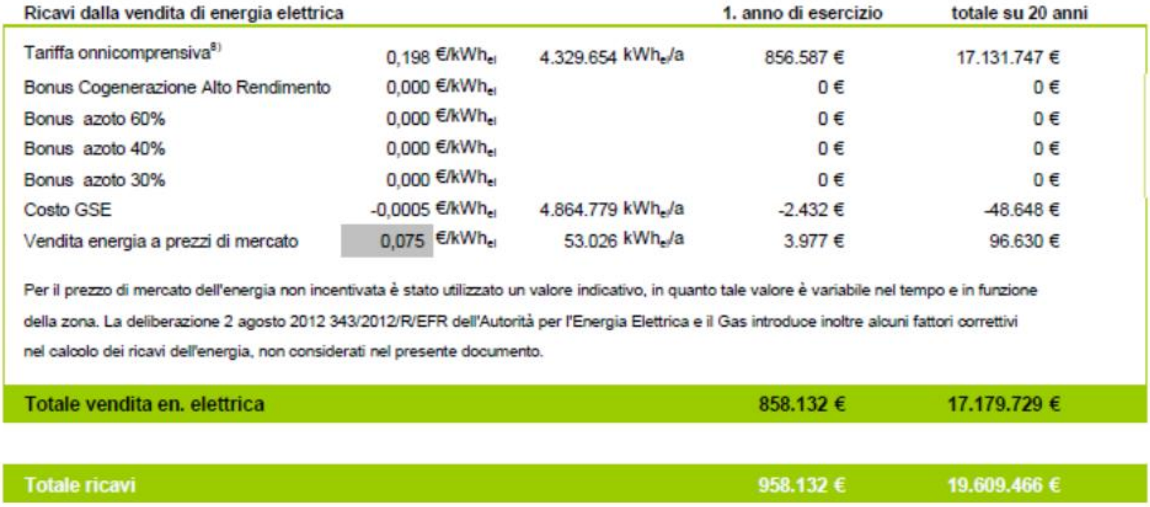
Table 4.14. Electricity production Simulation A



Energia termica		
Produzione annua lorda		4.897.211 kWh$_{th}$/a
Coefficiente di sicurezza	1,0%	48.972 kWh$_{el}$/a
Stima autoconsumo	21,40%	1.047.791 kWh$_{th}$/a
Produzione annua netta		**3.800.449 kWh$_{th}$/a**
Energia utilizzabile, di cui:		2.000.000 kWh$_{th}$/a
Utilizzo per edifici, stalle, ...		2.000.000 kWh$_{th}$/a
Energia disponibile per la vendita		0 kWh$_{th}$/a

Table 4.15. Thermal production Simulation A

Revenues (Table 4.16):



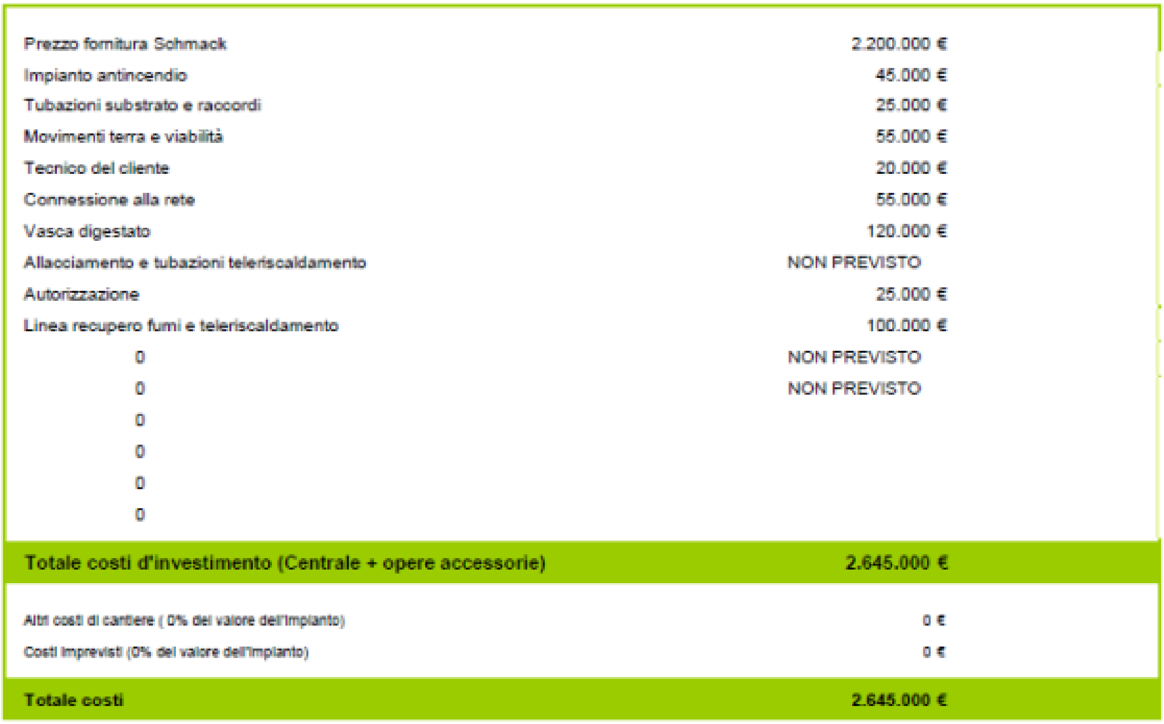
Ricavi dalla vendita di energia elettrica				1. anno di esercizio	totale su 20 anni
Tariffa onnicomprensiva[8)]	0,198	€/kWh$_{el}$	4.329.654 kWh$_e$/a	856.587 €	17.131.747 €
Bonus Cogenerazione Alto Rendimento	0,000	€/kWh$_{el}$		0 €	0 €
Bonus azoto 60%	0,000	€/kWh$_{el}$		0 €	0 €
Bonus azoto 40%	0,000	€/kWh$_{el}$		0 €	0 €
Bonus azoto 30%	0,000	€/kWh$_{el}$		0 €	0 €
Costo GSE	-0,0005	€/kWh$_{el}$	4.864.779 kWh$_e$/a	-2.432 €	-48.648 €
Vendita energia a prezzi di mercato	0,075	€/kWh$_{el}$	53.026 kWh$_e$/a	3.977 €	96.630 €

Per il prezzo di mercato dell'energia non incentivata è stato utilizzato un valore indicativo, in quanto tale valore è variabile nel tempo e in funzione della zona. La deliberazione 2 agosto 2012 343/2012/R/EFR dell'Autorità per l'Energia Elettrica e il Gas introduce inoltre alcuni fattori correttivi nel calcolo dei ricavi dell'energia, non considerati nel presente documento.

Totale vendita en. elettrica	**858.132 €**	**17.179.729 €**
Totale ricavi	**958.132 €**	**19.609.466 €**

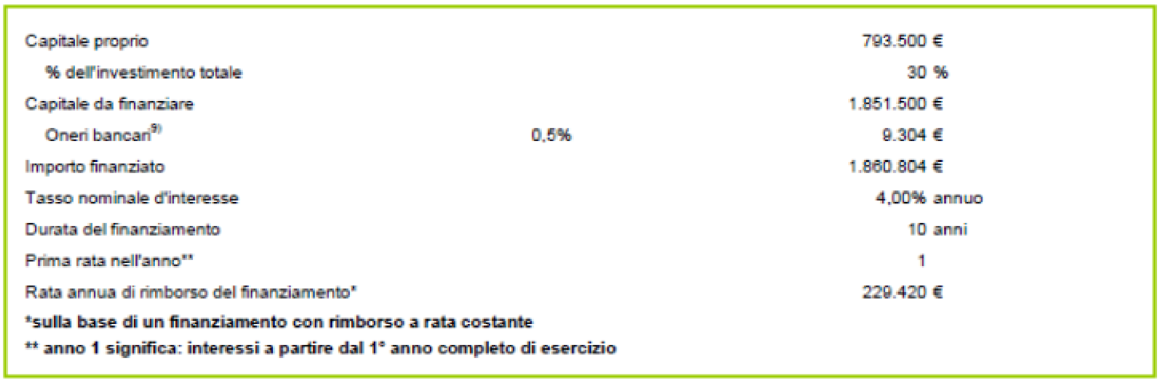
Table 4.16. Revenues from sales of electricity Simulation A.

Costs (Table 4.17-4.19):



Prezzo fornitura Schmack	2.200.000 €
Impianto antincendio	45.000 €
Tubazioni substrato e raccordi	25.000 €
Movimenti terra e viabilità	55.000 €
Tecnico del cliente	20.000 €
Connessione alla rete	55.000 €
Vasca digestato	120.000 €
Allacciamento e tubazioni teleriscaldamento	NON PREVISTO
Autorizzazione	25.000 €
Linea recupero fumi e teleriscaldamento	100.000 €
0	NON PREVISTO
0	NON PREVISTO
0	
0	
0	
0	
Totale costi d'investimento (Centrale + opere accessorie)	**2.645.000 €**
Altri costi di cantiere (0% del valore dell'impianto)	0 €
Costi imprevisti (0% del valore dell'impianto)	0 €
Totale costi	**2.645.000 €**

Table 4.17. Investment costs Simulation A

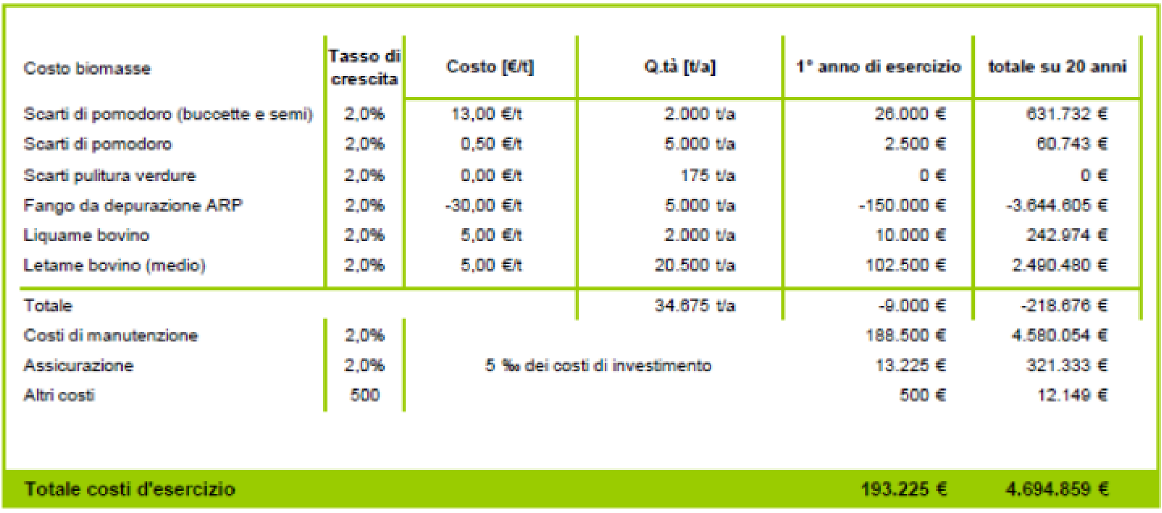


Capitale proprio		793.500 €
% dell'investimento totale		30 %
Capitale da finanziare		1.851.500 €
Oneri bancari[9]	0,5%	9.304 €
Importo finanziato		1.860.804 €
Tasso nominale d'interesse		4,00% annuo
Durata del finanziamento		10 anni
Prima rata nell'anno**		1
Rata annua di rimborso del finanziamento*		229.420 €

***sulla base di un finanziamento con rimborso a rata costante**

**** anno 1 significa: interessi a partire dal 1° anno completo di esercizio**

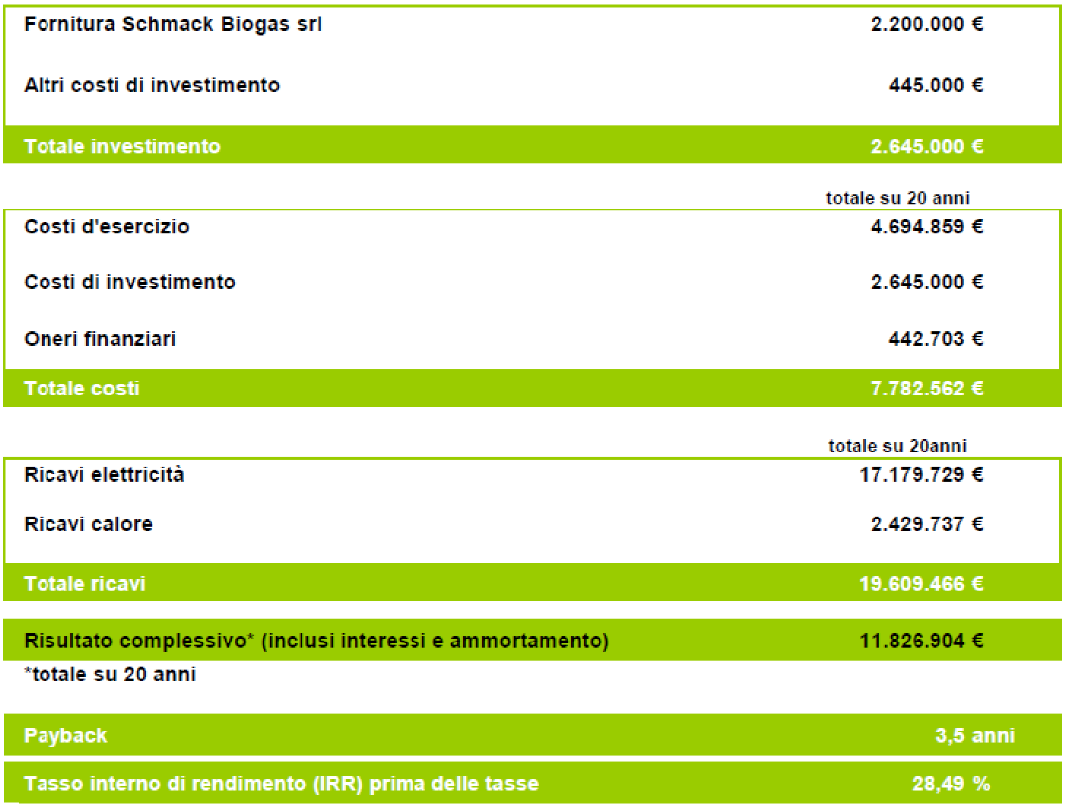
Table 4.18. Financial cost Simulation A



Costo biomasse	Tasso di crescita	Costo [€/t]	Q.tà [t/a]	1° anno di esercizio	totale su 20 anni
Scarti di pomodoro (bucette e semi)	2,0%	13,00 €/t	2.000 t/a	26.000 €	631.732 €
Scarti di pomodoro	2,0%	0,50 €/t	5.000 t/a	2.500 €	60.743 €
Scarti pulitura verdure	2,0%	0,00 €/t	175 t/a	0 €	0 €
Fango da depurazione ARP	2,0%	-30,00 €/t	5.000 t/a	-150.000 €	-3.644.605 €
Liquame bovino	2,0%	5,00 €/t	2.000 t/a	10.000 €	242.974 €
Letame bovino (medio)	2,0%	5,00 €/t	20.500 t/a	102.500 €	2.490.480 €
Totale			34.675 t/a	-9.000 €	-218.676 €
Costi di manutenzione	2,0%			188.500 €	4.580.054 €
Assicurazione	2,0%	5 ‰ dei costi di investimento		13.225 €	321.333 €
Altri costi	500			500 €	12.149 €
Totale costi d'esercizio				**193.225 €**	**4.694.859 €**

Table 4.19. Operating Cost Simulation A

In Table 4.20 it can be seen a summary of the costs and revenues from the realization of Simulation A: biogas plant built at the Soc. Coop. Agr. A.R.P. Tomato.



Fornitura Schmack Biogas srl	2.200.000 €
Altri costi di investimento	445.000 €
Totale investimento	**2.645.000 €**
	totale su 20 anni
Costi d'esercizio	4.694.859 €
Costi di investimento	2.645.000 €
Oneri finanziari	442.703 €
Totale costi	**7.782.562 €**
	totale su 20anni
Ricavi elettricità	17.179.729 €
Ricavi calore	2.429.737 €
Totale ricavi	**19.609.466 €**
Risultato complessivo* (inclusi interessi e ammortamento)	11.826.904 €
*totale su 20 anni	
Payback	**3,5 anni**
Tasso interno di rendimento (IRR) prima delle tasse	**28,49 %**

Table 4.20. Summary Simulation A.

4.5.3.2 Simulation B

To assess more in detail the new transport cost, the distances of farms compared to the new site should be recalculated. For caution, it has been decided to maintain the same parameter of cost, due to the longer distance.

In figures 20 and 21 two diagrams represent the percentages by mass and energy of the residues from company n. 3, as the place of plant construction (red), from the other partners (green) and those arising from A.R.P. (yellow) for the production of electricity.

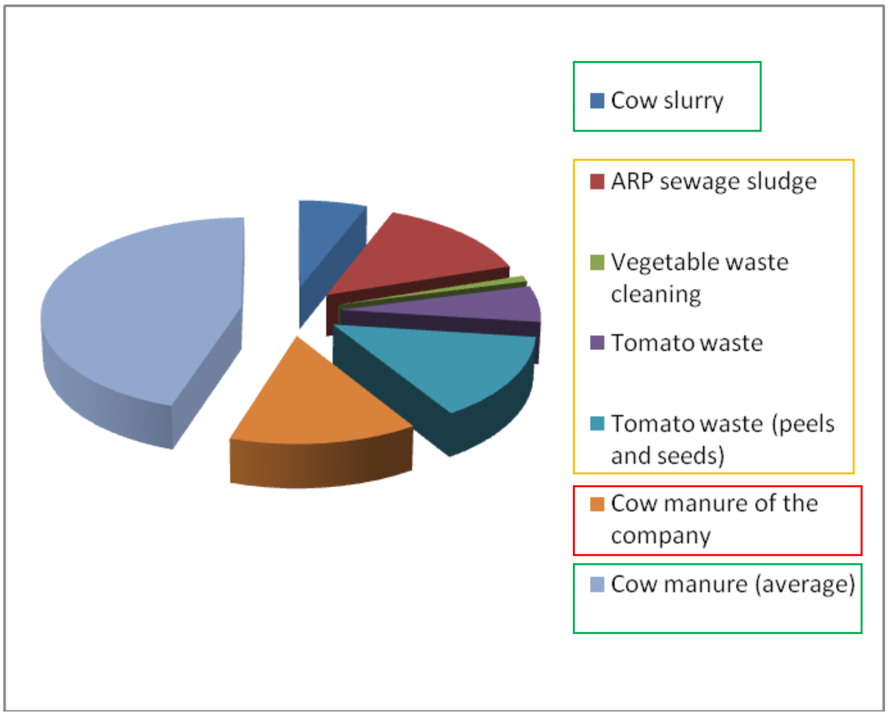


Figure 4.20. % mass of residues from company n. 3 and from the other members (including A.R.P.) for the production of electricity

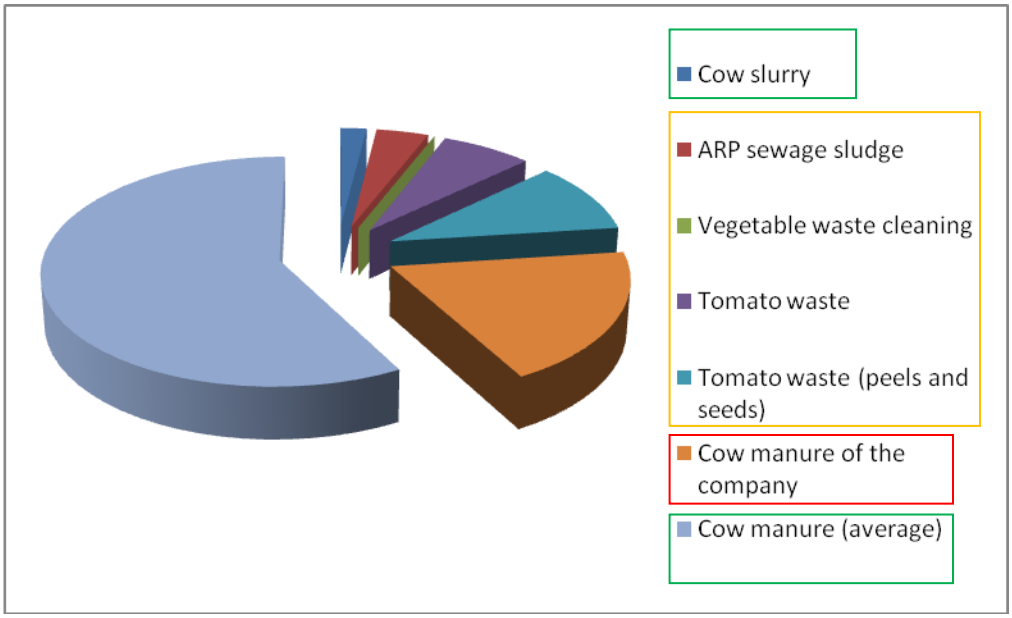


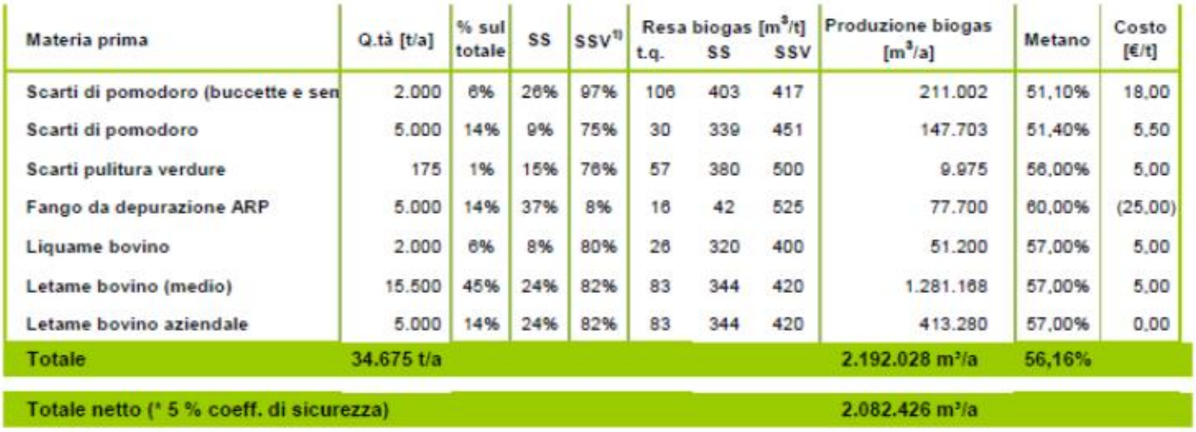
Figure 4.21. % energy of residues from company n. 3 and from the other members (including A.R.P.) for the production of electricity

Also in this case, the electricity produced cannot be self-consumed.

In the hypothesis of the non-exploitation of the sludge produced at A.R.P. there is no recovery of heat.

All the details of costs, revenues and recovery of Simulation B are in tables 4.21-4.29.

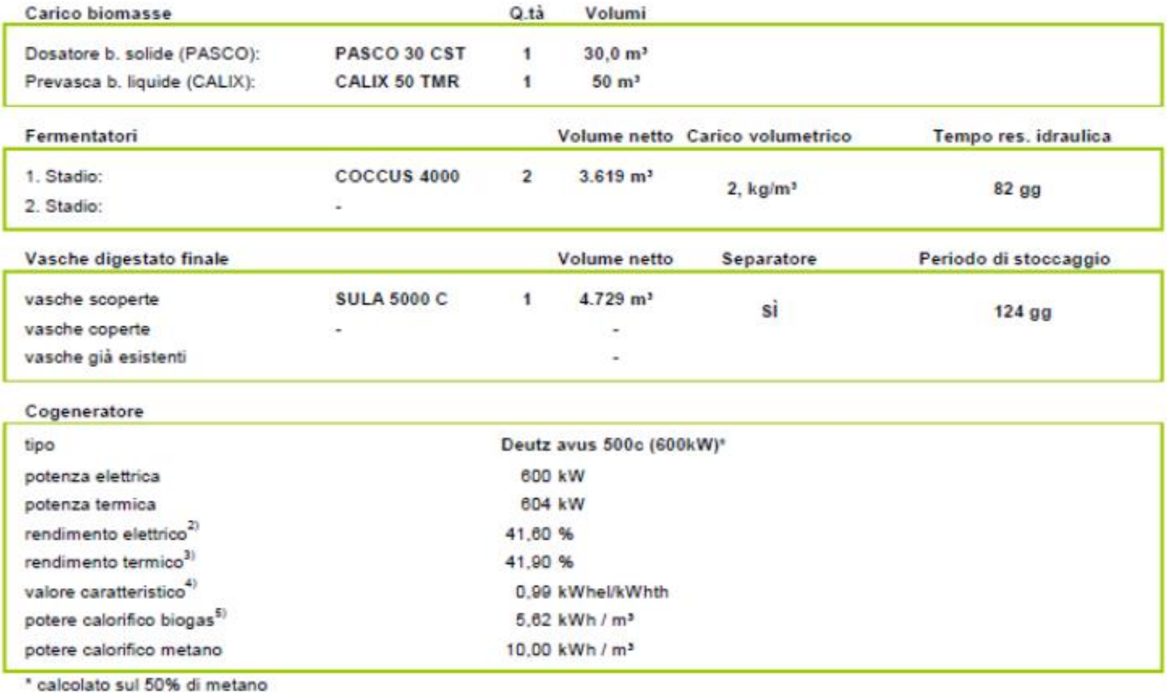
In Table 4.21 it can be seen to see the feed table suggested by Schmack:



Materia prima	Q.tà [t/a]	% sul totale	SS	SSV[1]	Resa biogas [m³/t] t.q.	SS	SSV	Produzione biogas [m³/a]	Metano	Costo [€/t]
Scarti di pomodoro (buccette e sen	2.000	6%	26%	97%	106	403	417	211.002	51,10%	18,00
Scarti di pomodoro	5.000	14%	9%	75%	30	339	451	147.703	51,40%	5,50
Scarti pulitura verdure	175	1%	15%	76%	57	380	500	9.975	56,00%	5,00
Fango da depurazione ARP	5.000	14%	37%	8%	16	42	525	77.700	60,00%	(25,00)
Liquame bovino	2.000	6%	8%	80%	26	320	400	51.200	57,00%	5,00
Letame bovino (medio)	15.500	45%	24%	82%	83	344	420	1.281.168	57,00%	5,00
Letame bovino aziendale	5.000	14%	24%	82%	83	344	420	413.280	57,00%	0,00
Totale	**34.675 t/a**							**2.192.028 m³/a**	**56,16%**	
Totale netto (* 5 % coeff. di sicurezza)								**2.082.426 m³/a**		

Table 4.21. Input plant built at company n. 3.

The plant data (Table 4.22-4.24):



Carico biomasse		Q.tà	Volumi
Dosatore b. solide (PASCO):	PASCO 30 CST	1	30,0 m³
Prevasca b. liquide (CALIX):	CALIX 50 TMR	1	50 m³

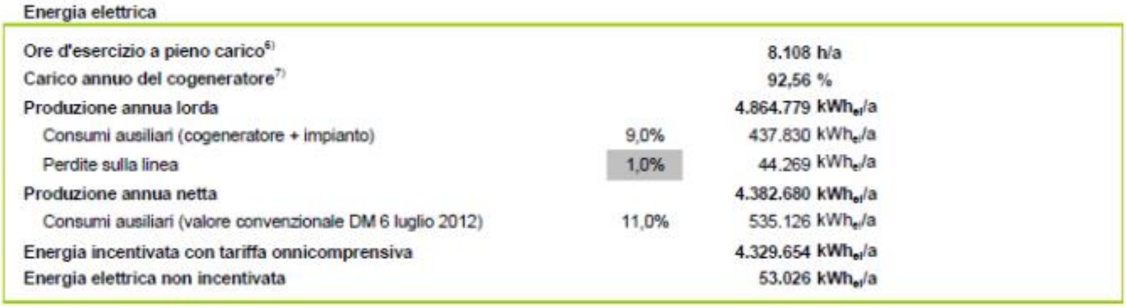
Fermentatori			Volume netto	Carico volumetrico	Tempo res. idraulica
1. Stadio:	COCCUS 4000	2	3.619 m³	2, kg/m³	82 gg
2. Stadio:	-				

Vasche digestato finale			Volume netto	Separatore	Periodo di stoccaggio
vasche scoperte	SULA 5000 C	1	4.729 m³	sì	124 gg
vasche coperte	-		-		
vasche già esistenti			-		

Cogeneratore	
tipo	Deutz avus 500c (600kW)*
potenza elettrica	600 kW
potenza termica	604 kW
rendimento elettrico[2]	41,60 %
rendimento termico[3]	41,90 %
valore caratteristico[4]	0,99 kWhel/kWhth
potere calorifico biogas[5]	5,62 kWh / m³
potere calorifico metano	10,00 kWh / m³

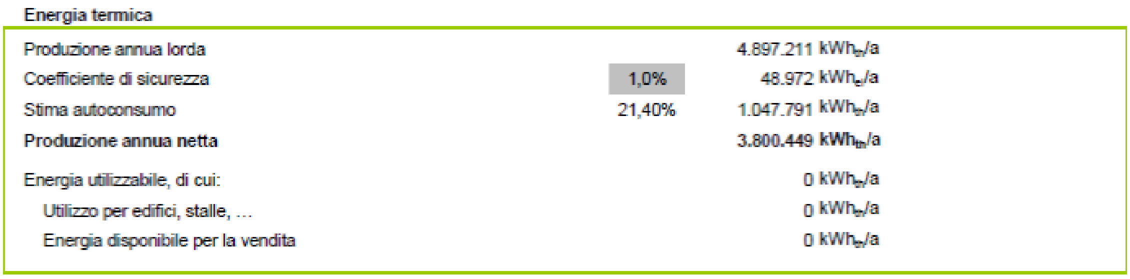
* calcolato sul 50% di metano

Table 4.22. Main component Simulation B.



Energia elettrica		
Ore d'esercizio a pieno carico[6]		8.108 h/a
Carico annuo del cogeneratore[7]		92,56 %
Produzione annua lorda		4.864.779 kWh_{el}/a
Consumi ausiliari (cogeneratore + impianto)	9,0%	437.830 kWh_{el}/a
Perdite sulla linea	1,0%	44.269 kWh_{el}/a
Produzione annua netta		4.382.680 kWh_{el}/a
Consumi ausiliari (valore convenzionale DM 6 luglio 2012)	11,0%	535.126 kWh_{el}/a
Energia incentivata con tariffa onnicomprensiva		4.329.654 kWh_{el}/a
Energia elettrica non incentivata		53.026 kWh_{el}/a

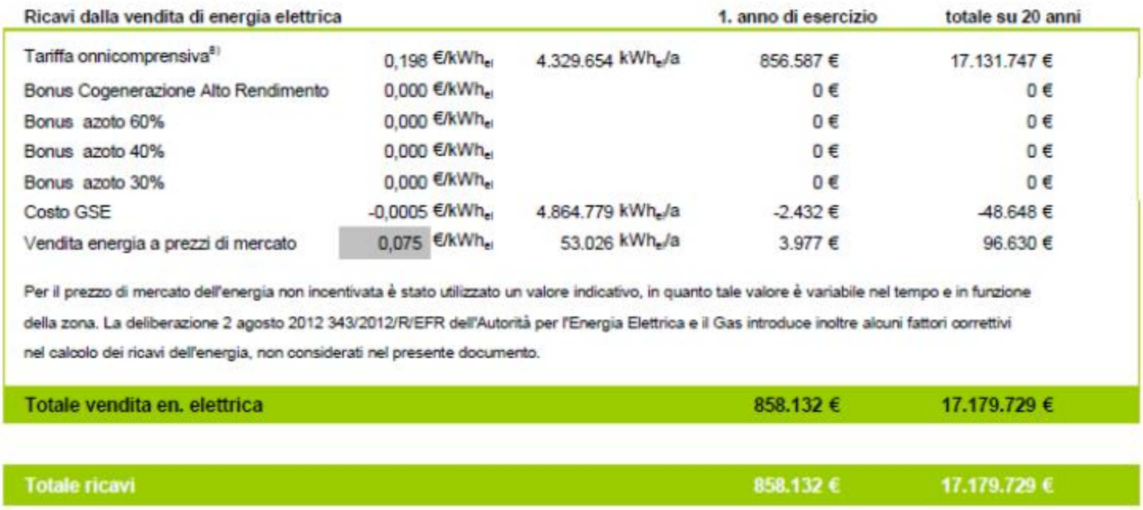
Table 4.23. Electricity production Simulation B.



Energia termica		
Produzione annua lorda		4.897.211 kWh$_{th}$/a
Coefficiente di sicurezza	1,0%	48.972 kWh$_{th}$/a
Stima autoconsumo	21,40%	1.047.791 kWh$_{th}$/a
Produzione annua netta		**3.800.449 kWh$_{th}$/a**
Energia utilizzabile, di cui:		0 kWh$_{th}$/a
Utilizzo per edifici, stalle, …		0 kWh$_{th}$/a
Energia disponibile per la vendita		0 kWh$_{th}$/a

Table 24. Thermal energy production Simulation B

Revenues (Table 4.25):

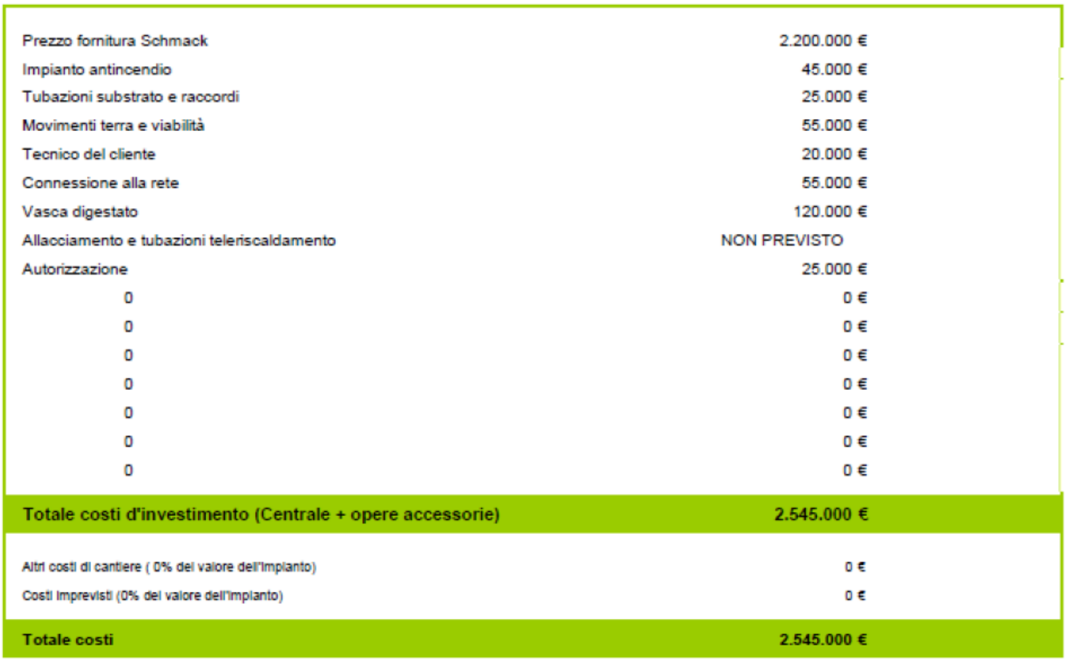


Ricavi dalla vendita di energia elettrica			1. anno di esercizio	totale su 20 anni
Tariffa onnicomprensiva[8]	0,198 €/kWh$_{el}$	4.329.654 kWh$_{el}$/a	856.587 €	17.131.747 €
Bonus Cogenerazione Alto Rendimento	0,000 €/kWh$_{el}$		0 €	0 €
Bonus azoto 60%	0,000 €/kWh$_{el}$		0 €	0 €
Bonus azoto 40%	0,000 €/kWh$_{el}$		0 €	0 €
Bonus azoto 30%	0,000 €/kWh$_{el}$		0 €	0 €
Costo GSE	-0,0005 €/kWh$_{el}$	4.864.779 kWh$_{el}$/a	-2.432 €	-48.648 €
Vendita energia a prezzi di mercato	0,075 €/kWh$_{el}$	53.026 kWh$_{el}$/a	3.977 €	96.630 €
Totale vendita en. elettrica			**858.132 €**	**17.179.729 €**
Totale ricavi			**858.132 €**	**17.179.729 €**

Per il prezzo di mercato dell'energia non incentivata è stato utilizzato un valore indicativo, in quanto tale valore è variabile nel tempo e in funzione della zona. La deliberazione 2 agosto 2012 343/2012/R/EFR dell'Autorità per l'Energia Elettrica e il Gas introduce inoltre alcuni fattori correttivi nel calcolo dei ricavi dell'energia, non considerati nel presente documento.

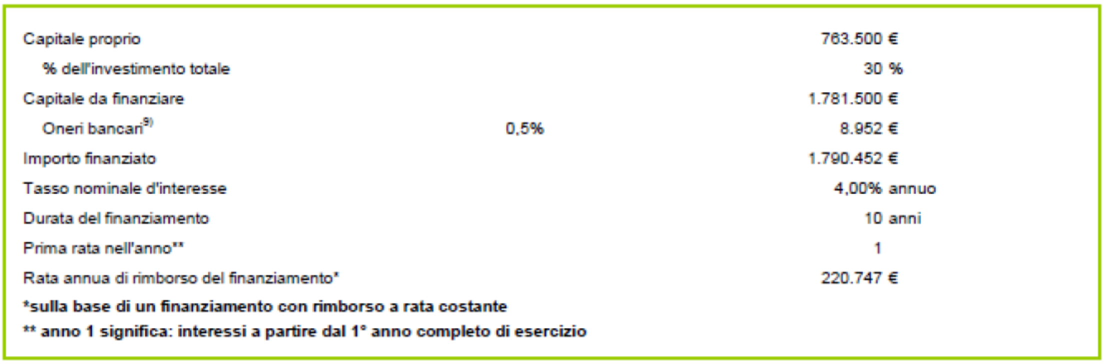
Table 4.25. Revenues Simulation B.

Costs (Table 4.26-4.28):



Prezzo fornitura Schmack	2.200.000 €
Impianto antincendio	45.000 €
Tubazioni substrato e raccordi	25.000 €
Movimenti terra e viabilità	55.000 €
Tecnico del cliente	20.000 €
Connessione alla rete	55.000 €
Vasca digestato	120.000 €
Allacciamento e tubazioni teleriscaldamento	NON PREVISTO
Autorizzazione	25.000 €
0	0 €
0	0 €
0	0 €
0	0 €
0	0 €
0	0 €
0	0 €
Totale costi d'investimento (Centrale + opere accessorie)	**2.545.000 €**
Altri costi di cantiere (0% del valore dell'impianto)	0 €
Costi imprevisti (0% del valore dell'impianto)	0 €
Totale costi	**2.545.000 €**

Table 4.26. Investment costs Simulation B.

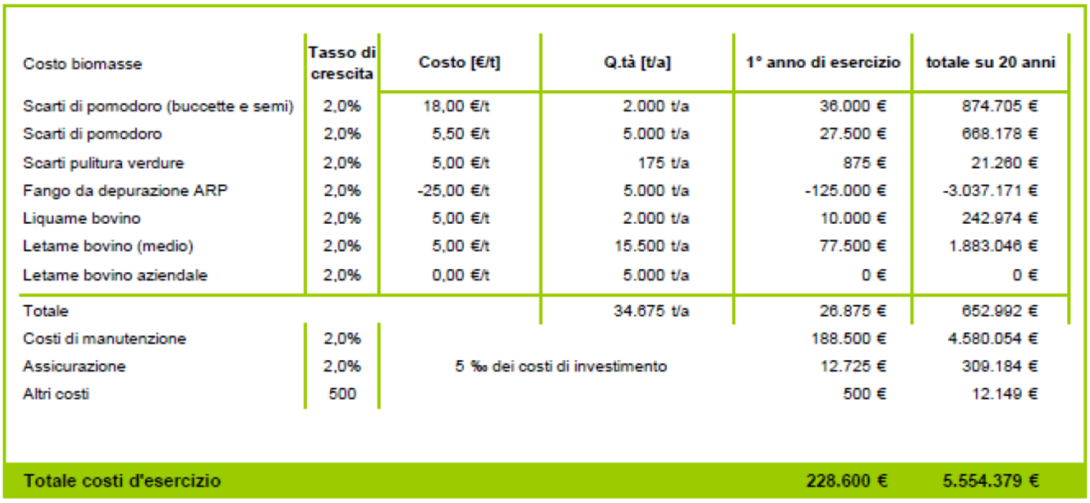


Capitale proprio		763.500 €
% dell'investimento totale		30 %
Capitale da finanziare		1.781.500 €
Oneri bancari[9)]	0,5%	8.952 €
Importo finanziato		1.790.452 €
Tasso nominale d'interesse		4,00% annuo
Durata del finanziamento		10 anni
Prima rata nell'anno**		1
Rata annua di rimborso del finanziamento*		220.747 €

***sulla base di un finanziamento con rimborso a rata costante**

**** anno 1 significa: interessi a partire dal 1° anno completo di esercizio**

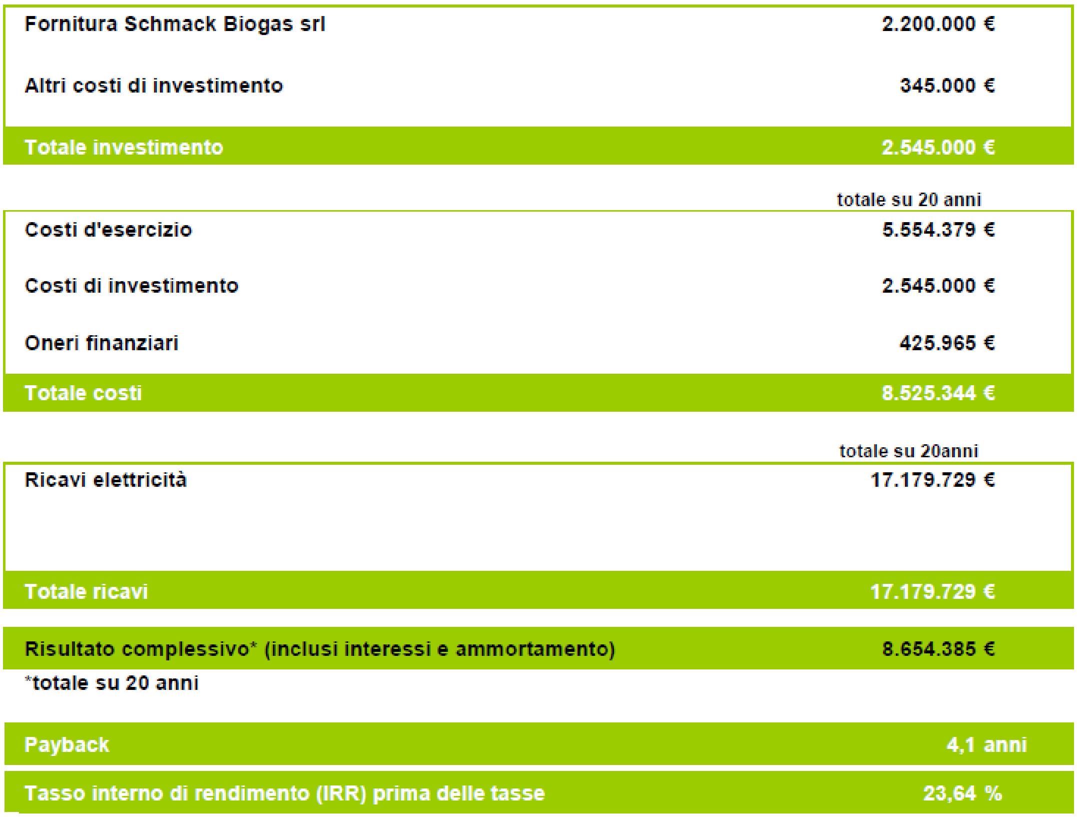
Table 4.27. Financial cost Simulation B.



Costo biomasse	Tasso di crescita	Costo [€/t]	Q.tà [t/a]	1° anno di esercizio	totale su 20 anni
Scarti di pomodoro (buccette e semi)	2,0%	18,00 €/t	2.000 t/a	36.000 €	874.705 €
Scarti di pomodoro	2,0%	5,50 €/t	5.000 t/a	27.500 €	668.178 €
Scarti pulitura verdure	2,0%	5,00 €/t	175 t/a	875 €	21.260 €
Fango da depurazione ARP	2,0%	-25,00 €/t	5.000 t/a	-125.000 €	-3.037.171 €
Liquame bovino	2,0%	5,00 €/t	2.000 t/a	10.000 €	242.974 €
Letame bovino (medio)	2,0%	5,00 €/t	15.500 t/a	77.500 €	1.883.046 €
Letame bovino aziendale	2,0%	0,00 €/t	5.000 t/a	0 €	0 €
Totale			34.675 t/a	26.875 €	652.992 €
Costi di manutenzione	2,0%			188.500 €	4.580.054 €
Assicurazione	2,0%	5 ‰ dei costi di investimento		12.725 €	309.184 €
Altri costi	500			500 €	12.149 €
Totale costi d'esercizio				**228.600 €**	**5.554.379 €**

Table 4.28. Operating costs Simulation B.

In Table 4.29 it can be seen a summary of the costs and revenues from the realization of Simulation B: plant realized at one of the others partners involved.



Fornitura Schmack Biogas srl	2.200.000 €
Altri costi di investimento	345.000 €
Totale investimento	**2.545.000 €**

	totale su 20 anni
Costi d'esercizio	5.554.379 €
Costi di investimento	2.545.000 €
Oneri finanziari	425.965 €
Totale costi	**8.525.344 €**

	totale su 20anni
Ricavi elettricità	17.179.729 €
Totale ricavi	**17.179.729 €**

Risultato complessivo* (inclusi interessi e ammortamento)	8.654.385 €

*totale su 20 anni

Payback	**4,1 anni**
Tasso interno di rendimento (IRR) prima delle tasse	**23,64 %**

Table 4.29. Summary Simulation B

4.5.4 Future scenarios: the new Decree for the promotion of biogas plants for the production of Biomethane

The decree of 5 December 2013 about the incentive of “bio-methane” was published in the Official Gazette of Italian Republic (G.U. 295 of 17/12/2013) [39]. It is a decision long-awaited also for the potential involvement of the agro-zoo-technical sector, because bio-methane represents an extension of the biogas chain, and thus it could also derived from agricultural products and by-products.

Bio-methane is the biogas subjected to chemical-physical treatments, which assumes characteristics wholly comparable to natural gas (methane). It must also be pointed out that the source of bio-methane differs substantially from methane because the former is renewable, the latter fossil. Another important feature of bio-methane is that it can be considered a biofuel, because it can be used in the transport sector.

Through the aid of the Smack Biogas s.r.l. company an estimation of the realization of the same plant converted to bio-methane has been assessed, obtaining that both simulations would have a flow rate of about 300 m^3/h of biogas (about 170 m^3/h of refined bio-methane).

4.5.5 Personal conclusions and recommendation

From the analysis of the results obtained, it appears that there is a greater convenience in making the anaerobic fermentation plant (biogas) at the SOC. COOP. AGR. A.R.P. Tomato considering different point of view.

Economic:

- realizing the plant at A.R.P. it has a higher gain due to the avoided cost of disposal of agro-industrial residues;
- realizing the plant at A.R.P. (Simulation A) an IRR (Internal Rate of Return) of 28.49% is obtained, against an IRR of 23.64% in the case of the construction of the plant at the company n. 3 (Simulation B).

Entrepreneurial:

- in both solutions, there is an increase in employment/job stability and an increase of the technical skills of the staff;
- in both solutions the new plant would allow the achievement of a “Greener” image of the company.

Managerial:

- realizing the plant at A.R.P. (Simulation A), it would be also possible to recycle the sludge arising from A.R.P. processes, which may not be used in the case that the plant is realized at the company n. 3;
- Realizing the plant at A.R.P. (Simulation A) a closure of business cycles would result.

Environmental:

- In both solutions the energy is produced from renewable sources contributing to pursuit the objectives set by the European Union for the use of renewable energy sources: 20%, -20%, -20% for renewable energy sources, energy savings and CO_2 emissions reduction to 2020 [3];
- in both solutions, there is a decrease of transport for disposal or transfer of agro-industrial residues;
- in both solutions, there is a decrease of waste produced and/or placed outside for disposal and/or recovery.

Other aspects should also be taken into account, such as the necessary remuneration of the company n. 3 for the activities carried out in case of Simulation B; in the case of the construction of the plant at A.R.P. (Simulation A) there may also be additional savings related to maintenance costs through the acquisition of skills by technicians already employed in A.R.P.

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5. Material recovery processes

5.1 The case study of a pyrolysis process applied to end-of-life tires

This work comes from a collaboration with the company Curti S.p.a.

5.1.1 Background and motivation

The sustainability report of Ecopneus 2015 [10] states that in 2014 were introduced in the national market more than 23 million of new tires, amounting to 256491 tons. The total collection of ELT (End of Life Tires) in 2015 amounted to 247966 tons and of these 246128 tons were managed.

Following the collection, ELT are down mixed between recycler and recovery plants; in fact the end of life of tires represent an important resource of materials (about the 40% in weight of the tire is composed of rubber, while the second major component by weight is steel) and energy both. The treatments carried out on ELT are mechanical and thermal.

The first treatment is a mechanical processing at room temperature, for crushing the ELT and the separation of the components, without chemically change the composition. For low added value manufacturing shredding technologies for ELT are adopted, which allow to obtain chips varying in size from more than 300 mm up to 50-20 mm, suitable for recovery as fuel for the production of energy in power and cement plants or as materials used in engineering works. The processes with higher added value couple to a first step of grinding of the ELT a further crushing process, for example with a mill technology, which allow the obtainment of homogeneous mixtures of granules and powders of different size (from 20 to 0.8 mm for the granules and <0.8 mm for powders). Specific process devices for cleaning the materials fed into the installations, as well as other standard technologies (downstream plant modules of granulators for the separation of steel from rubber, magnetically or gravimetrically, or of textile fibers through controlled aspiration) allow a high quality in terms of purity of recycled materials.

Instead, the second type of treatment provides the use of the entire or crushed ELT as alternative fuels for energy production, using the high calorific value of ELT, similar to that of coal. ELT are thermally treated in cement plants, paper mills, in lime manufacturing plants and in thermal power plants, so in highly energy-intensive plants.

An interesting treatment of ELT is pyrolysis, a chemical process which is carried out at high temperature and in the absence of oxygen, which allows the decomposition of the organic material. The resulting products are divided into three phases:

- Solid fraction: this is a carbonaceous residue (char) in which it is possible to find also metals or fibers, if these were contained in the starting matrix;
- Liquid fraction: it is an oil rich of organic molecules having different molecular weight, such as alcohols, aldehydes, acids and ketones;
- Gaseous fraction: it is composed of hydrocarbons, in addition to CO, CO_2, H_2O and H_2.

The process provides for initial phase of shredding of the tire, to obtain a 2 to 10 cm size. They are then loaded into the reactor (heated with the fumes of pyrolysis), in which the scission of chemical bonds occurs at 500°C, leading to the formation of a solid residue (coal and metals), gases and vapors. Vapors are then condensed to separate them from the gases. As regards the non-condensable, these are then burned to obtain electric and thermal energy, while the pyrolysis oil undergoes a decantation and centrifugation to separate it from water and sludge. The solid fraction needs further treatment too, in order to separate the metal from coal, while the exhaust gases are carried in a burner, in which a reduction of NOx by SNCR (selective non-catalytic reduction) with urea and a reduction of sulfur oxides and HCl with soda is made. Once purified, the fumes are released into the atmosphere.

The sustainability Ecopneus 2015 report evaluates the environmental impacts associated with the life cycle of ELT, considering the transport of ELT, their treatment and the recovery as fuel for energy production. The calculated impacts are negative as they are evaluated with the methodological approach of the replaced product, computing the avoided impact through the production and consumption of equivalent materials. Specifically, in cement factory, the use of ELT as fuel is taken into account, avoiding the use of coal and petroleum coke, while the steel and the combustion ash are incorporated into the cement, thus permitting a further saving of material. Similarly, the ELT sent to power plants for the production of electrical energy, avoid the use of an equal amount of the national energy mix. The steel that is obtained by crushing the ELT and by combustion in power stations represents another avoided impact, being recyclable as scrap iron. The ashes resulting from the combustion in power stations always bring a negative impact because they are recycled as binder for cement or as material for road infrastructure. Finally, the rubber recycled as granules and powder, coming from a mechanical treatment of ELT, provides a further negative impact avoiding the consumption of virgin material for the composition of new compounds.

Ecopneus expresses the environmental impacts associated with the energy recovery and recycling of ELT, through the carbon footprint (tons of equivalent CO_2), the material footprint (tons of resources) and the water footprint (m^3 of water), as shown in Table 5.1 and 5.2.

Energy recovery	$tCO_{2\ eq}$	tons of resources	m^3 of water
Emissions from processing and burning of ELT	171.174	16.870	291.222
Avoided emissions by replacing other fuels and materials	-356.618	-162.882	-840.112
Emissions balance	-185.444	-146.012	-548.890

Table 5.1. Emissions associated with the recovery of energy from ELT.

Recycling	$tCO_{2\ eq}$	tons of resources	m^3 of water
Emissions generated for the production of granules and powders of ELT	16.717	7.361	85.898
Avoided emissions by recycling of the component materials	-207.294	-214.114	-1.337.403
Emissions balance	-190.577	-206.753	-1.251.505

Table 5.2. Emissions associated with the recycling of ELT.

It is therefore clear that the energy recovery of ELT and their recycling represent environmental benefits.

Analyzing the data provided by the Ecopneus report, the 67.6% (in terms of carbon footprint) of emissions generated is given by the processing and combustion of ELT in cement plants: 3 in Italy and 8 abroad, located in Romania, Morocco, Turkey, Austria and Germany; Torretta et al. [11], compared how used tires are treated and disposed in two different countries (Italy and Romania) to investigate differences in terms of environmental impact. These allow the replacing of others fossil fuels, such as coal and petroleum coke, whose life cycle impact for the production of a quantity of thermal energy equivalent to that recovered from ELT is very high (56.8% of the avoided emissions). Otherwise, emissions from recovery of ELT in power station (11.6%) are not offset by the benefits resulting from the avoided production of an equal amount of electricity generated by the Italian energy mix (3.7% of the avoided emissions).

As regards the resources balance (material footprint), the 53.8% of their consumption is associated with the logistic (collection and transport of ELT to the treatment systems), which involves the use of fossil resources for the generation of fuel necessary to feed hundreds of vehicles and dozens of ships, which annually drive millions of kilometers carrying the ELT. The fact that 8 out of 11 cement factories are abroad, greatly affects the generated impacts. In a scenario in which the treatment of ELT is exclusively limited to the national territory, it would lead to a lower resources consumption and therefore greater environmental benefits.

Analyzing the data provided by the Ecopneus report, it is possible to see comparable avoided impacts (in terms of carbon and material footprint) associated with energy recovery and recycling of ELT. As regard the water footprint, the avoided consumption of water associated with the recycling of ELT (as powder and granules) is significant greater than that attributed to the energy recovery. With this comparison, in the Ecopneus report, the recycling of ELT for the production of powder and granules is defined the solution with the least environmental impact.

5.1.2 Goal and scope definition

The goal of the study is the assessment of the environmental impacts of the pyrolysis process of end of life tires (ELT) of the company Curti s.p.a. and to compare it with alternative valorization and/or disposal scenarios.

For this purpose the Life Cycle Assessment methodology (LCA) has been applied to determine the most critical stages of the process under study, the environmental benefits arising from the recovery of materials and energy and the greater or lower impact compared to the mechanical or thermal technologies already on the market. Even previous works studied the environmental impact of pyrolysis process, through LCA methodology, comparing it with different scenarios of management of ELT [12-14], taking into account, for the assessment, the indirect impacts caused by energy production stage, the direct impacts caused by ELT treatment process and the avoided impacts caused by valuable products (recycled materials and energy); Clauzade et al. instead carried out a comparative environmental evaluation of the various recovery alternatives aimed at identifying the strengths and weaknesses of each recovery method [15].

The boundaries of the system are “from gate to gate”, considering the life cycle phases regarding the following operations for the production of avoided products and energy:

- treatment process (including all input and output streams for the supply and distribution of materials and energy);
- materials recovery (sent to recycling plant);
- disposal of waste water/residues.

The functional unit is the physical quantity to which report all flows and impacts (input and output): 1 ton of ELT treated by the plant of pyrolysis has been chosen as functional unit, dimensioned on 4 tons/h (primary data plant).

5.1.3 Life Cycle Inventory (LCI)

In the Life Cycle Inventory step all mass and energy flows of the processes investigated have been considered.

First of all the environmental impact of the pyrolysis plant managed by the company Curti s.p.a. has been analyzed, considering the flow diagram shown in Figure 5.2.

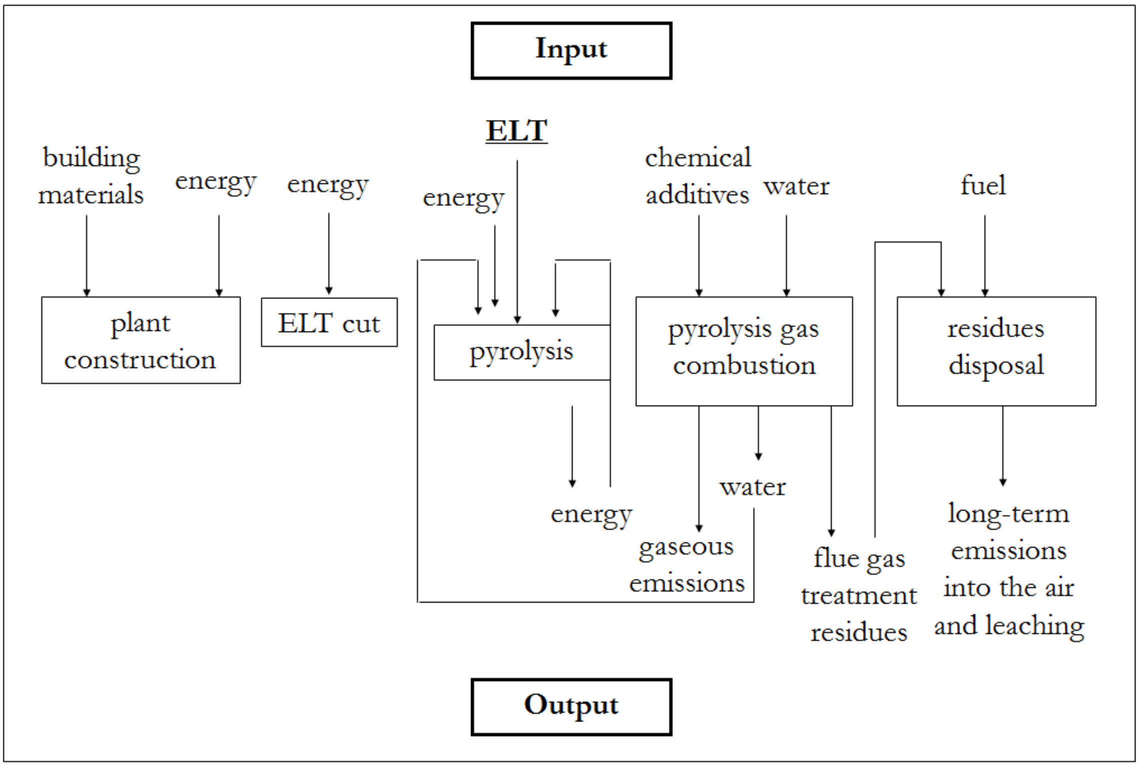

Figure 5.2. Flow diagram Curti s.p.a. pyrolysis plant.

Curti s.p.a. plant (Figure 5.2) is a pyrolysis process for the recovery of end of life tires to obtain three main products having a commercial value: carbon black, oil and steel. The peculiarity of this process object of study is that, in contrast to the common pyrolysis process, as the first step is not necessary the crushing of the tire but only the circumferential cutting of ELT, which must have a diameter of not more than 1400 mm.

All input and output considered in the scenario modelling have been reported to the functional unit chosen for the study: 1 ton of ELT treated in the plant.

Through the system it is so possible to obtain recovery of materials:

- carbon black. In the modelled scenario an equal amount of *Carbon black, at plant/GLO U* has been inserted (process already present in the reference database [5]);
- oil (a low sulfur diesel). In the modelled scenario an equal amount of *Diesel, low-sulphur, at refinery/CH U* has been inserted;
- steel. In the modelled scenario an equal amount of *Steel, low-alloyed, at plant/RER U* has been inserted.

In the model the consumption of air, sodium carbonate and urea has been inserted (necessary for the SNCR treatment) and two different input flows of electricity consumption (*Electricity, medium voltage, production IT, at grid/IT U*) considering the national energy mix: one necessary for the single cut of ELT and the other necessary for the pyrolysis process.

Moreover, the emissions into air of CO_2, NO_2 and SO_2 due to the combustion step and the waste water have been considered.

After the analysis of Curti process, a comparison between different pretreatment scenarios has been performed, considering different steps [12;14]:

- single cut, realized by Curti s.p.a.;
- grinding, with the production of ground particles of about 7-10 cm, that could be used for energy recovery (eg. electricity production, cement plant.. [10]);
- crushing, that is a further grinding to a size of about 2 cm that could be used for energy and material recovery purposes too;
- pulverization, to a size lower than 1 mm that could be used for material recovery (eg. sport floors, insulating, rubber goods..).

In every scenarios the electricity consumption and the consumption of the steel of the wear of the cutting blades have been considered, referred to 1 ton of ELT treated.

After this step Curti process has been compared to other scenarios of recovery of energy or material.

Considering the energy recovery processes, the management of 1 ton (the functional unit) of ELT has been compared for:

- Curti process;
- cement plant;
- Waste to energy process.

In the cement plant scenario the following input and output have been considered, according to Corti et al. 2004 [12]:

- the avoided use of coal (as *Hard coal supply mix/IT U*) and iron (as *Iron scrap, at plant/RER U*) due to the use of ELT (already containing the steel necessary as reinforcement for the cement);
- input of energy necessary for the co-combustion (diesel and electricity) and the electricity for the grinding step;
- emissions to air of CO, chromium, lead, NOx and NMVOC (non-methane volatile organic compound).

Concerning the waste to energy process scenario, a model containing primary data regarding a municipal solid waste (MSW) process, realized for a previous study [16], has been used.

In the second step the comparison of different recovery of material scenarios with the Curti s.p.a. process has been realized. It is known (e.g., in Ecopneus report [10]) that the recovery of materials from ELV could result in different uses: modified asphalts, sports surfaces, anti-trauma surfaces for playgrounds. Thus, the recovered ELV could substitute different kinds of material, and cannot be considered as a recycling of an equivalent amount of synthetic rubber (which has a very versatile use, in many different applications).

In order to take into account an avoided impact, due to the recycling of ELV, three different cases were considered:

- Case 1. In the first scenario the avoided impact due to the recovery of iron (*Iron scrap, at plant/RER U*), the recovery of plastic material as an avoided production of synthetic rubber (*Synthetic rubber, at plant/RER U*) and the recovery of the fiber as an avoided production of material for subfloor road, such as bitumen (*Bitumen, at refinery/RER U*), have been considered;
- Case 2. In the second scenario the avoided impact due to the recovery of iron and the recovery of the plastic material and of the fiber as an avoided production of the equivalent amount of different materials such as synthetic rubber, bitumen and sand (with the proportion of one third, each), have been considered;
- Case 3. In the third scenario the avoided impact due to the recovery of iron, the recovery of plastic material as an avoided production of natural rubber (to assess the difference of impact compared to the use of synthetic rubber), and the recovery of the

fiber as an avoided production of material for subfloor road, such as bitumen, have been considered.

All the three scenarios have been modelled considering the same functional unit (1 ton of recovered ELT) and in all the models the input of electricity necessary for the pulverization step and the emission of particulate matter into the air have been inserted.

5.1.4 Impact assessment and results interpretation

The Life Cycle Impact Assessment (LCIA) stage was carried out using the ReCiPe analysis method [6], considering five impact categories at midpoint level, such as climate change, human toxicity, particulate matter formation (PMF), fossil fuels depletion and metal depletion; and the three categories of damage to human health, to the ecosystem quality and to resources depletion. In the following paragraphs, the results related to different scenarios have been reported and discussed.

First of all, Curti process has been analyzed to obtain a global assessment in terms of endpoint (Figure 5.3) and midpoint categories (Figure 5.4).

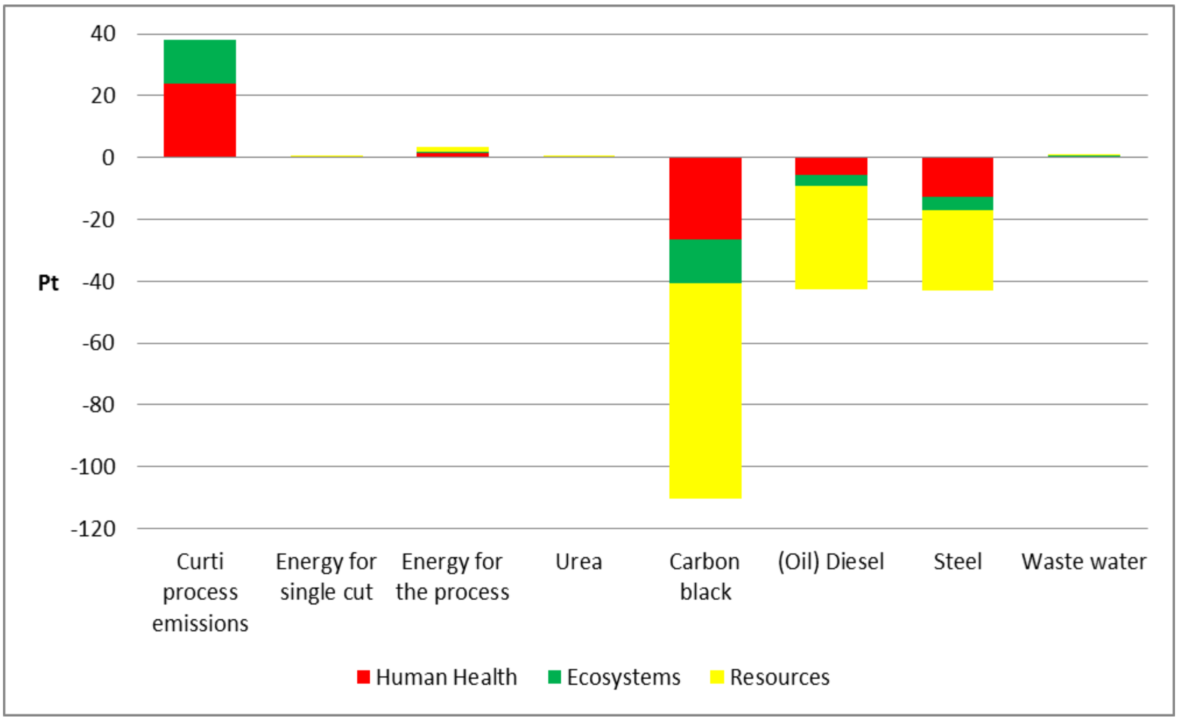

Figure 5.3. Single Point: impact of the Curti s.p.a. process, impact categories endpoint.

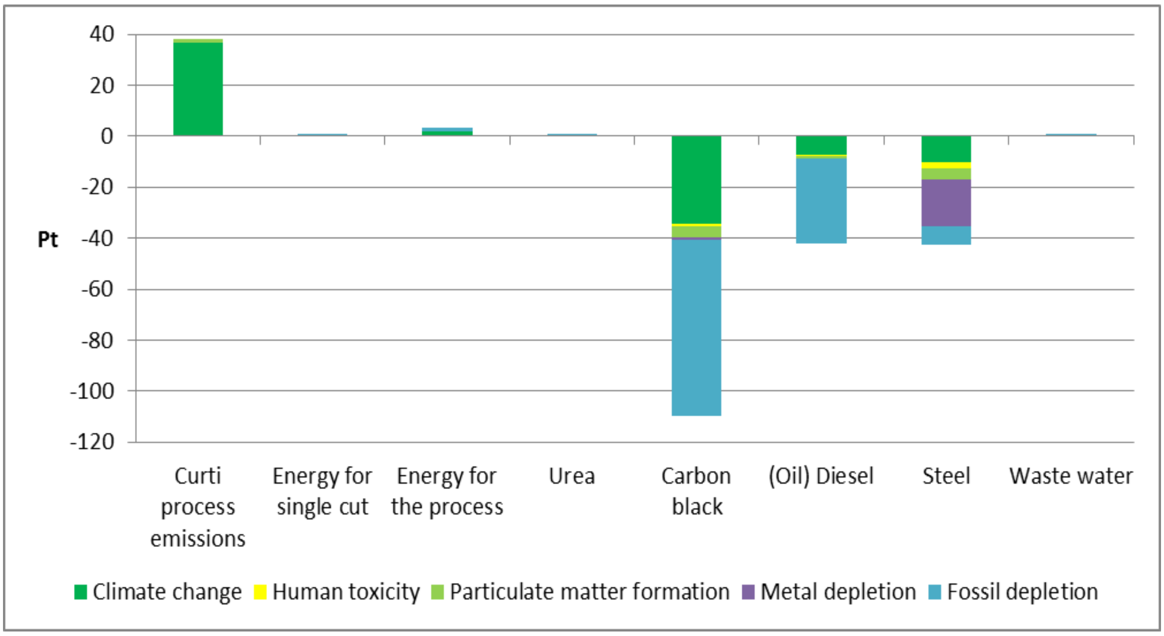

Figure 5.4. Single Point: impact of the Curti s.p.a. process, impact categories midpoint.

Results show how the avoided impact due to the recovery of carbon black, steel and oil fuel exceeds widely (more than an order of magnitude) the impact generated by the process (for which the power consumption for the cut and for the co-combustion accounts for about 10%), with a gain in terms of avoided impact especially related to damage category resources depletion (Figure 5.2, in yellow). Therefore the environmental benefits are greater than impacts, especially considering the impact categories of climate change, fossil fuel depletion and metal depletion (directly related to the recovery of steel), as shown in Table 5.3.

	Climate change	**Human toxicity**	**Particulate matter formation**	**Metal depletion**	**Fossil depletion**
Unit	Pt	Pt	Pt	Pt	Pt
Curti process emissions	3.66E+01	0	1.67E+00	0	0
Energy for single cut	4.02E-01	1.77E-02	5.49E-02	3.37E-03	2.85E-01
Energy for the process	1.68E+00	7.46E-02	2.31E-01	1.42E-02	1.20E+00
Urea	2.61E-01	1.92E-02	4.38E-02	1.72E-02	2.55E-01
Carbon black	-3.43E+01	-8.35E-01	-4.73E+00	-9.53E-01	-6.88E+01
Oil (Diesel)	-7.40E+00	-2.40E-01	-1.01E+00	-8.44E-02	-3.32E+01
Steel	-1.01E+01	-2.50E+00	-4.16E+00	-1.85E+01	-7.34E+00
Waste water	5.31E-01	8.21E-04	4.01E-02	7.76E-05	7.68E-02

Table 5.3. Single Point: impact of the Curti s.p.a. process, impact categories midpoint.

After the analysis of Curti process, a comparison between different pretreatment scenarios, upstream to the pyrolysis combustion, has been performed (Figure 5.5, Table 5.4).

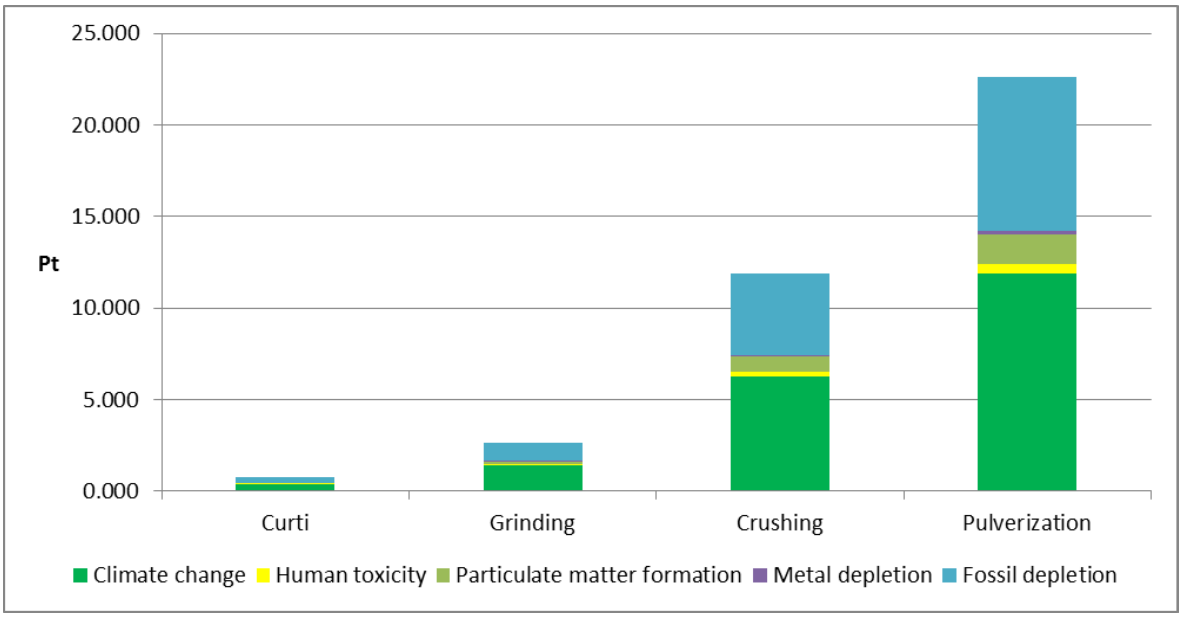

Figure 5.5. Single Point: impact of pretreatment processes, impact categories midpoint.

	Unit	Curti	Grinding	Crushing	Pulverization
Climate change	Pt	0.0402	1.391	6.240	11.870
Human toxicity	Pt	0.018	0.062	0.276	0.530
Particulate matter formation	Pt	0.055	0.190	0.854	1.630
Metal depletion	Pt	0.003	0.013	0.055	0.155
Fossil depletion	Pt	0.285	0.989	4.440	8.440

Table 5.4. Single Point: impact of the pretreatment processes, impact categories midpoint.

Considering only the pretreatment, Curti process has an environmental impacts equal to 1/3, 1/10 and 1/20 compared with the alternatives (grinding, crushing and pulverization), with a lower impact especially for the impact categories related to climate change and fossil depletion. This is due to the very low electricity consumption required by Curti pyrolysis for the single cut of the ELT, while for other recovery or recycling processes, a finer grinding is required, from a size of few centimeters to less than 2 millimeters (the finest fraction is generally employed for material recycling).

Considering others energy recovery processes, the management of 1 ton of ELT has been compared for Curti process, cement plant and waste to energy process (Figure 5.6-5.7, Table 5.5).

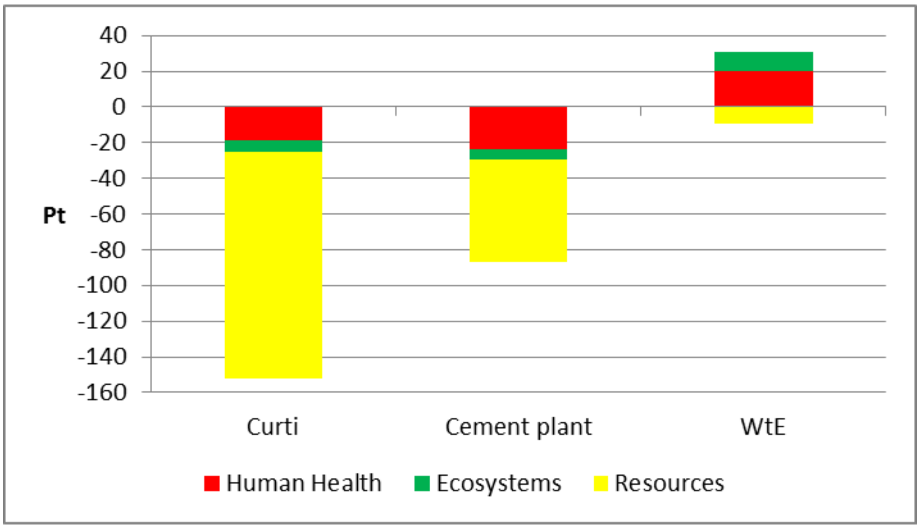

Figure 5.6. Single Point: impact of the energy recovery processes, impact categories endpoint.

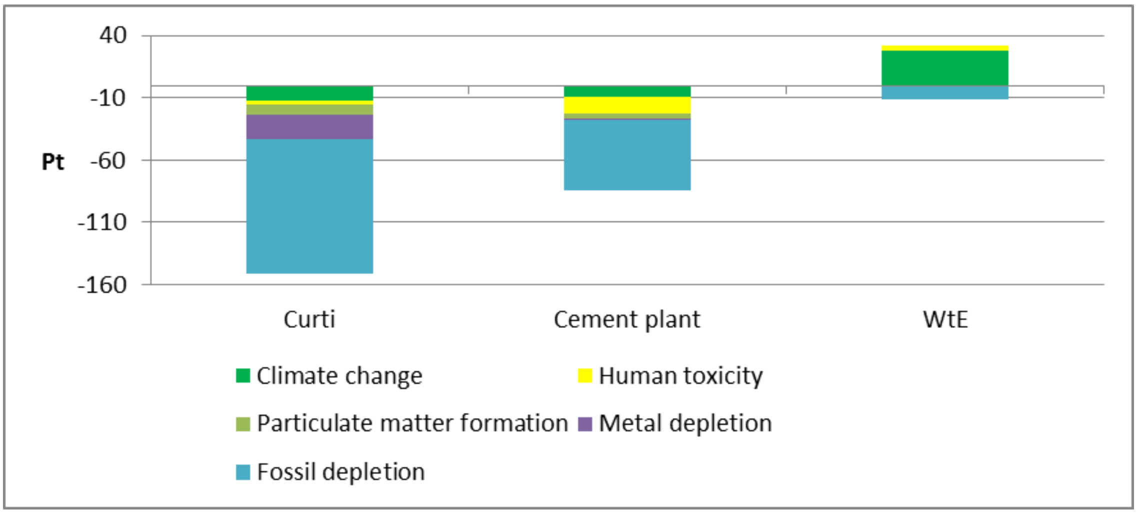

Figure 5.7. Single Point: impact of energy recovery processes, impact categories midpoint.

	Unit	Curti	Cement plant	WtE
Climate change	Pt	-12.39	-9.37	28.30
Human toxicity	Pt	-3.46	-13.00	3.80
Particulate matter formation	Pt	-7.86	-4.72	-1.28
Metal depletion	Pt	-19.50	-0.35	-0.11
Fossil depletion	Pt	-108.00	-57.00	-9.44

Table 5.5. Single Point: impact of energy recovery processes, impact categories midpoint.

Compared to other energy-recovery scenarios (recovery in cement plant and in a solid waste incineration plant) a greater advantage results from the environmental point of view of Curti process, especially for the fossil depletion impact category (light blue, Figure 5.6), directly connected to the resources depletion damage category (yellow, Figure 5.5). It could also be considered that in the recovery in cement factory, the coal providing the same amount of energy has been considered as an avoided impact. If another fuel (less impacting than coal) was considered, the avoided impact would result lower, for this scenario. It can be observed, on the other hand, that the waste to energy process results in a net positive impact, since the energy recovery does not offset the damages coming from the different emissions and consumptions.

The next step has been the comparison of the Curti process with different recovery of material scenarios (Figure 5.8-5.9, Table 5.6).

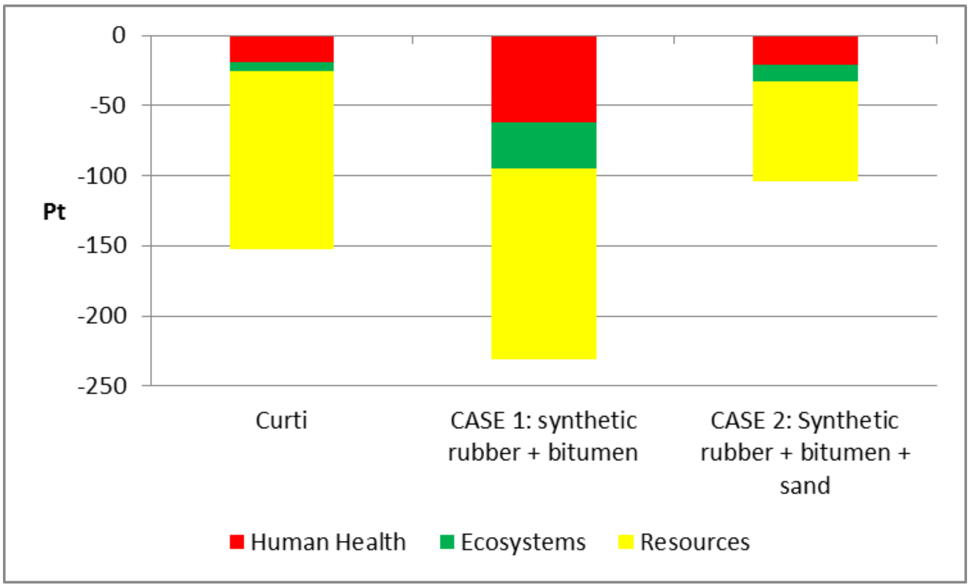

Figure 5.8. Single Point: impact of the material recovery processes, impact categories endpoint.

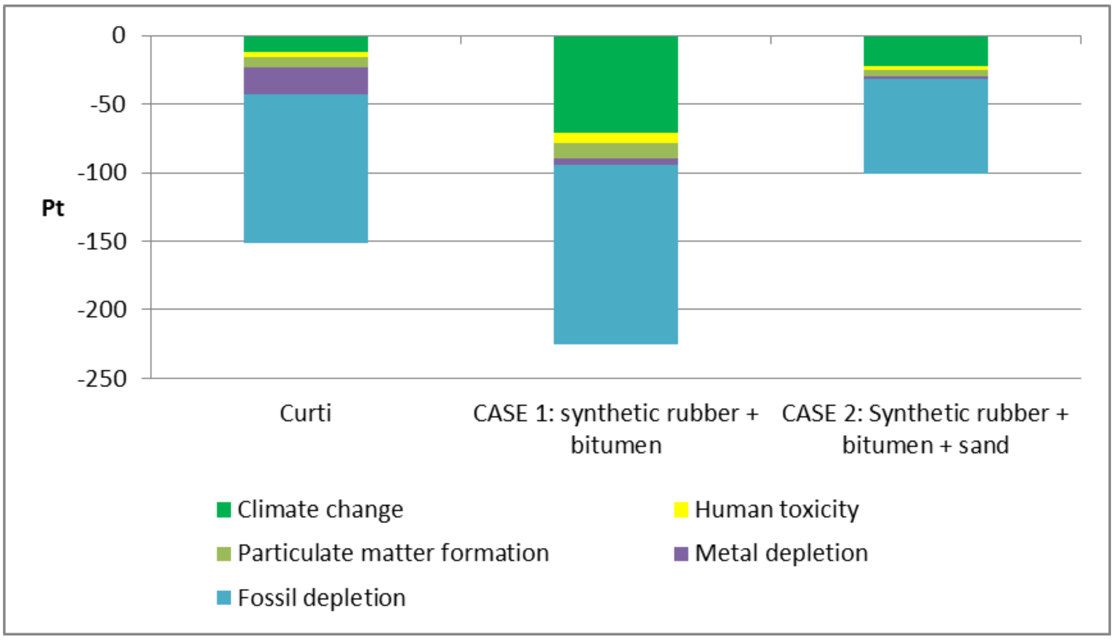

Figure 5.9. Single Point: impact of material recovery processes, impact categories midpoint.

	Unit	**Curti**	**CASE 1: synthetic rubber + bitumen**	**CASE 2: Synthetic rubber + bitumen + sand**
Climate change	Pt	-12.39	-71.20	-22.53
Human toxicity	Pt	-3.46	-7.46	-2.70
Particulate matter formation	Pt	-7.86	-11.20	-4.60
Metal depletion	Pt	-19.50	-4.76	-1.85
Fossil depletion	Pt	-108.00	-131.00	-69.60

Table 5.6. Single Point: impact of material recovery processes, impact categories midpoint.

Compared to other materials recovery scenarios, a huge influence is given by the different options of recovery of the granulate/powder considering which materials actually they replace in the recycling or recovery operations: a full recovery of metals and rubber (to replace the synthetic rubber) would bring to a greater advantage especially related to the impact categories of climate change and fossil depletion (Figure 5.9), intermediate options would generally bring to a greater gain from the environmental point of view for the Curti pyrolysis technology.

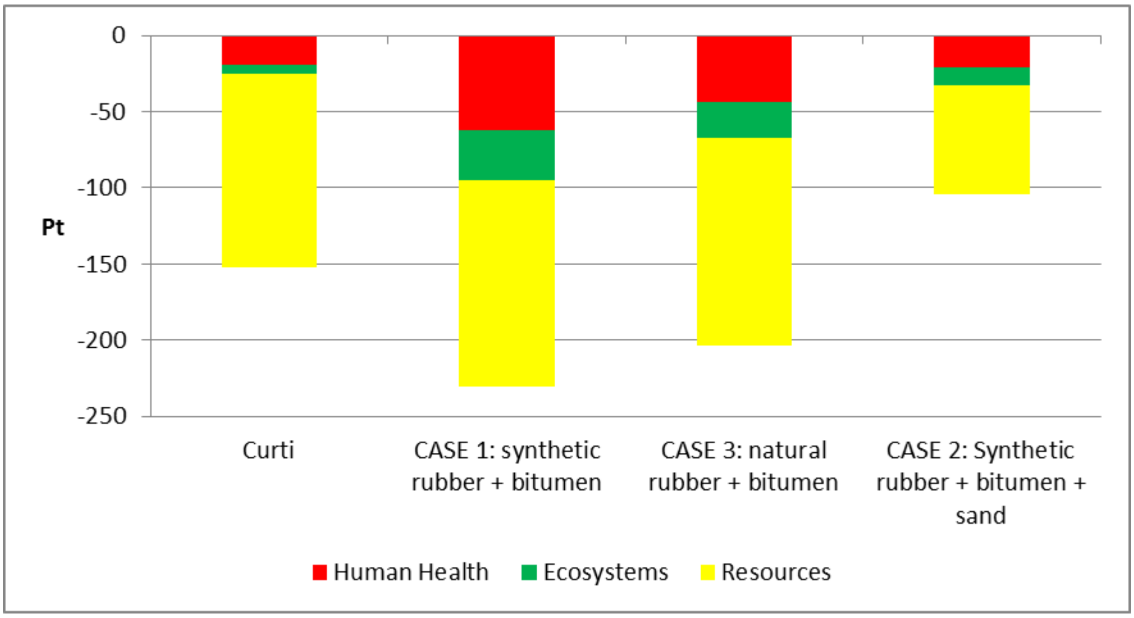

Figure 5.10. Single Point: impact of the material recovery processes, impact categories endpoint.

Moreover, taking into account the recovery of natural rubber instead of synthetic rubber (Figure 5.10), no significant change of impacts can be observed.

5.1.5 Future developments

The attention will be focused on the following study advances:

- to verify, through further data, others detailed material and energy recovery scenarios;
- to upgrade, according to new detections, the background information (such as the Italian energy mix to 2016, the different type of avoided fuel in cement production plants [17], etc..);
- to continue detailing the different material and energy recovery scenarios;
- to assess, through the application of a sensitivity analysis (such as the Monte Carlo method), the robustness of the model depending on the uncertainty of data used (especially of those collected from literature).

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6.Conclusions of the study, personal consideration and future developments

This doctoral thesis, *Application of environmental sustainability assessment methodologies to waste management systems and to energy and material recovery processes*, proposed to investigate the integrated waste management system in a view of Circular Economy.

The activity carried out results in line with the professional figure of an industrial chemist, able to analyze different technological solutions verifying which is the most suitable from and industrial and environmental point of view.

For this reason, the work done was intended to better understand all the fundamental steps of the LCA methodology. Some common aspect emerged from the several cases studies:

- the identification of a general approach to search and collect data useful for the inventory step;
- the selection of appropriate analysis methods taking into account the aim of the study and audience: midpoint oriented approach (e.g. ReCiPe method), CED (which studies all the energy flows involved), GWP (to identify the impact in terms of climate change).

Therefore, a more comprehensive awareness of what sustainability means is possible just through the application of a site-specific analysis which takes into account the topics availabilities and needs. For this reason, it was very important to collaborate with companies: the sharing of primary data is crucial. The analysis of the data has in fact provided a verification that the extension of the relational network is one of the strengths of the Circular Economy.

The doctoral work has allowed the development of numerous partnerships stimulated by the common interest in relation to an innovative theme, among these:

- Universities: Institut de Ciència i Tecnologia Ambientals of the Universitat Autònoma de Barcelona and University of Valencia;
- national and international companies: Romagna Compost srl, ARPA Marche, Cartiera Marchigiana S.r.l., Città Verde cooperative, GMP Bioenergy s.r.l., IRCI SpA, A.R.P. Soc. Agr. Coop., Schmack Biogas, Curti S.p.a;
- international organization: Climate-KIC.

The ability to connected companies, organizations and institutions, sharing information made it possible to make projects together and create a common culture in the area of closure of the production cycle. Several companies, in the past discouraged to approach to recycling, reuse and valorization of by-product processes due to the complexity of the regulatory framework, expressed at the end of the study the appreciation for what has been achieved.

However, if the goal of companies is to pursue a cleaner production, reaching also economic benefits, a deeper collaboration is mandatory because, to achieve the three targets of sustainability, it could be necessary to include also the social and the economic spheres, through the combination with other tools complementary to LCA (e.g. LCC, sLCA), as well as the application of the risk assessment analysis. For these reason, the research started with the PhD program will not stop with this thesis but it is intended to continue during the post-doc period with the purpose to investigate other case studies which cover different fields.