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Abstract

The search for new energy sources and the exploitation of renewable energies is moving on various fronts with the awareness of having to modify the abuse of fossil fuels. In these terms, the biomass gasification process is recognised as a sustainable energy production technology which, in addition, can also contribute to a circular economy. The study presents an Italian case study of a pilot micro-trigeneration plant based on the gasification of wood chips and residual lignocellulosic biomass. The pilot plant was designed to meet the demand for electricity, domestic hot water, heating and cooling of a municipal office. Using Life Cycle Assessment (LCA) techniques this study provides an estimation of resource consumption and emissions to air, water, and the soil of energy recovery from residual biomass. Results point out that greenhouse gas emissions are very low, thus biomass can consider a renewable source and its use represents an attractive sustainable alternative to fossil fuel.

Keywords: Life cycle assessment, bioenergy, wood chips, gasification, cogeneration.

Acronyms

CHP	Combined Heat and Power
CMD	Costruzioni Motori Diesel
DTI	Department of Trade and Industry
FU	Functional Unit
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
mCHP	micro–Combined Heat and Power
WHR	Waste Heat Recovery

1. Introduction

Energy plays a fundamental role in human life. The energy demand is constantly growing due to a constant increase in the world population (IEA, 2014). The current system is characterised by a global economy that requires increasing amounts of energy at a lower cost, at the expense of ecosystems and human health (Global Sustainable Development Report, 2019). Most of the energy still comes from exhaustible fossil sources. Beyond scarcity, fossil fuels are not evenly distributed and often come from politically unstable countries (IEA, 2010). In addition, producing energy from fossil fuels is responsible for high environmental impacts on a local, regional, and global scale (Hammond, 2004), as the distribution of fossil fuels is not uniform. With advancing climate change, the pressure to reduce CO_2 emissions is rising (Gompf et al., 2020). To address these problems, the scientific community is focusing on the effective use of energy, by optimizing its use and minimizing waste as well as by replacing energy from fossil fuels with energy produced from renewable sources (Rodrigues et al., 2019). Bioenergy is considered one of these possible sources of energy. Wood and other forms of biomass, such as energy crops and agricultural, forestry, and industrial waste, may represent easily available renewable energy resources (Bridgewater, 2004, Di Fraia et al., 2020). Replacing traditional energy sources with biomass reduces the dependence on imports of fossil fuels and positively affects the economic costs of energy supply as well its environmental impact (Miralles et al., 2020). In addition, recovering residual biomass allows reintroducing a waste in the cycle contributing to a circular economy. Different process can be used for energy recovery from biomass: thermochemical processes, biochemical/biological treatments, or mechanical extraction of oils (McKendry, 2002a). The thermo-chemical conversion includes combustion, pyrolysis, gasification, and liquefaction, whereas digestion and fermentation are classified as biochemical/biological conversion processes (McKendry, 2002b). In particular, thermo-chemical conversion appears to be suitable at a small scale when it is coupled to combined heat and power (CHP) systems (Chang et al., 2019) and trigeneration systems based on internal combustion engines. Trigeneration systems can use a variety of renewable energies, including jatropha oil (Temir et al., 2004), wood (Eicker et al., 2011), biogas from sewage (Bruno et al., 2009), willow, rice husk, miscanthus (Huang et al., 2011) and biomass (Wang et al., 2015). About biomass, among thermo-chemical processes, the gasification process is suitable for various types of biomass and is characterised by a lower environmental impact compared to conventional combustion (Werle, 2013). The most used method for assessing environmental impacts is Life Cycle Assessment (Quinteiro et al., 2019; Colangelo et al., 2020; Croft et al., 2019; Petrillo et al., 2016). There are several authors who have studied biomass gasification through this methodology. As regards the evaluation of the raw material, the GHG emissions produced by the biomass co-firing in coal-fired plants to produce electricity were studied, comparing the results with other feedstocks, such as coal and natural gas (Zhang et al., 2009; Froese et al., 2010). The analyses pointed out that reducing the use of fossil fuels and including biomass fuel substitution allows reducing GHG from the energy generation sector (Froese et al., 2010). Other research groups focused on district heating networks powered by gasification of different fuels, such as forestry residues, recycled wood, and natural gas (Puy et al., 2010; Pa et al., 2011; Pucker et al., 2012). The study of technology brings out information about the impacts of GHG emissions. Gonzales et al. (2012) define the biomass gasification process as an economically advantageous solution for producing syngas with medium/low heating value that can be transformed into electricity. Another study concerns the evaluation of biomass fed CHP compared to fossil fuels in a large-scale plant, which showed that the use of biomass reduced GHG emissions, but produced higher acidification impacts (Kimming et al., 2011). A study conducted by British Columbia analysed GHG emissions from bioenergy systems with different capacities and the results show that replacing fossil fuel with biomass generates a net reduction of up to 41E+06 CO_2 eq. (Cambero et al., 2015). In general, the analysis of the literature reveals that the production of electric energy through biomass gasification produces much lower CO_2 emissions than fossil fuel gasification processes (Barros et al., 2020; Agostini et al., 2020; Smith et al., 2019). In particular, a trigeneration system allows emissions to be reduced by 20% -35% compared to a conventional system that produces the same outputs separately (Leonzio, 2018). For this reason, this paper aims at assessing the environmental impact of a micro-trigeneration system based on residual biomass gasification. The peculiarity of this plant is represented by an ad hoc design. That is to say that the pilot plant has been designed to serve a fraction of the electricity demand of the municipal office of a city located in Campania (Southern Italy) and the heating and cooling of the rooms and the supply of domestic hot water. The success factor of the plant is at the local level. Cogeneration technology is very suitable for space heating. Southern Italy is characterised by a warm temperate climate and therefore the rooms heating needs exist only in winter, while in late spring and summer there is a strong need to cool them. The consequence is a high energy consumption which leads to peaks in electricity demand and an imbalance of the Italian electricity grid. Therefore, the main advantages of trigeneration are to lighten the electricity grid when the demand is very high and the reduction of CO_2 emissions (Salem et al., 2018). In addition, trigeneration plant realization has made it possible to combine projects for the recovery, transformation and enhancement of biomass with the generation of energy and the supply of services to the territory. Thanks to this process it is possible to maximize the productive and employment potential of the territory of southern Italy. The main novelty of the present sudy is that it is an original study well focused on an Italian case study. The study is based on real data, which is primary data (and not on scondary data). Therefore, the use of primary data based on specific industrial data, which often suffer from confidentiality problems, represent a great contribution from scientific point of vew. The results aims to be a guideline for decision makers and researchers interested in this topic. The rest of the paper is organized as follows: Section 2 presents methods applied in the context of LCA and system is described; Section 3 explains in detail goal and scope definition, function unit, system boundaries, inventory analysis; Section 4 discusses results of the study; Section 5 reports life cycle interpretation. Finally, in Section 6 main conclusions of the research are summarised.

2. Material and methods

2.1 Methodology

The adopted methodology consists of four steps to implement the well-consolidated LCA analysis. The LCA analysis methodology is structured according to 14040:2006 “Environmental management - Life cycle assessment - Principles and framework” standards which provide a methodological reference framework. In addition, ReCiPe 2016 method is used to quantify the life cycle impacts on human health, ecosystem services and natural resources. ReCiPe 2016 contributes to a better understanding of the environmental impact of goods, services and processes and products, compared to the previous version, is updated with current scientific knowledge (RIVM Report, 2016). The approach adopted in this LCA analysis focused on the evaluation of key issues, using the midpoint with a hierarchical perspective (ReCiPe midpoint (H)) is used. The hierarchical perspective (H) is based on the most common policy principles, which is why it is considered predefined, as it assesses the medium-term impacts (e.g., a 100-year timeframe for global warming) and it coincides with the view that impacts can be avoided with proper management**.** The choice to adopt the midpoint approach is based on the awareness that, in general, midpoint indicators are more comprehensive because they are detected for a wider variety of impacts (Bjørna and Hauschild, 2015; Wolfova et al., 2018; Alyaseri and Zhou, 2017; Teixeira, 2014; Takayama et al., 2013) and are specified at the intermediate level along the mechanism.

2.2 Biomass small-scale cogeneration plant

CMD ECO20 plant is designed by the Italian company Costruzioni Motori Diesel (CMD) S.p.A. for the combined production of electricity and heat by thermo-chemical decomposition of wood chips and residual lignocellulosic biomass at high temperature (from 600 to 1000 °C) in the absence or with minimum quantities of oxygen (pyro-gasification) (Stasi E. et al, 2020). The considered unit integrates an Imbert downdraft gasifier, syngas cleaning devices, a spark ignition reciprocating ICE and an electrical generator. The CMD ECO20 is designed to process woodchips or briquettes of residual materials from wood industry, agro-industry such as the olive oil, rice industry, canning industry and pruning of public green areas, Characterised by G30 size (1.50–3.00 cm) with a maximum humidity of 20%. The woodchips or briquettes of residual materials are moved to the gasifier through the hopper and a loading apparatus coupled with an auger placed on the top. The gasification reactions convert the raw materials into syngas. In particular, the gasification process converts biomass into a gaseous heating fuel at temperatures range of 300-900 °C, in the presence of a sub-stoichiometric percentage of an oxidizing agent, typically air for economic reasons. The product obtained is a mixture of gaseous fuel (crude syngas), consisting essentially of CO, CO_2 H_2, and CH_4. The syngas is sent to a cleaning system Characterised by a reactor cyclone, a cooler self-scrubber, a biological filter and a last cyclone. The filtered and cooled syngas is then aspirated by the engine. The internal combustion engine (ICE) produces the electrical energy that can be delivered to the national electric grid, while thermal energy can be recovered from ICE exhaust gases, by using the shell and tube heat exchanger, as well as by the engine cooling system using the plate heat exchanger. The thermal energy is used to provide hot water, space heating and space cooling. For space cooling an absorber must be implemented. After the heat exchange, the exhausts are released to the atmosphere. The system is fully automated, electronically managed at each stage of operation. The micro-CHP (mCHP) can produce electrical and thermal power up to 20 kWe and 40 kWth, respectively. Figure 1 shows the CMD ECO20 and the plant scheme.

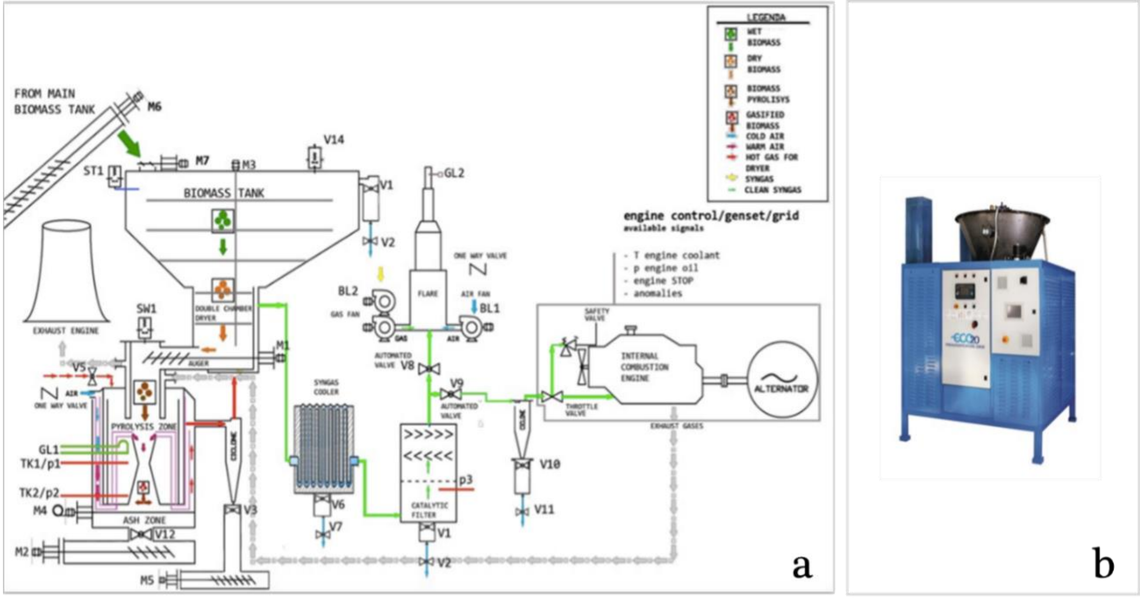

Figure 1: CMD ECO 20 plant: (a) plant scheme; (b) physical plant

3. Performing Life Cycle Assessment

3.1 Goal and scope definition

The main goal of this study is to assess the potential environmental impacts of the production of heat and power through biomass gasification. It is intended that the results generated can be used to understand the relative impacts of different aspects of the biomass gasification plant's construction and operation. Hence, the objective is to highlight the most important factors that affect the environmental load of the biomass gasification plant.

3.1.1 Functional unit

The functional unit (FU) of the study is 1 MJ of electricity produced from the plant. Total electricity and total thermal energy are produced in 3654 operating hours, corresponding to one year of operation, and amount to about 320 GJ/year and 110 GJ/year (Table 2). The hours of operation were estimated according to the operating hours established by the CMD company. Subsequently, functional unit of 1 MJ of electricity were fixed. In addition, it is also important to specify that the plant is sited in southern Italy. Indeed, the system serves a municipal office that has specific operating hours. For the LCA analysis, it is particularly interesting to understand the overall impacts also in relation to the useful life of the plant, that is estimated that it is equal to 12 years.

3.1.2 System boundaries

The system boundaries contain the main production processes of electricity and thermal energy. The study follows the cradle-to-gate approach (Adams et al., 2014). The reason for this choice is the awareness that the production is the most relevant phase in terms of environmental impact, as demonstrated by several authors (Khasreen et al., 2009; Schneider et al., 2011). The study includes plant construction and energy conversion, including materials and resources necessary for the construction and operation of the plant. Energy conversion concerns all the operations starting from the introduction of biomass inside the gasifier, through a hopper, up to the production of energy, supplied by a cogeneration engine that uses the syngas produced by the gasifier. Biomass that feeds the plant is supplied on site. The lack of information on local biomass used, for example in smallholder farming systems, has hampered the integration that would be possible using secondary data. This approach would take us away from the intent of our study, based entirely on primary data. Entering a part of the life cycle with secondary data would lead to greater uncertainty. Therefore, the pre-treatment (production and preparation) phase is not included in the study. Figure 2 shows a simplified schematization of the analysed system.

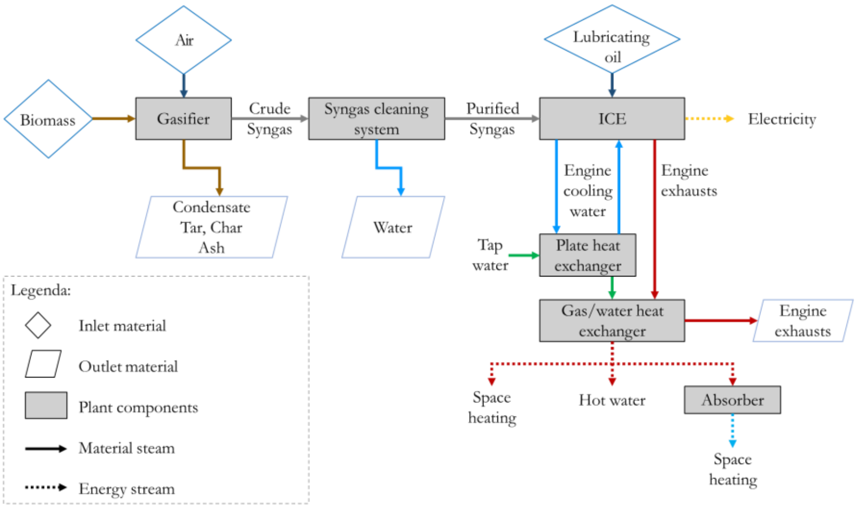

Figure 2: Simplified system diagram

The LCA analysis includes the phases of plant construction and its operation Figure 3 shows the system boundaries according to a cradle-to-gate approach, which include the construction and operation of the plant.

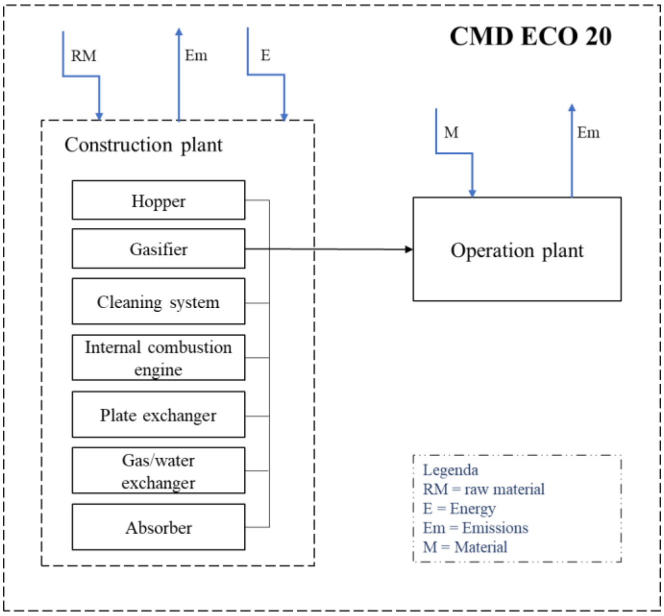

Figure 3: Plant system boundaries

Use phase and the end-of-life are excluded. In particular, for the end-of-life, the technology used for the plant is relatively new, therefore enough indications are not available to analyse the dismantling and disposal of the plant. It follows that these operations are not included in the study.

3.2 Life Cycle Inventory (LCI) analysis

In this section the data collection relating to the CMD ECO20 system is reported. A description of the main aspects of the LCI is presented here. A further detailed description of the LCI can be found in Supplementary Material.

3.2.1 Plant construction

All equipment elements in the plant have been included within the confines of the construction system. For the equipment, the respective information refers to the technical data sheets provided by the company CMD S.p.A., by the manufacturers. Both the technical data sheet and the available literature were consulted only for the absorber. The first component is the hopper. It consists of an auger, tank, and distributor loading system made of AISI 316L stainless steel and a conveyor belt loading system made of AISI 304 stainless steel and rubber. The second component of the plant is the gasifier. The ignition of the biomass requires electricity through an ignition electrode for triggering reactor. The raw material in a few minutes is ignited (15 - 30 minutes with a maximum humidity of 20%), therefore the associated amount of electricity can be neglected. The data relating to the gasifier have been provided by the company CMD S.p.A. and refer to the entire component. It consists of sheets, tubular profiles, and pipes made of AISI 316L stainless steel. The third element is the cleaning system, also made of the same steel. The next component is the internal combustion engine (ICE), the Vortec 4.3L V-6 model, produced by GM Powertrain. From the technical datasheet, it appears that the motor is mainly made of cast iron and has a total weight of 195 kg. Downstream of the ICE, there is the thermal side of the plant. It consists of two heat exchangers, that are one plate heat exchanger and one gas/water exchanger, and the absorber. The materials with which both exchangers are made are AISI 326L stainless steel. The gas/water exchanger is also made of cast iron. The last component is the absorber, which is made of stainless steel, aluminium, and copper (Beccali et al., 2010). In the absence of details about the type of stainless steel, it is assumed the use of stainless steel AISI 316, as it is widely used in aggressive contexts, where there are many corrosive factors prolonged over time. AISI 304 stainless steel is included, while AISI 316L stainless steel is not included. However, AISI 316 is present, which differs from the AISI 316L alloy in the percentage of carbon: the quantity present in AISI 316L stainless steel must be less than or equal to 0,03% while in AISI 316 stainless steel less than or equal to 0,07%; all the other elements present in the two alloys are equivalent. Furthermore, the creation of both alloys takes place through the same process and the same technology. It is, therefore, possible to consider AISI 316 stainless steel in place of 316L. Table 1 shows a summary of the data used for data collection relating to the plant construction.

Table 1: Life cycle inventory data for the plant construction

Component	Material	Weight [kg]	Origin of data	Type of data
Hopper	AISI 316L	17	CMD Spa	Primary
	Rubber	0.5		
	AISI 304	0.5		
Gasifier	AISI 316L	1650	CMD Spa	Primary
Cleaning system	AISI 316L	70	CMD Spa	
ICE	Cast iron	195	CMD Spa	
Plate exchanger	AISI 316L	6.6	Data sheet Maya Spa - Yazaki	Secondary
Gas/water exchanger	AISI 316L	11	Data sheet Maya Spa - Yazaki	Secondary
	Cast iron	5.6		
Absorber	Carbon steel	136	Beccali et al (2010)	Secondary
	AISI 316L	196		
	Aluminium	10		
	Copper	5		

3.2.2 Plant operation

This section provides an overview of the plant operation inventory data. CMD ECO20 operates for 3654 hours per year. The mCHP plant produces electricity equal to 320448 MJ/year and thermal energy equal to 111380 MJ/year. All data derive from an energy analysis based on data provided by the company CMD S.p.A.

Biomass and air

The biomass used is wood chips and it is considered as a product on site. Depending on the nature of the wood, the carbon content slightly varies. In the present case study, the wood chips have a carbon content of 37.2%. The wood chips also have a water content of 15.9% and an ash content of 0.3%. The required biomass flow rate for the gasification process is 21 kg/h. Air is used as a gasifying agent to produce syngas. The demand for air is 20 kg/h.

Ash

The biomass gasification process produces a certain amount of ash. From the analyses carried out by the company, it was found that the ash produced is about 5% of the total biomass introduced. Therefore, considering the average hourly capacity of the biomass, 1.05 kg/h of ash that is equivalent to 3837 kg/year will be produced. The ashes can be reused as constituents within building materials, such as concrete mixtures. For this reason, these are considered as waste for recovery.

Crude syngas

Crude syngas is the main product of gasification. Data on the flow rate of each element constituting the syngas leaving the gasifier have been obtained by experimental tests carried out by CMD S.p.A. The dry and tar-free gas flow rate calculated by the company is 36.1 kg/h that is 132 t/year.

Tar and char

Other products of gasification are the char, a carbon solid very similar to coal, and the tar consisting of aromatic hydrocarbons of the tar type, carbon dioxide and nano-particulates. Tar is a complex of liquid organic compounds present in gases produced during gasification, such as tar aromatic hydrocarbons, excluding C1 to C6 gaseous hydrocarbons, carbon dioxide and nano-particulates. In general, it is a contaminant that must be removed before syngas is used in the ICE. The tar can lead to the blocking of the system with inconveniences related to the operation and the relative intervention costs. The total quantity of tar produced by gasification is 18.3 g, consisting of 16.49 g water and 1.81 g tar. No primary end-of-life information is available for these substances. Therefore, they are considered waste.

Water and condensate

Water is used both in the cleaning system and in the thermal side of the plant. The cleaning system consists of a washing system and an exchanger to cool the syngas, before it enters the ICE. The washing system uses water with the function of purifying the crude syngas that is discharged downstream of the process. In this case, there is insufficient data available to characterise the process. For the heat exchanger, there is a closed circuit in which the flow rate of water circulating inside remains constant (Gallagher, 2009) and is equal to 0,125 m^3/h. The cooling of the syngas that takes place in the heat exchanger generates the condensate that is collected in a special container. The amount of condensate calculated is equal to 2 kg/h. Of this, it is estimated that 88% is water. Another quantity of water is used in the thermal side of the plant. The plate heat exchanger needs a quantity of water taken from the grid equal to 568 kg/h.

Purified syngas

The syngas purification process that takes place in the cleaning system produces a quantity of gas with a lower flow rate than the incoming one. In fact, the system separates the impurities contained in the crude syngas, reducing the gas mass flow rate by 27.4%. Therefore, the purified gas flow rate is 26.2 kg/h.

Lubricating oil and exhaust gas

Lubricating oil and exhaust fumes are two flows that affect the ICE. The lubrication is a function of fundamental importance in ICE. The lubricating oil flow rate is 4.25 l, or 3.74 kg and it is assumed that it will be replaced after one year of operation of the system. In cogeneration plants, the exhausts are used on the thermal side to produce thermal energy. Table 2 shows a summary of the data used for data collection relating to the plant operation.

Table 2: Life cycle inventory data for the plant operation, where 1 year is equal to 3654 h

Component	**Flow**	**Unit of measure**	**INPUT Flow rate**	**OUTPUT Flow rate**	**Origin of data**	**Type of data**
Hopper	Biomass	kg/year	76734	76734	CMD Spa	Primary
Gasifier	Biomass	kg/year	76734	-	CMD Spa	Primary
	Air	kg/year	73080	-		
	Crude syngas	kg/year	-	131909		
	Ash	kg/year	-	3837		
	Tar	kg/year	-	1096		
	Char	kg/year	-	5481		
	Condensate	kg/year	-	6431	Gallagher et al., 2002	Secondary
Cleaning system	Crude syngas	kg/year	131909	-	CMD Spa	Primary
	Purified syngas	kg/year	-	95735		

	Water	kg/year	-	-		
ICE	Purified syngas	kg/year	95735	-	CMD Spa	Primary
	Lubricating oil	kg/year	3.74	-		
	Engine cooling water	t/year	1590	1590		
	Engine exhausts	kg/year	-	380016		
	Electricity	MJ/year	-	320448		
Plate exchanger	Engine cooling water	t/year	1590	1590	CMD Spa	Primary
	Tap water	t/year	2075	2075		
Gas/water exchanger	Tap water	t/year	2075	-	CMD Spa	Primary
	Engine exhausts	kg/year	380016	380016		
	Thermal Energy	MJ/year	-	111380		
Absorber	Thermal Energy	MJ/year	45402	30033	CMD Spa	Primary
Thermal user	Space heating	MJ/year	30033	30033	CMD Spa	Primary
	Space heating	MJ/year	43632	43632		
	Hot water	MJ/year	24770	24770		

3.3 Life Cycle Impact Assessment

This section presents the results of the third phase of the LCA methodology. The third phase of the LCA study is the assessment of the life cycle impact assessment, based on the LCI. The impacts have been calculated with respect to the functional unit which corresponds to 1 MJ of energy produced by the CMD ECO20 plant. The analysis includes the operation and all the raw materials and equipment for the plant construction. The results were characterised according to ReCiPe 2016 Midpoint (H) method and subsequently normalised according to the ReCiPe 2016 v1.1 (H), Midpoint Normalization, World, excl biogenic carbon method to identify the impact categories with the highest equivalent person emission values, expressed in person equivalent (PE). Normalization showed that different impact categories have very small PE values (< 1 PE). Therefore, a cut-off equal to 1 PE has been set. Categories with impacts of less than 0.1 PE are not considered in the study. On the contrary, categories with values greater than 0.1 PE are analyzed. In this way, the Normalised results identified the key problems for the construction and operation of the plant. In both cases, there are significant impacts in four categories: climate change, human toxicity, freshwater consumption and fossil depletion. Metal depletion was found to be a key in plant construction, while terrestrial ecotoxicity in plant operation. Detailed results obtained during the impact assessment are shown in the next section dedicated to the results.

4. Results

This section is dedicated to the results of the LCA analysis. Therefore, the main results are commented on. A further detailed description of the results can be found in Supplementary Material.

4.1 Plant construction

Midpoint normalised data indicate that the most significant impact categories are climate change, freshwater consumption, metal and fossil depletion, and human toxicity. Identifying the most impactful categories thanks to normalisation, the results discussed below refer to the Characterised data. The midpoint characterised results for the identified categories are presented in Figure 4.

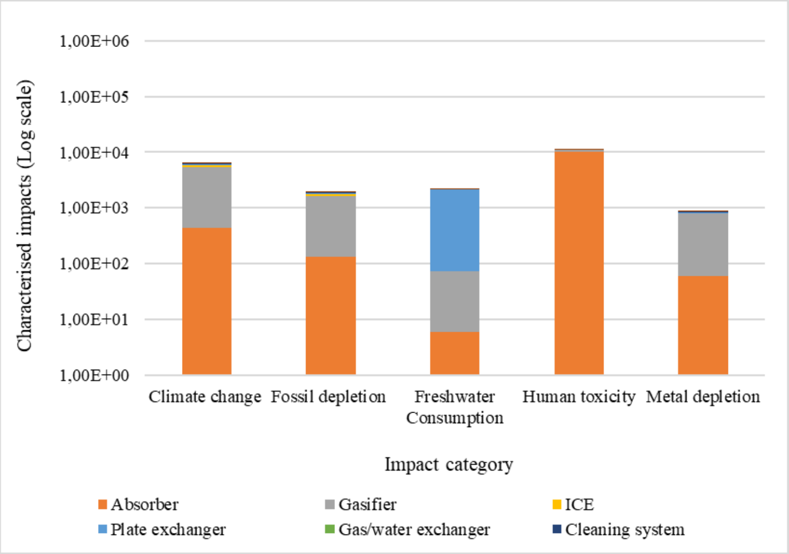

Figure 4: Characterised data for the plant construction (ReCiPe midpoint H).

In Table 3 is shown a detail of the impact categories.

Table 3: Life cycle impacts for the plant construction and for the plant operation (ReCiPe midpoint H)

Impact category	**Unit**	**Total CMD ECO20**
Plant construction		
Climate change	kg CO_2 eq.	6.31E+03
Fossil depletion	kg oil eq.	1.93E+03
Freshwater Consumption	m^3	2.16E+03
Human toxicity, non-cancer	kg 1.4-DB eq.	1.11E+04
Metal depletion	Kg Cu eq.	8.87E+03
Plant operation		
Climate change	kg CO2 eq.	202
Fossil depletion	kg oil eq.	65
Freshwater Consumption	m3	2083
Human toxicity	kg 1.4-DB eq.	80
Metal depletion	kg Cu eq.	44
Terrestrial ecotoxicity	kg 1.4-DB eq.	52

4.1.1 Climate change

The impacts of this category are closely related to the consumption of fossil fuels in the plant construction components. Figure 5 shows that the largest contribution comes from inorganic emissions to air.

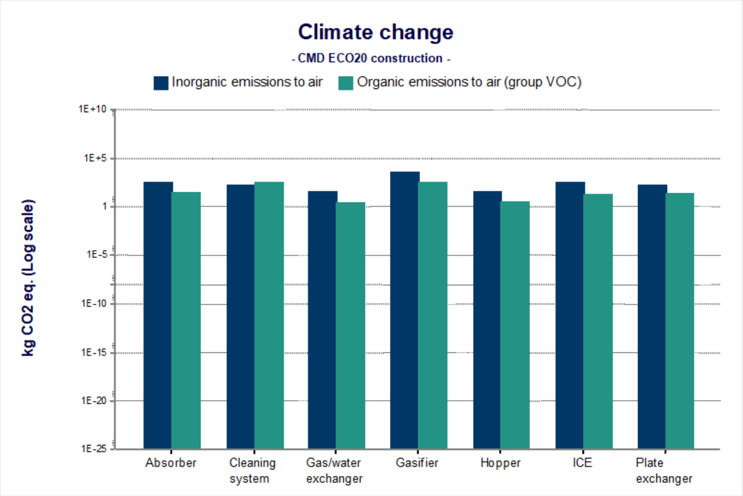

Figure 5: Climate change data for the plant construction (ReCiPe midpoint H)

The organic emissions to air shown in Figure 5 concern mainly CO_2. The most responsible component of the impacts is the gasifier, with 78% of CO_2 emissions, that are equal to 5700 kg CO_2 eq. All the other components have a lower impact. In particular, the absorber and the ICE produce the same amount of CO_2, which is equivalent to 7% of the total CO_2 emissions of the system. The remaining 8% is produced by other components, with an average of 2% for each component. Among inorganic emissions, NOx is also found. These are produced in smaller quantities. They account for 7% of total inorganic emissions in the system. The component responsible for NOx emissions is mainly the gasifier with 70% of NOx emissions. The absorber, the ICE, and the plate exchange they contribute the remaining 30%, although the emissions come mainly from the last two components mentioned. Emissions from the VOC group are also recorded (560 kg CO_2 eq.), and they are in the form of methane mainly attributed to the gasifier, with 81% of methane emissions. Among the remaining 19%, methane emissions come mainly from the absorber (7%). All other components produce methane almost equally. In fact, the hopper and the gas/water exchanger are attributed the lowest emissions, both of CO_2 and methane.

4.1.2 Water consumption

This impact also includes both water as input but also as output. As regards inputs, the gasifier contributes a water consumption of approximately 21000 m^3. The inputs associated with the plate heat exchanger amount to 2400 m^3. By analysing the outputs, the emissions from the gasifier are equal to the input value, which is about 21000 m^3. The emissions from the plate heat exchanger are approximately 340 m^3. Thus, the total sum of resources (input) and emissions to freshwater (output) causes the contribution for this category to be associated with the plate heat exchanger.

4.1.3 Human Toxicity

Human toxicity is also a particularly significant impact category in plant construction. In this study, human toxicity related to carcinogenic and non-carcinogenic substances, that are heavy metals to air and to water. In the case of carcinogenic substances, the release of toxic substances is caused by absorber and gasifier construction, with 74% and 17% of total emission respectively. Arsenic is the most widely produced element to air and to water. Among the emissions of heavy metals to air, lead was also recorded, in quantities just below arsenic. With regard to non-cancerous emissions, the absorber is the component responsible for emissions of heavy metals, with the 91% of total emissions, while the gasifier produces only 7% of total emissions. Heavy metals to air and water and are mainly zinc, arsenic, and lead, which is higher in the form of emission to air. The main results for human toxicity are summarized in Supplementary Material (Table S20).

4.1.4 Resource depletion

In this category fossil and metal depletion are presented. Fossil depletion concerns the consumption of energy resources and material resources. The analysis showed that the consumption of energy resources is higher than the material resources, the quantities of which are to be considered negligible. In fact, all construction materials used in plant construction require energy that is almost always provided by fossil fuels. Fossil fuel consumption is attributed to the gasifier. For a total of about 1.8 t oil eq., the gasifier contributes with the consumption of 1.5 t oil eq. About 300 kg oil eq. of crude oil and about 230 kg oil eq. of uranium are used for the construction of the gasifier. Consumption of hard coal and natural gas is much more consistent, respectively equal to 628 kg oil eq. and 640 kg oil eq. Metals are a finite resource and are the most consumed elements in the plant for its construction, so it is understandable that metal depletion is a potential problem. The material resources used in construction plant are non-renewable elements and they are mainly associated with the gasifier. In fact, this component has a steel structure with significant mass and much higher than the other components (Table 1). The non-renewable resources most used by the gasifier are magnesium (220 kg Cu eq.), molybdenum (260 kg Cu eq.), nickel (145 kg Cu eq.), and silicon (130 kg Cu eq.).

4.2 Plant operation

This section shows the results for the operating phase of the CMD ECO20 plant. From the Midpoint normalised it emerges that the most significant impact categories are climate change, freshwater consumption, metal and fossil depletion, human toxicity and terrestrial ecotoxicity (details are shown in Table 3).

The midpoint characterised results for the identified categories through normalization are presented in this section. From the analysis, the water of network is the flow that gives a particularly wide contribution to almost all the categories of impact against the amount of water of network that feeds the plant, that is of 568 kg/h. The midpoint results for these impact categories are presented in Figure 6.

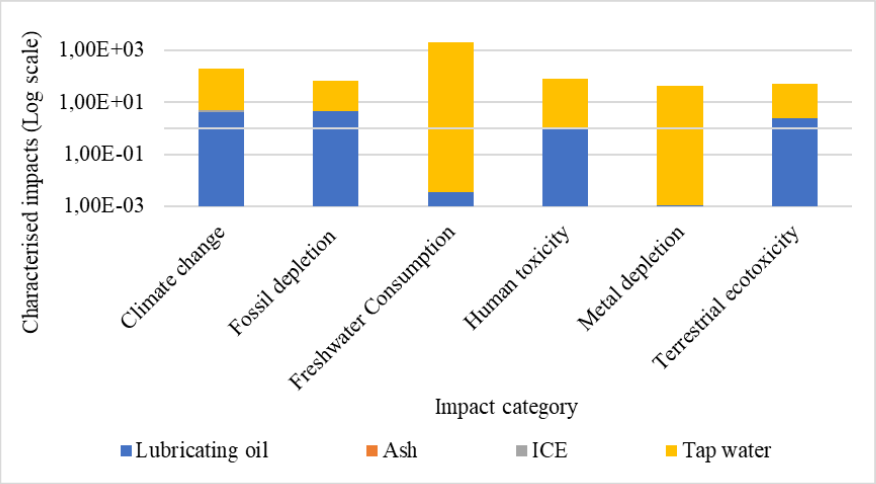

Figure 6: Characterised data for the plant operation (ReCiPe midpoint H)

4.2.1 Climate change

In plant operation stage, climate change refers to emissions to air, that are inorganic and organic. The emissions are recorded (202 kg CO_2 eq.) and they are mainly related to the tap water (Figure 7).

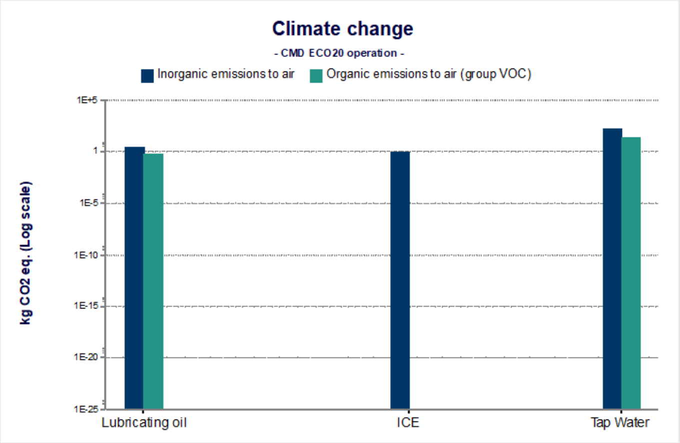

Figure 7: Climate change data for the plant operation (ReCiPe midpoint H)

The water flow rate amounts to 568 kg/h and is therefore more responsible for emissions to air. For this impact category there is a total of 200 kg CO_2 eq. of which 197 kg CO_2 eq. are associated with water. The remaining 3 kg CO_2 eq. are associated with the oil used for the lubrication of ICE components. In detail, the reported emissions are related to carbon dioxide: out of a total CO_2 emissions of 170 kg CO_2 eq., tap water contributes 165 kg CO_2 eq. Although negligible compared to CO_2, the use of the plant also generates organic emissions of the VOC group (volatile organic compounds), that is methane and methane biotic (produced by bacteria or by the degradation of organic matter), for a total of 29 kg CO_2 eq. of which 28 kg CO_2 eq. are associated with water. In particular, the methane emission amounts to about 14 kg CO_2 eq. (of which 13 kg CO_2 eq. are attributed to water) and that of biotic methane at 15 kg CO_2 eq. fully associated with water. The main results for the climate change category in plant operation are summarized in Supplementary Material (Table S21).

4.2.2 Water consumption

The water consumption category was found to be relevant following the normalisation of the results. Specifically, this category describes the freshwater consumption that is related to the use of tap water in plant operation. In fact, use of tap water with a value of about 2100 m^3. Both input and output contribute to this category. The input represents the flows referring to the water use as a renewable resource for a total of 2400 m^3 and the output concerns emissions of water to freshwater for a total of 260 m^3. Thus, total consumption amounts to 2140 m^3 of water.

4.2.3 Toxicity

The observed toxicity for the operation of the plant concerns human and terrestrial toxicity. Even in these two categories, emissions are associated with tap water. It is recalled that the use of water for the operation of the plant is very large, with an annual consumption of more than

2000 tonnes (Tab. 2). The total emissions in human toxicity category amount to 80 kg 1.4-DB eq. In detail, the nature of emissions is that of heavy metals in freshwater and agricultural soil. Emissions to freshwater amount to 21 kg 1.4-DB eq. that are divided mainly between arsenic (+V) and zinc. Emissions to agricultural soil are higher: out of a total of 58 kg 1.4-DB eq., these mostly concern zinc. For the terrestrial ecotoxicity category, out of a total of 52 kg 1.4-DB eq., water contributes with 50 kg 1.4-DB eq. The metals emitted are more mercury and less silver, copper, zinc and vanadium. The main results for the toxicity categories in plant operation are summarized in Supplementary Material (Table S22).

4.2.4 Resource depletion

Finally, there are considerable impacts for the categories that refer to the available resources, that are fossil and metal depletion. In fossil depletion impact category water use has greater impact than the lubricating oil. In fact, out of a total of about 65 kg oil eq., water contributes with 61 kg oil eq. while lubricating oil contributes only with 4.5 kg oil eq. Use of various non-renewable resources contributes to fossil depletion. Water is responsible for the consumption of 13 kg oil eq. of crude oil, 14.5 kg oil eq. of coal and 26 kg oil eq. of natural gas, while lubricating oil is responsible for the consumption of only 4 kg oil eq. of crude oil. In metal depletion category, the use of water causes an impact of 44 kg Cu eq. that is connected to non-renewable resources. To a large extent, they concern sulphur dioxide in quantities of 42 kg Cu eq. To a lesser extent they are non-renewable elements that concern iron in quantities of just 0.3 kg Cu eq.

4.3 Extension of the plant construction

In this section are reported the main results calculated with respect to the useful life of the plant, averaging 12 years. Midpoint data normalised for 12 years of operation show that the most significant impact category is the same for the plant construction referring to 1 year of operation. The midpoint results for these impact categories are presented in Figure 8.

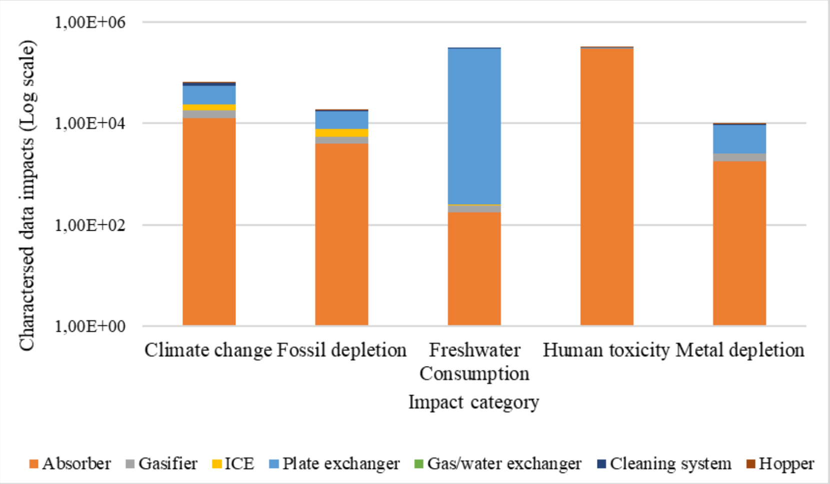

Figure 8: Characterised data for the plant construction, referred to the plant useful life (ReCiPe midpoint H)

Table 8 shows a detail of the impact categories.

Table 4: Life cycle impacts for the plant construction, referred to the plant useful life (ReCiPe midpoint H)

Impact category	**Unit**	**Total CMD ECO20**
Climate change	kg CO_2 eq.	6.26E+04
Fossil depletion	kg oil eq.	1.81E+04
Freshwater Consumption	m3	3.00E+05
Human toxicity	kg 1.4-DB eq.	3.14E+05
Land use	Annual crop eq.·y	2.53E+03
Marine ecotoxicity	kg 1.4-DB eq.	2.72E+03
Metal depletion	kg Cu eq.	9.82E+03
Terrestrial ecotoxicity	kg 1.4-DB eq.	3.45E+06

4.3.1 Climate change

The plant construction in relation to its useful life produces a total of 6.26E+04 kg CO_2 eq. This value is to be attributed to the plate heat exchanger (Figure 9) which produces 3.11E+04 kg CO_2 eq. This value is associated with the production of carbon dioxide in quantities equal to 2.62E+04 kg CO_2 eq. Although to a lesser extent, there are also VOC group emissions to air: the plate heat exchanger produces 4.25E+03 kg CO_2 eq. of methane. The components with the lowest impact are the gas/water exchanger and the hopper. The gas/water exchanger produces 490 kg CO_2 eq. of carbon dioxide as an inorganic substance emitted into the air and 38.6 kg CO_2 eq. of organic emission of the VOC group, in the form of methane. The minimum impacts between all components are linked to the hopper. In this case, in fact, the carbon dioxide production amounts to 48.8 kg CO_2 eq. and methane production in an amount equal to 4.52 kg CO_2 eq.

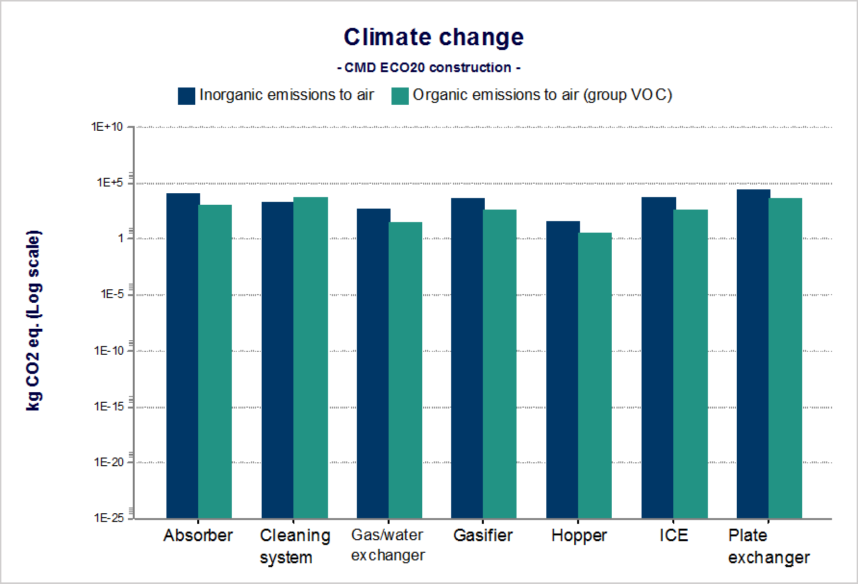

Figure 9: Climate change data for the plant construction, referred to the plant useful life (ReCiPe midpoint H)

4.3.2 Water consumption

Freshwater consumption has a lesser impact than terrestrial and human toxicity, but in any case, they are associated with considerable resources and emissions amounts. Freshwater consumption relating to the plant construction is entirely borne by the plate exchanger with a total of 3E+05 m^3 of water. This value is the sum of the water as resource and the water emitted in freshwater. In particular, the water withdrawn amounts to 3.5E+05 m^3 while the poured water amounts to 4.88E+04 m^3.

4.3.3 Human toxicity

This group includes human toxicity. For this category, non-carcinogenic heavy metals are considered, as they are those that are released in greater quantities than carcinogenic ones. For emissions to air (1.75E+05 kg 1.4-DB eq.), the heavy metals produced in considerable quantities are lead, zinc, arsenic (+V), mercury and cadmium. The heavy metals emitted to freshwater, on the other hand, only concern arsenic in greater quantities and zinc out of a total of emissions in water which amounts to 1.25E+05 kg 1.4-DB eq. Other emissions in the form of heavy metals in the soil (agricultural, specifically) derive from the absorber, for a total of 8320 kg 1.4-DB eq. Zinc is the metal that is emitted in large quantities, while less heavy metals are cadmium and silver. The heavy metals emitted into the air and to freshwater are mainly copper, zinc and arsenic (+V). The main results for the toxicity categories in extension of plant construction are summarized in Supplementary Material (Table S23).

4.3.4 Resource depletion

The categories to which flows with significant quantities are associated are those also related to the availability of resources: fossil depletion and metal depletion. Fossil depletion is borne by most of the components of the plant. By analysing the components individually, the plate heat exchanger is the component that consumes most fossil resources, especially natural gas, hard coal and crude oil (Table 10). The absorber and the gasifier are responsible for the considerable consumption of hard coal and natural gas, while crude oil and uranium consumption is lower. For the ICE, consumption of natural gas and crude oil is predominant. Table 10 shows the resources consumed.

Table 5: Main emissions for fossil depletion in extension of plant construction

Fossil depletion [kg oil eq]	**Natural gas**	**Hard Coal**	**Crude oil**	**Lignite**	**Uranium**
Absorber	1300	1310	680	-	480
Gasifier	485	510	250	-	180
Plate Exch.	4030	2380	2020	640	500
ICE	690	270	600	375	215

The consumption of metals is an impacting category for the construction of the plant, as already defined in the paragraph 3.3.1. Therefore, it is understandable that metal depletion comes out as potential issue. Both the absorber (1790 kg Cu eq.) and the plate heat exchanger (6790 kg Cu eq.) are responsible for the metal depletion. The way in which the two components are responsible for metal depletion is different. The absorber consumes non-renewable elements that are copper, iron, magnesium, molybdenum, nickel and silicon. The plate heat exchanger consumes mainly non-renewable resources that concern silicon dioxide and, in much smaller quantities, calcium carbonate. This component also consumes non-renewable elements, but to a lesser extent both compared to resources and to the elements consumed by the absorber. The main results for metal depletion in extension of plant construction are summarized in Supplementary Material (Table S24).

4.4 Electricity and Heat demand analysis

Combined electricity and heat production offers an increase in fuel efficiency, leading to a decrease in environmental charges per unit of useful energy. The impact assessment results (presented in section 4.1) assumed that the heat was not used and emitted as waste heat. This indeed meant that the environmental costs of the plant were allocated 100% to electricity. However, as a cogeneration plant, heat is produced and used. Annual production is 320 GJ of electricity and 110 GJ of heat. However, as suggested by ISO 14044:2006 “Environmental management — Life cycle assessment — Requirements and guidelines”, it is advisable to avoid allocation where possible. Avoiding allocation means that electricity and heat are not treated separately, keeping the electricity to heat ratio of 1:0.34. The functional unit avoids allocation and leads to 74% of the impacts deriving from electricity and the remaining 26% from the overall heat produced. The electricity produced in the cogeneration plant is used locally or re-injected into the Italian national grid if in excess. The situation with the use of thermal power depends on the heat demand of the end user. The heat produced is divided into three modes of use. It is used for heating in winter and for cooling in summer, resulting in waste of heat. A third way is to use it to obtain domestic hot water. It is necessary to consider that the production of biomass is not included in this study, as a secondary raw material in the circular economy perspective. The use of waste on site will therefore produce much more favourable results than the cultivation of off-site biomass.

5. Discussion

This section highlights and discusses the significant issues of each aspect of the construction and operation of the plant that have emerged and are presented in Section 3.3. Therefore, this section provides more details on each key aspect.

5.1 Overral results

The results section showed that the construction of the CMD ECO20 plant has a more significant potential impact on the environment than its operation. The gasifier is the component that provides a contribution in almost all categories, because of the large quantity of steel for its realization. The steel production process is linked to the use of fossil fuels in important quantities to feed and keep the furnaces at very high temperatures. The impacts analysed would be re-modulated if a different model of gasifier were chosen. This should be an optimized choice according to the syngas amount to power the ICE, on which depends the supply of electricity and heat to users. The same applies to the two heat exchangers, whose construction materials contribute to impact in different categories. On them also depends on the tap water taken from the network, whose production determines a significant impact, since the flow rate taken is very substantial. The categories of impact that the construction of the plant involves are basically the same emerged for its operation. A substantial difference between the two cases occurs in the metal depletion category, and this is understandably due to the metals used for the construction of the plant, including the gasifier with a steel structure with very high mass. Another category is the human toxicity, for which the absorber is still responsible. Therefore, any action should also be directed to that component. Other differences are the impact of the terrestrial ecotoxicity category, that are recorded especially in the case of operation of the plant. This studies how environmental pollutants affect soil-dependent organisms and their environment, whose effects on the ecosystem and organisms must be carefully monitored to prevent damage. In fact, terrestrial organisms can be exposed to pollutants through skin, oral, inhalation and food chain exposure and it is therefore important to try to reduce emissions. For this category, the use of large quantities of water makes the most contribution with heavy metals to air. Overall, the impact categories most affected by the operation of the plant are more than one and they are all associated with the use of water. This is since the plant needs a large flow of water taken from the network, especially for the thermal side: about 600 kg/h are needed, that correspond to about 2 t of water at the end of the year of operation. The category of freshwater is the one that has the greatest impact identified by normalised midpoint data, according to which different plant choices could be assigned, resulting in remodulation of the other categories. In numerical terms, considering climate change as the reference category, the plant construction has an impact of about 6E+03 kg CO_2 eq. while the operation gives a contribution of about 0.2E+03 kg CO_2 eq. In general, the construction and operation of the plant contribute on average to 70% and 30% respectively.

5.2 Significant issues for plant operation

The plant operation has a much lower impact, compared to its construction. This result derives mainly from the absence of the process of pre-treatment of biomass and the use of electricity. Biomass is a processing waste that in the system has been considered already processed and ready for use. No information on previous life cycle phases is available. The biomass used in the system is a secondary certified raw material. In particular, the wood must be chipped by a chipping machine (which uses steel engines powered by electricity) and, subsequently, must be stored in special silos. Therefore, if the pre-treatment process were also considered in the LCA study, it would lead to impacts on climate change, metal depletion and land use. Land use would also be quite high because of the area required for the storage of wood chips and the upstream processes associated with the production of electricity.

One of the advantages of the plant is the autonomy and energy self-sufficiency of the gasifier. It should be remembered that the ignition of the biomass in the gasifier is switched on in a few minutes through electrodes, thus the amount of electricity used is completely negligible. The absence of electricity supplying the plant means that the operation has a relatively low impact. Other elements that allow the operation to have an overall low impact are the ash, that is the inorganic residue that remains after the combustion of biomass in the gasification process. The ash is classified as hazardous waste. At present, ash is widely studied and used for applications in the construction sector, in particular in the construction of eco-sustainable materials, in partial or total replacement of Portland cement. For this reason, in this study, the ash is considered as waste for recovery. In general, the composition of the ashes depends on different elements that constitute them. Calcium oxide, carbon monoxide, chlorine monoxide, sodium oxide are the most common compounds in ash. However, they are found in rather small quantities and therefore do not affect the impact categories, so much so that they never appear as an impacting element. However, if the ash is considered as waste for disposal, the potential impacts of ash disposal would include ecotoxicity, human toxicity, and eutrophication of freshwater. This is due to the emissions into soil and water of metals such as chromium, copper, iron, lead and zinc, contained in the ash. The impacts would result also from the treatment of ash, as it cannot be disposed of in landfill without prior treatment. Finally, a consideration has also be made for lubricating oil. The fossil fuels depletion is the main impact category contributing to the use of lubricating oil. Its disposal has not been included in the study as it is replaced beyond the year of operation. However, if disposal is included, a potential impact on carcinogens and toxicity would be likely. Figure 12 shows the main results in graphic terms.

5.3 Benchmarking to CO_2 emission

Climate change category represents the main reference of environmental impacts since climate change mitigation is one of the key factors for bioenergy development. The gasification of biomass produces syngas, which results in clean and efficient combustion with no particulate emissions, rather than burning them directly (Jithin et al., 2021). For the production of electricity, the LCA analysis returned an overall CO_2 emission value equal to 20 g CO_2 eq./MJ_{el}, generated at the cogeneration plant. This result derives from the environmental impact assessment of a small-scale pilot plant. There are many studies concerning the efficiency of the plants. However, the uncertainty of estimating CO_2 emissions is high. In fact, the estimates of total emissions strongly depend on the emission factors used to evaluate the emissions (Zhang et al., 2013). An extensive review of 53 studies involving biopower LCA analyzes (including CHP) undertaken by NREL (2010) calculated lifecycle GWP values for biomass electricity generation ranging from 1.4 to 25 CO_2 eq./MJ_{el}. To remain in the context of the Italian reality, Boschiero et al. (2016) calculated a contribution of emissions between 14.9 and 23.7 g CO_2 eq./MJ_{el}. The results calculated in this study are within the range of previous studies. Other more recent studies have been undertaken. Sornek et al. (2020) calculated an overall CO_2 value of 0.11 g CO_2 eq per 1 m^3 of biomass entering the plant. Johar et al. (2020) calculated the emissions of a micro-cogeneration plant, whose emissions decrease as the size of the plant increases. This suggests that the larger the plant size, the better the environmental performance if biomass is used as a fuel (Cambero et al., 2015). Finally, Chen et al. (2020) suggested that the CO_2 emission amount to 23 g CO_2 eq./MJ_{el}. Other literature case studies are shown in Supplementary Material (Table S25). The literature is also quite rich in studies on the impacts arising from fossil fuel cogeneration systems and provides the scientific community with always up-to-date results. For example, some studies with reference to the climate change show that diesel generators have values between 86 and 100 g CO_2 eq./MJ_{el} (Bianchi et al., 2012; EIA) and that the natural gas generators have values about 70 g CO_2 eq./MJ_{el} (Balcombe et al., 2016; JRC, 2017; Aksyutin et al., 2018). The plant in question, however, has an overall impact (considering both construction and operation) equal to 20 g CO_2 eq./MJ_{el}. CO_2 emission values make it possible to affirm that the CMD ECO 20 plant is sustainable from an environmental point of view thanks to the obviously lower impacts compared to traditionally used fossil fuels.

6. Conclusion

The LCA study analysed a sub-scale biomass gasification plant, which fell into the reality of a city in southern Italy. It is a really working plant with the aim of feeding a municipal building. The aim of this paper was to assess the main environmental issues associated with a biomass gasification plant. The problems analysed include resource consumption, greenhouse gas emissions, land use, water consumption, eutrophication, biodiversity, and air quality. The calculated impacts are assessed and quantified to provide a rational basis for examining the feasibility and acceptability of individual bioenergy pathways. In this respect, informed choices need to be made regarding production and consumption, and this should be based on potential damage to human health, ecosystems, and available resources and not just on the economic issue. Life cycle assessment helps to provide criteria for making more informed choices about sustainable development. In carrying out this study, some key issues have been identified that could improve the environmental impacts of the plant. To reduce the environmental impacts resulting from the construction of the plant, it is conceivable to use several types of biomass. Or it is conceivable to use alternative materials with lower environmental impacts. In fact, one of the critical issues is the production of stainless steel of which the components are made. Therefore, these components offer greater potential for improvement. The disposal phase of the plant has not been included in this study as no end-of-life information is available. The analysis considered biomass as a material produced on site and ready for use in the plant. The composition of the biomass can influence several releases from the plant, including ash, tar and char, condensate, and various gaseous emissions. Contaminants such as metals can reduce the conversion efficiency of gasification by increasing the volume of waste such as ash. The biomass used in this specific case study ensures optimal performance, as biomass is consistent with the operating parameters of the plant, to maximize conversion efficiency, which corresponds to 74% (CMD SpA). The results obtained from the analysis can be considered individually, as they analyse and discuss the potential environmental impacts of the specific installation chosen for the specific case study. The most significant advantage of the plant lies in the energy self-sufficiency of the plant. The minimization of start-up times and the lack of energy required at this stage, allow to reduce the impacts resulting from a possible use of electricity or natural gas in the Italian grid. Among future research it would be interesting to include all those processes to obtain biomass, such as cultivation, and to study the variation of the calculated impacts. In addition, the information submitted could be part of a broader analysis on the use of biomass. In this case it is essential to choose a clean biomass and consistent with the plant parameters, to ensure smooth operation, continuous and with high conversion efficiencies of gasification. Other future research is similar assessments that could also be undertaken for other raw materials and conversion technologies to build the complete framework for producing energy from biomass. Similar assessments could also be undertaken for other raw materials and conversion technologies to build the complete framework to produce energy from biomass. A comparative study could consider a natural gas installation as a comparison term between it and the ECO20 CMD installation. However, this would be a hypothetical plant, a purely theoretical model with poor data quality, and this would not allow for an inventory analysis suitable for the study. Therefore, it would be necessary to refer to the literature for the collection of most of the data, making the comparison pleonastic. This analysis demonstrates the benefits of using a wood waste product for energy production in this category and beyond. Overall, the analysis shows that small-scale gasification of biomass has good potential for use in industry.

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