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Life Cycle Assessment of electricity production from refuse derived fuel: A case study in Italy

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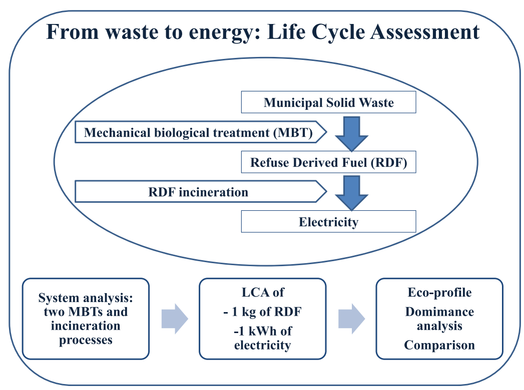
HIGHLIGHTS

- Assessment of environmental profile of electricity from refuse derived fuel (RDF)
- Chimney direct emissions from RDF that can significantly contribute to the impacts
- Cogeneration and valorisation of ferrous metal and dry fraction reduce the impacts.
- Electricity from RDF is worse than electricity from the grid or PV for some impacts.
- Resource Depletion impact is lower for electricity from RDF.

GRAPHICAL ABSTRACT



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ABSTRACT

Biomasses and bio-waste have an important role in decarbonizing the European energy mix, the latter contributing to the transition towards a circular economy. In particular, Refuse Derived Fuel (RFD) - a biofuel obtained from dry residue of waste – appears a really interesting energy option. In this framework this study aims at assessing the environmental profile of electricity generation from RDF in Italy, comparing two different kinds of RDF production and combustion plants. The functional unit is 1 kWh of net electricity from RDF delivered to the grid. Two Italian plants are examined: one located in Ravenna (RDF is produced in a direct flow treatment plant) and the other one in Bergamo (RDF is produced in a unique flow treatment plant and electricity is generated in a cogenerator).

Results show that, comparing the plants, it is not possible to identify an option for RDF production or electricity generation characterized by lowest impacts for all the examined impact categories. However, cogeneration process and the avoided burdens due to the valorisation of ferrous metals and dry fractions during RDF production can reduce most of the environmental impacts. A dominance analysis reveals that chimney direct emissions generated during RDF combustion significantly contribute to some impact categories, as well as electricity consumption during RDF production. Furthermore, disposal of incineration wastes is a relevant contributor to human toxicity and freshwater eutrophication.

The eco-profile of electricity from RDF is compared with electricity from the Italian grid and from multi-Si PV. The comparison highlights that electricity from RDF performs worse for relevant environmental impact categories such as climate change, human toxicity and photochemical oxidant formation. On the other hand, electricity from RDF performs better than electricity from the grid and from photovoltaic for resource depletion, an impact category of growing importance in the framework of circular economy.

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1. Introduction

The European Union has set the ambitious goal to move towards a reduction of 80–95% of greenhouse gas (GHG) emissions by 2050 compared to 1990 levels. The challenges behind this goal significantly involve the entire European energy system. Facing this challenge requires a radical and comprehensive change, the so-called energy transition, which involves a dramatic increase of renewable energy sources, as confirmed by all the decarbonization scenarios developed by the European Union for the 2050 European energy mix (European Commission, 2011). In this framework a growing role will be played by biomasses. According to the European Energy Roadmap the share of electricity produced from biomasses and waste in 2050 will range between 7.3 and 10.8%, which means that biomasses and waste will be the second or the third renewable primary energy source contributing to the European energy mix in 2050 (European Commission, 2011). Focusing in particular on waste-to-energy pathways, it should be underlined that they can play an important role also in the transition towards a circular economy, provided that it happens in accordance with the European waste hierarchy (Prevention-Reuse-Recycling-Recovering-Disposal) and with a high rate of energy recovery (European Commission, 2017). The framework briefly outlined shows that promoting the use of biomass and waste for energy can actively contribute to an energy system increasingly independent from fossil sources and, broadening the view to a circular economy contest, increasingly “sustainable”. In this contest, Refuse Derived Fuel (RFD) - a biofuel obtained from the dry residue of waste that can be used as input for energy production – appears as a really interesting energy option, as far as it is generally characterized by a high quality than original waste. However, the potential environmental advantages of using RDF as fuel have to be examined in a life cycle perspective, taking into account the direct emissions due to its combustion and the impacts due to the fuel production and to the supply of all the process inputs. Only with this life cycle perspective, it is possible to assess if and how far waste-to-energy processes are to be considered sustainable and can contribute to increase the national energy mix sustainability. Taking into consideration the input and output flows of the systems which realize the energy conversion of waste and the number of variables involved, the Life Cycle Assessment (LCA) has been identified as the most appropriate approach to achieve a holistic and systematic assessment of the positive and negative environmental effects of these processes within different environmental sectors and during different stages of the supply chain.

The research activities here described aim at estimating, in a life cycle perspective, the energy and environmental impacts associated with the production of electricity from RDF in Italy, with particular reference to the supply chain which leads to RDF starting from Municipal Solid Waste (MSW), going through its Mechanical Biological Treatment (MBT). To this end, a detailed analysis of the RDF production and use processes, based on primary data, has been carried out. Primary data came from annual environmental declaration of industrial site registered to the European Eco Management and Audit Scheme (EMAS), an exceptional source of primary data for LCA studies that have been little exploited by the LCA community.

2. State of the art

The topic of LCA applied to wastes is discussed by many authors. In detail, authors analysed and compared different ways of managing wastes (landfill, MBT, recycling, incineration). In that cases, being the function of the examined systems the “treatment of wastes”, the selected functional unit is generally the amount of waste treated (Rigamonti et al., 2013), even if some studies identified as functional unit the amount of energy generated (Astrup et al., 2015). Furthermore, for most of the studies the problem of multi-functionalities is solved with the system expansion.

The object of the LCA studies is generally MSW and a global MSW management strategy includes recycling, composting, RDF or waste incineration and landfill. By increasing the percentage of recycled fraction it is possible to improve the environmental footprint of the waste management for many impact categories (Beccali et al., 2001). Also the efficiency of waste selection plays an important role in the impacts of waste management processes. For example, Rigamonti et al. (2009) pointed out that reducing the selection efficiency of 15% implies a worsening of the impact on global warming of 26%. Some exceptions can occur: De Feo and Malvano (2009) pointed out that a scenario with the highest percentage of separate collection corresponds to the highest impact for “non-hazardous waste” and “mineral and quarried matters” impact categories.

Among waste management strategies, production in MBT plants and its use for energy generation (waste- to-energy) shows some advantages, as the reduction of waste in landfill and the related environmental impacts, the recovery of metals, the reduction of fossil fuels (e.g. coal), the co-production of compost. For example, rejected streams of mechanical treatment and composting coming from MSW are usually landfilled in developing countries, but they can be converted in RDF to be used as energy source. This allows for reducing the environmental pollution and energy consumption in these countries (Shumal et al., 2020).

Abeliotis et al. (2012) found that MBT plant is preferable to landfill: if all the avoided impacts due to MBT output (compost, RDF, ferrous and non-ferrous metals) are taken into account, negative impact values are obtained for all the examined impact categories, with the only exception of abiotic depletion. In detail, ferrous metals recovery mainly contributes to the reduction of photochemical oxidation potential, aluminium recovery to the reduction of human toxicity, the use of compost as P fertilizer to the reduction of eutrophication potential. Furthermore, waste treatment in MBT plants as alternative to landfill reduces the impact on global warming of about 15%, and the impact on human toxicity and photochemical oxidation of one order of magnitude.

It is important to highlight that appropriate design and management of the MBT plants can lead to reduction of environmental impacts, as well as the use of innovative MBT plants able to operate with higher efficiency and to recover valuable fractions from wastes (Arena et al., 2015; Ripa et al., 2017). Furthermore, incineration of waste and RDF without energy recovery or with low energy recovery, or its use in countries with low-carbon electricity systems cannot be significantly beneficial than sanitary landfill (Liikanen et al., 2018; Lima et al., 2018). For example, electricity production from RDF generates more GHGs than the average electricity production in Brazil, as about 75% of electricity in this country comes from hydropower (Liikanen et al., 2018).

In addition, comparing RDF combustion with direct waste incineration, Yi and Jang (2018) calculated better or worse performance for the last option depending on the drying method used for producing RDF. In detail, RDF produced without a drying method using fossil fuels can be preferred over incineration. Conversely, incineration should be preferred if there is no low distance demand for heat or power energy produced.

Among waste-to-energy strategies, RDF can be used as an alternative fuel in cement industry, avoiding fossil fuels consumption. The use of RDF in substitution to a conventional fuel (e.g. coal or petroleum coke) in cement industry reduces the impact on cumulative energy demand, GHG emissions and other environmental impacts (Lima et al., 2018), even if not all the pollutant emissions decrease. Also Reza et al. (2013) found that RDF production and use is less energy resource demanding (4.7 GJ/ton clinker) than hard coal and allows for reducing the CO_{2eq} emissions of 863–888 kg per ton of clinker production depending on the waste composition. Furthermore, a reduction of NO_x emissions causes a decrease of the impact on acidification and eutrophication. However, RDF combustion in cement kilns, if compared with coal, increases the emissions of SO_2, NH_3, HCl and HF. Also the co-combustion in a coal power plant is preferable when compared to waste combustion without any pre-treatment or to RDF combustion in a dedicated plant. This outcome is not valid if the direct waste combustion produces heat and electricity in plants with high conversion efficiency (Rigamonti et al., 2012).

If RDF is used as fuel or auxiliary fuel in an incinerator or as input in a gasification and generation system (Kabalina et al., 2017), most of the impacts caused by its production are offset by the power generation during its combustion and this practice is preferable to landfill. Chen et al. (2007) and Panepinto et al. (2015) found better values of different impacts for incineration, while Evangelisti et al. (2015) showed that gasification and plasma processes have better environmental performance than conventional waste treatment technologies. Aracil et al. (2018) pointed out that gasification yields lower GHG emissions than incineration and both the treatments contribute to GHGs reduction if compared with landfill (GHGs in landfill are released through biogas combustion and biogas leaking from the landfill site). Also the outcomes derived from a study made by Cherubini et al. (2009) suggested RDF combined with biogas production as the best option for wastes if compared with landfill (without or with biogas combustion) and incineration, even if authors pointed out the non-negligible problems of local emissions. Conversely, Consonni et al. (2005) found that a direct combustion of waste has environmental advantages if compared with pre-treated waste or RDF: the high heating value of RDF does not counterbalance the electricity consumed during the waste treatments.

Waste composition and typology and technical features of the plants (recovery efficiency, type of biological treatment, etc.) can play an important role on the final life cycle performances of RDF and on direct emissions of waste-to-energy facilities (Astrup et al., 2015). For example, Montejo et al. (2013) found a strong correlation among the environmental performances and the efficiency of energy and materials recovery processes. A comparison of the life cycle impacts of different RDF typologies (fluff, dry fluff, and pellet) in distributed or centralized incineration systems in the Italian region of Tuscany (Corti and Lombardi, 2001) showed that none of the examined scenarios performs better for all the examined impact categories. However, authors pointed out the importance of transports on the impacts: most indicators increase with the distance. The role of transport is also outlined by Grzesik and Malinowski (2016): the collection and transportation of input waste, identified as the most fuel and energy-consuming process, caused 51% of total impacts during the RDF production in a MBT plant in Poland.

The analysis of the above studies reveals that different authors addressed the topic of waste management, also including information on the RDF environmental aspects. However, few of them proposed a detailed analysis of the RDF production and use processes, based on primary data and presenting results by applying a dominance analysis. In this context, to enrich the existing literature, the proposed paper focus on existing MBT and incinerator plants, it is based on detailed and reliable primary data and it presents an in-depth analysis of the materials and processes that mainly contribute to the total impacts, allowing to propose some qualitative actions for improving the environmental performance of the examined systems.

3. Application of the Life Cycle Assessment methodology

3.1. Goal and scope definition

The study aims at assessing the environmental impacts caused by the electricity generation from RDF in Italy and comparing the impacts with those of electricity from the Italian grid and from multi-Si PV.

The LCA methodology is applied to a supply chain that starts from the waste management in a MBT plant to obtain RDF and ends with the generation of electricity from the RDF combustion. The study is developed according to the international standards UNI EN ISO 14040 and UNI EN ISO 14044 (ISO 14040, 2006a; ISO 14044, 2006b). In detail, the analysis is carried out by following two consecutive steps:

- Assessment of the environmental impacts due to the RDF production by applying two different MBT processes (described in the next section): Different Flows (DF) treatment (Scenario 1) and Unique Flow (UF) treatment (Scenario 2).
- Assessment of the environmental impacts due to the electricity generation from RDF obtained with the two MBT processes cited above.

Two Italian plants are selected for the analysis: one located in Ravenna (Scenario 1) and the other one in Bergamo (Scenario 2).

3.1.1. Refuse derived fuel

RDF is a fuel obtained from non-dangerous urban and special wastes. It is obtained by two processes occurring in a MBT plant (ENEA, 2007; Rigamonti et al., 2012):

- Mechanical process: wastes are subjected to a shredding for the volume reduction and to a screening for separating the different fractions. An aeraulic-pneumatic separation is applied for reducing the chlorine content in PVC products (if any). Then, a metal removal allows for reducing the risk of damage to the system, recovering precious materials and improving the quality of the final product.
- Biological process: wastes undergo a stabilization of the organic fraction, a sanitization through pasteurization and a volume reduction.

The MBT plants can be divided into:

- Different Flows (DF) treatment plants: a mechanical pre-treatment of waste allows for obtaining an organic fraction for biological treatment and a dry fraction to be used as energy source or to be sent to landfill;
- Unique Flow (UF) treatment plants: all the waste entering the plant undergoes a biological treatment, while mechanical treatment is limited to a simple crushing of waste without preliminary separation of the dry and wet fraction.

The obtained RDF can be used as energy source for the generation of electrical and/or thermal energy in specific plants (waste-to-energy plants, thermoelectric plants, district heating plants) or in industrial sites where RDF is co-burned with traditional fuels (thermoelectric plants, cement plants, lime production plants, steel plants).

3.1.2. Functional unit and system boundaries

The function of the examined system (from waste-to-energy) is the generation of electricity sent to the grid. Thus, according to reference documents on LCA for electricity generation (EPD International AB, 2020), the selected functional unit is 1 kWh of net electricity from RDF delivered to the grid. The reference flow is the amount of RDF (in kg) for the generation of the functional unit, which is about 2.12 kg of RDF for the first scenario and about 1.28 kg of RDF for the second one. The difference of the above values comes from an energy yield of the plant in Scenario 1 lower (0.47 MWh of net energy per ton of RDF) than that of the plant in Scenario 2 (0.78 MWh of net energy per ton of RDF).

The system boundaries are selected according to the “zero burden” assumption, namely hypothesizing that waste in input to the RDF production plant has no environmental burdens (Rigamonti et al., 2012). In detail, the system boundaries include:

- The production of materials, fuels and electricity used for the RDF production and combustion;
- The RDF production process;
- The generation of electricity from RDF;
- The end-of-life of process wastes.

Considering that capital goods involved in the generation of the functional unit have a long useful life, the impacts due to their production are considered as negligible compared to the impacts generated during their use (Panahandeh et al., 2017). Thus, the buildings and plants production is not included in the analysis.

The transport of natural gas, electricity, thermal energy (avoided impact) and coal (avoided impact) are modelled according to secondary data (Wernet et al., 2016).

The emissions of some pollutant are neglected, as only the concentration is known and it is not possible to calculate the respective quantities to be included in the analysis.

The impact of activated carbon, used during the biostabilization process for the abatement of odorous substances in one of the examined plants, is neglected due to lack of data on the quantity used.

Finally, the impacts due to the production of some components used in the electricity generation process are neglected, whose function is known (e.g. additives) but not the specific materials.

The analysis is referred to the year 2015.

3.1.3. Allocation rules

The RDF production and its combustion for electricity generation can be multi-output processes. In particular, the RDF production process can generate different RDF typologies (RDF with different qualitative characteristics) and sub-products that are potential substitutes of primary materials. Furthermore, the RDF combustion process can generate electricity and heat (co-product); this last co-product can be used to replace heat generated by other energy sources.

The selection of the most suitable procedure for dealing with the multifunctionality problem requires an in-depth analysis of the product system and the related co-products. Furthermore, according to the indications of ISO 14044 (ISO 14044, 2006b), when possible allocation should be avoided and division of the process in sub-processes or expansion of the product system (avoided impact method) should be applied. If allocation cannot be avoided or it is considered the most appropriate approach, physical or economic relationships can be used for the partitioning of inputs and outputs.

To solve the multifunctionalities of this case study, in the most cases authors applied the avoided impact method. In detail, the avoided impacts due to primary materials potentially replaceable with sub-products were subtracted to the impacts caused by the RDF production process. Similarly, the impacts generated by electricity from RDF are reduced considering the avoided heat generation from non-renewable sources. Physical or economic allocation is not taken into account due to the different characteristics of the co-products (different masses, function, quality, energy content) or to difficulties in defining data for calculating the allocation factors (e.g. difficulty to find reliable and fixed economic values for co-products).

Focusing on the co-production of different RDF typologies, a mass allocation is applied, as in this case it is considered the most appropriate choice. When the co-product can be considered "burden free" or reliable information for the input/output process modelling is not available, a cut-off is applied.

3.1.4. Environmental impacts categories and impact assessment methods

The environmental impact categories selected to describe the performance of the functional unit are listed in Table 1. These categories refer to global and local mid-point impacts and cover different environmental aspects that can be influenced by the eco-profile of the examined product system (resource consumption, human toxicity, climate change, eutrophication, etc.).

The following impact assessment methods are used:

- IPCC 2013 GWP 100a, for the calculation of the impact on climate change (IPCC, 2013). This method is developed by the International Panel on Climate Change and includes climate change characterization factors for the direct global warming potential of emissions to air, with a timeframe of 100 years. The method excludes indirect effects, e.g. the indirect dinitrogen monoxide that is formed from nitrogen emissions, the carbon dioxide formation from carbon monoxide emissions; it also excludes the radiative forcing due to emissions NO_x, water, sulphate, etc. in the lower stratosphere and upper troposphere;
- ILCD 2011 Midpoint+, for the other impact categories (European Commission and Joint Research Centre, 2012). The method, also defined as ILCD recommendations for LCIA in the European context, is proposed by the European Commission and includes a wide range of environmental indexes. It is based on the analysis of the existing methodologies for the LCA impact assessment and aims at identifying and promoting recommended existing methods (e.g. the recommended method for calculating human toxicity is the USEtox model (Rosenbaum et al., 2008)). Further details can be found in the ILCD Handbook of the European Commission (European Commission - Joint Research Centre, 2011).

Table 1
Environmental impact categories.

Impact category	Unit of measure	Acronym
Climate change	kg CO_{2eq}	CC
Ozone Depletion Potential	kg CFC-11$_{eq}$	ODP
Human toxicity, cancer effects	CTUh	HTC
Human toxicity, non- cancer effects	CTUh	HTNC
Photochemical ozone formation	kg $NMVOC_{eq}$	POF
Acidification	molc H^+_{eq}	AC
Terrestrial eutrophication	molc N_{eq}	TE
Freshwater eutrophication	kg P_{eq}	FE
Marine eutrophication	kg N_{eq}	ME
Particulate matter	kg PM2.5$_{eq}$	PM
Resource depletion, mineral, fossil and renewable	kg Sb_{eq}	RD

3.2. Inventory analysis

The inventory analysis allows for calculating the eco-profile of 1 kg of RDF and 1 kWh of electricity generated by RDF combustion, considering the two scenarios of RDF production (DF and UF). Primary and secondary data are elaborated by using the LCA software SimaPro (PRè, 2019) and the inventory results are calculated in terms of raw materials consumption, emissions to air, water and soil.

3.2.1. Primary data collection

The first step of the inventory analysis is the primary data collection for the RDF production and the electricity generation. Primary data for the reference year 2015 are taken from the EMAS Environmental Declarations of the two selected plants (Herambiente, 2016, 2017; A2A Ambiente, 2016, 2017) and from other sources (ISPRA, 2016, 2017; ARPA Lombardia, 2015; ARPA Emilia Romagna, 2015). In detail, the owners of the selected plants developed an environmental declaration, according to the EMAS (eco-management and audit scheme) regulation (EU, 2009). The environmental declaration is a publically available document used by organizations to evaluate the performance of the company's environment management system and to measure the

Table 2
Output flows (non-hazardous) from the RDF-DF plant.

	Quantity (ton)	Treatment
RDF	44,084	Energy recovery
Process losses in the biostabilization process	2,914	–
Wet fraction	36,234	Composting
Dry fraction	58,624	Disposal
Dry fraction	524	Energy recovery
Biostabilized	19,031	Material recovery
Ferrous metal	1,358	Material recovery
Other wastes	70	Disposal

Table 3
Input flows to ER plant.

Inputs	Quantity
Tap water (m^3)	528
Process water (m^3)	36,218
Sorbalite (95%[a] hydrated lime, 5%[a] activated carbon) (ton)	393
Dolomite (ton)	622
Sodium hydroxide 30% (ton)	37
Ammonia solution 25% (ton)	350
Electricity from the grid (MWh)	1,023
Natural gas[a] (supporting fuel) (MWh)	3,411.9
Diesel[a] (supporting fuel) (MWh)	379.1

[a] Estimated percentage/value.

environmental performance of the plants and the results achieved with respect to established environmental targets. This declaration contains detailed information about the organisation, the plant-related site, the environmental aspects as materials and energy consumption, emissions, waste production and treatment processes, valuable outputs. The environmental declaration is used in this study to obtain information on the plant operation processes and to collect primary data on the inputs and outputs related to the production of RDF and electricity. The above information and data are described in detail in Sections 3.2.1.1 and 3.2.1.2.

3.2.1.1. The plant located in Ravenna. The examined plant (Herambiente, 2016, 2017), owned by Herambiente, is part of a group of installations for the treatment of liquid, solid and slurry wastes. It is composed by a DF plant for the RDF production (authorized to treat 180,000 tons of wastes per year) and a plant for the energy recovery (ER).

3.2.1.1.1. The RDF-DF plant. The input flows for the RDF-DF plant are non-hazardous wastes. In detail, in 2015 a total of 162,839 tons of wastes are treated: 70.7% are non-differentiated urban wastes collected in the Province of Ravenna and 29.3% are special wastes assimilated to urban wastes (paper, plastic film, wood, packaging, etc.) coming from productive activities. The yearly RDF production is 44,084 tons.

During the RDF production process wastes entering the plant are stored, then they are shredded and screened for separating the wet and the dry fraction. The latter is sent to the recovery of ferrous materials (deferrization), while the wet fraction partially goes to the biostabilization process and partially to the composting. The biostabilized material, coming from the biostabilization process, is used to cover landfills. After a further shredding and deferrization, the dry fraction is sent to a pneumogravimetric separation system, where an upward current of air drags the light parts (RDF) upwards, separating them from inerts and heavy parts (dry fraction). Pelletizers machines increase the specific weight of RDF, allowing for an adequate permanence in the combustion chamber. The RDF is then stored in a silo, from which it is extracted to supply the ER plant.

The output flows from the RDF-DF plant are showed in Table 2. The emission of particles from the pneumogravimetric separation system (annual average <0.1 mg/m^3) is neglected, considering that the average concentration is lower than the limit prescribed by law (20 mg/m^3).

Table 4
Wastes of ER plant.

Waste typology	Quantity (ton)	Treatment
Slag and sand (non-hazardous)	337	Material recovery
Slag and sand (non-hazardous)	1,320	Disposal
Light ashes (hazardous)	4,774	Disposal
Pumpable sludge (hazardous)	25	Disposal
Flue gas wash water (hazardous)	2,528	Disposal
Storm water first rain (non-hazardous)	67	Disposal

Table 5
Emissions of ER plant.

Substance	Quantity (ton)
CO_2[a]	44,624
CO	2.02
NMVOC (as TOC)	$79.92 * 10^{-3}$
NO_x	43.51
SO_2	$30.00 * 10^{-3}$
Mercury and mercury compounds	$2.00 * 10^{-4}$
PCDDs + PCDFs	$2.80 * 10^{-9}$
PAHs	$2.00 * 10^{-6}$
HCl	0.22
HF	$3.80 * 10^{-3}$
Particles	0.41

[a] Considering that RDF is obtained from different waste typologies, authors hypothesized a percentage of fossil CO_2 equal to 50% of the total (IPCC, 2013).

The electricity consumption of the RDF-DF plant is 5,028 MWh, of which about 88% coming from the ER plant, while the remaining 12% is taken from the grid.

3.2.1.1.2. The ER plant. In 2015, the ER plant used 51,746 tons of wastes as fuel (98.6% of RDF and the remaining 1.4% of special wastes[1]) for the generation of 24,086 MWh of net electricity. Because of the amount of RDF produced in 2015 is lower than that used in the ER plant, authors assumed that the missing quantity was stored during the previous years.

The input of energy and materials for the electricity generation are summarized in Table 3, while Tables 4 and 5 show the outputs of the plant, wastes and emissions, respectively.

3.2.1.2. The plant located in Bergamo. The examined system is located in Bergamo (A2A Ambiente, 2016, 2017) and it is managed by A2A Ambiente. The system includes a UF plant for the RDF production and a cogenerative incinerator (CI) powered with RDF.

3.2.1.2.1. The RDF-UF plant. The plant, authorized to treat 72,000 tons of wastes per year, receives urban solid wastes from the city of Bergamo and other cities of the surrounding areas. In 2015, the plant treated 53,043 tons of wastes, of which 97.8% non-differentiated urban wastes and 2.2% other urban wastes.

After control and weighting procedures, input wastes are sent to a breaker - primary shredder for grinding. Then, the material is treated with a biological drying process that produces a first RDF output (RDF1) (30,469 tons in 2015) and a dried material that is further refined by a screening process for the production of a second typology of RDF (RDF2) (3566 tons in 2015); the remaining dried material undergoes an iron removal, a shredding and a pressing process (optional), to obtain a RDF characterized by high quality (RDF3) (8,882 tons in 2015) that is used as fuel in the CI plant.

During the drying process, about 20% of wastes weight is loss due to the oxidation of part of the biodegradable material and to the evaporation of water. The drying air is treated in a purification plant before being released into the environment.

RDF1 and RDF2 are used for energy recovery in other plants managed by A2A Ambiente.

Inputs (materials and energy) and outputs of the RDF-UF plant are showed in Table 6. The emissions of particles (<0,055 mg/Nm^3) and ammonia (<0,64 mg/Nm^3) are neglected: the average yearly concentration is lower than the limit prescribed by law (10 mg/Nm^3 for particles and 5 mg/Nm^3 for ammonia).

3.2.1.2.2. The CI plant. The CI plant has a thermal power of 48 MW and it is powered with RDF produced by the RDF-UF and by external plants.

[1] According to the “zero burden” assumption, the impact of special wastes in input to the plant is assumed to be negligible (Rigamonti et al., 2012).

Table 6
Input flows to RDF-UF plant.

	Quantity
Input	
Tap water (m^3) (Used in the waste storage and purification process)	7,153
Mineral oil (ton)	1
Electricity from the grid (MWh)	2,142
Output	
Wastewater to the purifier (m^3)	2,370
Ferrous metals for material recovery (ton)	269

In 2015, it used 61,122 tons of RDF (14.5% produced by the RDF-UF plant and 85.8% by other plants[2]) for generating 47,800 MWh of net electricity and 108,593 MWh of thermal energy sent to a district heating plant. The inputs and outputs (wastes and emissions) of the CI plant are illustrated in Tables 7 (inputs), 8 (wastes) and 9 (emissions).

3.2.2. Allocation procedures

As indicated in Section 3.1.3, the avoided impact method is applied to manage the multifunctionalities of the examined processes, except for the co-production of different RDF typologies in Scenario 2. In this case, a mass allocation is applied.

Table 10 gives a detail of the primary materials and energy sources that can be substituted by the sub and co-products generated from the RDF and electricity production processes, when the avoided impact method is applied.

Focusing on Scenario 1, at the end of the shredding and primary screening of the RDF production, 0.822 kg of wastes/kg of RDF leave the system and are used as compost. Because of this compost does not substitute any primary material, in this case a cut-off is applied. Furthermore, adopting a “burden free” assumption for it, the impacts due to the shredding and primary screening processes are totally assigned to the RDF produced by the plant.

Due to the lack of information on the recovery process and use of slags and sands produced in the combustion process, a cut-off is applied also in this case.

Similarly, a cut-off is applied in Scenario 2 for the recovery process of slags and sands and for the management of hazardous wastes produced by the fumes treatment in the CI plant. Furthermore, considering that the RDF-UF plant in Bergamo produces three RDF typologies, in order to allocate the inputs (water, mineral oil and electricity) and outputs (wastewater) and the process losses (that occur during the biological drying process) to the main product of the plant (RDF3), a mass allocation is performed. Focusing on the electricity consumption, based on the different steps of the process, authors hypothesized that 25% of that is used only for RDF3, while the remaining 75% is allocated to the three co-products.

In detail, after the biological drying process, a flow of 30,469 tons of RDF1 leaves the plant, and at the end of the screening process there are two output flows: 3,566 tons of RDF2 (output) and 9,151 tons of material that is further treated to obtain the RDF3. Thus, the allocation factor (AF) for RDF3 is calculated as follows (Eq. (1)):

$$FA = 9,151\ \text{tons}/(30,469\ \text{tons} + 3,566\ \text{tons} + 9,151\ \text{tons}) = 0.212 \quad (1)$$

Starting from the allocation procedure, the inputs and outputs for each scenario and for each plant are calculated, as showed in Figs. 1–4.

3.2.3. Secondary data

The database Ecoinvent 3.3 – Allocation, recycled content (Wernet et al., 2016) is used for calculating the eco-profiles of materials and energy sources, including electricity from the grid and from PV used for the comparison.

The eco-profile of electricity from the grid refers to the electricity fed and transport into the low voltage transmission network in Italy. It includes the steps of fuel supply, electricity transmission and losses, direct emissions to air. The electricity mix is the following (IEA, 2017): 14.9% of imported electricity, 24.6% of electricity from natural gas, 18.7% from hydropower, 12.8% from hard coal, 10.9% from PV, 4.8% from wind, 6.9% from other renewables (biogas, wood and geothermal), 6.4% from other non-renewables (waste, oil, lignite, coal gas and blast furnace gas).

Focusing of the plant located in Bergamo, the eco-profiles of the refrigerants R407C and R507C are not available in the consulted environmental databases (PRè, 2019). Thus, they are modelled as refrigerant R134a. Furthermore, for the same reason, the eco-profile of sodium bicarbonate is modelled by using data for sodium percarbonate.

3.3. Life cycle impact assessment and interpretation: results and discussion

The inventory analysis consists in collecting primary and secondary data, elaborating them and calculating the eco-profile of the functional unit. In detail, the eco-profile is represented by a huge number of environmental indicators representing the raw materials used (e.g. aluminium, barite, gallium, magnesite, etc.), the emissions to air (e.g. butane, carbon dioxide, ethane, nitrate, etc.), water (e.g. cadmium, phenol, sulphate, toluene, etc.) and soil (e.g. arsenic, boron, mercury, potassium, etc.) during the whole life cycle of the examined functional unit. Analysing the environmental performance of a product by examining its eco-profile is a complex task due to the high number of indicators that make it up. Thus, the above indicators are grouped into impact categories as follows (Eq. (2)):

$$I = \sum_{1}^{n} m_i \times CF_i \quad (2)$$

where “I” is the selected impact category (e.g. CC), “m_i” is the mass of the i-substance taken from the eco-profile that contributes to the

Table 7
Input flows to CI plant.

	Quantity
Electricity from the grid (MWh)	8,000
Natural gas (as support fuel) (kSm^3)	862
Tap water (m^3)	5,973
Chloridric acid (solution 30%[a]) (ton)	11.1
Sodium hydroxide (solution 30%[a]) (ton)	16.5
Dolomite (ton)	968
Activated carbon (ton)	70
Sodium bicarbonate (ton)	834
Sand (ton)	362
Ammonia solution 25% (ton)	157
Lubricating oil (ton)	0.4
Alkalising, deoxygenating additives for the thermal cycle (ton)	0.4
Refrigerant greenhouse gases (R407C - R507C - R134a) (ton)	0.007

[a] Estimated percentage.

Table 8
Wastes of CI plant.

Waste typology	Quantity	Treatment
Heavy ashes and slag (non-hazardous) (ton)	1,313	Material recovery
Ferrous material (non-hazardous) (ton)	47	Material recovery
Other wastes (non-hazardous) (ton)	19	Disposal
Ashes (hazardous) (ton)	3,089	Disposal
Particles from fumes treatment (hazardous) (ton)	996	Material recovery
Wastes from fumes treatment (hazardous) (ton)	3,264	Disposal
Other wastes (hazardous) (ton)	22	Disposal
Wastewater (m^3)	5,973	Purifier

[2] Authors hypothesized that the production of RDF in external plant has the same impacts than that produced in the RDF-UF plant.

Table 9
Emissions of CI plant.

Substance	Quantity (ton)
NO_x	29.84
Ammonia	0.37
Particles	0.38
HCl	1.96
CO_2[a]	53,475

[a] No data available. Authors assumed a CO_2 emissions value per kg of RDF equal to that of the plant in Ravenna.

selected impact category (e.g. for the impact category CC the i-substance can be CO_2, CH_4, N_2O, etc.), "CF_i" is the characterization factor for the i-substance and expresses the impact of this substance to the impact category "I" with respect to a reference substance (e.g. for CC the reference substance is CO_2 and the CF for methane (fossil) is about 25 $kgCO_{2eq}/kg\ CH_4$). The CFs are taken from the impact assessed methods described in Section 3.1.4.

Starting from the inventory results and following the procedure described above, authors calculated the life cycle environmental impacts of the selected function unit (1 kWh of electricity) and of 1 kg of RDF. The results of the life cycle impact assessment for 1 kg of RDF and 1 kWh of electricity are discussed in the following sections.

3.3.1. Environmental impact of RDF production

Table 11 reports the results of the life cycle impact assessment for the production of 1 kg of RDF in the two examined scenarios, including the benefits due to the avoided impacts.

Comparing the RDF in the two Scenarios (1 and 2), best performances are related to Scenario 2, except for PM, AC and RD. It is important to point out that the above consideration is valid also if the avoided impacts are excluded from the counting.

In detail, focusing on the results that include the avoided impacts:

- PM and RD are negative for both scenarios, with the first scenario characterized by higher environmental gains;
- negative values (environmental gains) are obtained in Scenario 2 for CC, HTNC, HTC, POF, FE and ME, due to the avoided impacts of the ferrous metals that offset the environmental burdens due to the production process and to the waste treatments; positive values (environmental impact) are obtained in Scenario 1 for the above impact categories, where the avoided impacts of the sub and co-products are lower than the process impacts;
- better performances for AC are observed in Scenario 1, while worst performances are obtained for the remaining impact categories (ODP and TE).

If the avoided impacts are not taken into account, going from Scenario 1 to Scenario 2 the environmental impacts decrease significantly for human toxicity (90–99%), water eutrophication (66–78%), climate change (68%) and photochemical ozone formation (67%). A lower decrease (9–11%) occurs for ozone depletion and terrestrial eutrophication. Conversely, a relevant increase of the impact on particulate matter (94.3%) is obtained as well as a worsening of the impact on acidification (35%) and resource depletion (17.5%).

A dominance analysis for Scenario 1 (Fig. 5) indicates that ferrous metal recovered generates >83% of the environmental gains, with the only exception of the avoided resource depletion due both to the ferrous metal (53.3%) and the biostabilized material used as landfill covering (45.5%). A negative contribution on PM comes also from the electricity from RDF (6.3%). More than 61% of almost all the environmental impacts of the process (this percentage is >97.5% for the impact on human toxicity) are caused by electricity from RDF. Some exceptions occur: the main responsible of resource depletion (78.3%) and particulate matter (72.6%) is the disposal of process waste, which also contributes to about 47% of ODP.

Focusing on Scenario 2, the major contribution to the environmental impacts generated by the system is the electricity from the grid (contribution higher than 97%), that is partially offset by the benefit due to the ferrous metal recovery. A negligible impact is caused by the other inputs (lower than 2.6%) and by the wastewater treatment (lower than 2.8%).

Identifying electricity as one of the main contributors to the impacts allows for suggesting some strategies for reducing the burdens due to RDF production. In detail, it is possible to act on two fronts: reducing energy consumption through the use of energy efficient machineries and using "clean" energy sources (e.g. electricity from RDF characterized by lower impacts or the installation of a PV plant). Obviously, the above strategies require an economic investment; they can be put in place in a medium-long term and after carefully evaluating their economic feasibility and the availability of incentives.

3.3.2. Environmental impact of electricity production

Table 12 shows the results of the LCA for 1 kWh of electricity in the two Scenarios, and also includes the environmental impacts of 1 kWh of electricity from the Italian grid (low voltage) and from multi-Si PV (low voltage) located in Italy.

Based on the modelling assumptions, electricity produced in the plant of Bergamo with RDF from the UF system (Scenario 2) has better performance than electricity from the plant in Ravenna obtained with RDF from the DF system (Scenario 1). This result is mainly due to the avoided impacts associated to the ferrous metal and heat in the co-generation plant located in Bergamo. There are some exceptions: a positive PM in Scenario 2 versus a negative one for Scenario 1, a RD impact in Scenario 2 higher than Scenario 1.

Comparing the eco-profile of electricity from RDF in Scenario 1 with that of electricity from the Italian grid, the last performs worse for 5 out of 11 impact categories (ODP, PM, AC, TE and RD). The above value is 7 when the comparison is made with Scenario 2 (the same impact categories than in Scenario 1 and POF and ME). An important topic to be examined in detail is the impact on human toxicity. In this case, electricity from RDF is characterized by higher impacts, mainly due to the final disposal of incineration wastes.

The electricity from PV has the highest impact on the category RD if compared with the other scenarios, due to the high consumption of raw materials during the production process of PV panels and cells. This

Table 10
Avoided impact method assumptions.

Scenario	Sub and co-products	Use	Primary materials/energy sources
1	Biostabilized material	Coverage of landfill	Sand and gravel
1	Ferrous materials	Material recovery	Pig iron[a]
1	Dry fraction	Energy recovery	Coal[b]
2	Ferrous materials	Material recovery	Pig iron[a]
2	Heat	District heating	Heat from natural gas[c]

[a] The database Ecoinvent (Wernet et al., 2016), suggests using pig iron production process to assess the impacts/benefits due to the recycling of ferrous materials.
[b] Coal is the fuel usually used in co-combustion with RDF (e.g. in the cement plants) (Rigamonti et al., 2012). Only the avoided impacts due to the coal production are considered; the impacts of the coal combustion are taken into account in the combustion plant.
[c] The district heating of the city of Bergamo is powered by natural gas.

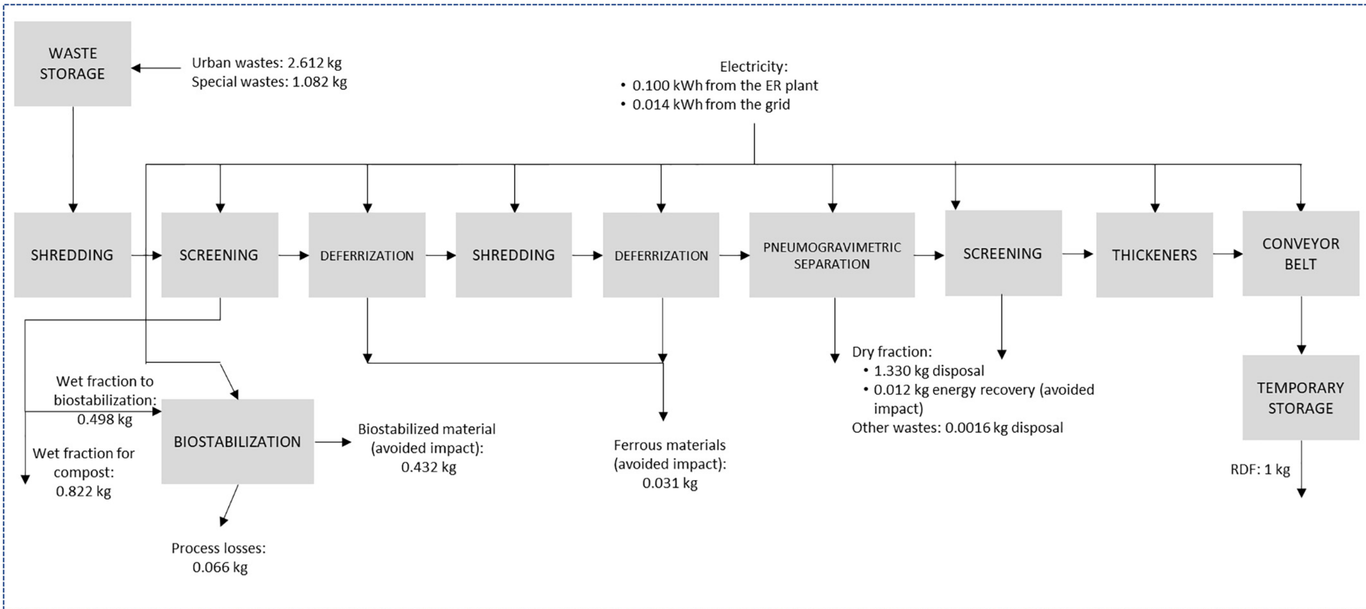

Fig. 1. Flowchart of the RDF-DF plant in Ravenna (data referred to 1 kg of RDF).

result points out that future strategies aimed at improving PVs eco-profiles have to introduce an eco-design approach and circular models in the PVs manufacturing processes.

Conversely, best performances are obtained for the other environmental impact categories when electricity comes from PV, except for PM for both Scenarios and ODP for Scenario 2.

The comparison of the electricity from RDF and from PV is influenced by different parameters regarding the PV panels used (Muteri et al., 2020), e.g. their efficiency, the materials used/recycled, the processes involved in the manufacturing of the single cell/module (Parisi and Basosi, 2015).

Although silicon-based panels are most used and mature today (Aberle, 2006), their substitution with second or third generation panels can involve a change (increase or decrease) in the values of some environmental indexes. For example, Mohr et al. (2012) compared a a-Si/nc-Si (efficiency: 10%) PV system with a multi-Si PV system (efficiency 14.4%) and obtained a lower energy payback time for the first system, even if the calculated damage score resulted higher. As showed by Tsang et al. (2016), organic photovoltaic (third generation) performed better (impacts from 32% to 97% lower) than multi-Si except for the impact on metal depletion, which in 21% higher for organic PV. Conversely, impacts of perovskite devices can be higher than mc-Si, a-Si, CdTe and CIS solar cells, as demonstrated by Celik et al. (2016).

The results of the comparison can address the selection of the most suitable source of electricity depending on the specific environmental problem to be faced (both local and global). It is important to highlight that the obtained RDF electricity eco-profile includes the avoided impacts. If these avoided impacts are excluded, the above results and considerations change in absolute value and in some cases reveal different

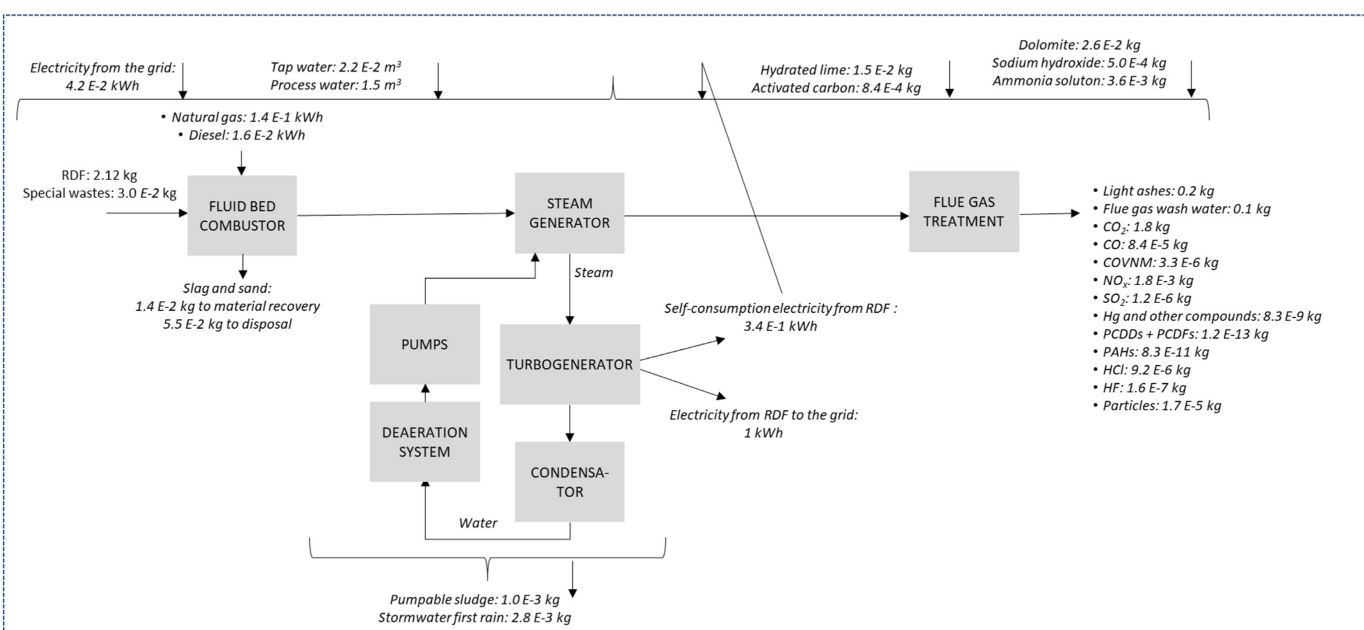

Fig. 2. Flowchart of the ER plant in Ravenna (data referred to 1 kWh of electricity).

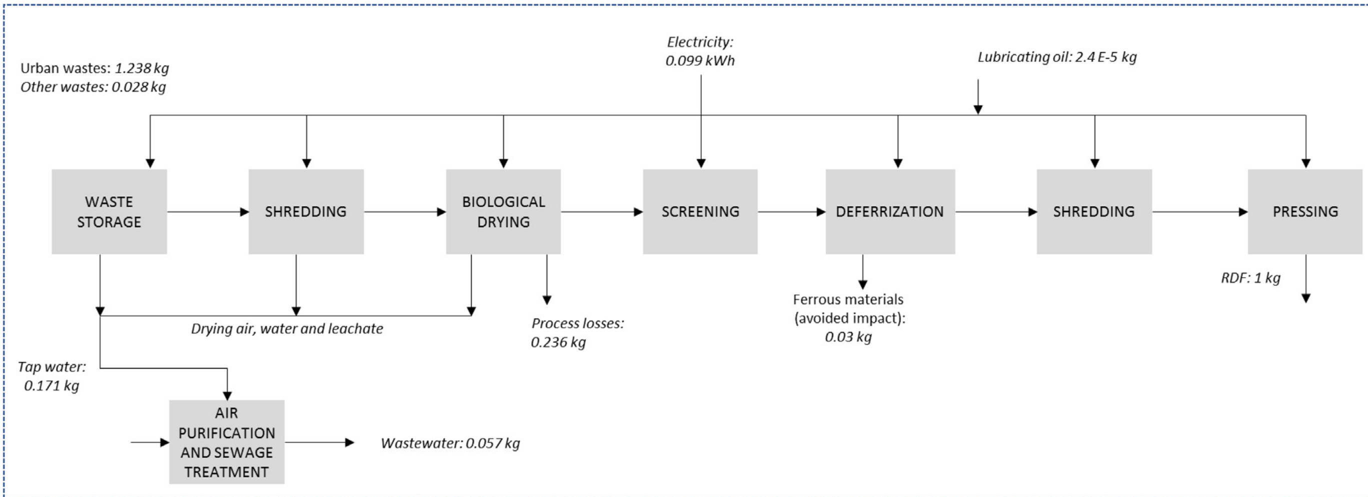

Fig. 3. Flowchart of the RDF-UF plant in Bergamo (data referred to 1 kg of RDF).

environmental performance hierarchies, highlighting that the allocation procedures can influence the analysis.

The comparison of electricity from RDF with or without avoided impacts for the two scenarios shows that:

- for Scenario 1, RD increases of one order of magnitude and PM has a positive value; the other impact categories have an increase variable from 0.2% (human toxicity – cancer effect) to 30% (acidification);
- for Scenario 2, a positive result is obtained for ODP, three impact categories (CC, PM and POF) vary of one order of magnitude and the remaining impact categories show an increase from 0.6% (human toxicity – cancer effect) to 70.2% (marine eutrophication).

Taking into account the electricity from the grid, no variations are observed in the hierarchies for Scenario 1. For Scenario 2 there is a worsening of the impact categories POF and ME, whose values become higher than those of the electricity from the grid. Electricity from PV has the low impact values (also for PM and POF), even if its impact on resource depletion remains higher.

A dominance analysis of Scenario 1 (Fig. 6) shows that the direct process of RDF combustion has a null impact on the categories ODP, HTNC, HTC, FE and RD: based on the available and declared data there are no direct emissions contributing to these impacts. The emissions generated during the RDF combustion (direct process) cause 1.31E-05 kg $PM2.5_{eq}$ (19.6% of the positive impact) and are responsible of >63% of the remaining categories. The incidence of direct emissions on particulate matter highlights that efficient systems for the fumes treatment could reduce the problem of particulate emissions, frequently linked to the combustion of biomasses and wastes.

The materials in input to the process (dolomite, hydrated lime, water, etc.) as well as the wastewater treatment have not dominant values of impact, with a total incidence lower than 19%. This percentage does not account the impact of ammonia for RD (19.7% of the total), and PM (about 29% of positive impact). The energy sources used in the process (including RDF) cause from 11.7% (POF) to 27% (TE) of the positive impacts and are dominant contributors for ODP (70.4%). In particular, about 34% of the positive value of these impacts is due to natural gas. Thanks to the avoided burdens of RDF production, a negative

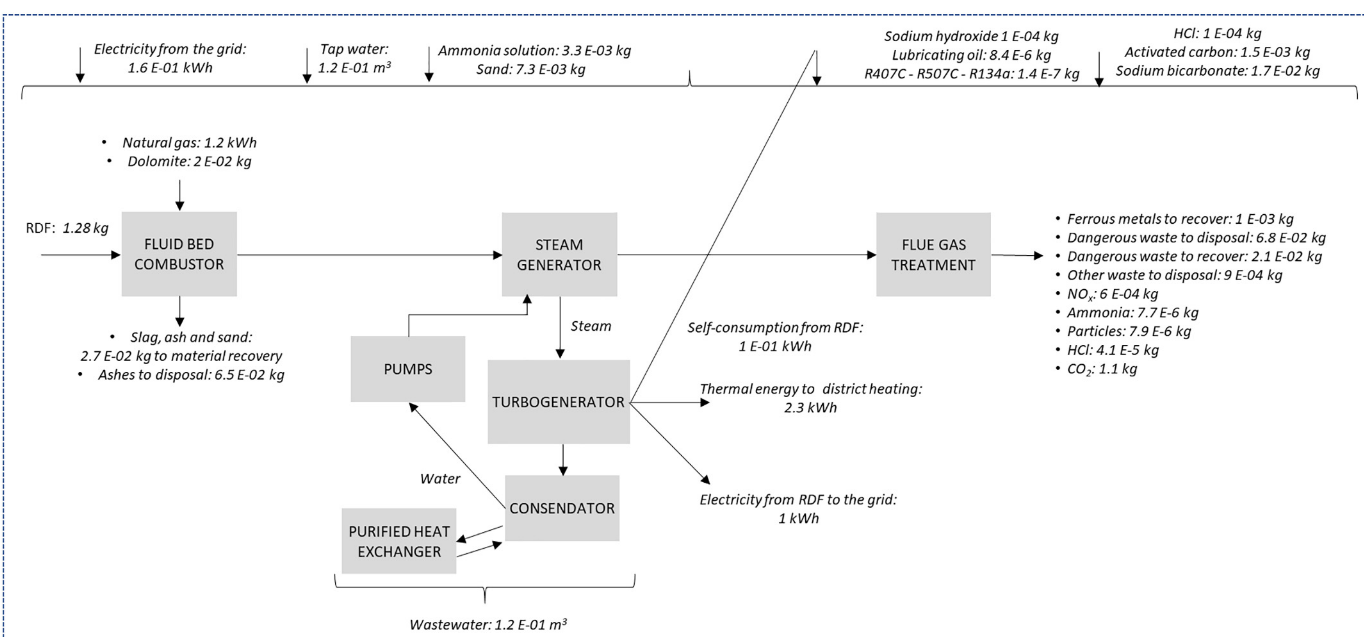

Fig. 4. Flowchart of the ER plant in Bergamo (data referred to 1 kWh of electricity).

Table 11
Environmental impacts of 1 kg di RDF.

Impact categories	Scenario 1 (total)	Scenario 1 (impacts, excluded the avoided impacts)	Scenario 2 (total)	Scenario 2 (impacts, excluded the avoided impacts)
CC [kg CO_{2eq}]	8.19E−02	1.37E−01	−7.71E−03	4.24E−02
ODP [kg CFC-11$_{eq}$]	2.36E−09	5.43E−09	2.25E−09	4.93E−09
HTNC [CTUh]	6.24E−08	7.39E−08	−2.79E−09	6.96E−09
HTC [CTUh]	1.89E−07	1.91E−07	−5.67E−10	1.48E−09
PM [kg PM2.5$_{eq}$]	−4.97E−05	1.05E−05	−3.18E−05	2.04E−05
POF [kg NMVOC$_{eq}$]	5.02E−05	3.15E−04	−1.34E−04	1.02E−04
AC [molc H^+_{eq}]	5.11E−05	3.48E−04	2.16E−04	4.69E−04
TE [molc N$_{eq}$]	1.00E−03	1.64E−03	9.42E−04	1.46E−03
FE [kg P$_{eq}$]	3.47E−05	5.84E−05	−6.31E−06	1.30E−05
ME [kg N$_{eq}$]	6.92E−05	1.27E−04	−5.71E−06	4.25E−05
RD [kg Sb$_{eq}$]	−3.65E−07	2.23E−07	−4.14E−08	2.62E−07

Table 12
Environmental impacts of electricity from RDF and Italian electricity mix.

Impact categories	Scenario 1	Scenario 2	Electricity from Italian grid (low voltage)	Electricity from multi-SI PV (low voltage)
CC [kg CO_{2eq}]	1.24E+00	6.21E−01	4.10E−01	6.83E−02
ODP [kg CFC-11$_{eq}$]	2.20E−08	−3.40E−08	4.73E−08	7.06E−09
HTNC [CTUh]	7.20E−07	3.27E−07	9.85E−08	9.67E−08
HTC [CTUh]	1.91E−06	8.00E−07	1.86E−08	1.09E−08
PM [kg PM2.5$_{eq}$]	−3.81E−05	1.78E−05	2.09E−04	7.37E−05
POF [kg NMVOC$_{eq}$]	2.29E−03	4.03E−04	9.99E−04	2.76E−04
AC [molc H^+_{eq}]	2.11E−03	1.55E−03	4.55E−03	5.43E−04
TE [molc N$_{eq}$]	1.17E−02	5.94E−03	1.40E−02	8.98E−04
FE [kg P$_{eq}$]	5.58E−04	2.85E−04	1.42E−04	6.94E−05
ME [kg N$_{eq}$]	9.77E−04	2.58E−04	4.06E−04	8.91E−05
RD [kg Sb$_{eq}$]	1.24E−07	2.87E−06	8.71E−06	2.56E−05

contribution comes from this input for PM and RD. The treatment of incineration waste in landfill causes 80–85% of the impact on human toxicity and freshwater eutrophication, and 56% of resource depletion.

Going to Scenario 2, by analysing the contribution of the different involved processes and materials/energy sources (Fig. 7), it can be observed that also in this case there are no direct emissions contributing to ODP, HTNC, HTC, FE and RD. Looking at the remaining impact categories and focusing on the positive values, direct emissions are responsible of more than 59% of CC, POF and ME, of about 5.3% of PM and 22.5% of AC.

By summing the contribution of input materials and wastewater treatment (excluding PM and RD for sodium bicarbonate), values lower than 16% are obtained. The contribution of sodium bicarbonate on PM and RD is 23.8% and 75.5%, respectively.

Waste incineration disposal is the main contributor to the impacts on human toxicity (>90%) and FE (82.7%), while the contribution of energy sources is lower than 20.5% except for OPD, PM, AC and TE (higher than 44.6%). The relevant contribution of waste incineration disposal on human toxicity highlights the importance of future researches aimed at identifying innovative technologies for the final treatment and stabilization of these wastes as well as for their reduction during the incineration process.

The avoided impacts due to the production of ferrous metals and the heat generation totally offset the high contribution due to the energy consumption (electricity from the grid, natural gas and RDF) to ODP, and also contribute to the reduction of the other examined impacts.

In detail, the environmental benefits due to heat generation represent >61% of the total avoided impacts for almost all the examined impact categories, highlighting that recovering waste heat is paramount for improving the environmental performances of the system. The main benefit on avoided PM (about 63.5%) and FE (about 52.2%) comes from RDF production. A contribution lower than 4.2% results from ferrous metals.

4. Conclusions

The research aimed at assessing the life cycle environmental performances of electricity generated by RDF, once obtained from wastes treated in MBT plants.

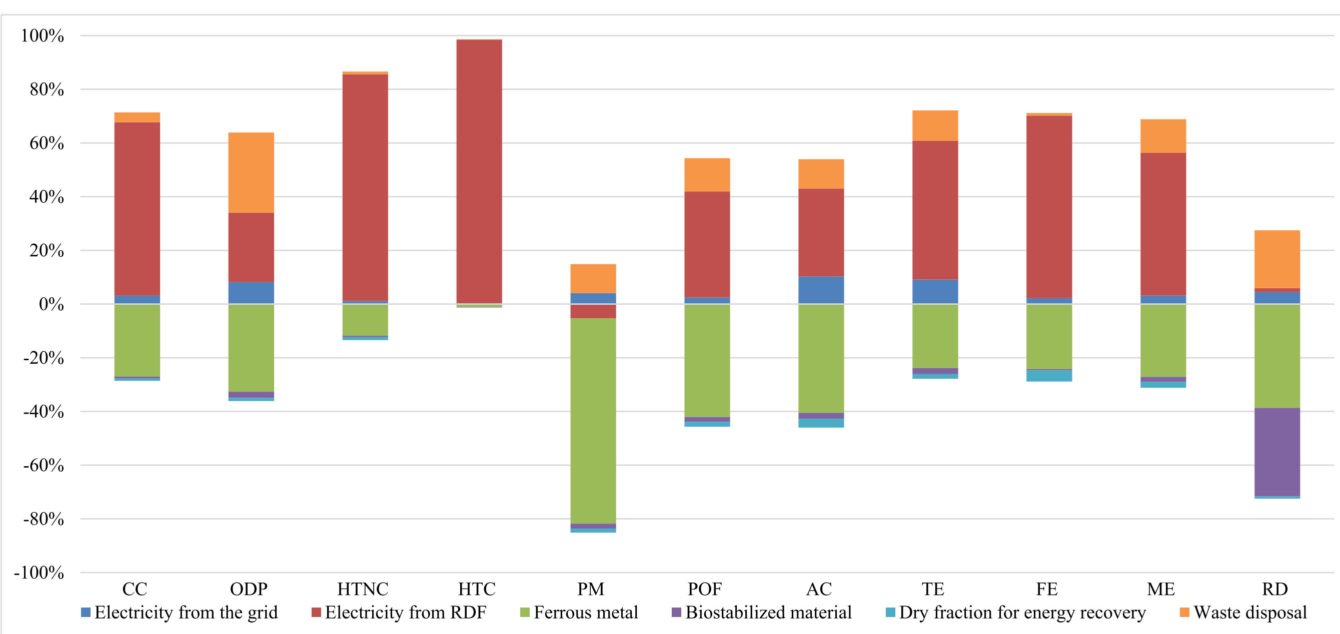

Fig. 5. Production of 1 kg of RDF - Dominance analysis for Scenario 1.

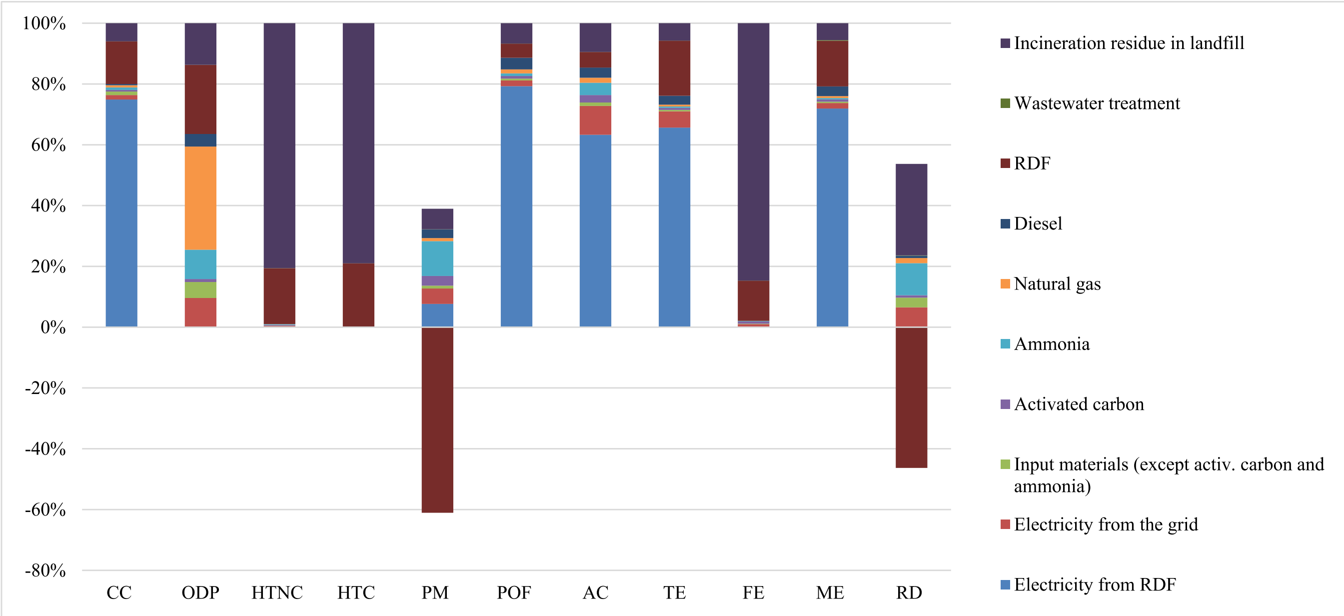

Fig. 6. Environmental impacts of 1 kWh of electricity from RDF (Scenario 1): dominance analysis.

The results of the LCA study of RDF obtained from two different production processes (DF vs. UF) and of electricity from RDF generated in two different plants (Ravenna and Bergamo) are based on the quality of used data and the assumptions made, in particular the inclusion of the avoided impacts in the analysis. These results showed that it is not possible to identify an option for RDF production or electricity generation from RDF characterized by best impact values for all the examined impact categories. The selection of the most suitable RDF or electricity production process has to be integrated with a detailed analysis of the local scale, in order to evaluate additional local environmental problems, social acceptability, adaptability and resilience of the receiving ecosystem without inducing permanent and/or irreversible impacts.

Starting from the results of the dominance analyses, some considerations helping for the improvement of the examined systems can be made. Focusing on RDF production, most of the environmental impacts are caused by the electricity consumption during the production process. Therefore, the use of energy from renewable sources and the use of machinery characterized by greater energy efficiency could reduce the impacts from RDF. In addition, the valorisation of the ferrous metals and the dry fractions (biostabilized material used as landfill cover and

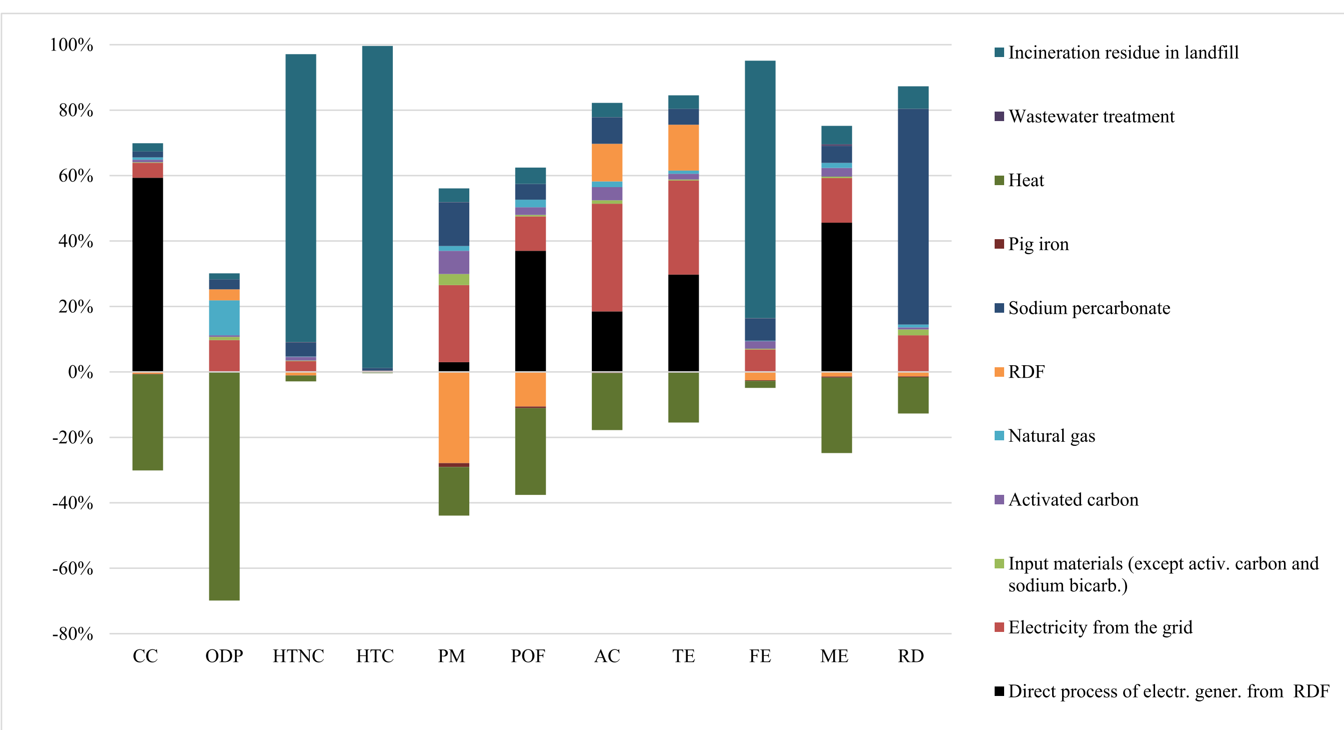

Fig. 7. Environmental impacts of 1 kWh of electricity from RDF (Scenario 2): dominance analysis.

dry fraction sent to energy recovery) in the RDF production generates environmental gains for most of the examined impact categories, that in some cases counterbalance the impacts.

By examining the electricity generation, it can be highlighted that electricity from RDF is responsible of chimney direct emissions that can significantly contribute to some impact categories. Thus, further improving combustion processes and fumes treatment technologies that allow for reducing these emissions can help to improve the environmental performances of the examined systems. Also the cogeneration process can cut most of the environmental impacts thanks to the avoided burdens due to the thermal energy co-production. Furthermore, disposal of incineration wastes is a relevant contributor to human toxicity and freshwater eutrophication, mainly due to the dangerousness of wastes. This is a general problem related to the waste combustion that could be addressed in the future innovation strategies in the energy field.

Electricity from PV is preferable to electricity from RDF, being characterized by best environmental performances for most of the assessed impact categories. However, the future eco-oriented strategies of PV supply chain will have to aim to the reduction of the impacts on resource consumption and particulate emissions.

Finally, comparing the electricity from RDF and from the grid, also in this case it is not possible to make a “best” choice for all the impact categories: climate change, human toxicity and freshwater eutrophication have worse performances for electricity from RDF for both scenarios. Thus, based on a “product-based” approach, the above impacts can be managed only favouring the use of electricity from the grid. However if the environmental key-issue is, for example, resource depletion, electricity from RDF should be preferred.

By extending the view on a large scale analysis, an increasing share of electricity from RDF into the grid could influence the environmental performances of the national electricity mix and, in turn, the new electricity mix could have effects on the RDF production.

This case, which could occur if the electricity from RDF represents an important rate of the total electricity produced at national level, and that is not foreseen from the present energy policies, needs a dynamic approach able to take into account the interrelations among the involved systems and their changes in the time.

CRediT authorship contribution statement

Sonia Longo: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing – review & editing, Visualization. **Maurizio Cellura:** Conceptualization, Methodology, Validation, Formal analysis, Supervision. **Pierpaolo Girardi:** Conceptualization, Writing - original draft, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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