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Abstract: Plastic films can be considered as a high-value auxiliary material in agriculture with multiple important uses to fulfil, including greenhouse coverage. Such an application enables several benefits and, therefore, it is going through an important upsurge, especially in regions where protected crop cultivation is highly widespread. However, the increase in the demand for these films to be treated as wastes after usage posed relevant environmental challenges as related to consumption of Non-Renewable Primary Energy (NRPE) resources and emission of Greenhouse Gases (GHGs). Environmental analysis is needed to find and follow cleaner paths for the management and treatment of this Agricultural Plastic Waste (APW), especially in the light of the gap currently existing in the specialised literature.
In this context, this paper reports upon findings from a combined Life Cycle Assessment (LCA) of single environmental issues (i.e., energy and water consumption, and GHG emissions) applied to a Sicilian firm, representative of the agricultural plastic waste (APW) collection and recycling of Low-Density Polyethylene (LDPE) granules.
The results showed that electricity consumption for the whole process is the most NRPE resource demanding and the most GHG emitting input item, and APW cleaning is the most water demanding phase within the system. Potential improvements could be achieved through a change in the energy source, by shifting from fossil to renewable. The installation of a wind power plant would lead to around 56% and 85% reduction in NRPE resource exploitation and GHG emission, respectively. Finally, despite the huge consumption of water and NRPE resources and the resulting GHG emissions, the production of recycled-LDPE granules is far more sustainable than the virgin counterpart.

Energy and environmental assessment of plastic granule production from recycled greenhouse covering films in a circular economy perspective

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*Cover Letter

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Catania, August 01, 2019

Editor-in- Chief

Journal of Environmental Management

Dear Editor,
here I enclose the manuscript of the paper “Energy and environmental assessment of plastic granule production from recycled greenhouse covering films” authored by Stefano Cascone, Carlo Ingrao, Francesca Valenti, and Simona M.C. Porto for your consideration to publish it in Journal of Environmental Management.

Please know that I am the corresponding author of the paper and so the person to whom address any kind of information related to this paper's submission process.

All authors have seen and approved the manuscript and have contributed significantly for the paper.

The manuscript is about 6600 words and contains 8 figures and 8 tables.

Submission declaration

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We hope you will find the paper to be suitable for Your magnificent Journal and you will subsequently send it out for review, so that we will be provided constructive review comments enabling improvement of the paper.

Sincerely

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- Single-issue LCA was applied to recycled greenhouse covering films
- The functional unit was chosen to be 1 ton of produced LDPE-granules
- Primary and secondary data were inventoried
- Environmental criticalities were highlighted
- Sensitivity analyses were carried out to identify potential improvements

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Abstract

Plastic films can be considered as a high-value auxiliary material in agriculture with multiple important uses to fulfil, including greenhouse coverage. Such an application enables several benefits and, therefore, it is going through an important upsurge, especially in regions where protected crop cultivation is highly widespread. However, the increase in the demand for these films to be treated as wastes after usage posed relevant environmental challenges as related to consumption of Non-Renewable Primary Energy (NRPE) resources and emission of Greenhouse Gases (GHGs). Environmental analysis is needed to find and follow cleaner paths for the management and treatment of this Agricultural Plastic Waste (APW), especially in the light of the gap currently existing in the specialised literature.

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The results showed that electricity consumption for the whole process is the most NRPE resource demanding and the most GHG emitting input item, and APW cleaning is the most water demanding phase within the system. Potential improvements could be achieved through a change in the energy source, by shifting from fossil to renewable. The installation of a wind power plant would lead to around 56% and 85% reduction in NRPE resource exploitation and GHG emission, respectively. Finally, despite the huge consumption of water and NRPE resources and the resulting GHG emissions, the production of recycled-LDPE granules is far more sustainable than the virgin counterpart.

Keywords: greenhouse cultivation; agricultural plastic waste; LCA; secondary raw material; LDPE-granules

1 Introduction

Plastic films are utilised in greenhouse cultivation system as covering materials, in the form of transparent sheets for under-tarp moisture collection or as black sheets for crops mulching (Granadosa et al., 2012). With regard to covering materials in greenhouse cultivation system, usage of plastic films has been increasing since the middle of the twentieth century due to several benefits such as: increase in crop yield; earlier harvest; reduced consumption of both herbicides and pesticides; frost protection; and water conservation (CPCB, 2016). By analysing official statistical data (Istat, 2018), a large amount of plastic films was found as being utilised in the Mediterranean countries where protected crops are widely cultivated (Scarascia-Mugnozza et al., 2012). In detail, the consumption of plastic films as greenhouse and low tunnel covering material is about 72,000 and 75,000 tons per year, respectively (Plastics Europe, 2016). Because of direct exposure to both solar radiation and wind, greenhouse plastic coverings are replaced every 6 to 45 months (Barnes et al., 2009; Scarascia-Mugnozza et al., 2012; Nanna et al., 2018). At the end of their useful life, these covers are taken off and treated as waste in two different ways: one is about disposing them of in landfills, often equipped with energy recovery systems; while the other regards recycling them into secondary raw materials for a wide range of applications, including rubbish bags and boxes, so contributing to reduction of the environmental impact overall associated with the film life cycle (Montero et al., 2014; Aryan et al., 2019). Unfortunately, to-date, around 50% of plastic wastes generated by agricultural activities is treated in landfills, so emphasising upon the urgent need to find and follow alternative, more sustainable routes (Briassoulis et al., 2013).

In Italy, each year, more than 350,000 t of agricultural plastic materials are utilised with a consequent post-consumption material flow of about 200,000 t (Picuno et al., 2012). With regard to protected cultivation areas, more than 2 million hectares are covered by greenhouses (Istat, 2018), i.e. approximately 21% of the whole cultivated surface.

In this context, given the relevance of plastic film amount to be collected and recycled, evaluations would be desirable to check upon energy-efficiency and sustainability related issues of raw materials obtained from recycled greenhouse covering films: Life Cycle Assessment (LCA) could be one valid tool for such a purpose. As a matter of fact, it has been used by authors like Horodytska et al. (2018), to identify and pursue the best environmentally performing waste treatments among a set of alternatives. In details, the authors reviewed previously published LCAs on waste management. While several LCA studies were carried out in different counties to assess the municipal solid waste management, only few LCAs were focused upon flexible plastic film waste management. According to the authors, this can be attributed - even only in part - to a lower degree of sorting and recycling technologies development as compared with rigid plastics and the modelling of e.g. shredding, washing, and drying operations is required to better understand and improve the plastic films recycling processes. Gu et al. (2017) presented a detailed LCA investigation on plastic from various sources, such as agricultural wastes, by analysing a recycling company in China. The results demonstrated that the extrusion process was the primary process in determining the overall impacts of recycled plastic production, while the introduction of fillers and additives contributed the most significant part in the environmental impacts associated with recycled composite production. Finally, Hottle et al. (2017) explored the impacts associated with the production and disposal of biopolymers compared to fossil-based plastics by means of LCA. The authors found that recycling resulted in significant life cycle impact reductions.

Although the topic of plastic waste management and recycling is an important environmental issue at the global level, the review conducted highlighted a gap in the literature of LCAs on the production or recycling process of flexible film used for agricultural purposes. Moreover, another gap stays in the fact that, though mechanical recycling of agricultural post-consumer films is highly recommended because of the high amount of homogenous, single polymer waste available

(Martínez-Lera et al., 2013), to the authors' knowledge, no research studies have been conducted thus far to assess the environmental impact deriving from such recycling process.

This research was designed to contribute filling those two gaps, with the final objectives of stimulating creation of cleaner paths for plastic waste disposal, as well as of enriching the current specialised literature with findings obtained and lessons learned.

It reports upon a combined evaluation of environmental issues, like consumption of water and energy, and resultant emissions of Greenhouse Gases (GHGs), arising from manufacturing plastic granules by utilising Agricultural Plastic Waste (APW) as a zero-burden material input.

A Sicilian firm operating in the sector was positively involved in giving all technical support to this author team as needed for development of the study. The latter addresses energy and environmental issues related to the reuse of plastic covering films for producing recycled granules as a secondary raw material. To this end, a Life Cycle Assessment (LCA) approach was adopted according to the specific International Standards 14040-44:2006 (ISO, 2006a, ISO, 2006b) and applied to a Sicilian firm, representative of the agricultural plastic waste (APW) collection and recycling.

Apart from the above-reported introduction, the study was conducted through the framework depicted in Fig.1.

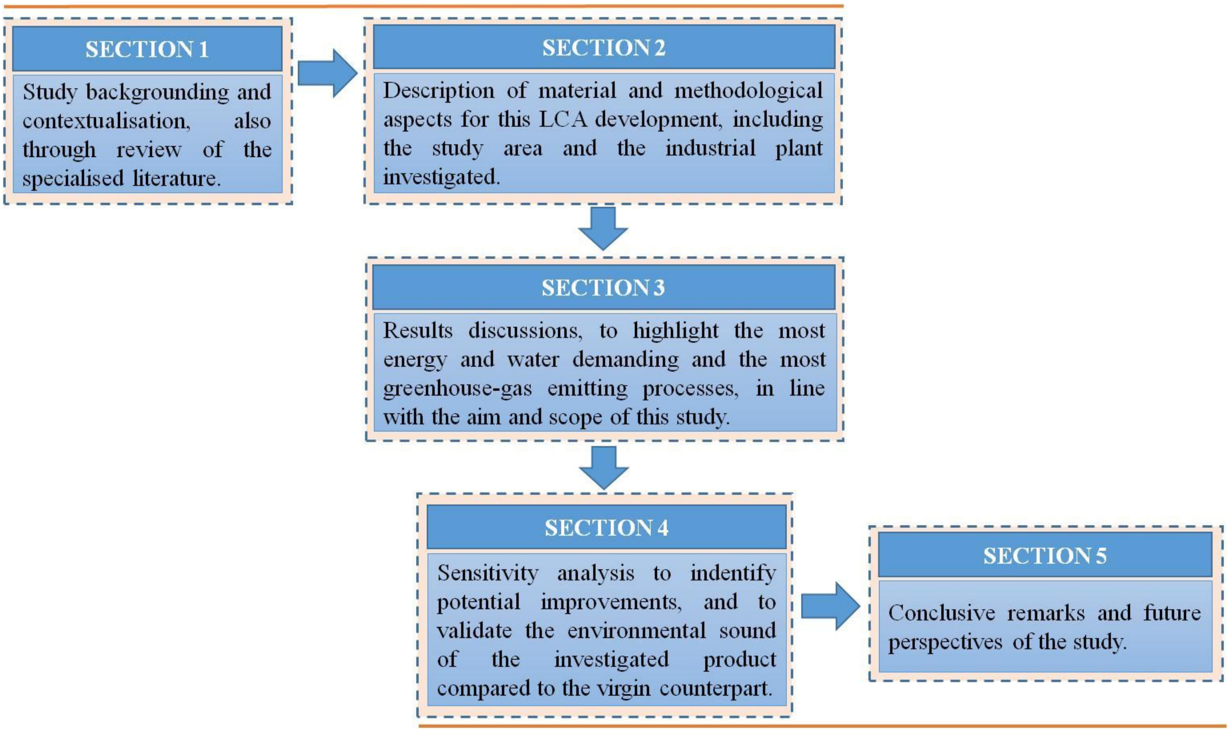


Fig.1. Study content framework

2 Materials and methods

2.1 Study area

Sicily is the Italian region with the highest percentage (76.1%) of greenhouse surface (GHS) among the total cultivated surface (TCS), followed by Campania e Lazio (Table 1).

Within Sicily, Ragusa is the province with the largest protected cultivation area (Arcidiacono and Porto, 2010), which covers about 470,000 ha and is nearly 68% of the protected cultivation of the whole region (Istat, 2018). In particular, that area is invested as follows: 58.7%, for tomatoes; 33.6%, for other vegetables; and the remaining 6.7%, for flowers and ornamental plants.

This has led increase in supply chains being implemented for manufacturing and distribution of plastic covering films, especially in those parts of Sicily (e.g., the province of Ragusa) where protected crop production was documented to be significant. However, to meet the necessary demand for those films to be treated as waste after usage, those chains are increasingly expanding to incorporate industrial plants for sustainable treatment of those films at the end of their service life, so reducing harmful consequences to the environment and to the health of humans. As the result of this, several firms have been founded over last thirty years or so, to deal with recycling of post-use covering films, so to convert them into value-added material commodities in line with the principle of circular economy. One of those firms was involved to technical support this study development: its geographical position within the province of Ragusa was depicted in Figure 2. It collects and recycles Agricultural Plastic Waste (APW) to obtain Low-Density Polyethylene (LDPE) granules, which find application as a secondary raw material in a wide range of sectors. These recycled granules are generally characterised by quality rates that are highly comparable to the virgin counterparts and, therefore, are suitable for manufacturing of printed materials, pipes and bituminous membranes, and new films (Aryan et al., 2019).

Table 1. Cultivated and greenhouse surfaces in Italy.

Italian regions	**Cultivated surface (TCS)**	**Greenhouse surface (GHS)**	
	[ha]	**[ha]**	**[GHS/TCS]**
Abruzzo	481,043.2	22,588.5	4.7%
Apulia	855,847.2	125,094.5	14.6%
Basilicata	471,100.2	45,793.0	9.7%
Calabria	507,203.0	55,737.0	11.0%
Campania	479,295.2	355,096.0	74.1%
Emilia-Romagna	783,905.2	49,697.4	6.3%
Friuli-Venezia Giulia	94,425.7	5,891.0	6.2%
Lazio	666,610.3	312,409.0	46.9%
Liguria	58,921.2	58,336.0	99.0%
Lombardy	498,982.2	72,525.0	14.5%
Marche	366,105.0	13,492.9	3.7%
Molise	148,728.0	1,665.4	1.1%
Piedmont	505,085.5	45,426.0	9.0%
Sardinia	994,106.2	64,779.5	6.5%
Sicily	902,429.3	686,758.0	76.1%
Trentino Alto Adige	541,410.6	4,541.0	0.8%
Tuscany	846,496.7	69,648.7	8.2%
Umbria	354,323.1	5,562.0	1.6%
Valle d'Aosta	34,393.4	130.0	0.4%
Veneto	551,923.1	169,525.7	30.7%
Total	10142,334.2	2164,696.6	21.3%

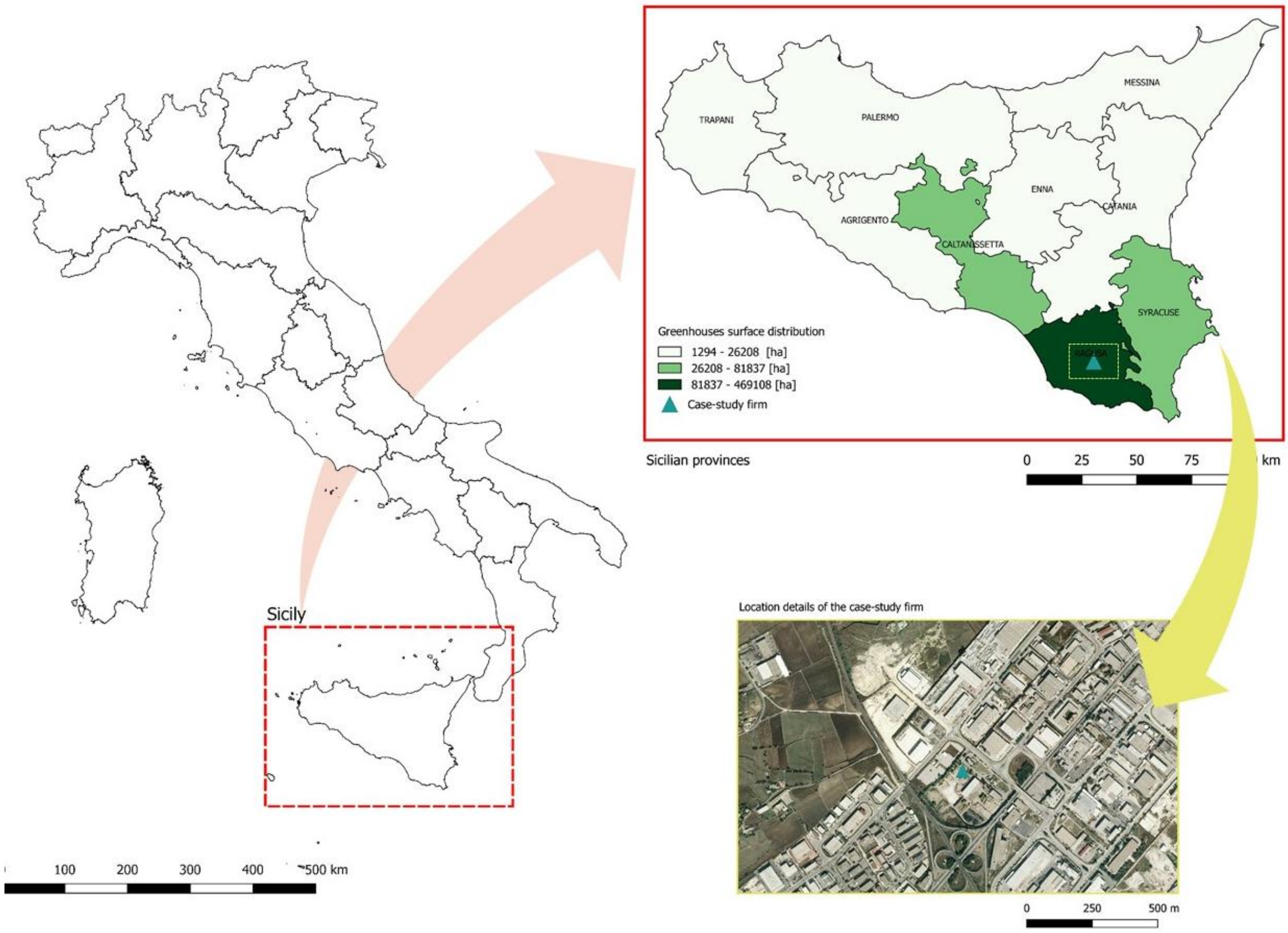


Figure 2. Geographic position of the study area and the firm considered in the case study.

2.2 Description of the analysed industrial process

The production process of the considered firm starts with supply of APWs, which is entirely collected from the surrounding areas and stored before being processed (Figure 3). APW is initially subjected to grinding and to a first phase of pre-washing and spinning. After these phases, all macroscopic impurities are eliminated through decantation in a water tank. The post-use water is treated in an adjacent plant and stored in tanks before being pumped back to the LDPE-granule production process, so it continuously feeds the recycling process.

The sludge resulting from the wastewater treatment is decanted and extracted from the bottom of the tanks for the dehydration process on drying beds. Next, the APW goes through a subsequence of processes to eliminate all the impurities and humidity within the material by washing, drying, and milling. During the final step of the entire transformation chain, material (in small pieces) is melted, extruded and stored in silos before marketing and distribution.

2.3 Assessment of energy and environmental issues

To estimate energy and environmental impacts of the production process of recycled LDPE granules above-described, an LCA approach was developed according to the specific International Standards 14040-44:2006 (ISO, 2006a, ISO, 2006b) and organised in the standard phases, i.e. Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Life Cycle Interpretation. The development of each of these phases was discussed in the sections below.

2.3.1 Goal and scope definition

The study was developed by following the LCA standard framework and the LCIA phase was focused upon single issues, such as water consumption, primary-energy sources exploitation, and GHG emissions. In fact, based upon the inventory analysis, they were found to be both highly representative of the analysed process and a priority in the EU agricultural policy for their impact reduction (Caffrey and Veal, 2013; Cerutti et al., 2015; EC, 2013). To this end, Carbon Footprint (CF), Cumulative Energy Demand (CED) and Water Footprint (WF) were applied as they are worldwide known as key indicators for the assessment of energy and environmental performance.

The Functional Unit (FU) and the system boundaries were defined by following the International Standards (ISO, 2006a, ISO, 2006b), in order to best represent the investigated process and be consistent with the aim of the study. The FU represents the unit of product and provides a reference through which inputs are linked to outputs and to the resulting impacts and damages (Arzoumanidis et al., 2013): in this case study, the FU was chosen to be 1 ton of produced LDPE-granules.

As regards the system boundaries (see Figure 3), they were defined to include: 1) APW acquisition, pre-treatment and transformation into the reference finished-product (1t recycled-LDPE); 2) preparation and acquisition of auxiliaries, oils, and energy; 3) the treatments of all waste materials as generated by the recycling process; and 4) the annexed plant for treatment and recirculation of the APW-cleaning water.

Those boundaries were designed based upon information provided by the supporting firm to clearly highlight the material and energy flows throughout the investigated chain, which enabled connecting the up-stream processes to the down-stream ones. Furthermore, as emerges from Figure 3, all transports for input material supply and for delivery of the wastes generated by the process to treatment were considered in the assessment. Only the recycled-LDPE distribution was excluded because it was considered as pertaining to the utilisation phase and, therefore, the downstream border of the system was set at the firm exit gate. All transport flows considered were detailed in the following section, together with the related diesel consumptions and Ecoinvent modules used for the system assessment based upon information provided by the firm.

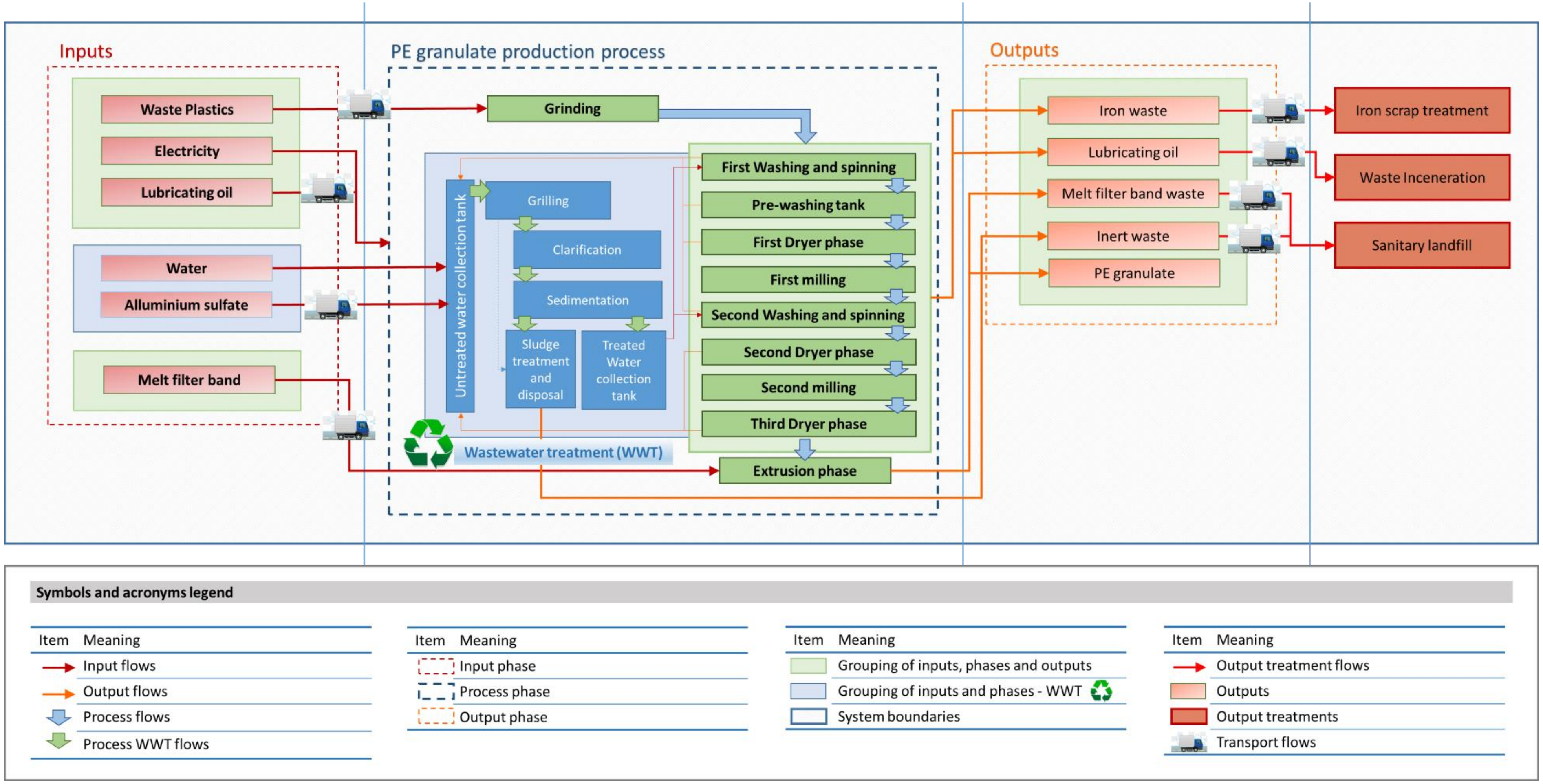


Figure 3. Boundaries of the system investigated.

2.3.2 Life cycle inventory (LCI)

This is the key phase of any LCA since it deals with compilation, qualification and quantification of all input and output streams, as needed for the goal achievement. The inputs considered are the resources, materials, fuels, and energies, while the outputs are the material emissions in air, water and soil, as well as the exploitation of natural and primary-energy resources (Ingrao et al., 2018).

In this context, since it comes to investigation of a system being highly interconnected with the local territory, the LCI was centred upon collection of site-specific data (primary data), regarding typologies and amounts of both inputs and outputs. A specific questionnaire was developed to be filled in through interviews with technicians and to gather firm-management related information, like main structural and economic features; production system; the product obtained (i.e., the recycled granule), and the wastes to be treated (Valenti et al., 2016).

The questionnaire was organised into five different parts: i) a general section containing questions aimed at getting information about the input materials, such as water and covering plastic films (the amount of product to be processed); ii) the second section, ‘electricity consumption’, for acquiring information on the type of process and its electricity consumption, the techniques and the machinery utilised; iii) the third section aimed to acquire data related to the production process, i.e. the type and amount of the obtained products and which kind of auxiliary materials were adopted during the process; iv) the waste disposal section was aimed to collect information about typologies and quantities of by-products and wastes obtained during the production and which kind of disposal processes was adopted; v) the last section, ‘supplying section’, contained information related to the logistics phases, before, during and after process production. In detail, in this section of the questionnaire, information about distances in kilometres were required to detail as much as possible the logistics phase with regard the transport flows, which often in Sicily region represent a key factor for managing sustainable processes.

Primary data were combined with background ones extrapolated from the database of acknowledged scientific value and relevance, like Ecoinvent v.3 as available in SimaPro 8.1. This database was used because it is recognised worldwide as accommodating most of the background materials and processes often used in LCAs (Frischknecht and Rebitzer, 2005), which contributes making it suitable for the modelling of industrial systems like the one investigated in this study.

Data collection regarded a 3-year campaign between 2015 and 2017 and information used for the LCI were reported in Table 2 and Table 3. In detail, Table 2 shows that data related on LDPE granules production differ only about 5% during the three years analysed, confirming the standardisation of the process. Therefore, the LCA developed in this study is representative of the production process of LDPE granules from recycled greenhouse covering films.

Table 2. Data collected at the LDPE granules production site from 3-year campaign and the annual average base. All data reported are referred to the annual production.

Outputs				
Items	***Amount***			***UM***
	2015	**2016**	**2017**	
Products				
LDPE granules	11445	11536	12359	ton
Waste streams				
Inert	5923	6213	6988	ton
Exhausted mineral oil	3778	4000	4889	kg
Steel	11000	21800	24290	kg
Inputs				
Items	***Amount***			***UM***
	2015	**2016**	**2017**	
Material and energy commodities				
Underground water without treatment (production and distribution)	43051	51617	45528	ton
Aluminium sulphate	24600	29760	20860	kg
Mineral oil	3778	4000	4889	kg
Steel	11000	21800	24290	kg
Diesel*	34500	37000	35000	l
Electricity	1.115E7	1.094E7	1.011E7	kWh
Melt filter band	15000	18000	24000	m

*All emissions related to Diesel combustion were extrapolated from Ecoinvent and referred to the Diesel consumption volume

Table 3. Transport flows related to the system investigated, calculated from average values.

Transport	Raw material	Waste	Flow (kgkm)	Diesel consumption (kg)	Ecoinvent module
T1	Aluminium sulphate	-	219.39	23.91	Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Alloc Def, S
T2	Plastic waste	-	8.649E4	9.43E3	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Def, S
T3	Mineral oil	-	39.38	4.29	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RoW}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Alloc Def, S
	-	Exhausted oil	132.82	14.48	
T4	Steel wire	-	2.75	0.30	Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Def, S
	-	Iron waste	4.893	0.53	

For the assessment, the collected data were averaged to obtain a yearly LDPE-granule production of about 11780 tons and an electricity consumption of about 1.11E7 kWh, i.e. approximately 950 kWh are required to produce 1 ton of LDPE-granules. In Table 3, forward and reverse transport flows were detailed and the chosen Ecoinvent modules were reported. All the data recorded and averaged (Table 2 and Table 3) were then elaborated to be referred to the system FU, namely 1 ton of recycled LDPE, and reported in Table 4.

Table 4. Average data from Tables 2 and 3 referred to the system FU, namely 1 ton recycled LDPE

Outputs

Items	**Average U.M/ton_{LDPE}**	***UM***
Products		
LDPE granules	1.000	ton
Waste streams		
Inert	0.521	ton
Exhausted mineral oil	0.358	kg
Steel	1.615	kg

Inputs

Items	**Average U.M/ton_{LDPE}**	***UM***
Material and energy commodities		
Underground water without treatment (production and distribution)	3.882	ton
Aluminium sulphate	2.128	kg
Mineral oil	0.358	kg
Steel	1.615	kg
Diesel	3.014	l
Electricity	942.275	kWh
Melt filter band	1.613	m
Total of transports (as sum of values in Table3)		
Raw material supply	7.364	kgkm
Waste to treatment	0.012	kgkm

Considering the uncertainty and variability in LCA studies, it is important to determine both the validity of the collected data (Cerutti et al., 2015) and the reliability and robustness of the results

(Notarnicola et al., 2017). As reported by Huijbregts (1998), the different types of uncertainties can be distinguished in: parameter uncertainties, model uncertainty and uncertainty linked with choices. The robustness of data and modelling of this study should be considered very high since the analysis is based on real acquired data, during a 3-years campaign.

2.3.3 Life cycle impact assessment (LCIA)

Within the LCIA step, two approaches of characterisation, i.e. mid-point and end-point, can take place along the pathway of an impact indicator. According to De Benedetto and Klemes (2010), LCIA phase was carried out by aggregating the output flows, previously quantified in the LCI phase, in a limited set of Impact Categories (ICs), by adopting a mid-point approach. Then, the study was extended to the damage assessment as part of the end-point approach, and the ICs were grouped into Damage Categories (DCs) which are the environmental compartments that suffer the damage caused by the LDPE granule production during its life cycle.

To this aim, the authors accessed and used the classification/characterisation framework provided by three single-issue impact assessments i.e., CF, CED, WF, available in Simapro 8.1, to evaluate the created inventory dataset (Table 4).

2.3.3.1 Carbon Footprint (CF)

The CF is one of the most popular ‘impact category indicators’, for the climate change category. The emissions of different greenhouse gases are weighted based on their global warming potential (GWP) relative to carbon dioxide (e.g., one kg of methane has a much greater GWP than one kg of carbon dioxide). The weighting is technically called ‘characterisation’ of the inventory results, and the GWPs of different greenhouse gases are the characterisation factors. The resultant CF is expressed in terms of CO_2 equivalent (CO_{2eq}) (Wiedmann and Minx, 2008, Maalouf et al., 2018).

In this study, among the mid-point approaches the IPCC 2013 GWP 100a method (IPCC, 2013) was used, which was developed by the Intergovernmental Panel on Climate Change and it contains the climate change factors of IPCC with a timeframe of 100 years.

According to eq. (1) by Maalouf et al. (2018):

$$CF_i = \sum_j GWP_j * e_j \tag{1}$$

where:

- e_j is the emission (in mass unit) of the j-th GHG associated with the given process;
- GWP_j is the Global Warming Potential of the j-th GHG for a 100-year temporal horizon (GWP100), which is required for any CF assessment.

Table 5 reports the GWP100 of the GHGs that were considered by the authors as the most representative of the investigated system and extrapolated by Simapro 8.1.

Table 5. Global Warming Potential of relevant GHGs. Conversion factors from IPCC (2013).

GHG	**Formula**	**GWP_{100} [gCO_{2eq}/gGHG]**
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265

At the end-point approach, the computed impacts were transformed into damages using conversion factors based upon the classification scheme provided by ‘ReCiPe Endpoint’ (Goedkoop et al., 2013) in the Egalitarian perspective (E/E) for the CF. ReCiPe method was used, in particular, for quantification of environmental damages that the emissions of the most significant GHGs generate - upon the DCs, i.e. Climate Change (CC), Human Health (HH) and Ecosystem Quality (EQ).

2.3.3.2 Cumulative Energy Demand (CED)

The CED is an impact indicator that expresses the energy utilisation throughout the life cycle of a product or a service (Hischier et al., 2010). So, it can be considered as an indicator of environmental impacts with regard to the energy resource depletion (Gürzenich et al., 1999).

According to Wiesen and Wirges (2017), CED was calculated based upon the 'Cumulative Energy Demand'method described in the Ecoinvent database. The aim of the method is both to calculate the direct and indirect energy used throughout the life cycle of the LDPE-granules and differentiate among renewable and non-renewable energy sources (Huijbregts et al., 2006). Therefore, this method allows the evaluation of environmental effects related to both the emissions and energy consumption (Girgenti et al., 2013). In detail, the method includes the direct and indirect uses of energy and it is organised in eight different impact categories. Normalisation or weighting data are not included in the method. In this study, the CED was calculated by including both non-renewable (from fossil fuels, nuclear, and non-renewable biomass) and renewable (from wind, solar, geothermal, and water) energy sources, associated to each input considered in the LDPE granules production process.

2.3.3.3 Water Footprint (WF)

Among the methods involved in LCA-based water footprint, the Water Footprint Assessment (WFA) was adopted, according to Pfister et al. (2009). This method is centred upon computation of the Water Stress Index (WSI), which calculates the water impact on the consumption-to-availability perspective of freshwater deprivation, corresponding to the 'blue water' in the WFA methodology. The Water Stress Index was used as a general screening indicator or characterisation factor for the freshwater consumption at the mid-point approach for all three areas of protection: Resources, Ecosystems and Human Health. Then, at the end-point approach, the damages using conversion factors based upon the classification scheme provided by Eco-indicator 99 (Goedkoop and Spriensma, 2001) were computed. In detail, Eco-indicator-99 was used for estimating the environmental damages as the consequence of water consumption upon DCs, i.e. Resources (Re), Human Health (HH) and Ecosystem Quality (EQ).

3 Results and discussion

3.1 Carbon Footprint assessment

The assessment showed that CO_2, CH_4 and N_2O are the most significant GHGs since they represent the 94.87% of the CF associated to the system investigated. In particular, CO_2 is characterised by the highest GWP_{100}, as shown in Table 6, and it is the most emitted GHG, as reported in Figure 4.

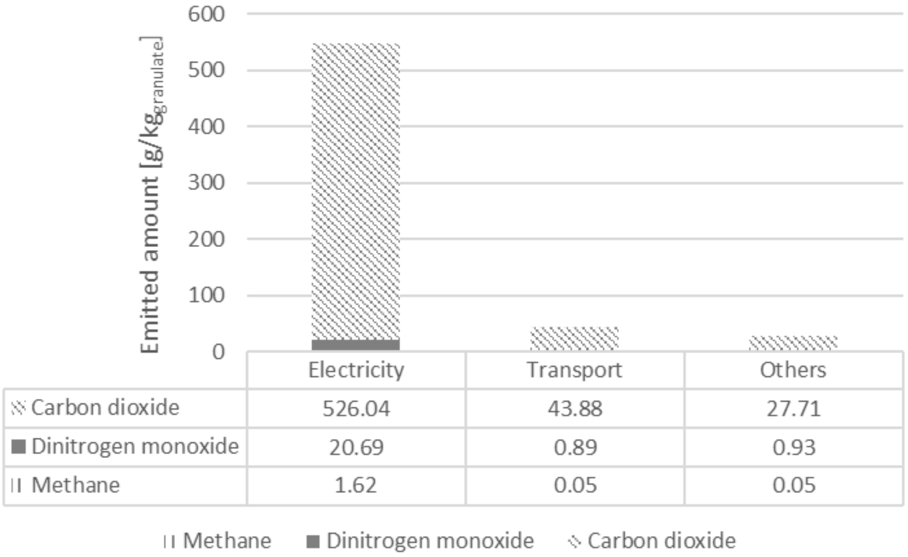


Figure 4. Emitted GHGs, with aggregated and disaggregated values

Two different results can be gathered from Figure 4: one per emitted GHG by taking into account the considered phases (horizontal sum); and the other one per each considered phase by taking into account the three selected gases (vertical sum). Furthermore, the following materials, fuels and activities were grouped in the '*Others*' category since they contribute with less than 5% to the GHG emissions: production of diesel (and emissions from its combustion), tap water, aluminium sulphate, lubricating oil; manufacturing of steel wire and of filtering material; as well as treatment of inert waste, waste mineral oil, and steel waste pre-treatment.

From Figure 4 there is evidence that the most contributing phases are: the production and distribution of electricity required for the process working and the transports (Table 3). Electricity, in particular, is the largest contributor for each of GHG emissions, with percentage values (up to the total ones) equal to: 88.02% (CO_2); 91.90% (N_2O); and 94.63% (CH_4). Contribution from the transport section is far lower and ranges from 2.74% in the case of CH_4 to 7.34% as per CO_2-emission.

Mid-point results demonstrate that CF is equal to 655.46 $kgCO_2$, which, based upon results shown in Table 6, is due for the major percentage (91.18%) to CO_2. As anticipated in the methodological-approach discussion, the study was extended to incorporate the damages assessment phase as part of the end-point approach, so considering the environmental damage that each emitted GHG considered causes to CC, HH and EQ. The end-point categories affected by the three GHGs were reported in Table 6.

Table 6. Mid-point and end-point results per each GHG emitted considered in the assessment

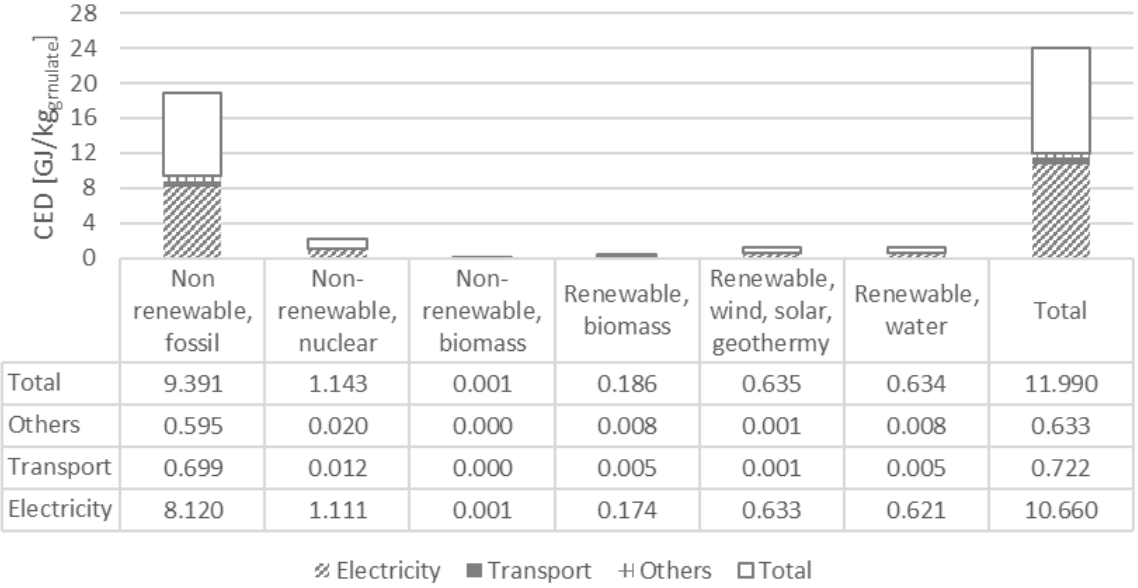
GHG	Mid-point analysis* Characterisation	Endpoint analysis Damages assessment		
	GWP_{100}	CC	HH**	EQ**
	$kgCO_2$ eq	$kgCO_2$ eq	DALY	species.yr
CO_2	597.63	597.63	2.10E-03	1.12E-05
CH_4	47.97	47.97	4.57E-05	2.43E-07
N_2O	5.97	5.97	1.21E-05	6.44E-08

* IPCC 2013

** values are referred to kg of emitted substance (ReCiPe Endpoint (E/E))

3.2 Cumulative Energy Demand assessment

The CED was found 12.015 GJ per kg of recycled-LDPE granules, with electricity contributing 88.72%, as evident from Figure 5. In addition, from this figure emerges that the electricity utilised in the recycling process is 76.17% of fossil origins.



	Non renewable, fossil	Non-renewable, nuclear	Non-renewable, biomass	Renewable, biomass	Renewable, wind, solar, geothermy	Renewable, water	Total
Total	9.391	1.143	0.001	0.186	0.635	0.634	11.990
Others	0.595	0.020	0.000	0.008	0.001	0.008	0.633
Transport	0.699	0.012	0.000	0.005	0.001	0.005	0.722
Electricity	8.120	1.111	0.001	0.174	0.633	0.621	10.660

Figure 5. Primary-energy resources considered for CED estimation, with aggregated and disaggregated values.

As shown in Table 7, gas natural, crude oil, and hard coal represent 77.3% of the overall amount of fossil primary-energy resources, and so can be considered as the most consumed ones within the process.

Electricity is the most impacting item, with the aforementioned energy resources exhibiting comparable values in the range 90-98% as of Table 7, except for crude oil, with a far lower contribution rate being around 54%. This should be attributed to the transport issue showing – as expected - its greatest contribution (26.3%) in crude oil rather than in the other ones.

Table 7. Inventory and CED values for each of the most contributing fossil primary energy resources, with details on the contributions given by electricity, transports, all of the other processes, materials and phases

Primary Energy Resources	Inventory		CED	Electricity	Transport	Others
	Amount	UM	GJ		[%]	
Gas, natural	95.6	kg	5.41	97.9	0.9	1.2
Oil, crude	49.6	kg	2.27	53.7	26.3	20.0
Coal, hard	81.5	kg	1.56	93.9	3.0	3.1
Others (*)	66.6	kg	0.15	90.1	4.3	5.6

These are the resources that contribute far less than the others and are represented by coal brown, peat and gas mine. ‘Others’ represent 1.60 % of the total primary energy resources.

The same was found for '*Others'*, as they contribute a total of 20% to the CED associated with crude oil, which is far higher than that shown in the case of the other energy resources (1.2-5.6%). This should be attributed to materials, processes, and phases grouped in this category consuming, overall, more crude oil than gas natural or hard coal or other minor energy resources, as considered by the CED assessment method used in this study.

3.3 Water footprint assessment

At the mid-point approach, the WSI resulted equal to 4.15 m^3, and was significantly due to the cleaning steps as operational water and to the consumption of electricity as virtual water. With regard to the damage assessment step, Table 8 shows the DCs affected by the overall consumption of water. In detail, '*water*', '*electricity*', '*transportation*' and '*others*' columns refer to water consumption due to the recycling-process and water consumption embodied in the electricity consumed as well as in the transports and in all the other materials, processes, grouped under the '*others*'.

As for the CF assessment, it was not possible to weigh the three DCs and identify the most affected one, because each of them is assigned a specific damage indicator, which is established by Eco-Indicator 99. However, from Table 8, it is possible to assert that for each DCs the most damaging issue is the consumption of operational water with contribution around 65%, followed by electricity with a 25.15% average contribution.

Table 8. Results from the WF-related damages assessment (endpoint approach), with percentages for the most contributing items within the system investigated.

Damage categories (DCs)	Damages assessment		Water	Electricity	Transport	Others
	UM	Amount	[%]			
Resources	MJ surplus	1.24E+01	69.29	21.07	2.07	7.57
Ecosystem Quality	PAF*m2yr	3.69E+00	61.97	29.05	1.95	7.03
Human Health	DALY	4.45E-06	65.32	25.33	2.03	7.31

4 Interpretation and improvements

The study highlighted that the electricity required by the process for 1 ton of recycled-LDPE production (942.75 kWh) is the largest contributor to both the CF and CED, so emphasising upon the importance to search for potential improvements. In agreement with the firm technicians, it was understood that no solutions are viable at the plant level by improving the technical quality and energy efficiency of machineries used in the production process. Therefore, electricity consumption is with no doubt the major energy and environmental issue of the whole system. Nonetheless, the energy/environmental burden associated with the electricity consumption may be reduced through a change in the energy source, by shifting it from fossil to renewable. A valid solution could be to install a wind power plant to cover the whole energy demand. In this regard, a first sensitivity analysis conducted for the purpose highlighted significant reductions for all the three indicators that have been addressed in this study, with CED and GWP_{100} showing the greatest reduction of about 56% and 85%, respectively, as they are clearly most affected by electricity use (Figure 6). It should be observed that this is just a preliminary evaluation that must be checked in terms of technical and economic feasibility.

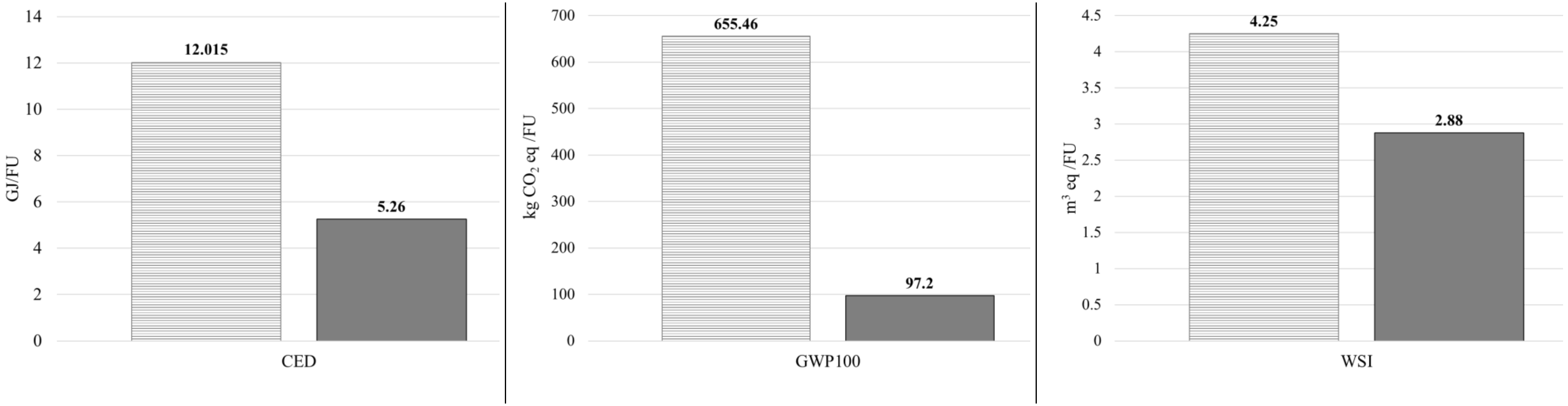


Figure 6. Comparison based upon application of the wind power based solution. The horizontal lines-column is referred to results from the first study, while the grey column reports results from the improved study.

By contrast, no solutions were found to be viable for reduction of the water consumption demanded by the process in the cleaning steps.

Finally, to validate the energy and environmental sound of the recycled-LDPE granule, another sensitivity analysis was conducted with the virgin counterpart of the LDPE granule, on the same base of FU and system boundaries. In addition, a comparable quality level was assumed between the two differently produced LDPE granules. It was found that, for all indicators considered in the study, i.e. CF, CED and WF, production of LDPE from APW is far more sustainable than the virgin counterpart (Figure 7), mainly because the recycled-LDPE granules is produced from a zero-burden resource, like the AWP utilised, rather than crude oil as happens for the virgin equivalent. In detail, the considered indicators decreased of about 85% (CED), 69% (GWP_{100}) and 32% (WSI). Such a result contributes validating processes like this as viable for production of comparable-quality secondary raw materials for application in the market.

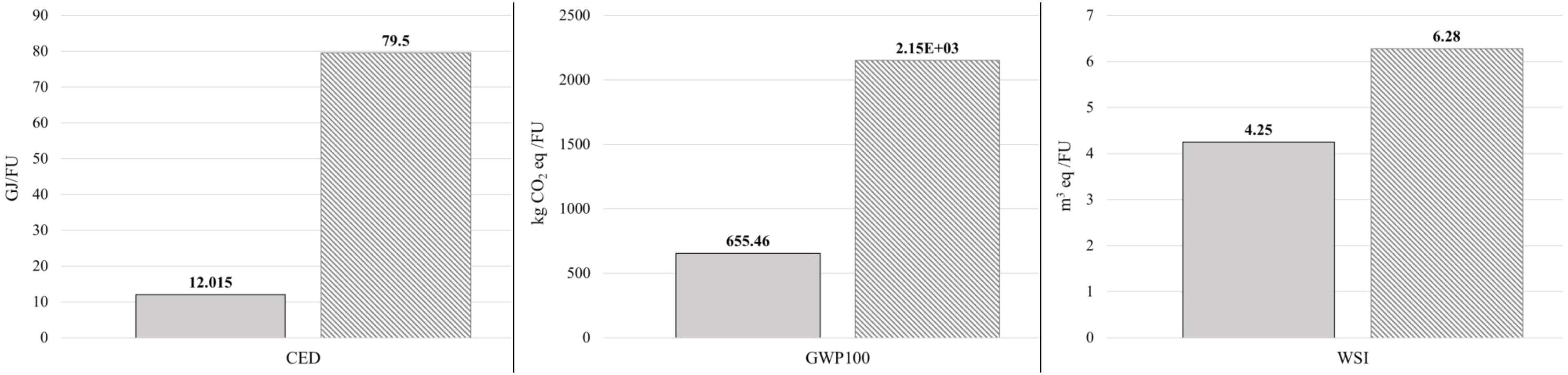


Figure 7. Comparison between the recycled-LDPE (light grey column) and the virgin counterpart (diagonal lines-column).

5 Conclusion

The study attained the proposed goal of evaluating the environmental impacts generated from the recycling of plastic films used for greenhouse cultivation system. To this end, a Life Cycle Assessment (LCA) approach was adopted and applied to an Italian firm located in Sicily, representative of the agricultural plastic waste (APW) collection and recycling.

The main conclusions related to the key indicators for the assessment of energy and environmental performance are the following:

- The CF was equal to 655.46 kgCO_2, showing that CO_2, CH_4 and N_2O are the most significant GHGs emitted, since they represent the 94.87%, and electricity was the largest contributor for each of these GHGs.
- The CED was found 12.015 GJ per kg of recycled LDPE granules, with electricity contributing 88.72% produced from fossil origins for 76.17%. Gas natural, crude oil, and hard coal represented 77.3% of the fossil primary-energy resources.
- The WSI was 4.15 m^3, with significant contributions coming from the cleaning steps of the process as operational water, and from the consumption of electricity as virtual water.

Other important lessons were learned through the two sensitivity analyses that were incorporated in this study. The first showed that the energy and environmental impacts associated with the electricity consumption could be reduced through the installation of a wind power plant, resulting in significant reductions in all the three indicators addressed. While, the second allowed to understand that, despite the huge consumption of energy and water and the resultant GHG emissions characterising the recycling process, the production of recycled-LDPE resulted as far more sustainable than the virgin counterpart, mainly because it is produced from a zero-burden resource rather than crude oil as happens for the virgin equivalent.

Such recycled granules can be considered as intermediate products for the manufacture of bags, pipes, and other products for several applications. Such transformations generally take place in industries outside Sicily, resulting in potentially high environmental impacts, mainly related to transport. For example, using polyethylene granules for construction applications, such as for the drainage layer in green roofs, is an innovative way of using this material, transforming it from an unfinished product into a finished product. The polyethylene granule as drainage material could be a cost-effective solution compared to those used for green roofs, from an environmental, economic and social point of view.

Furthermore, by considering the widespread diffusion of the eco-industrial technology, hydroponics, polyethylene granules could be used as an alternative substrate. In detail, this could contribute to reduce the use of inert substrates made of natural non-renewable materials and improve the environmental sustainability of the soilless crops production process in a circular economy perspective.

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