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

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Corresponding Author: Dr. Francesca Valenti, Ph.D.

Corresponding Author's Institution: University of Catania

First Author: Stefano Cascone

Order of Authors: Stefano Cascone; Carlo Ingrao; Francesca Valenti, Ph.D.; Simona M.C. Porto

**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**

Stefano Cascone<sup>a</sup>, Carlo Ingrao<sup>b</sup>, Francesca Valenti<sup>c \*</sup>, Simona M.C. Porto<sup>c</sup>

<sup>a</sup> Department of Civil Engineering and Architecture, University of Catania, Via Santa Sofia 64,  
95123, Catania, Italy

<sup>b</sup> Faculty of Engineering and Architecture, Kore University of Enna, Cittadella Universitaria -  
94100 Enna, Italy

<sup>c</sup> Department of Agriculture, Food and Environment (Di3A), University of Catania, Via S. Sofia,  
100 - 95123 Catania, Italy

\* Corresponding author: Francesca Valenti, email: francesca.valenti@unict.it



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Di3A

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

Ph.D. Eng. Francesca Valenti (Corresponding Author)  
Department of Agriculture, Food and Environment  
University of Catania  
via S. Sofia 100, 95123 Catania, Italy,  
e-mail address: francesca.valenti@unict.it  
mob. +39 3348066812

- 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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2    **greenhouse covering films in a circular economy perspective**

3  
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25    counterpart.

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

29

## 30 **1 Introduction**

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

50 In Italy, each year, more than 350,000 t of agricultural plastic materials are utilised with a  
51 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



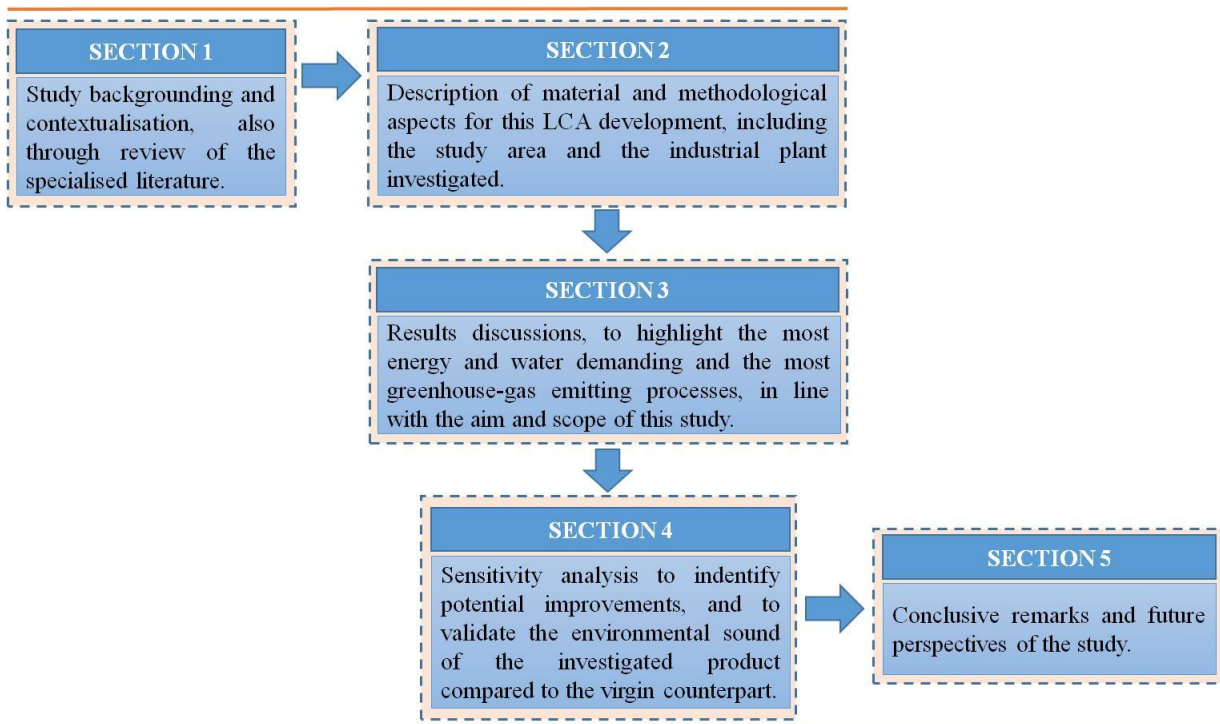
78 (Martínez-Lera et al., 2013), to the authors' knowledge, no research studies have been conducted  
79 thus far to assess the environmental impact deriving from such recycling process.

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

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

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

92 Apart from the above-reported introduction, the study was conducted through the framework  
93 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

110 this, several firms have been founded over last thirty years or so, to deal with recycling of post-use  
111 covering films, so to convert them into value-added material commodities in line with the principle  
112 of circular economy. One of those firms was involved to technical support this study development:  
113 its geographical position within the province of Ragusa was depicted in Figure 2. It collects and  
114 recycles Agricultural Plastic Waste (APW) to obtain Low-Density Polyethylene (LDPE) granules,  
115 which find application as a secondary raw material in a wide range of sectors. These recycled  
116 granules are generally characterised by quality rates that are highly comparable to the virgin  
117 counterparts and, therefore, are suitable for manufacturing of printed materials, pipes and  
118 bituminous membranes, and new films (Aryan et al., 2019).

119

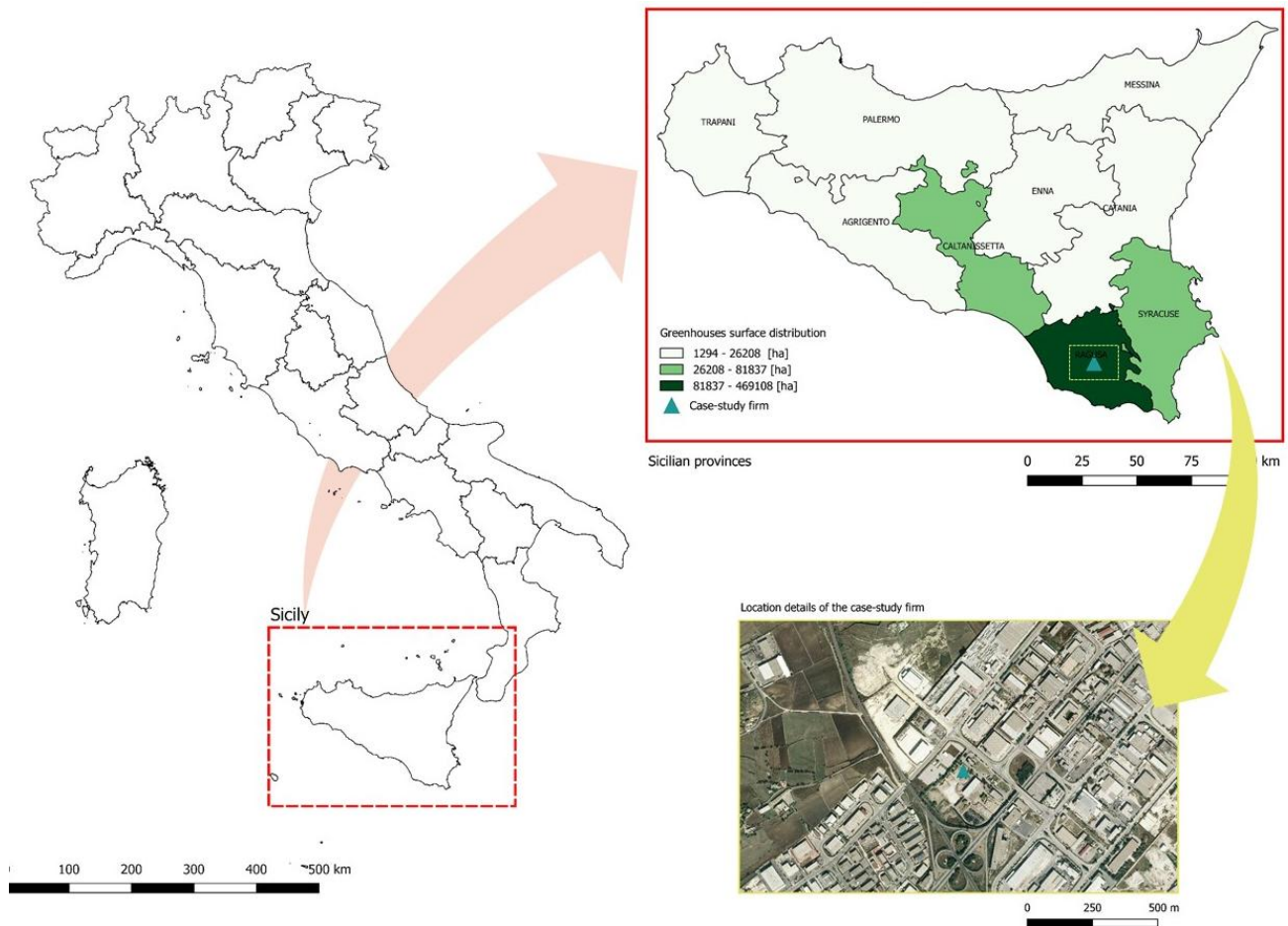
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**Table 1. Cultivated and greenhouse surfaces in Italy.**

| Italian regions       | Cultivated surface<br>(TCS) | Greenhouse<br>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%     |

121

122



**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

136 milling. During the final step of the entire transformation chain, material (in small pieces) is melted,  
137 extruded and stored in silos before marketing and distribution.

138

### 139 2.3 Assessment of energy and environmental issues

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

145

#### 146 2.3.1 Goal and scope definition

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

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

159 As regards the system boundaries (see Figure 3), they were defined to include: 1) APW acquisition,  
160 pre-treatment and transformation into the reference finished-product (1t recycled-LDPE); 2)  
161 preparation and acquisition of auxiliaries, oils, and energy; 3) the treatments of all waste materials

162 as generated by the recycling process; and 4) the annexed plant for treatment and recirculation of  
163 the APW-cleaning water.

164 Those boundaries were designed based upon information provided by the supporting firm to clearly  
165 highlight the material and energy flows throughout the investigated chain, which enabled  
166 connecting the up-stream processes to the down-stream ones. Furthermore, as emerges from Figure  
167 3, all transports for input material supply and for delivery of the wastes generated by the process to  
168 treatment were considered in the assessment. Only the recycled-LDPE distribution was excluded  
169 because it was considered as pertaining to the utilisation phase and, therefore, the downstream  
170 border of the system was set at the firm exit gate. All transport flows considered were detailed in  
171 the following section, together with the related diesel consumptions and Ecoinvent modules used  
172 for the system assessment based upon information provided by the firm.

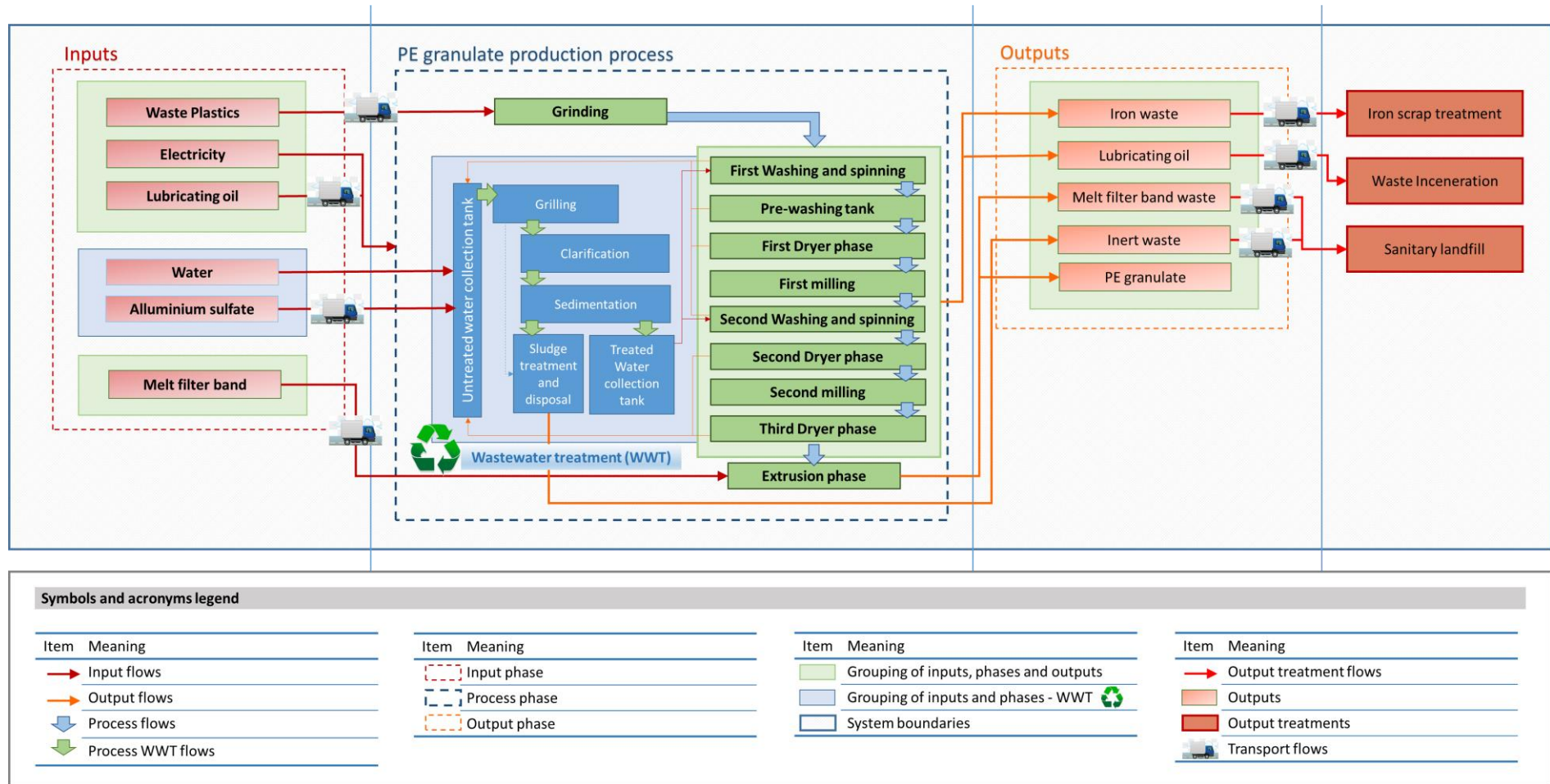


Figure 3. Boundaries of the system investigated.

### 175 2.3.2 *Life cycle inventory (LCI)*

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

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

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

199 Primary data were combined with background ones extrapolated from the database of  
200 acknowledged scientific value and relevance, like Ecoinvent v.3 as available in SimaPro 8.1. This



201 database was used because it is recognised worldwide as accommodating most of the background  
 202 materials and processes often used in LCAs (Frischknecht and Rebitzer, 2005), which contributes  
 203 making it suitable for the modelling of industrial systems like the one investigated in this study.  
 204 Data collection regarded a 3-year campaign between 2015 and 2017 and information used for the  
 205 LCI were reported in Table 2 and Table 3. In detail, Table 2 shows that data related on LDPE  
 206 granules production differ only about 5% during the three years analysed, confirming the  
 207 standardisation of the process. Therefore, the LCA developed in this study is representative of the  
 208 production process of LDPE granules from recycled greenhouse covering films.

209

210 **Table 2. Data collected at the LDPE granules production site from 3-year campaign and the annual average**  
 211 **base. All data reported are referred to the annual production.**  
 212

| 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

213

214

215

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

| Transport | Raw material       | Waste         | Flow    | Diesel consumption | Ecoinvent module  |
|-----------|--------------------|---------------|---------|--------------------|---|
|           |                    |               | (kgkm)  | (kg)               |   |
| 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               |   |

216

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**

| <b>Outputs</b>   |   |           |
|--|---|-----------|
| <i>Items</i>   | <b>Average</b><br><b>U.M/ton<sub>LDPE</sub></b> | <b>UM</b> |
| <i>Products</i>  |   |           |
| LDPE granules  | 1.000   | ton       |
| <i>Waste streams</i>   |   |           |
| Inert  | 0.521   | ton       |
| Exhausted mineral oil  | 0.358   | kg        |
| Steel  | 1.615   | kg        |
| <b>Inputs</b>  |   |           |
| <i>Items</i>   | <b>Average</b><br><b>U.M/ton<sub>LDPE</sub></b> | <b>UM</b> |
| <i>Material and energy commodities</i>                               |   |           |
| Underground water without treatment<br>(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         |
| <i>Total of transports (as sum of values in Table3)</i>              |   |           |
| 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

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

232

### 233 2.3.3 *Life cycle impact assessment (LCIA)*

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

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

244

#### 245 2.3.3.1 *Carbon Footprint (CF)*

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

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

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

256 
$$CF_i = \sum_j GWP_j * e_j \quad (1)$$

257 where:

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

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

263

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

| GHG            | Formula          | GWP <sub>100</sub><br>[gCO <sub>2eq</sub> /gGHG] |
|----------------|------------------|--|
| Carbon dioxide | CO <sub>2</sub>  | 1  |
| Methane        | CH <sub>4</sub>  | 28   |
| Nitrous oxide  | N <sub>2</sub> O | 265  |

265

266 At the end-point approach, the computed impacts were transformed into damages using conversion  
 267 factors based upon the classification scheme provided by ‘ReCiPe Endpoint’ (Goedkoop et al.,  
 268 2013) in the Egalitarian perspective (E/E) for the CF. ReCiPe method was used, in particular, for  
 269 quantification of environmental damages that the emissions of the most significant GHGs generate -  
 270 upon the DCs, i.e. Climate Change (CC), Human Health (HH) and Ecosystem Quality (EQ).

#### 271 2.3.3.2 *Cumulative Energy Demand (CED)*

272 The CED is an impact indicator that expresses the energy utilisation throughout the life cycle of a  
273 product or a service (Hischier et al., 2010). So, it can be considered as an indicator of environmental  
274 impacts with regard to the energy resource depletion (Gürzenich et al., 1999).  
275 According to Wiesen and Wirges (2017), CED was calculated based upon the ‘Cumulative Energy  
276 Demand’ method described in the Ecoinvent database. The aim of the method is both to calculate the  
277 direct and indirect energy used throughout the life cycle of the LDPE-granules and differentiate  
278 among renewable and non-renewable energy sources (Huijbregts et al., 2006). Therefore, this  
279 method allows the evaluation of environmental effects related to both the emissions and energy  
280 consumption (Girgenti et al., 2013). In detail, the method includes the direct and indirect uses of  
281 energy and it is organised in eight different impact categories. Normalisation or weighting data are  
282 not included in the method. In this study, the CED was calculated by including both non-renewable  
283 (from fossil fuels, nuclear, and non-renewable biomass) and renewable (from wind, solar,  
284 geothermal, and water) energy sources, associated to each input considered in the LDPE granules  
285 production process.

286

#### 287 2.3.3.3 *Water Footprint (WF)*

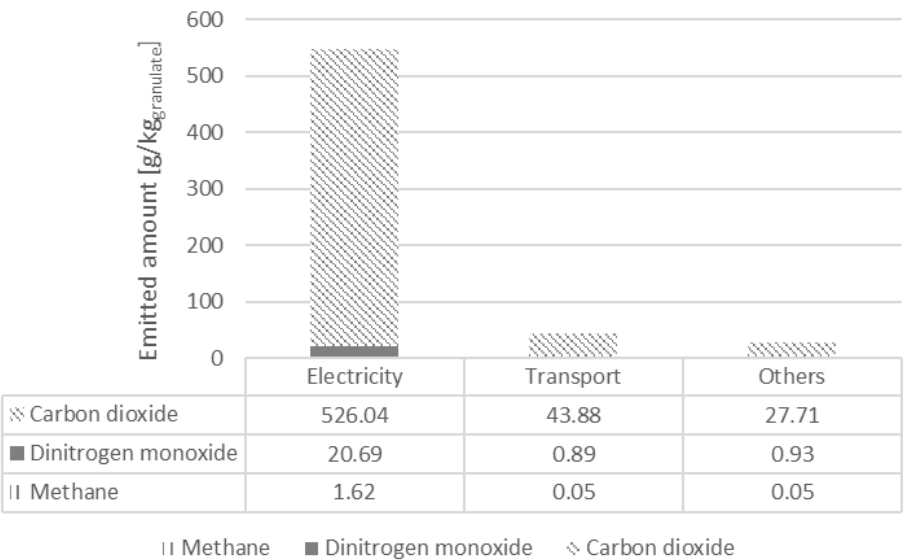
288 Among the methods involved in LCA-based water footprint, the Water Footprint Assessment  
289 (WFA) was adopted, according to Pfister et al. (2009). This method is centred upon computation of  
290 the Water Stress Index (WSI), which calculates the water impact on the consumption-to-availability  
291 perspective of freshwater deprivation, corresponding to the ‘blue water’ in the WFA methodology.  
292 The Water Stress Index was used as a general screening indicator or characterisation factor for the  
293 freshwater consumption at the mid-point approach for all three areas of protection: Resources,  
294 Ecosystems and Human Health. Then, at the end-point approach, the damages using conversion  
295 factors based upon the classification scheme provided by Eco-indicator 99 (Goedkoop and  
296 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<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O are the most significant GHGs since they represent the 94.87% of the CF associated to the system investigated. In particular, CO<sub>2</sub> is characterised by the highest GWP<sub>100</sub>, 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<sub>2</sub>); 91.90% (N<sub>2</sub>O); and 94.63% (CH<sub>4</sub>). Contribution from the transport section is far lower and ranges from 2.74% in the case of CH<sub>4</sub> to 7.34% as per CO<sub>2</sub>-emission.

Mid-point results demonstrate that CF is equal to 655.46 kgCO<sub>2</sub>, which, based upon results shown in Table 6, is due for the major percentage (91.18%) to CO<sub>2</sub>. 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*  | Endpoint analysis    |          |            |
|------------------|----------------------|----------------------|----------|------------|
|                  | Characterisation     | Damages assessment   |          |            |
|                  | GWP <sub>100</sub>   | CC                   | HH**     | EQ**       |
|                  | kgCO <sub>2</sub> eq | kgCO <sub>2</sub> eq | DALY     | species.yr |
| CO <sub>2</sub>  | 597.63               | 597.63               | 2.10E-03 | 1.12E-05   |
| CH <sub>4</sub>  | 47.97                | 47.97                | 4.57E-05 | 2.43E-07   |
| N <sub>2</sub> O | 5.97                 | 5.97                 | 1.21E-05 | 6.44E-08   |

\* IPCC 2013

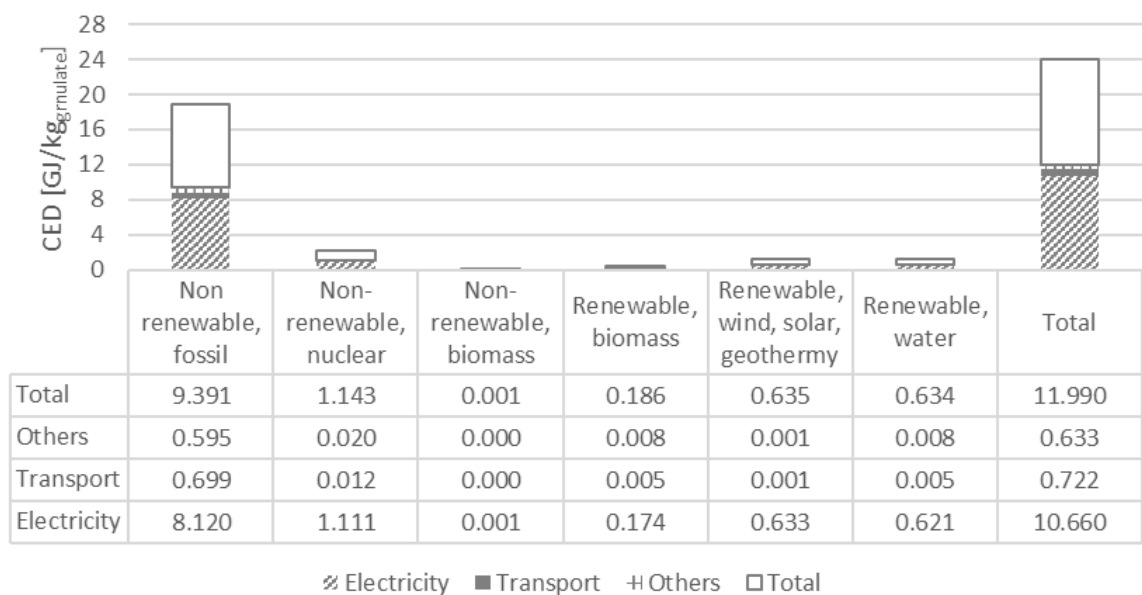
\*\* values are referred to kg of emitted substance (ReCiPe Endpoint (E/E))

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.



335



336  
337  
338

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

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

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

346

347 **Table 7. Inventory and CED values for each of the most contributing fossil primary energy resources, with**  
348 **details on the contributions given by electricity, transports, all of the other processes, materials and phases**  
349

| 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.

350

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

356

### 357 3.3 Water footprint assessment

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

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

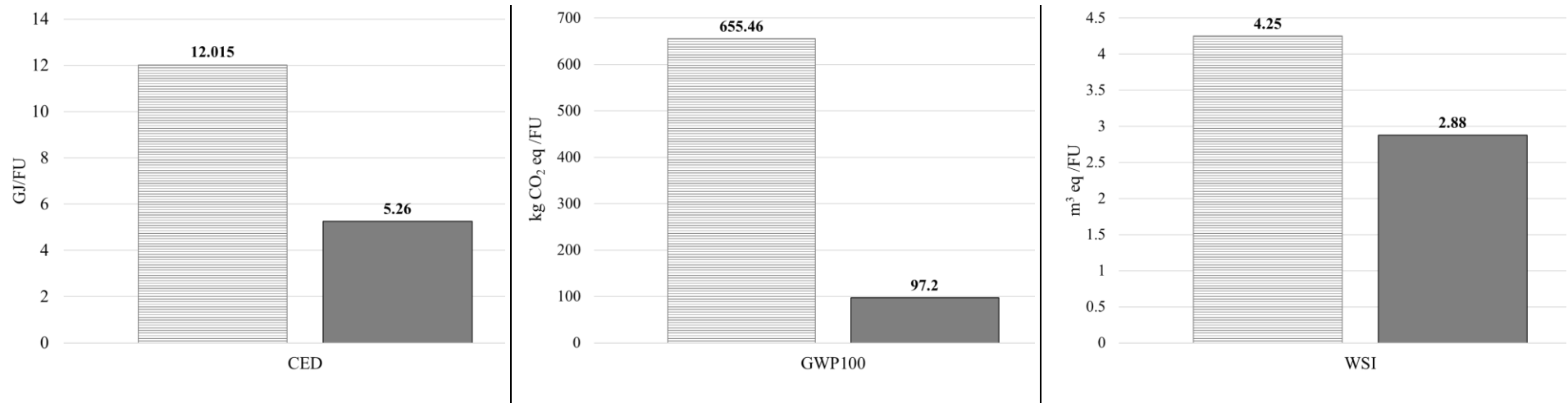
370

371 **Table 8. Results from the WF-related damages assessment (endpoint approach), with percentages for the most**  
 372 **contributing items within the system investigated.**  
 373

| Damage categories<br>(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   |

#### 374    **4    Interpretation and improvements**

375    The study highlighted that the electricity required by the process for 1 ton of recycled-LDPE  
376    production (942.75 kWh) is the largest contributor to both the CF and CED, so emphasising upon  
377    the importance to search for potential improvements. In agreement with the firm technicians, it was  
378    understood that no solutions are viable at the plant level by improving the technical quality and  
379    energy efficiency of machineries used in the production process. Therefore, electricity consumption  
380    is with no doubt the major energy and environmental issue of the whole system. Nonetheless, the  
381    energy/environmental burden associated with the electricity consumption may be reduced through a  
382    change in the energy source, by shifting it from fossil to renewable. A valid solution could be to  
383    install a wind power plant to cover the whole energy demand. In this regard, a first sensitivity  
384    analysis conducted for the purpose highlighted significant reductions for all the three indicators that  
385    have been addressed in this study, with CED and GWP<sub>100</sub> showing the greatest reduction of about  
386    56% and 85%, respectively, as they are clearly most affected by electricity use (Figure 6). It should  
387    be observed that this is just a preliminary evaluation that must be checked in terms of technical and  
388    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.**

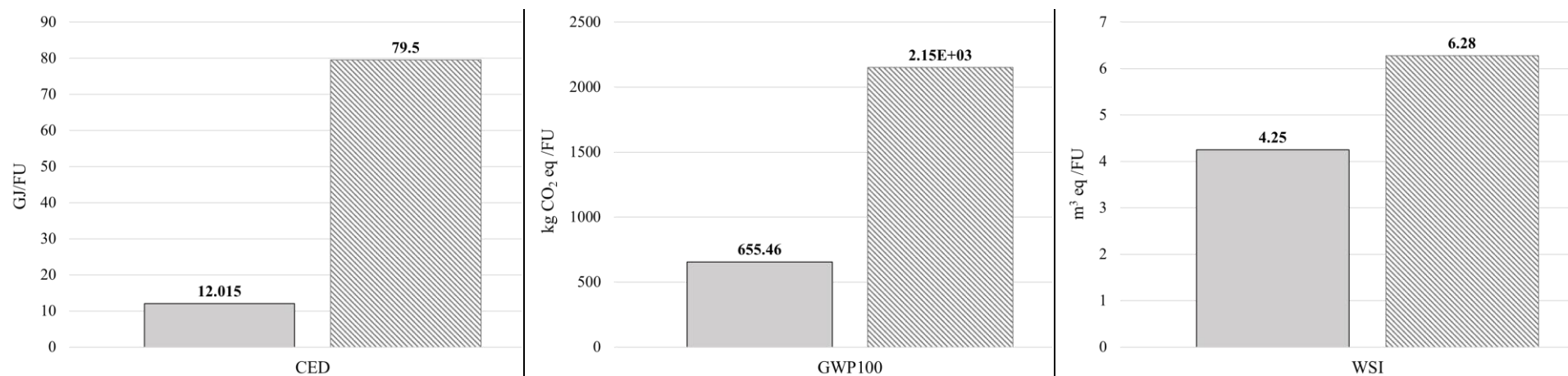
397 By contrast, no solutions were found to be viable for reduction of the water consumption demanded  
398 by the process in the cleaning steps.

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

409

410

411



412

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

## 413    **5    Conclusion**

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

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

- 420        • The CF was equal to 655.46 kgCO<sub>2</sub>, showing that CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O are the most  
421            significant GHGs emitted, since they represent the 94.87%, and electricity was the largest  
422            contributor for each of these GHGs.
- 423        • The CED was found 12.015 GJ per kg of recycled LDPE granules, with electricity  
424            contributing 88.72% produced from fossil origins for 76.17%. Gas natural, crude oil, and  
425            hard coal represented 77.3% of the fossil primary-energy resources.
- 426        • The WSI was 4.15 m<sup>3</sup>, with significant contributions coming from the cleaning steps of the  
427            process as operational water, and from the consumption of electricity as virtual water.

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

436    Such recycled granules can be considered as intermediate products for the manufacture of bags,  
437    pipes, and other products for several applications. Such transformations generally take place in  
438    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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