

Life Cycle Assessment of Distributed Plastic Recycling via Additive Manufacturing

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Abstract

Distributed recycling via additive manufacturing (DRAM) emphasizes a technical to recycle waste plastic directly by 3D-printing it into valuable products. Major progress have been reported to validate the technical feasibility, and economic viability of the system. However, little work has been done for the preparation and recovery stages, which involve the pertinent supply recycling network. Thus, this work makes a comparative environmental performance using a life cycle analysis (LCA) to evaluate the potential impacts of virgin and recycled polylactic acid, examining the case of an university Fab Lab located in Nancy, France. Four impact categories were considered : climate change, potential eutrophication, resource depletion, and ion radiation. Three of these categories demonstrated environmentally favorable results in comparison of a virgin supply chain. These results provide an environmental overview of the benefits and disadvantages of developing a DRAM system in a specific context.

Keywords : *LCA ; Distributed Recycling ; Plastic ; Additive Manufacturing, Circular Economy*

1. Introduction

Since the early 20th century, the invention of plastic, or synthetic organic polymers, has changed the landscape of various industrial sectors. Production increased at a compound annual growth rate of 8.4%, rising from 2Mt in 1950 to 368Mt in 2019 (Geyer et al., 2017). This versatile material stands out thanks to its easy processing and handling in shape, color, texture, thermal and barrier properties, and its mechanical and chemical resistance (Andrade and Neal, 2009 ; Thompson et al., 2009). In consequence, 39.6% of the demand comes from the packaging industry, followed by the construction and automotive industries with 20.4% and 9.6% of the production share respectively (Plastic Europe -, 2020). Unfortunately, the main problem is associated with multiple environmental damages throughout its life cycle. Terrestrial, aquatic, and atmospheric ecosystems are not exempt from the externalities of this innovation, which represent a major issue (Kumar et al., 2021). Micro-, meso-, and nano-plastic pollution contribute to the detriment of ecosystem services such as the ability to sequester carbon (Wang et al., 2022), soil productivity (Zhang et al., 2022), and eutrophication (Vuori

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14 and Ollikainen, 2022).
15 Indeed, plastic pollution in aquatic ecosystems such as standing waters can act as a vector of
16 toxic chemicals that affect biogeochemical cycles. In 2010, Jambeck et al. (2015) estimated
17 that between 1.75–4.62% mismanaged plastic waste reached the oceans equivalent to 4.8
18 to 12.7 million MT in 192 coastal countries. A total of 150 million tons of plastic has been
19 dumped into the sea to date (Pinto Da Costa et al., 2020). The presence of these solid plastic
20 wastes has become a threat to marine ecosystems (Shi et al., 2022). Additionally, the transfer
21 of plastic into the food chain is a clear danger to animals, and certainly to humans as well.
22 Therefore, reducing the production of plastics is of great importance in the long term.

23 Adequate use and disposal of plastics is a wicked problem, characterized by high complexity
24 and multifaceted feedback loops. A systemic view of the entire plastics value chain is needed,
25 including petrochemical companies (de Vargas Mores et al., 2018; Iles and Martin, 2013),
26 converters (Paletta et al., 2019), brand owners or manufacturers (Gong et al., 2020; Ma et
27 al., 2020), retailers and consumers (Confente et al., 2020; Filho et al., 2021; Friedrich, 2020),
28 and recycling operators (Huysveld et al., 2019; Pazienza and De Lucia, 2020), as well as the
29 influences of policy-makers on wider economic and societal changes (Paletta et al., 2019). The
30 European Union (EU) intends to develop a circular economy (CE) based on a production and
31 consumption model with key activities such as “sharing,” “reducing,” “reusing,” “repairing,”
32 “renewing,” and “recycling” the existing materials and products as many times as possible, in
33 order to create added value by extending the life cycle of products (European Commission,
34 2018; Matthews et al., 2020). Several criticisms have been raised, given the thermodynamic
35 constraints based on biodiversity and thermodynamics, arguments for a fully circular economy
36 (Corvellec et al., 2021; Giampietro and Funtowicz, 2020). Nevertheless, as part of the European
37 Green Pact presented on March 20, 2020, there are plans to establish an action plan involving
38 the circular economy, mainly promoting the development of sustainable products, reducing
39 waste, and empowering citizens as key players (European Commission, 2018). Considering
40 the French context, a target was established that by 2025 all plastic waste should be recycled,
41 but currently recycling statistics in France are only reaching levels close to 25%. Despite these
42 ambitious objectives, plastics recycling has historically been an expensive process due to the
43 inherent separate collection, transportation, processing, and remanufacturing (Hopewell et
44 al., 2009; Singh et al., 2017). The economies of scale have been leveraged to reduce these
45 costs with centralized and global recycling chains (Kreiger et al., 2013; Kreiger and Pearce,
46 2013). Nevertheless, in order to carry out this recycling system, multiple steps need to be
47 accomplished that integrate the sorting phase, long-distance transport, waste treatment, and
48 remanufacturing. The high costs of these processes and the low selling price (mainly due
49 to the dependence of the recycled plastic price on the petroleum and virgin prices) seldom
50 generate benefits and often require costly public subsidies (Hamilton and Steven, 2019). In
51 addition, these centralized plastic manufacturing and recycling lines lead to soil, water, and
52 air pollution (Arena et al., 2003; Carlsson Reich, 2005). In addition to the current problems
53 in the plastic recycling network, we can highlight that supply chains in general are under
54 increasing pressure from various stakeholders to make decisions from a sustainable perspective;
55 in other words, based on economic, environmental, and social objectives (Hassini et al., 2012).

56 Additive manufacturing technology (also known as 3D printing) enables the potential
57 of distributed manufacturing (DM) for products of high added value (Bonnín Roca et al.,
58 2019; Petersen and Pearce, 2017; Woern and Pearce, 2017). Nowadays, the accessibility of
59 freely available designs has increased significantly, together with the development of open-
60 source technologies and the supply of raw materials (virgin and recycled filaments) for 3D

printing (Hunt et al., 2015). Distributed manufacturing is defined as the decentralization of production through the installation of multiple production factories with similar technology distributed geographically (Bonnín Roca et al., 2019). It is characterized by local production that thrives on the synergy of the emerging capabilities of digital manufacturing, information, and communication technologies, and the peer-to-peer production approach (Kostakis et al., 2018 ; Kostakis, 2013 ; Pavlo et al., 2018). Indeed, DM offers the possibility to decentralize production structures, the flexibility to reflect local customer needs, lower logistics costs, shorter lead times, and lower environmental impacts (Petersen and Pearce, 2017 ; Woern and Pearce, 2017). Based on the DM paradigm, a new possibility of plastic recycling supported by additive manufacturing, called distributed recycling by additive manufacturing (DRAM), has emerged in the literature (Cruz Sanchez et al., 2020 ; Hart et al., 2018). Promoted by the development of 3D printing in an open-source context, DRAM is proposed to provide recycled plastic feedstock to the various 3D printers in a DM context. This recycled plastic can take the form of a filament, and recent works have dealt with the validation of a granular form (Alexandre et al., 2020 ; Justino Netto et al., 2021). The 3D printing feedstock is then obtained via plastic recycling on a local scale using open-source machines such as shredders and extruders (Zhong and Pearce, 2018).

The main feature of DRAM is the reduction of the impact in the collection phase, favoring shorter and simpler supply chains (Despeisse et al., 2017 ; Garmulewicz et al., 2018). Several works have focused on the validation of the DRAM approach from a technical (López et al., 2022 ; Mohammed et al., 2022), economic, and environmental perspective (Cañado et al., 2022 ; Wu et al., 2022). Cruz Sanchez et al. (2020) conducted a systematic literature review to examine the level of development of the different DRAM stages from a technical perspective. Their results show that significant progress has been made in the stages of compounding, feedstock, printing and quality assessment. However, they also show that little work has been done for the preparation and recovery stages in spite of this. In another work, Santander et al. (2020) proposed an initial model to study the economic and environmental feasibility of DRAM from a logistical point of view. Their results have shown the feasibility of the system in economic terms and in the reduction of CO₂ emissions when implementing the system. From an environmental point of view, the DRAM and DM approaches have been evaluated mainly using the Life Cycle Assessment (LCA) approach.

LCA is one of the most widely used environmental impact assessment methodologies. LCA corresponds to an ISO 14040 certified methodology, which has even been used for environmental regulations in different parts of the world. In the context of DM/DRAM-related research, LCA has been applied in various ways. For example, Kreiger and Pearce (2013) conducted a life cycle analysis, in terms of energy consumed and emissions involved, to compare centralized manufacturing and distributed manufacturing using RepRaps (3D printers) for the distributed production of goods. The results showed that the use of Poly Lactic Acid (PLA) in a distributed manufacturing context reduces energy demand and system emissions, which can be greatly diminished if a solar photovoltaic (PV) array is used. Later, Kreiger et al. (2014) explored the environmental benefit of distributed recycling using open-source extruders (RecycleBots), which have been used to obtain 3D printing filament from post-consumer goods. Focusing on the use of High Density Poly-Ethylene (HDPE) for the material, they performed an LCA of energy consumption and CO₂ emissions to compare distributed recycling to standard centralized recycling. Their results showed that distributed recycling of HDPE uses less energy than the best-case scenario investigated for centralized recycling, and it can achieve savings of over 80%. Kerdlap et al. (2021), through a simulation approach, quantified the plastic

108 life-cycle environmental impact of small-scale sorting and recycling systems in comparison
109 to traditional large-scale centralized systems in Singapore, with the aim of determining the
110 conditions under which distributed recycling can be environmentally beneficial. Their results
111 showed that the environmental impacts in terms of climate change, water depletion and
112 terrestrial ecotoxicity were higher compared to the centralized systems. Their results showed
113 that the environmental impacts in terms of climate change, water depletion, and terrestrial
114 ecotoxicity were higher compared to the centralized systems. However, these results are mainly
115 related to the means of transport considered for each system (commercial van for distributed
116 recycling and large trucks for centralized recycling), since the use of large trucks decreases
117 the total impact.

118 In conclusion, even though different studies have been conducted aiming to validate the
119 distributed recycling approach from a technical, economic, and environmental perspective,
120 only the work of Kreiger et al. (2014) is focused on the environmental assessment of distributed
121 recycling for 3D printing purposes. However, their research is limited to the consideration of
122 energy and CO_2 emissions as environmental indicators. Therefore, major efforts need to be
123 made in order to evaluate, in a holistic way, the environmental impacts of the global DRAM
124 value chain. Thus the contribution of this research lies in the evaluation of environmental
125 impacts from the implementation of distributed recycling via an additive manufacturing
126 approach in a territory. Specifically, an environmental evaluation using life cycle assessment
127 (LCA) is conducted, comparing a distributed plastic recycling system to produce 3D filament
128 with a traditional production system of virgin plastic filament for 3D printing. From this
129 evaluation, the environmental impacts (positives or negatives) of implementing DRAM have
130 been analyzed and discussed.

131 This article is structured as follows. Section 2 presents the system (case study) evaluated.
132 Section 3 materials and methods, where life cycle analysis methodology is explained. Section 4
133 presents the life cycle analysis performed. Section 5 presents the discussion of results. Finally,
134 Section 6 presents the main conclusions and recommendations for future works.

135 2. Case study : The Lorraine Fab Living Lab

136 In order to achieve the objectives of this research, a case study with the following
137 characteristics was selected :

- 138 1. Existence of a favorable context to implement a DRAM recycling system. A favorable
139 context is defined as a considerable amount of plastic waste to be treated, as well as
140 initiatives for the widespread use of 3D printing.
- 141 2. Existence of a space dedicated to the recycling of plastic for 3D printing.

142 Under these considerations, the selected context for this study was the Lorraine Fab
143 living Lab (LF2L)², an innovation space located in Nancy, France. This university laboratory
144 has been selected mainly for the following reasons : (1) Innovation spaces such as Fablabs,
145 Maker spaces, design factories among others have proven to be favorable environments for eco-
146 innovations facilitating the implementation of circular economy strategies (Coskun et al., 2022).
147 Previous studies show that these collaborative environments foster sustainable experimental
148 learning, provide methodologies and tools for the co-creation of circular solutions, drive the
149 transition toward sustainable smart cities, foster the creation of new sustainable business

2. <https://lf2l.fr/projects/green-fablab/>

models, and facilitate knowledge exchange on circular solutions (Kasmi et al., 2021). (2) Since 2014, the LF2L has been studying the possibility of recycling, in their installations, PLA for reuse in 3D printing. The pilot recycling process present in this center has been developed in the research work of Cruz Sanchez et al. (2017), and the possibility of implementing this recycling process in the region is being evaluated. (3) An investment program has been launched by the Grand Est region to promote the implementation of Fablabs, and consequently the use of 3D printers, in the schools and high schools of the region (Canopé, 2022). The goal of this investment plan is to ensure that all the schools and high schools in the region will be equipped with this technology in the near future. This corresponds to the future scenario evaluated in the work of Santander et al. (2020). However, in contrast to Santander et al. (2020), in our research work a complete environmental evaluation of the scenario is carried out. Consequently, this case study has been selected because of their experience in experimenting with the DRAM strategy, as well as the availability of technical and economic data and the aforementioned scientific publications that provide details on its local implementation.

For this study, the context described above has been simplified in terms of geographical scale, and the following assumptions are considered.

- Consideration is given to only one type of plastic waste to be recycled. Specifically, PLA has been considered. This is mainly because PLA is one of the most used plastics in 3D printing (Bikas et al., 2016). For the plastic waste sources, PLA waste from schools and high schools (who have 3D printers) has been considered. PLA has been selected as feedstock material due to the fact that (1) in Europe, PLA is considered a “miscellaneous product” (Maga et al., 2019) because of its classification as a Bioplastic and because, at least in Europe, there is no defined recycling strategy for these types of plastics so they are usually sent to a landfill or are incinerated ; and (2) PLA is one of the most widely used plastics in 3D printing.
- The recycling system modeled does not consider the sorting, separation, and cleaning process because the collected material corresponds to non-contaminated waste : for example, discarded 3D printing parts used for prototyping.
- From a geographical point of view, only schools and high schools in the Lorraine region of France have been considered, and the route of recovery and delivery considered is obtained in the work of Santander et al. (2020).
- Each school and high school requires 1 kg of filament per month.
- The 3D printing activities carried out in these establishments have the specific purpose of making product prototypes and mock-ups, which allows them to generate testing activities, design evaluations, functional evaluations, and corrections. Therefore, after a short lifetime, 3D printing can be a source of significant amounts of plastic waste due to printed parts that do not possess the desired quality, unused raw materials, or products that have already fulfilled their life cycle (Jaafarnia et al., 2021).

3. Material and methods

The chosen methodology is Life Cycle Assessment (LCA) because, unlike other analytical methodologies with an environmental focus, such as Material Flow Analysis (MFA), Substances Flow Analyses, and Environmental Risk, it allows us to evaluate the environmental impacts of the system value chain to be modeled (Mahmud et al., 2021 ; Pryshlakivsky and Searcy, 2021).

The LCA represents a different tool and different techniques created to determine in an

195 effective and fast way the results to help with managerial decision-making in environmental
196 terms and in the deepening of the sustainable development policy ([Guinée, 2002](#)). Life Cycle
197 Assessment (LCA) is a structured, comprehensive and internationally standardized method
198 in accordance with ISO 14040 and 14044. It defines all the steps for its use : goal and scope
199 definition, inventory analysis, impact assessment, and interpretation ([Pennington et al., 2004](#)).
200 LCA is a tool for quantitative evaluation of materials, energy flows, and the potential impact
201 of products, services, or technologies ([Dehghanian and Mansour, 2009](#)). The analysis takes
202 into account the entire life cycle of a product : from resource extraction, through production,
203 use, and recycling, to the disposal of the remaining waste ([IES, 2010](#)). LCA is considered a
204 legitimate environmental methodology that enables systems analysis for waste policy and
205 strategy ([Gontard et al., 2022](#)).

206 A life cycle analysis has four main stages : the definition of objectives and approach (Stage
207 1), inventory analysis (Stage 2), impact assessment (Stage 3), and interpretation (Stage 4)

- 208 1. **Goal and Scope Definition** : This is the first stage and serves to orient the study
209 bases. It defines the main objectives of the life cycle analysis, the target audience of
210 this report, the functional unit that is the reference point from which the potential
211 environmental impacts will be obtained, the limits of the system under study, the
212 categories of environmental impacts to be evaluated, and the hypotheses to be used in
213 different stages of the LCA.
- 214 2. **Inventory Analysis** : Inventory is the stage in which the flows are quantified. It sets
215 out the database used, the energy and material input, the calculations performed, and
216 how the system was modeled.
- 217 3. **Impact Assessment** : This stage presents the software used and the calculation
218 methodology used to transform flows and characterize them in the impact categories
219 evaluated. From this characterization, the impact profile of the system under study is
220 obtained.
- 221 4. **Interpretation** : This is the conclusion of steps 2 and 3, presenting the results obtained
222 from the hypotheses used, the considerations, and the functional study that has been
223 defined. The phases of the life cycle that have the most impact are identified, and
224 sensitivity analyses can be carried out to evaluate the behavior of the systems according
225 to the variation of certain parameters. The inter-phase analysis stage is fundamental
226 for decision-making, as it identifies critical points and provides a basis for future
227 improvements.

228 The LCA methodology is mostly used in an iterative way, allowing a better definition of
229 the objectives to be achieved and the system to be analyzed.

230 In the following sections, an LCA is presented for DRAM using the Lorraine Fab Living
231 Lab as a case study.

232 4. LCA application and results

233 4.1. Goal and Scope Definition

234 The main objective of this life cycle analysis is to compare the potential impacts produced
235 by a DRAM chain with the impacts produced by a traditional chain of virgin plastic filament
236 for 3D printing.

237 4.1.1. *The functional unit*

238 As mentioned above, this study will compare the environmental impact of two PLA 3D
 239 filament supply systems. By way of context for this study, the 3D filament will be supplied to
 240 all schools and high schools located in the city of Nancy, France. To compare two or more
 241 systems, it is necessary to define a functional unit that represents the service delivered by
 242 both systems. In this case the main service consists of the following :

243 “*A monthly delivery of 1 kg of ‘standard’ plastic filament (PLA) to each school and high
 244 school in Nancy during ten months of the year.*”

245 4.1.2. *System boundary*

246 Figure 2 shows the two systems compared in this study and the processes integrated into
 247 the life cycle analysis. As can be observed, there are three different boundaries represented by
 248 the colors green, blue, and red. The first boundary (green box) corresponds to the Biosphere,
 249 which represents everything related to nature, such as raw materials from natural resources,
 250 ecosystems, and solar energy. The second boundary (dark blue box) corresponds to the
 251 Technosphere limit, representing human activity (e.g. use of electricity, fuel, etc.). Here, we
 252 can observe all the material flows that are considered for the life cycle analysis, the flows
 253 between processes, or the flows that are part of the functional unit mentioned above. Finally,
 254 the boundary in a light blue color represents the limit of the services and processes taken into
 255 consideration in this study. On the one hand, in the upper process flow, we can observe the
 256 processes considered in the system to produce filament from virgin plastic. The process starts
 257 with PLA production, which is followed by PLA transportation, filament production, and
 258 finally product delivery. On the other hand, Fig. 1 shows the recycling process enclosed in
 259 the orange box. The process starts with the collection of waste produced by schools and high
 260 schools, then the plastic recycling process, the production of filament, and the delivery of
 261 filament are carried out.

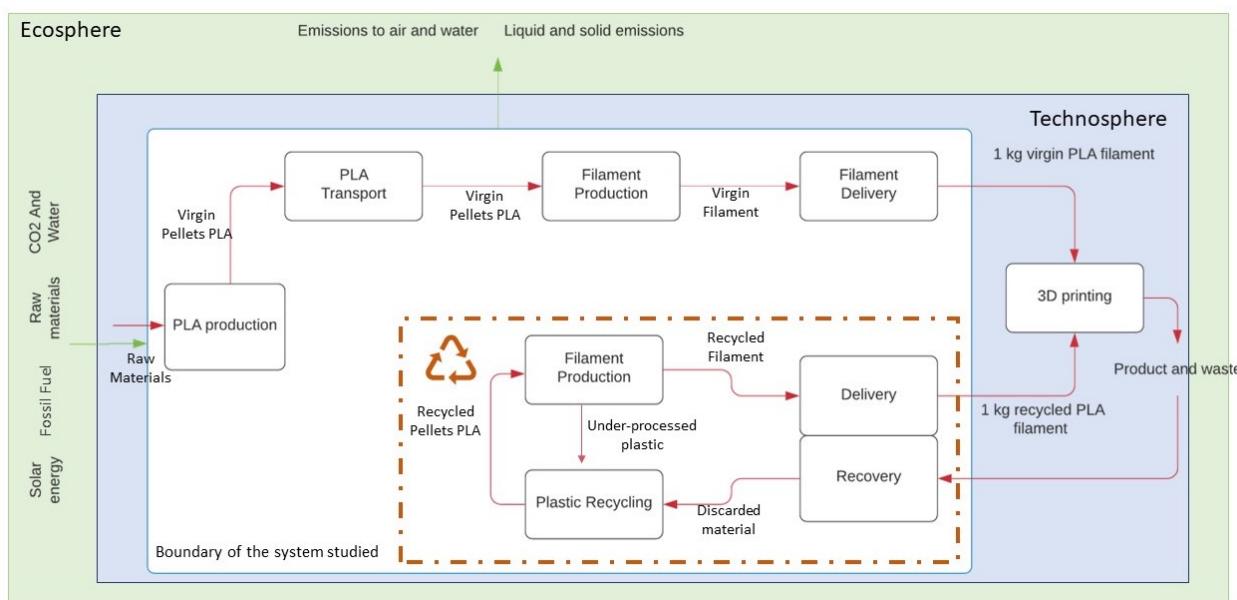


FIGURE 1: System limits for life cycle analysis

262 4.1.3. *Selected impact categories*

263 The objective of performing a life cycle analysis is to determine and evaluate the potential
264 environmental impacts produced at different stages in the life cycle of a product, service,
265 activity, or process. However, it is quite difficult to identify, a priori, the categories of impacts
266 in which the system under study is most detrimental (climate change, eutrophication, etc.).
267 To resolve, it was decided to analyse relevant literature of LCA applied on the bioplastics and
268 additive manufacturing separately. First, the production of plastics (in this case bioplastics)
269 compared to the recycling of plastics. Second, the integration of these materials in additive
270 manufacturing as raw material for the subsequent printing of products.

271 Concerning the plastic perspective, Bishop et al. (2021) compared the impact of bioplastics
272 (such as PLA) regarding the petrochemical plastics considering the impact categories across
273 44 relevant articles that used LCA evaluation. Their results pointed out the most used impact
274 category for bioplastics evaluation is climate change, followed by potential eutrophication
275 variations, resource depletion, human toxicity, photochemical oxidant formation, ozone de-
276 pletion, ecotoxicity, particulate matter formation, energy consumption, land use, and water
277 consumption.

278 On the other hand, it was found that the cumulative energy demand (CED) of the system is the most evaluated LCA impact category (Cerdas et al., 2017; Kellens et al., 2017;
279 Kreiger and Pearce, 2013; Quinlan et al., 2017) in the context of additive manufacturing. In
280 addition, It was also considered climate change, potential eutrophication, and human toxicity
281 as the main impact categories included in the LCA. In conclusion, it was decided to use the
282 predominant impact categories in each of the industries, namely climate change, potential
283 eutrophication, and resource depletion (fossil and water) after analyzing the LCA results of
284 the two domains .

286 4.1.4. *Assumptions and limitations*

287 The realization of a full LCA involves the collection of information and data related to
288 the different processes, flows, and activities. Due to the difficulty of obtaining the necessary
289 data, it is permissible to formulate hypotheses to partially make up for the lack of data, on
290 the condition that the hypotheses used, and the conditions under which they are formulated,
291 are made transparent.

292 The hypothesis formulation was mainly used to model the virgin plastic filament production
293 system. The main hypotheses used are based on :

- 294 — Location of polylactide acid production : This hypothesis indicates the location where
295 the polylactic acid production process takes place.
- 296 — Location of filament manufacturer : Due to the uncertainty about filament production,
297 two companies with different locations that are engaged in the production of plastic
298 filaments have been modeled.
- 299 — Filament production machine : The machine PEEK 3d Printer Filament Production
300 Line³ has been considered, which corresponds to the machine used by the two filament
301 manufacturers considered.
- 302 — Performance of the filament production machine : The machine selected to carry out
303 the filament production process has a range of transformation from plastic pellets to

3. More information about the machine can be found at www.acceextrusion.com/product/peek-3d-printer-filament-production-line.html (Accessed on 09/09/2022)

- filament. The range of the machine chosen for the evaluation has an output between 20 and 25 kg of filament per hour. This range directly affects power consumption.
- Type of energy source used to conduct the recycling processes : Each country has its own technological mix to supply its electrical energy consumption, such as nuclear, solar, and wind. These different sources of electricity are considered in the evaluation.
 - Transportation of raw material and filament (virgin and recycled) : The different options for methods of raw material transportation and filament transportation are considered in the evaluation.

Based on these hypotheses, two scenarios were created to model the possible operation of the virgin plastic filament production system (see Table 1). A third scenario represents the distributed recycling system for filament production, so the complete system is modeled with information obtained from the LF2L.

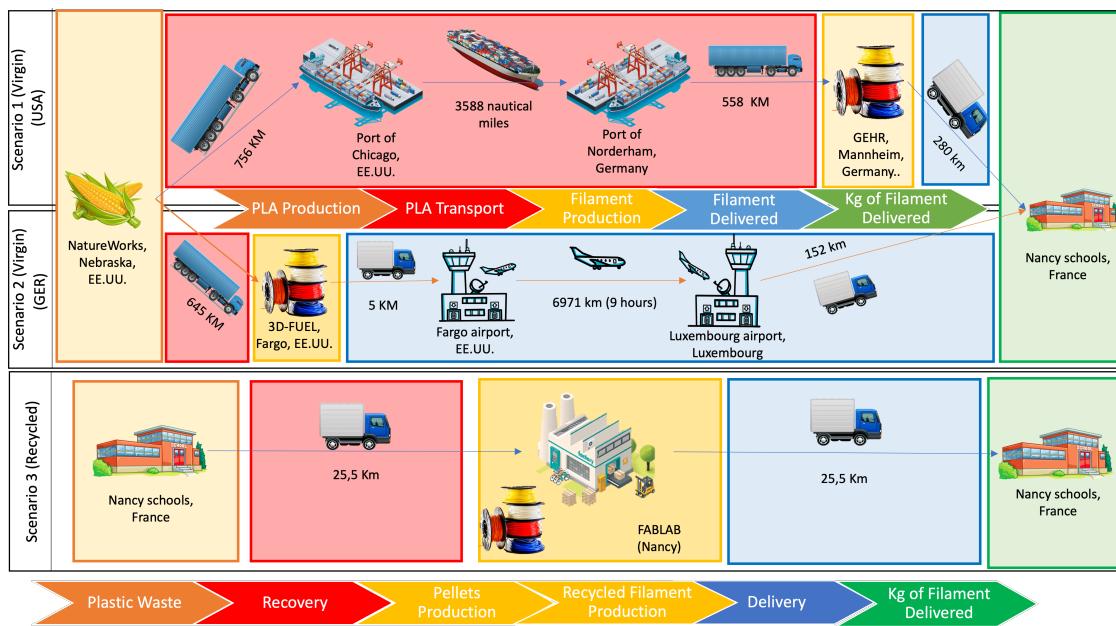


FIGURE 2: Representation of the 3 scenarios

TABLE 1: Scenario definition

Scenario	Description
Virgin Filament	
1	Scenario 1 begins with the production of PLA at the NatureWorks factory in Nebraska, USA. The PLA is transported by a combination of land and sea to bring the plastic from the United States to the filament manufacturing company, called GEHR, which is located in the city of Mannheim in Germany. In Germany, electricity is produced from wind power. From this location, the virgin filament is shipped directly to Nancy by light road transport.
2	factory in Nebraska, USA. The pellets of PLA are transported by road to the filament manufacturing company, called 3D-Fuel, which is located in Fargo, USA. In the United States, electricity is produced from natural gas. From the USA, the filament is shipped directly to Luxembourg by air freight. Then the filament is transported to Nancy using a lightweight vehicle.

Recycled Filament

3 This scenario starts with the collection of PLA 3D printing waste from the schools and high schools. The PLA waste is transported to the recycling point (Lorraine Fab Living Lab) using light road transport. At this center, the size reduction process and the extrusion process necessary to produce the recycled filament are performed. The recycled filament is then delivered to the same schools and by the same means of transport as where the waste was collected.

316 *4.2. Life Cycle Inventory Analysis (LCIA)*

317 *4.2.1. Data source*

318 To obtain the necessary data, different data sources were used to carry out the LCIA.
319 On the one hand, for virgin PLA filament production there are various life cycle analyses
320 published by NatureWorks ([Vink et al., 2003](#); [Vink and Davies, 2015](#)), where the results have
321 been incorporated into the EcoInvent database. These articles helped us to understand the
322 PLA production process, considering the production center in Nebraska, USA. For virgin
323 PLA filament manufacturing, NatureWorks proposes a catalog of customers who manufacture
324 filament from PLA produced by the company, which facilitated the modeling of the supply
325 chain to sell its product in the city of Nancy, France.

326 On the other hand, for the plastic recycling process the data concerning the input/output
327 materials and the machines used in the recycling process were obtained directly from the
328 Lorraine Fab Living Lab and from the thesis works conducted at the ERPI laboratory related
329 to DRAM ([Cruz Sanchez et al., 2020, 2017](#); [Santander et al., 2020](#)) (see the Appendix A).
330 These data allowed us to model and understand the recycling network, its main functions,
331 and its limitations in consideration of the case study presented in Section 3.

332 *4.3. Impact Assessment (LCIA)*

333 *4.3.1. Calculation methodology*

334 *4.3.1.1. Choice of software.* The software used to perform this life cycle analysis was OpenLCA
335 1.10.3. The main reason for its use was because it is open-source software. This software
336 makes it possible to perform full life cycle analysis and carbon footprint analysis, allowing us
337 to install a wide variety of databases. For this case, the database used was the EcoInvent 3.5.

338 *4.3.1.2. Choice of calculation methodology and impact indicators.* In analyzing the impact
339 methodologies and considering the selected impact categories for this study (see Section 4.1.3),
340 ReCiPe (Global-Hierarchist version) has been chosen as the impact calculation methodology.
341 The ReCiPe method ([Goedkoop et al., 2009](#)) has been chosen mainly because it is widely used
342 in various areas of research ([Dekker et al., 2020](#)). In addition, ReCiPe is an LCIA method
343 that is harmonized in terms of modeling principles and choices, offering results at both the
344 midpoint and endpoint level ([Goedkoop et al., 2009](#)). In addition, it is used for various life
345 cycle analyses in the area of additive manufacturing with a hierarchical cultural perspective
346 ([Saade et al., 2020](#)). Finally, the set of impact categories chosen are presented in Table 2.

347 *4.3.1.3. Impact studies.* Table 3 presents the results of the comparison, showing for the
348 virgin and recycled scenario the amount of impact that is generated in each impact category
349 evaluated. In addition, the percentage reduction (comparing the recycling scenarios with
350 the virgin scenario) is presented. To construct this table, the best virgin scenario (least
351 impactful) was considered for comparison. As a result, it can be observed that the production
352 of filament from recycled plastic has a significant advantage in five of the six impact categories
353 (climate change, fossil depletion, freshwater eutrophication, marine eutrophication, and water
354 depletion), which corresponds to the categories that are considered essential for DRAM. In

TABLE 2: Table of impact indicators and their unit of measure

Impact Category	Methodology		Unit
Climate Change	ReCiPe (H)		$KgCO_2 - Eq$
Resources Depletion	Fossil Depletion	ReCiPe (H)	$KgOil - Eq$
	Water Depletion	ReCiPe (H)	$KgP - Eq$
Eutrophication Potential	Freshwater Eutrophication	ReCiPe (H)	$KgN - Eq$
	Marine Eutrophication	ReCiPe (H)	$m3$

355 each of the categories there is a reduction of at least 97% compared to the impact produced by
 356 the virgin scenario. For the Ion Radiation category, however, the recycling system has a greater
 357 impact than the virgin scenario (best scenario in this case). In the recycling scenario, the
 358 amount of ion radiation equals approximately 2.8 times the emissions of the virgin scenario.

359 Figure 3 presents the impacts obtained for each scenario studied. As can be observed, the
 360 distributed recycling system to produce 3D filament (Recycling Scenario or Scenario 3) is
 361 the least impactful scenario, taking into account the five categories considered pertinent to
 362 DRAM.

363 The result shows that, in each impact category, the recycling scenario pollutes less than
 364 5% compared to the two scenarios that integrate the production of virgin plastic. In other
 365 words, the recycling system to produce 3D filament manages to reduce emissions and impacts
 366 by at least 95%.

367 Regarding the other impact categories present in the ReCiPe methodology, it is necessary
 368 to emphasize that the recycling system has a significant impact on the category that measures
 369 the radiation of ions equivalent to Uranium 235. As can be seen in Figure 3, even Scenario
 370 3, which takes recycling into account, reaches a high radioactive emission compared to the
 371 scenarios that use virgin filament. Scenario 1 represents approximately 25% of the impact
 372 produced by the recycling system, while Scenario 2 (pessimistic scenario of virgin filament)
 373 represents approximately 60% of the impact produced by Scenario 3.

TABLE 3: Scenario definition

Impact categories	Scenarios	Impact of each process				Total
		PLA Production	Supply Transport	Filament production	Delivery	
Climate change (kg CO₂-Eq)	Virgin [1-2]	337.36	[5.69- 18.19]	[1.94 – 32.60]	[54.43 – 785.24]	[411.92- 1160.88]
	Recycled	-	5.4523	2.289	4.957	12.699 (-97%)
Fossil Depletion (kg oil-Eq)	Virgin [1-2]	96.79	[2.30 - 6.96]	[0.50 - 13.13]	[19.58- 285.14]	[123.83 - 397.36]
	Recycled	-	1.961	0.615	1.783	4.359 (-97%)
Freshwater Eutrophication (kg P-Eq)	Virgin [1-2]	0.14	[0.001- 0.002]	[0.001- 0.003]	[0.011- 0.024]	[0.159 0.168]
	Recycled	-	0.0011	0.0016	0.0010	0.004(- 98%)
Ionizing Radiation (kg U235-Eq)	Virgin [1-2]	26.51	[0.45-1.49]	[0.12-0.15]	[4.46- 52.78]	[32.61- 79.86]
	Recycled	-	0.476	122.98	0.406	123.83 (+74%)
Marine Eutrophication (kg N-Eq)	Virgin [1-2]	0.89	[0.004- 0.041]	[0.003- 0.009]	[0.09-1.30]	[1.02-2.20]
	Recycled	-	0.009	0.011	0.008	0.029 (-97%)
Water Depletion (m³)	Virgin [1-2]	37.3669	[0.005- 0.028]	[0.008- 0.112]	[0.064- 0.439]	[37.46- 37.92]
	Recycled	-	0.006	0.546	0.006	0.56 (-99%)

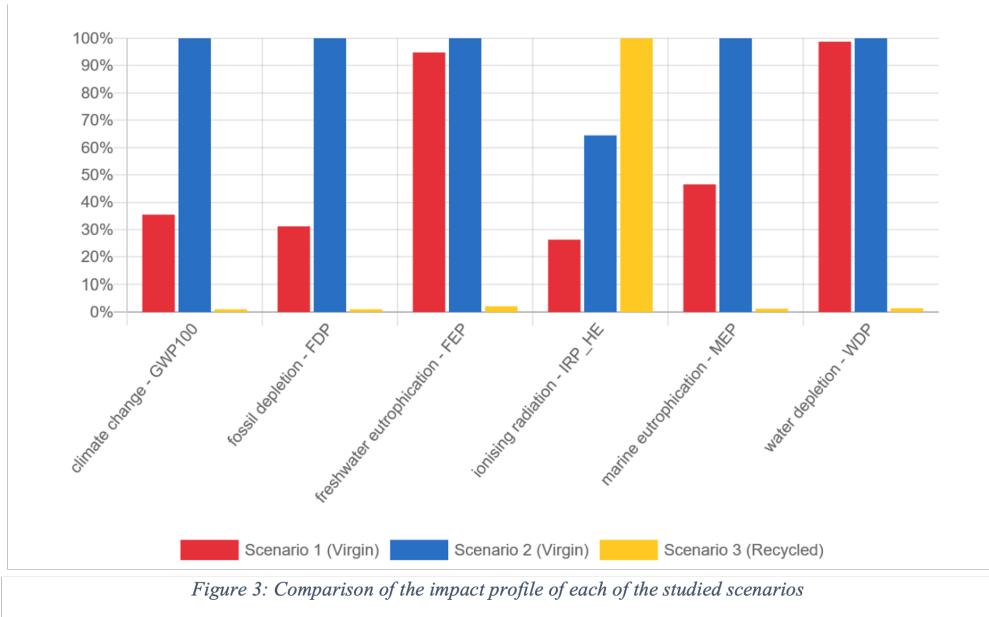


Figure 3: Comparison of the impact profile of each of the studied scenarios

FIGURE 3: Comparison of the impact profile of each of the studied scenarios

374 4.4. Interpretation and Recommendations

375 4.4.1. Sensitivity analysis

376 In order to evaluate the response of each of the systems to context variations, a sensitivity
 377 analysis has been conducted. The sensitivity analysis consists of analyzing the results of the
 378 system against the variation of one of the parameters. This activity allows us to identify
 379 the key contextual parameters that affect the results of the evaluation. These results can
 380 be favorable as well as negative, being able to identify the effect called transfer of impacts.
 381 This effect consists in the fact that while in a specific impact category a reduction in the
 382 level of emissions is achieved through a change of parameters (technology, raw material,
 383 process, type of energy), at the same time there is one or multiple impacts in which an
 384 increase in the emissions or impacts produced can be reflected. This effect (impact transfer)
 385 is fundamental when proposing improvements in products or services. In this study, to have a
 386 better visualization of the transfer of impacts, the complete set of impacts evaluated by the
 387 ReCiPe (H) methodology have been taken into account.

388 *4.4.1.1. Location of PLA production.* A recent project by Total Corbion has been proposed in
 389 Grandpuits (Seine-et-Marne). The purpose of this project is to build a polylactic acid (PLA)
 390 production plant with a capacity of up to 100,000 tons per year. This first European plant is
 391 to be installed in France⁴. Considering this, a sensitivity analysis has been performed for this
 392 scenario. In this new scenario, the PLA production facility is situated in France at Total's
 393 Grandpuits facility.

394 Figure 4 shows the result of the change in the location of the PLA production plant
 395 (from the United States to France). To represent the sensitivity of the system, only the first
 396 scenario was considered because it has a logistics chain with less impact than Scenario 2.
 397 Thus, it is interesting to see the changes with respect to this scenario. As can be observed,
 398 the result has a relatively small variation. Even though an improvement was obtained in

4. <https://www.usinenouvelle.com/article/bientot-du-pla-made-in-france.N1216857>

399 some categories, such as particle formation, use of fossil raw materials, or ozone depletion,
 400 the result is relatively small. The impact was not greatly reduced with respect to Scenario 1
 401 because PLA production is the main source of impact in this scenario.

402 In conclusion, it was observed that there is a slight improvement in the environmental
 403 performance of the production system, but it is not sufficiently attractive with respect to the
 404 level of impact obtained in the recycling of plastic to produce filament. To obtain a significant
 405 improvement, it is necessary to continue optimizing the PLA production process, which is
 406 enabled mainly by technological advances. This can be a great solution only if it manages to
 407 identify a slight transfer of impacts.

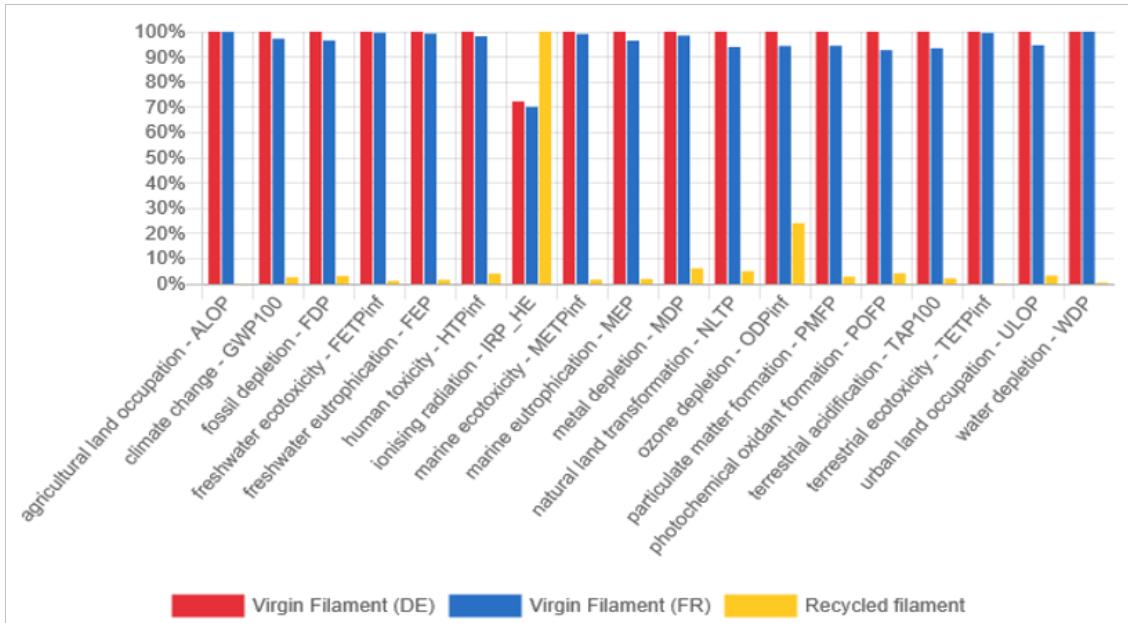


FIGURE 4: Comparison of the impact profile of each of the studied scenarios

408 *4.4.1.2. Energy Source.* The results presented in Section 4.3.1.3 have shown that distributed
 409 plastic recycling to produce filament demonstrates broad environmental advantages compared
 410 to production from virgin plastic. In almost all impact categories it had an impact of less
 411 than 5% of the impact caused by virgin filament production systems, except in the category
 412 related to the emission of radioactive particles. These emissions are closely related to the
 413 production of electricity from nuclear energy, which in France accounts for 77.5% of the total
 414 energy produced in the country. Currently, the french electricity system produce is 77.7%
 415 nuclear, 9.7% hydro power, 3.8% wind power, 3.5% natural gas, 2.2% coal, 1.5% solar PV,
 416 1.3% biofuels and wastes, and 0.3% oil (Pereira and Marques, 2020). For this reason, it is key
 417 to see the response of the system and the possible transfer of impacts when using other forms
 418 of energy production, including mainly the use of clean energy (solar and wind). Figure 5
 419 presents the environmental performance of the recycling system using three different types of
 420 energy (nuclear, wind, and solar).

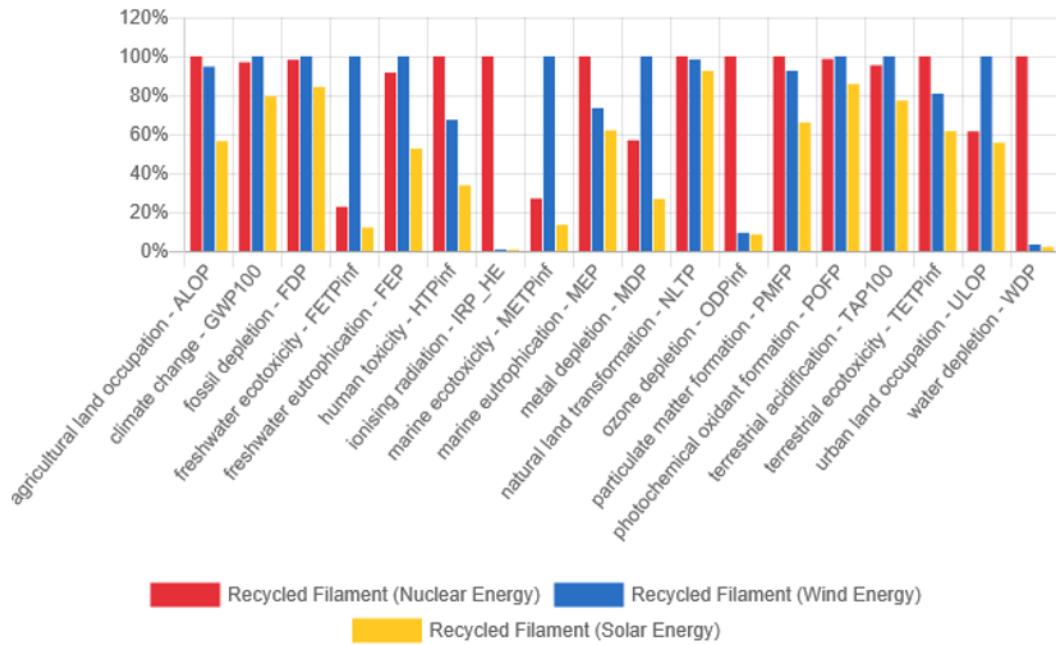


FIGURE 5: Sensitivity analysis respect to the type of energy used

421 As can be observed in Figure 5, solar energy and wind energy have different responses
 422 with respect to the use of nuclear energy. On the one hand, the solar energy (shown in
 423 yellow) considerably improves the environmental performance of the system, especially in the
 424 category of radioactive emissions, which are reduced by approximately 98%. It is important
 425 to remember that this category is the critical point in the comparison of the two filament
 426 production systems. In addition, a considerable improvement can be observed in the categories
 427 that consider ozone depletion and water use, with reductions of more than 70%. No transfer of
 428 impacts is observed in any of the impacts evaluated. According to the impacts assessed, there
 429 is no transfer of impacts to other categories, this being a more environmentally friendly option
 430 than the use of nuclear energy. On the other hand, wind energy (shown in blue) also achieves
 431 significant reductions in the categories of impacts related to radioactive ion emissions, ozone
 432 depletion, and water use. However, on this occasion, a transfer of significant impacts can be
 433 observed since the impact category measuring, for example, ecotoxicity in water (marine and
 434 fresh) increases its impact by 80% with respect to the use of nuclear energy, while the need
 435 for metals increases by 40%.

436 In conclusion, the use of solar energy may seem the best option among the energy sources
 437 evaluated. This type of energy presents a circumstantial improvement in the critical point of
 438 the use of nuclear energy without suffering a transfer of impacts. The use of wind energy does
 439 not have the same result ; although it manages to reduce radioactive emissions, the use of this
 440 type of energy increases the toxicity present in the water, which can directly affect various
 441 ecosystems as well as human health. To determine if this type of energy is suitable for the
 442 recycled filament production system, it is necessary to deepen the comparison between these
 443 two ways of producing electricity.

444 5. Discussion

445 Distributed recycling via additive manufacturing (DRAM) is been considered by different
446 authors as an additional path to increase the low plastic recycling rates given the major
447 democratization of material extrusion based systems ([Beltrán et al., 2021](#); [Pinho et al., 2020](#);
448 [Wu et al., 2022](#)). Several researchers have studied this recycling approach from a technical and
449 logistical perspective ([Mohammed et al., 2022](#); [Stefaniak et al., 2022](#); [Wu et al., 2022](#)). Other
450 studies that evaluated the environmental impact of this recycling approach only took the
451 recovery and recycling stages into consideration ([Kerdlap et al., 2021](#); [Kreiger et al., 2014](#);
452 [Kreiger and Pearce, 2013](#)). However, an assessment of the positive and negative environmental
453 impacts of implementing this plastic recycling approach with consideration for the whole chain
454 (recovery, recycling, and use) had not been conducted, until now. In this study, a life cycle
455 assessment has been conducted in order to evaluate the environmental impact of implementing
456 a DRAM system to produce recycled PLA filament, compared to traditional virgin PLA
457 filament production systems. In order to carry out this case study, a favorable context was
458 defined in which a considerable amount of plastic is treated, 3D printing is widely used, and
459 there is a dedicated space for plastic recycling via 3D printing.

460 The results of the environmental assessment of this system have shown that the recycling
461 system for filament production reduces the impacts produced by the best scenario of filament
462 production from virgin plastic by at least 97%. The categories of impacts considered were
463 greenhouse gas emissions (climate change), consumption of fossil materials (fossil depletion),
464 overfeeding of aquatic ecosystems (potential eutrophication), and water consumption (water
465 depletion). On the other hand, there is a transfer of significant impacts that is not considered
466 in the relevant impacts of the production system, since, due to the use of nuclear energy to
467 produce electricity in France, the emissions of radioactive ions increased by 280%, which means
468 that the recycling process has worse environmental performance in this category. Despite the
469 assumptions made, the scenarios related to virgin filament production have a major drawback,
470 which is that their most impactful or most influential phase in multiple categories is the
471 production of plastic. For this reason, the change in the location of the production plant
472 only produces a minor environmental improvement. This means that, in order to improve the
473 environmental performance of these systems, it is essential to develop new technologies and
474 optimize the polylactide acid production processes.

475 For the recycling system, the sensitivity analysis performed has shown that the integration
476 of solar energy can greatly reduce the impacts produced using nuclear energy, making it an
477 extremely viable alternative for the recycling system. Wind energy, on the other hand, has a
478 significant transfer of impact to the toxicity present in different types of water, which does not
479 allow us to define in the first instance whether it would be more convenient. In addition, the
480 results showed that the DRAM approach is advantageous considering other energy sources
481 (other than nuclear) that are used in other parts of the world. The environmental assessment
482 carried out in this study extends the results obtained by Kreiger et al. ([2014](#)) and Kerdlap et
483 al. ([2021](#)), showing, based on LCA indicators, the environmental benefits posed by distributed
484 plastic recycling, and more specifically, by implementing a DRAM system. In addition, the
485 environmental benefits are independent of the energy source considered. Therefore, this study
486 indicates that, in environmental terms and under certain conditions, the implementation of
487 DRAMs would have a positive impact on the area of application and could have positive
488 impacts in other contexts. Most notably, to the best of our knowledge, this is the first study to
489 investigate the multidimensional environmental impact of implementing DRAM. The results

490 show a huge potential, in environmental terms, of implementing DRAM and suggest the
491 application of this recycling approach in different contexts, mainly due to the results obtained
492 when considering various energy sources. However, this study is not exempt of limits to be
493 considered in future works. For this reason, the following recommendations can be followed :

- 494 — In order to reduce the complexity of the system studied, in different hypotheses, such
495 as in the recycling system, we considered only one material collected in a clean state
496 and fixed demand from schools. However, in the virgin production system the entire
497 supply and production chain was formulated through hypotheses. Future research could
498 conduct an environmental assessment incorporating these complexities.
- 499 — This study is limited to the comparison of DRAM with virgin filament production. It
500 would be interesting to evaluate the environmental performance of a DRAM system
501 with respect to other possible life-ends for PLA, such as incineration, landfill, or even a
502 system where virgin material is incorporated into the recycling process. This is because
503 the mixture of virgin and recycled material allows for considerable improvement in
504 filament properties and printing quality.
- 505 — Finally, this evaluation was carried out by placing the DRAM system in the specific
506 context of a developed country. It could be interesting to perform the same analysis in
507 developing countries, which currently have major problems in the treatment of plastic
508 waste.

509 6. Conclusions

510 Using the LCA methodology, this work evaluated the environmental benefits of a distri-
511 buted closed-loop supply chain network for plastic recycling using open-source 3D printing
512 technologies in a specific context. The use of polylactic acid (PLA) in the context of Nancy,
513 France considered in the analysis based on three scenarios (two virgin and one recycled). The
514 impact categories studied were climate change, resources depletion (fossil and water) and
515 eutrophication potential (freshwater and marine). The results shown that distributed plastic
516 recycling to produce filament demonstrates broad environmental advantages compared to
517 production from virgin plastic. The comparison shows a reduction of up to 97% in most of the
518 impacts considered for the study. However, given the french electrical mix, the recycling system
519 has a greater impact than the virgin scenario for the Ion Radiation category. Additionally,
520 the sensitivity analysis suggested minor environmental benefits if the production of virgin
521 PLA is placed from USA to France.

522 The results obtained by the application of the LCA methodology to the case study
523 and its sensitivity analysis suggest the application of this recycling approach in various
524 energy contexts (solar, wind, and nuclear), acting in parallel to the existing centralized plastic
525 recycling networks in order to increase plastic recycling rates, which are currently low. It seems
526 interesting for future works to reduce the assumptions used with respect to the production of
527 virgin filament and to integrate the current complexity of carrying out the plastic recycling
528 process. Furthermore, assessing the impacts of this system in various areas allows us to obtain
529 a global vision of the performance of this system and to determine which context would be
530 most favorable for its development.

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⁵³⁵ **Declaration of Competing Interest**

⁵³⁶ The authors declare that they have no known competing financial interests or personal
⁵³⁷ relationships that could have appeared to influence the work reported in this paper.

⁵³⁸ **Highlights**

- ⁵³⁹ — A comparative LCA for distributed recycling via additive manufacturing (DRAM)
⁵⁴⁰ — Three scenarios are considered (two virgin and one recycled)
⁵⁴¹ — DRAM impacts are less than 5% regarding virgin supply chain except in one category

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Annex 1 Table of reference flows

Scenario 1 Virgin filament System:

Phase	Process	Transport (km)	Transport Type	weight (kg)	weight (t)	t*km
Transport to the filament producer	Plant-Port	756	transport, freight, lorry >32 metric ton, EURO6	1	0,001	0,756
	Port-Port	5.774	Container ship	1	0,001	5,774326
	Port-Plant	558	transport, freight, lorry >32 metric ton, EURO6	1	0,001	0,558

Phase	Machine	Process	Flux	Rate used (kg/h)	Puissance (kw)	Temps d'utilisation (h)	Energie Consomation (kwh)
Filament Product	PEEK 3d Printer Filament Production Line	Extrusion	électricité	20	15	0,05	0,75
				25	15	0,04	0,6

Phase	Process	Transport (km)	Transport Type	weight (kg)	weight (t)	t*km
Filament Transport to the Client	Plant-Client	280	small cargo vehicle	1	0,001	0,28

Scenario 2 Virgin filament System:

Phase	Process	Transport (km)	Transport Type	weight (kg)	weight (t)	t*km
Transport to the filament producer	Plant-Plan	645	transport, freight, lorry >32 metric ton, EURO6	2,1	0,0021	1,3545

Phase	Machine	Process	Flux	Rate used (kg/h)	Puissance (kw)	Temps d'utilisation (h)	Energie Consomation (kwh)
Filament Product	PEEK 3d Printer Filament Production Line	Extrusion	électricité	20	15	0,05	0,75
				25	15	0,04	0,6

Phase	Process	Transport (km)	Transport Type	weight (kg)	weight (t)	t*km
filament Transport to the client	Plant-Airport	5	transport, freight, lorry >32 metric ton, EURO6	2	0,002	0,01
	Airport-Airport	6.971	Airplane	2	0,002	13,942
	Airport-client	152	Cargo truck	2	0,002	0,304

Scenario 3 Recycled filament system:

Phase	Machine	Process	Flow	Power (kw)	Time of Use (h)	Energie Consomation (kwh)		
					Min	Max	Min	Max
Production Pellets	Retsch SM 300	Size reduction	Electricity	3	0,05	0,08	0,15	0,24
Filament Product	Nostek Xcalibur	Extrusion	Electricity	1,6	0,3	1	0,48	1,6

Phase	Transport(km)	Process	Transport type	Weight (fonctional unit) (kg)	Weigth (t)	t*km
Collection/ Delivey	25,52	Recovery Transport	Light Commercial Vehicle	1	0,001	0,02552
		Produit Transport		1	0,001	0,02552

Transport route for the recycling scenarios:

