Life Cycle Assessment of Distributed Plastic Recycling via Additive Manufacturing

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Abstract

Distributed recycling via additive manufacturing (DRAM) emphasizes an emerging approach to locally recycle waste plastic directly by 3D-printing it into valuable products. During the last decade, major progress has been reported to validate the technical feasibility, and economic viability of the system. Although, significant research has been made to validate the technical feasibility and economic viability of DRAM system, the environmental evaluation of such system is still at its early stage. This study expands on the environmental assessment of plastic recycling network system (DRAM) to accelerate the implementation of such systems for waste plastic management extending the lifetime of plastic material. This work is based on a university operational physical demonstrator in Nancy France. It aims to evaluate the environmental impact of a DRAM unit as a basis scenario compared to two scenarios of the traditional centralized recycling value chain. To achieve this goal this work makes a comparative environmental performance using a life cycle assessment (LCA) to evaluate the multidimensional potential impacts of virgin and recycled polylactic acid. Four impact categories were considered : climate change, potential eutrophication, resource depletion, and ion radiation. For the first three of these impact categories, the results show a minimum 97% reduction in environmental impact compared to a virgin supply chain. On the other hand, the amount of ion radiation equals approximately 2.8 times the emissions of the virgin scenario due mainly to the specific situation in France, where most of the energy is produced by nuclear means. 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*

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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,

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texture, thermal and barrier properties, and its mechanical and chemical resistance (Andrady and Neal, 2009; Thompson et al., 2009). Thanks to these properties, today 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 (Plasctic 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 and Ollikainen, 2022).

Therefore, the adequate use and disposal of plastics became an urgent problem, which is characterized by high complexity and multifaceted feedback loops. As a consequence, a systemic view of the current entire plastics value chain is needed, including petrochemical companies (de Vargas Mores et al., 2018; Iles and Martin, 2013), converters (Paletta et al., 2019), brand owners or manufacturers (Gong et al., 2020; Ma et al., 2020), retailers and consumers (Confente et al., 2020; Filho et al., 2021; Friedrich, 2020), and recycling operators (Huysveld et al., 2019; Pazienza and De Lucia, 2020), as well as the influences of policy-makers on wider economic and societal changes (Paletta et al., 2019). The European Union (EU) intends to develop a circular economy (CE) based on a production and consumption model with key activities such as "sharing," "reducing," "reusing," "repairing," "renewing," and "recycling" the existing materials and products as many times as possible, in order to create added value by extending the life cycle of products (European Commission, 2018; Matthews et al., 2020). As part of the European Green Pact presented on March 20, 2020, there are plans to establish an action plan involving the circular economy, mainly promoting the development of sustainable products, reducing waste, and empowering citizens as key players (European Commission, 2018).

Considering the French context, a target was established that by 2025 all plastic waste should be recycled, but currently recycling statistics in France are only reaching levels close to 25%.

Despite these ambitious objectives, plastics recycling has historically been an expensive process due to the inherent separate collection, transportation, processing, and remanufacturing (Hopewell et al., 2009; Singh et al., 2017). The economies of scale have been leveraged to reduce these costs with centralized and global recycling chains (Kreiger et al., 2013; Kreiger and Pearce, 2013). Nevertheless, in order to carry out this recycling system, multiple steps need to be accomplished that integrate the sorting phase, long-distance transport, waste treatment, and remanufacturing. The high costs of these processes and the low selling price (mainly due to the dependence of the recycled plastic price on the petroleum and virgin prices) seldom generate benefits and often require costly public subsidies (Hamilton and Steven, 2019). In addition, these centralized plastic manufacturing and recycling lines lead to soil, water, and air pollution (Arena et al., 2003; Carlsson Reich, 2005). In addition to the current problems in the plastic recycling network, we can highlight that supply chains in general are under increasing pressure from various stakeholders to make decisions from a sustainable perspective; in other words, based on economic, environmental, and social objectives (Hassini et al., 2012).

Additive manufacturing technology (also known as 3D printing) enables the potential of distributed manufacturing (DM) for products of high added value (Bonnín Roca et al., 2019; Petersen and Pearce, 2017; Woern and Pearce, 2017). Nowadays, the accessibility of freely available designs has increased significantly, together with the development of open-source technologies and the supply of raw materials (virgin and recycled filaments) for 3D printing (Hunt et al., 2015). It has opened the path to design distributed and more flexible manufacturing systems that will integrated in a more symbiotic manner within the urban areas close to the raw materials sink, that is our domestic waste (**Hermman2020 ?**) For example, recent studies such as Zhong and Pearce (2018) demonstrated that the coupling of an OS extruder (recyclebot) and RepRap 3D printer *"brings a traditional industrial system into a single small home, business or community center"*. Furthermore, various studies in the literature show the technical feasibility of this distributed plastic recycling approach. More recently, Santander et al. (2020) demonstrates how of poly lactic acid (PLA) waste from a local network of secondary schools could be designed and implemented to be treated in a single small size and open-source recycling facility. THe authors, explored the economic and environmental scenarios of this configuration through an optimization approach. However, the study did not include the multidimensional environmental impacts as only emissions of CO_2 equivalent were considered.

From an environmental point of view, the DRAM and DM approaches have been also evaluated mainly using the Life Cycle Assessment (LCA) approach. For example, Kreiger and Pearce (2013) and 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. Their results show that significant savings could be obtained. However, their research is limited to the consideration of energy and CO_2 emissions as environmental indicators. More recently, Kerdlap et al. (2021) through a simulation approach, quantified the plastic life-cycle environmental impact of small-scale sorting and recycling systems in comparison to traditional large-scale centralized systems. However, it does not consider the use of Open Source Technologies. Therefore, major efforts need to be made in order to evaluate, in a holistic way, the environmental impacts of the global DRAM value chain. Thus, this paper aims to contribute to this field thorugh the in the evaluation of multidimentional environmental impacts from the implementation of distributed recycling via an additive manufacturing approach in a territory. Specifically, an environmental evaluation using life cycle assessment (LCA) is conducted, comparing a distributed plastic recycling system to produce 3D filament with a traditional production system of virgin plastic filament for 3D printing. From this evaluation, the environmental impacts (positives or negatives) of implementing DRAM have been analyzed and discussed.

This article is structured as follows. Section 2 outlines an overview of the environmental impacts studies in the DRAM context. Section 3 presents the system (case study) evaluated. Section 4 materials and methods, where life cycle analysis methodology is explained. Section 5 presents the life cycle analysis performed. Section 6 presents the discussion of results. Finally, Section 7 presents the main conclusions and recommendations for future works.

2. Overview DRAM system and environmental impacts studies

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 (Fused Filament Fabrication), and recent works have dealt with the validation of a granular form Fused Deposition Modeling (Alexandre et al., 2020; Justino Netto et al., 2021) FDM (Fused Deposition Modeling) is currently the most widely used AM technology for plastic recycling (**Kuclourya2022 ?**). 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.

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 a methodology standardized by ISO 14040 and ISO 14044., 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 assessment, 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, several works related to plastic recycling using 3D printing has focused on demonstrating the technical capability of this technology to perform mechanical recycling. In environmental terms, the advantages that can be obtained with the use of 3D printing to produce specific products have been evaluated in comparison with their conventional mode of production (**Top2022 ?**). On the other hand, several studies have been carried out to demonstrate the environmental benefits of distributed recycling compared to centralized recycling.

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 CO_2 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%. In terms of the different existing options for end-of-life (EOL) treatment of plastic waste, mechanical recycling via AM has shown positive results compared to incineration and landfill if it is closed loop.

Table X represents in summary the different articles that have worked on environmental assessment using LCA in the DRAM concept either from a distributed recycling point of view, additive manufacturing or the whole of distributed recycling via additive manufacturing. The table organizes the previous works according to the level of approach that allows identifying which was their subject of study ; the comparison made identifying if it is DM vs CM or DR vs CR ; the use of recycled material in their studies, the identification of the DRAM concept in their methodology ; the economic aspect and finally the identification of some of the categories of impacts considered in the LCA carried out.

Table 1: Overview of the studies on environmental impact about DRAM

Source	Scope level	Comparaison	Recycled plastic	DR	AM	Economique aspect	CED	APO	GWP	ADP	FDP	HTP	MAETP	FAETP	FEP/MEP	TEP	WDP	IRP_HE
Kreiger and Pearce (2013)	Home based manufacturing	DM vs CM	x		x	x	x		x		x							
Kreiger and Pearce (2014)	Home based manufacturing	DRAM vs CR	x	x	x		x		x		x							
Cerdas et al. (2017)	Product manufacturing	DM vs CM			x	x		x	x	x		x	x	x	x	x		
Gaikwad et al., (2018)	Product manufacturing	DRAM vs CM	x	x	x				x									
Zhao et al., (2018)	Product manufacturing	DRAM vs CR	x	x	x				x		x		x		x	x		
Santander et al.(2020)	City manufacturing system	DRAM vs CM	x	x	x	x			x									
Kerdlap et al. (2021)	Regional recycling system	DR vs CR	x	x					x		x				x		x	
Garcia et al. (2021)	Product manfacturing	DM vs CM	x		x		x		x									
Top et al. (2022)	Product manfacturing	DM vs CM			x				x									

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

The technological efficiency in environmental terms of AM and DR has already been proven. This work seeks to analyze the environmental impact of a localized recycling system oriented to the production of filament to meet part of the demand in a specific city. even though different studies have been conducted aiming to validate the distributed recycling approach from a technical, economic, and environmental perspective, only the work of Kreiger et al. (2014) is focused on the environmental assessment of distributed recycling for 3D printing purposes. However, their research is limited to the consideration of energy and CO_2 emissions as environmental indicators. This is the first study that seeks to analyze using LCA methodology the DRAM concept as a new production system that allows to respond in part to the demand for plastics and to complement the current recycling systems. In conclusion, even though different studies have been conducted aiming to validate the distributed recycling approach from a technical, economic, and environmental perspective, only the work of Kreiger et al. (2014) is focused on the environmental assessment of distributed recycling for 3D printing purposes. However, their research is limited to the consideration of energy and CO_2 emissions as environmental indicators.

3. Case study : The Lorraine Fab Living Lab

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

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

Under these considerations, the selected context for this study was the Lorraine Fab living Lab (LF2L) [2], an innovation space located in Nancy, France. This university laboratory has been selected mainly for the following reasons :
(1) Innovation spaces such as Fablabs, Maker spaces, design factories among others have proven to be favorable environments for eco-innovations facilitating the implementation of circular economy strategies (Coskun et al., 2022). Previous studies show that these collaborative environments foster sustainable experimental learning, provide methodologies and tools for

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

the co-creation of circular solutions, drive the transition toward sustainable smart cities, foster the creation of new sustainable business 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).

4. 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 effective and fast way the results to help with managerial decision-making in environmental terms and in the deepening of the sustainable development policy (Guinée, 2002). LCA is a structured, comprehensive and internationally standardized method in accordance with ISO 14040 and 14044. It defines all the steps for its use : goal and scope definition, inventory analysis, impact assessment, and interpretation (Pennington et al., 2004).

LCA is a tool for quantitative evaluation of materials, energy flows, and the potential impact of products, services, or technologies (Dehghanian and Mansour, 2009). The analysis takes into account the entire life cycle of a product : from resource extraction, through production, use, and recycling, to the disposal of the remaining waste (IES, 2010). LCA is considered a legitimate environmental methodology that enables systems analysis for waste policy and strategy (Gontard et al., 2022). The four main stage for a life cycle assessment are :

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

The LCA methodology is mostly used in an iterative way, allowing a better definition of the objectives to be achieved and the system to be analyzed. In the following sections, an LCA is presented for DRAM using the Lorraine Fab Living Lab as a case study.

5. LCA application and results

5.1. Goal and Scope Definition

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

5.1.1. The functional unit

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

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

The 10 months correspond to the normal operation of a school from September to June.

5.1.2. System boundary

Figure 1 shows the two systems compared in this study and the processes integrated into the life cycle assessment. As can be observed, there are three different boundaries represented by the colors green, blue, and red.

The first boundary (green box) corresponds to the Biosphere, which represents everything related to nature, such as raw materials from natural resources, ecosystems, and solar energy. The second boundary (dark blue box) corresponds to the Technosphere limit, representing human activity (e.g. use of electricity, fuel, etc.). Here, we can observe all the material flows that are considered for the life cycle assessment, the flows between processes, or the flows that are part of the functional unit mentioned above. Finally, the boundary in a light blue color represents the limit of the services and processes taken into consideration in this study. On the one hand, in the upper process flow, we can observe the processes considered in the system to produce filament from virgin plastic. The process starts with PLA production (the whole production process detailed by (**Vink2003 ?**)) which is followed by PLA transportation, filament production, and finally product delivery. On the other hand, Fig. 1 shows the recycling process enclosed in the orange box. The process starts with the collection of waste produced by schools and high schools, then the plastic recycling process, the production of filament, and the delivery of filament are carried out.

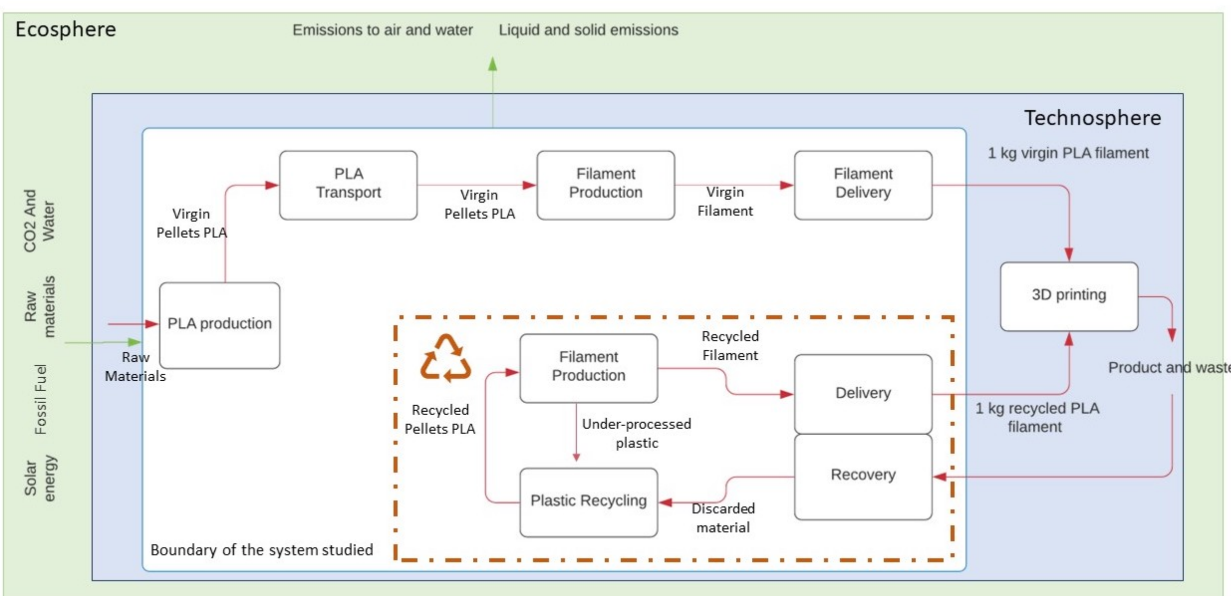

FIGURE 1: System limits for life cycle assessment

5.1.3. Selected impact categories

The objective of performing a life cycle assessment is to determine and evaluate the potential environmental impacts produced at different stages in the life cycle of a product, service, activity, or process.

However, it is quite difficult to identify, a priori, the categories of impacts in which the system under study is most detrimental (climate change, eutrophication, etc.). To resolve, it was decided to analyse relevant literature of LCA applied on the bioplastics and additive manufacturing separatly.

These two domains were considered because they can be considered closely related to a DRAM system. First, the production of virgin bioplastics can be confronted with the recycling of bioplastics. Secondly, the integration of these materials in additive manufacturing as a viable solution for plastic waste management.

Concerning the plastic perspective, Bishop et al. (2021) compared the impact of bioplastics (such as PLA) regarding the petrochemical plastics considering the impact categories across 44 relevant articles that used LCA evaluation. Their results pointed out the most used impact category for bioplastics evaluation is climate change, followed by potential eutrophication variations, resource depletion, human toxicity, photochemical oxidant formation, ozone depletion, ecotoxicity, particulate matter formation, energy consumption, land use, and water consumption. On the other hand, it was found that the the cumulative energy demand (CED) of the system is the most evaluated LCA impact category (Cerdas et al., 2017 ; Kellens et al., 2017 ; Kreiger and Pearce, 2013 ; Quinlan et al., 2017) in the context of additive manufacturing. In addition, It was also considered climate change, potential eutrophication, and human toxicity as the main impact categories included in the LCA. In conclusion, it was decided to use the predominant impact categories in each of the industries, namely climate change, potential eutrophication, and resource depletion (fossil and water) after analyzing the LCA results of the two domains .

5.1.4. Assumptions and limitations

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

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

— Location of polylactide acid production : This hypothesis indicates the location where the polylactic acid production process takes place.

— Location of filament manufacturer : Due to the uncertainty about filament production, two companies with different locations that are engaged in the production of plastic filaments have been modeled.

— Filament production machine : The machine PEEK 3d Printer Filament Production Line [3] has been considered, which corresponds to the machine used by the two filament manufacturers considered.

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

- Performance of the filament production machine : The machine selected to carry out the filament production process has a range of transformation from plastic pellets to 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.
- We do not take into account the end of life of the filament, since we consider that the waste produced at the "end of life" is the beginning of the collection phase (I).
- 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 2). A third scenario represents the distributed recycling system for filament production, so the complete system is modeled with information obtained from the LF2L.

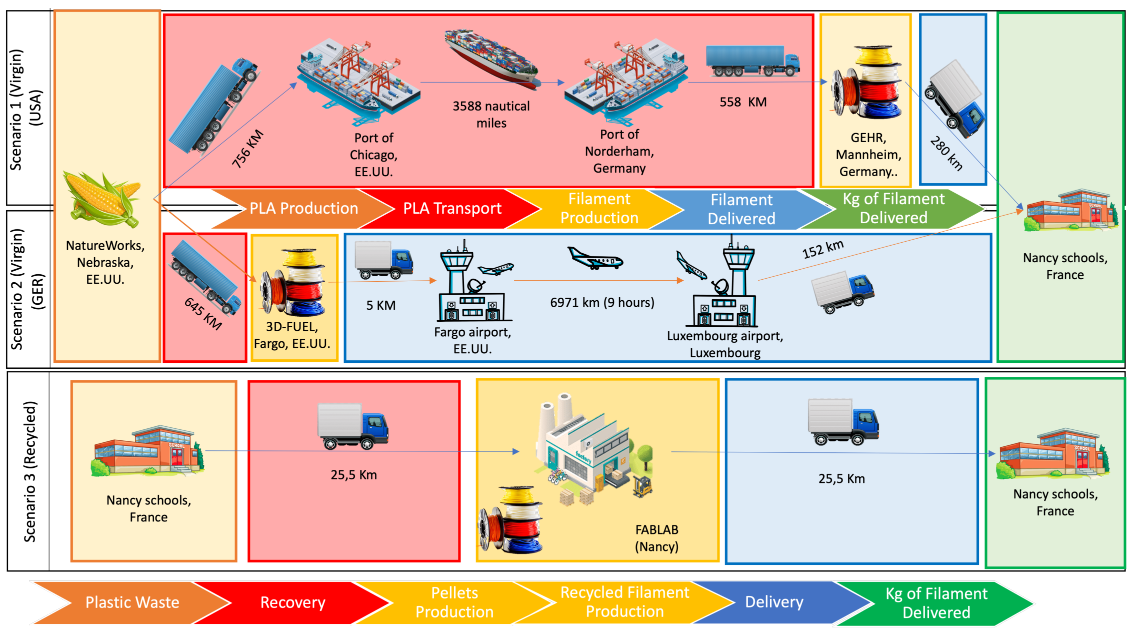

FIGURE 2: Representation of the 3 scenarios

TABLE 2: 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.

5.2. Life Cycle Inventory Analysis (LCIA)

5.2.1. Data source

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

On the other hand, for the plastic recycling process the data concerning the input/output materials and the machines used in the recycling process were obtained directly from the Lorraine Fab Living Lab and from the thesis works conducted at the ERPI laboratory related to DRAM (Cruz Sanchez et al., 2020, 2017; Santander et al., 2020) (see the Appendix A). These data allowed us to model and understand the recycling network, its main functions, and its limitations in consideration of the case study presented in Section 4.

5.3. Impact Assessment (LCIA)

5.3.1. Calculation methodology

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

5.3.1.2. Choice of calculation methodology and impact indicators. In analyzing the impact methodologies and considering the selected impact categories for this study (see Section 5.1.3), ReCiPe (Global-Hierarchist version) has been chosen as the impact calculation methodology. The ReCiPe method (Goedkoop et al., 2009) has been chosen mainly because it is widely used in various areas of research (Dekker et al., 2020). In addition, ReCiPe is an LCIA method that is harmonized in terms of modeling principles and choices, offering results at both the midpoint and endpoint level (Goedkoop et al., 2009). In addition, it is used for various life cycle analyses in the area of additive manufacturing with a hierarchical cultural perspective (Saade et al., 2020). Finally, the set of impact categories chosen are presented in Table 2.

5.3.1.3. Impact studies. Table 4 presents the results of the comparison, showing for the virgin and recycled scenario the amount of impact that is generated in each impact category evaluated. In addition, the percentage reduction (comparing the recycling scenarios with

Table 3: 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)	$m3$

the virgin scenario) is presented. To construct this table, the best virgin scenario (least impactful) was considered for comparison. As a result, it can be observed that the production of filament from recycled plastic has a significant advantage in five of the six impact categories (climate change, fossil depletion, freshwater eutrophication, marine eutrophication, and water depletion), which corresponds to the categories that are considered essential for DRAM. In each of the categories there is a reduction of at least 97% compared to the impact produced by the virgin scenario. For the Ion Radiation category, however, the recycling system has a greater impact than the virgin scenario (best scenario in this case). In the recycling scenario, the amount of ion radiation equals approximately 2.8 times the emissions of the virgin scenario.

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

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

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

Table 4: 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%)

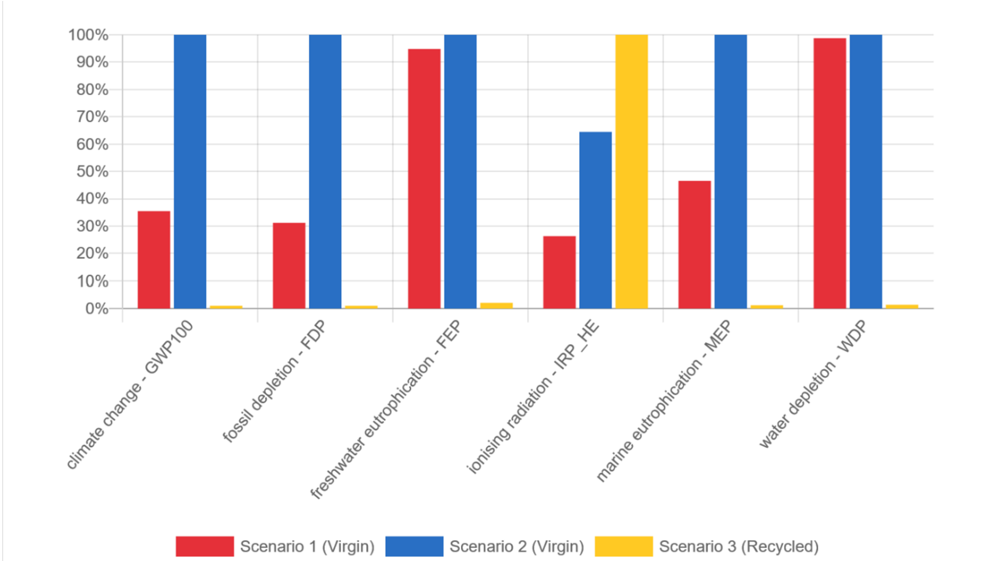

Figure 3: Comparison of the impact profile of each of the studied scenarios

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

5.4. Interpretation and Recommendations

5.4.1. Sensitivity analysis

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

5.4.1.1. Location of PLA production. A recent project by Total Corbion has been proposed in Grandpuits (Seine-et-Marne). The purpose of this project is to build a polylactic acid (PLA) production plant with a capacity of up to 100,000 tons per year. This first European plant is to be installed in France [4]. Considering this, a sensitivity analysis has been performed for this scenario. In this new scenario, the PLA production facility is situated in France at Total's Grandpuits facility.

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

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

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

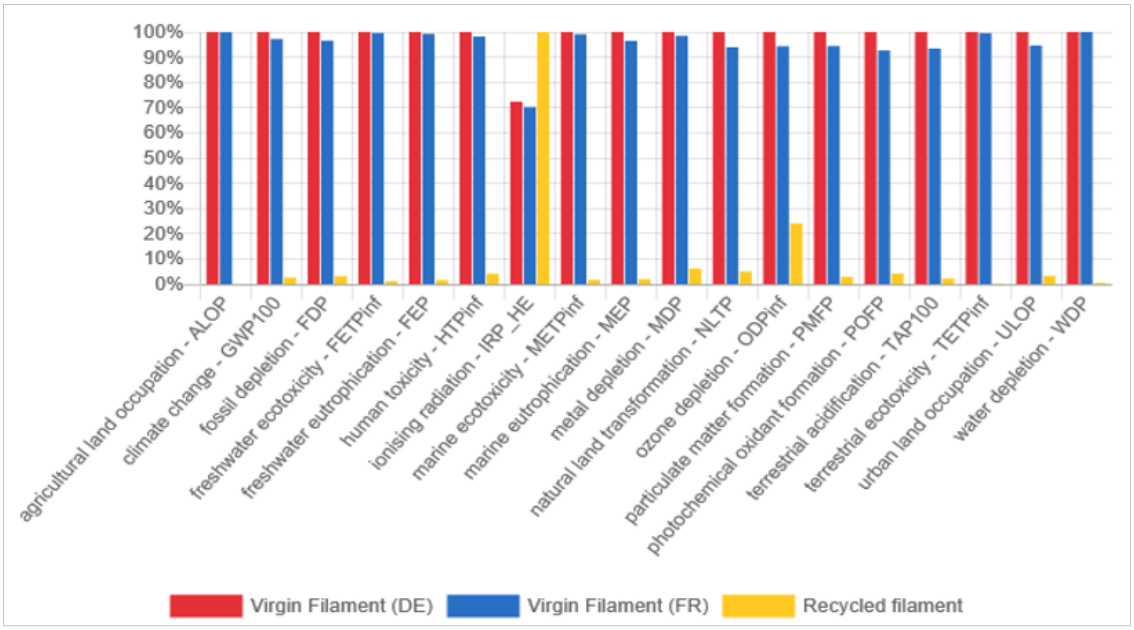

FIGURE 4: Comparison of the impact profile of each of the studied scenarios

5.4.1.2. Energy Source. The results presented in Section 5.3.1.3 have shown that distributed plastic recycling to produce filament demonstrates broad environmental advantages compared to production from virgin plastic. In almost all impact categories it had an impact of less than 5% of the impact caused by virgin filament production systems, except in the category related to the emission of radioactive particles. These emissions are closely related to the production of electricity from nuclear energy, which in France accounts for 77.5% of the total energy produced in the country. Currently, the french electricity system produce is 77.7% nuclear, 9.7% hydro power, 3.8% wind power, 3.5% natural gas, 2.2% coal, 1.5% solar PV, 1.3% biofuels and wastes, and 0.3% oil (Pereira and Marques, 2020). For this reason, it is key to see the response of the system and the possible transfer of impacts when using other forms of energy production, including mainly the use of clean energy (solar and wind). Figure 5 presents the environmental performance of the recycling system using three different types of energy (nuclear, wind, and solar).

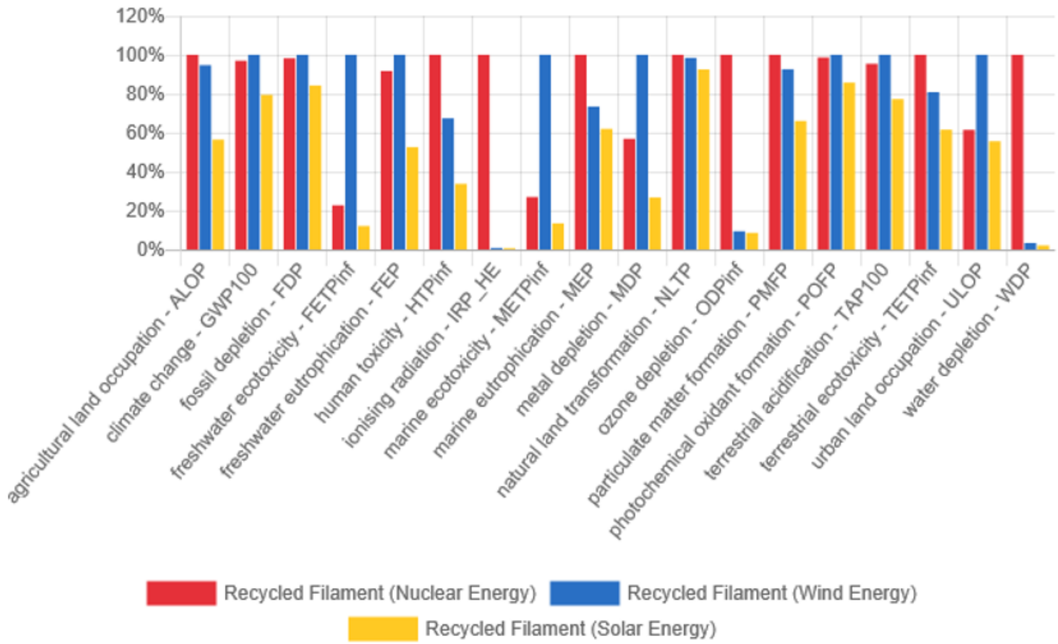

Figure 5: Sensitivity analysis respect to the type of energy used

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

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

6. Discussion

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

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

For the recycling system, the sensitivity analysis performed has shown that the integration of solar energy can greatly reduce the impacts produced using nuclear energy, making it an extremely viable alternative for the recycling system. Wind energy, on the other hand, has a significant transfer of impact to the toxicity present in different types of water, which does not allow us to define in the first instance whether it would be more convenient. In addition, the results showed that the DRAM approach is advantageous considering other energy sources (other than nuclear) that are used in other parts of the world. The environmental assessment carried out in this study extends the results obtained by Kreiger et al. (2014) and Kerdlap et al. (2021), showing, based on LCA indicators, the environmental benefits posed by distributed plastic recycling, and more specifically, by implementing a DRAM system. In addition, the environmental benefits are independent of the energy source considered. Therefore, this study indicates that, in environmental terms and under certain conditions, the implementation of DRAMs would have a positive impact on the area of application and could have positive impacts in other contexts. Most notably, to the best of our knowledge, this is the first study to investigate the multidimensional environmental impact of implementing DRAM. The results show a huge potential, in environmental terms, of implementing DRAM and suggest the application of this recycling approach in different contexts, mainly due to the results obtained when considering various energy sources. However, this study is not exempt of limits to be considered in future works. For this reason, the following recommendations can be followed :

— In order to reduce the complexity of the system studied, in different hypotheses, such as in the recycling system, we considered only one material collected in a clean state and fixed demand from schools. However, in the virgin production system the entire supply and production chain was formulated through hypotheses. Future research could conduct an environmental assessment incorporating these complexities.

— This study is limited to the comparison of DRAM with virgin filament production. It would be interesting to evaluate the environmental performance of a DRAM system with respect to other possible life-ends for PLA, such as incineration, landfill, or even a system where virgin material is incorporated into the recycling process. This is because the mixture of virgin and recycled material allows for considerable improvement in filament properties and printing quality.

— Finally, this evaluation was carried out by placing the DRAM system in the specific context of a developed country. It could be interesting to perform the same analysis in developing countries, which currently have major problems in the treatment of plastic waste.

7. Conclusions

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

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

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Declaration of Competing Interest

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

Highlights

— A comparative LCA for distributed recycling via additive manufacturing (DRAM)
— Three scenarios are considered (two virgin and one recycled)
— 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

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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: