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Position Paper: the Sustainability of Plastics

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Plastic materials are characterized by exceptional physical and chemical properties which have made them essential in many applications. Their unique performances entail their massive production and use with consequently generation of huge amount of plastic waste, which can cause significant impact on the environment, if not properly managed.
Institutional and industrial actions are required to face the ever-increasing plastics demand while making the entire chain more sustainable, from the selection of raw materials to production, use, and final disposal of plastic materials. Here, an overview of plastics properties and applications, as well as main issues related to the plastic waste management is presented along with a discussion on the emerging technologies that have been launched to increase the sustainability of the entire plastics industry. These latter include both recycling processes and the use of renewable raw materials, including waste streams, for the production of biobased and bio-attributed products.

1. Properties and applications of plastic materials

Plastics are part of everyday life. Thanks to their unique properties, which make them versatile and resistant, they are able to satisfy many functional and aesthetic needs, as well as to overcome a series of technological challenges, such as drinking clean water and eating fresh food, playing sports, and enjoying the comforts of own home.
Plastic materials are used for a wide range of applications like packaging, which accounts for 44% of the total demand, building and construction with a share of 18%, and many others like transportation, household appliances and electronic products, agricultural production, medical and pharmaceutical products.
In 2021, the global plastics production increased to 390.7 million tonnes, of which approximately 90% was fossil based. Post-consumer recycled plastics and bio-based/bio-attributed plastics accounted only for 8.3% and 1.5%, respectively (*Figure 1*). Europe accounted for almost 15% of global production, with 57.2 million tonnes (Plastics Europe, 2022).

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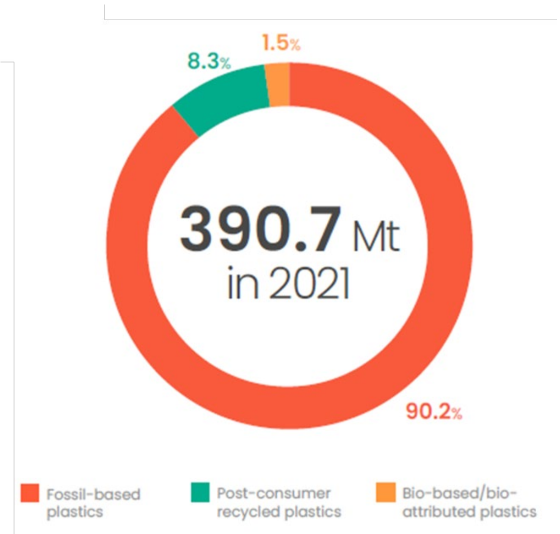

Figure 1: World plastic production in 2021 (Plastics Europe, Plastics The Fact 2022)

The key factors that make plastics necessary in many applications are:
- Cheapness: their production cost is usually cheaper than other materials
- Lightness: very low density, maintaining excellent mechanical properties
- Flexibility, elasticity, malleability, depending on the polymer structure
- Resistance to atmospheric, chemical and/or biological agents
- Durable over time
- Thermal and electric insulators
- Recyclability

The unique properties of plastic goods are obtained with a proper combination of specific components, namely: (i) polymers, (ii) additives, and sometimes (iii) fillers.

(i) Polymers are long molecules formed by the repetition of simpler chemical units called monomers and they can be classified into three main groups:

- Thermoplastic polymers, normally made up of molecular chains (linear or branched) held together by intermolecular forces. They soften and melt at high temperatures, while return in solid state again at lower temperatures.
- Thermosetting polymers, made up of polymeric chains which during the manufacturing phases form highly branched structures, held together by strong chemical bonds. Once the formation of the macromolecular structure is completed, they remain solid, and they cannot be melted or dissolved.
- Elastomeric polymers, consisting of macromolecules which are often weakly cross-linked in the manufacturing phase, and characterized by high elasticity.

(ii) Additives are chemical substances added to polymers to improve specific properties, such as the processing, anti-stickiness, or aesthetic factors. They are usually added in percentages ranging from about 0.5% to 5%.

(iii) Fillers are usually inorganic materials (glass fibers, carbon fibers, etc.) which provide reinforcing and structural properties, improving robustness and elasticity. They are the basis for making the so-called composite materials.

Figure 2 shows the distribution of the global plastic production by type of polymers.

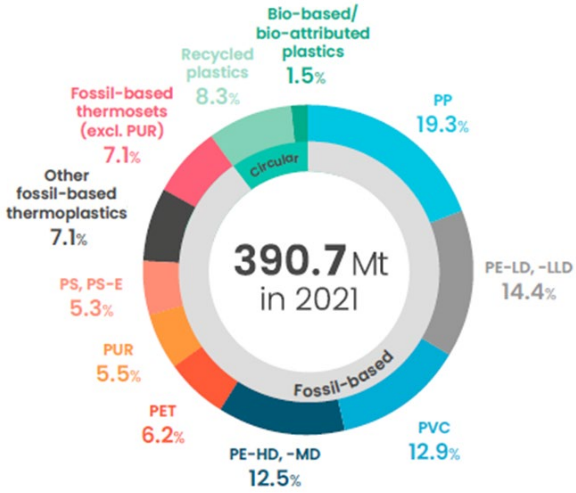

Figure 2: Distribution of the global plastics production by type (Plastics Europe, Plastics The Fact 2022)

The materials composed by one or more polymers, additive and/or fillers, are defined compound or composites. Unlike basic plastics, they are characterized by greater performances and can be used in higher value applications.

Plastics materials have helped making our lives easier, safer, healthier, cheaper. They also contribute to reduce GHG emissions in many applications, such as in food and beverage, where plastic packaging is essential to preserve the quality, guarantee the chemical-physical stability (and therefore prevent deterioration) and microbiological stability (to avoid contamination by pathogenic and dangerous agents for humans). The plastic materials protect the products from reactions with external agents such as oxygen or UV rays and allow the shelf life to be significantly increased, in some cases up to 18 months without the need to add preservatives or use refrigeration. In the case of fresh food, the use of plastic packaging increases the shelf life from 5 to 10 days, and therefore reduces food waste from 16% to 4% (British Plastics Federation, 2022).

According to the study “Climate impact of plastics” by McKinsey & Company (Hundertmark et al., 2018), plastics have proved to be more sustainable than alternative materials in 13 of the 14 applications examined. Greenhouse gas savings range from 10% to 90%, considering both the product life cycle and the impact during use.

Moreover, plastics materials (compound and composites included) are driving the energy transition, since they are used in the manufacturing of photovoltaic panels, wind blades, batteries and to build lighter vehicles. For instance, the rapid spread of wind energy has been possible thanks to the use of composite materials: the high mechanical performances combined with a great lightness have contributed to the development of larger wind turbines. Furthermore, the use of composites makes it possible to reduce transport, assembly and above all maintenance costs, compared to traditional materials.

2. Plastic waste management

The widespread use of plastic materials has led to large volumes of production and, consequently, to the generation of huge amount of plastic waste with significant impact on the environment, especially if not properly managed. From 1950 until today it is estimated that 8.3 billion tons of plastic have been globally produced, generating about 6.3 billion tons of waste. Of these, 79% was sent to landfills or mismanaged by ending up released into the environment, 12% was incinerated and only 9% recovered through recycling. To date, it is estimated that around 150 Mton of plastic waste is present in the oceans, with an estimated growth rate of around 8 Mton per year (European Parliament, 2018).

This situation requires a rational analysis and must be tackled rapidly at different levels, implementing concrete actions to prevent further release of plastic materials into the environment (Gontard et al., 2022).

In recent years, microplastics, that are the solid plastic particles with a dimension lower than 5 mm, have become the subject of growing concerns related to both the environment and human health, because they have been found practically everywhere, both in ecosystems and in animals, including humans. The potential negative impacts of microplastics on human health are still to be established, but governments and industry have taken actions to close the gaps in scientific knowledge on risk related to microplastics and reduce their dispersion in the environment also through agreements and cooperations.

The issue of plastic waste is caused by the incorrect management of the end-of-life products. According to a study published in 2018 by McKinsey&Company, entitled "How plastics waste recycling could transform the chemical industry", only 15 countries contribute for about 80% of the total waste. Among these, some Asian countries, such as India, Indonesia, Thailand and Vietnam, have not yet reached suitable management levels: from 75% to 85% of plastic waste is mismanaged, resulting in significant environmental impacts (Hundertmark et al., 2018). This aspect is related to the fact that these countries lack organized waste management systems. Building a comprehensive waste management system would require significant governmental, intergovernmental and private sector funding. Moreover, the numbers reported above are also the result of unbalanced trade arrangements in which the local waste management infrastructure is overwhelmed by imports from other countries, thus resulting in mismanagement that is difficult to avoid.

In Europe and United States, which together produce almost 30% of the world's plastic waste, the situation is certainly better. To date, almost 100% of the plastic waste produced is managed being transferred to landfills with suitable standards, incinerated or recycled.

Focusing on Europe, 29.5 Mt of plastic waste was collected in 2020, of which around 60% came from packaging. Plastic waste management has significantly improved in recent years: from 2006 until today, the total amount of post-consumer plastic waste sent for recycling has more than doubled, reaching 35% of the total, while landfilling has become the least option (*Figure 3*).

The numbers are even more positive if the analysis is restricted to plastic packaging waste which accounts for 17.9 Mt. In this case, in fact, the recycling rate rises to 46%, while waste-to-energy (also called «energy recovery») and the transfer to landfills drop to 37% and 17%, respectively.

This remarkable result was achieved thanks to improvements in separate collection systems and sorting and separation technologies for mixed waste: when plastics are collected and managed separately, the recycling rate is 13 times higher.

In Italy, 3.5 Mt of plastic waste was collected in 2020, of which approximately 62% came from the packaging sector. In line with other European countries, plastic waste management in Italy has also improved drastically in recent years: from 2006 to today, the total amount of post-consumer plastic waste sent to recycling has increased by 77%, waste-to-energy has grown by 58%, while landfilling dropped by 52%.

If only packaging waste is analysed, in Italy the recycling rate is 49% and waste-to-energy accounts for 44%, being both approaches at higher percentage than the rest of European countries. On the other hand, the percentage sent to landfill is considerably lower than the European average, amounting to around 7%. These results lead Italy to be very close to the EU recycling targets of plastic packaging waste equal to 50% by 2025 and 55% by 2030, and demonstrate our country's attention and commitment to environmental issues.

However, it is necessary to continue this path and further increase the circularity of plastics, and it is essential to extend virtuous management methods to developing countries, because the environmental issue is a global issue, no matter which countries it comes from.

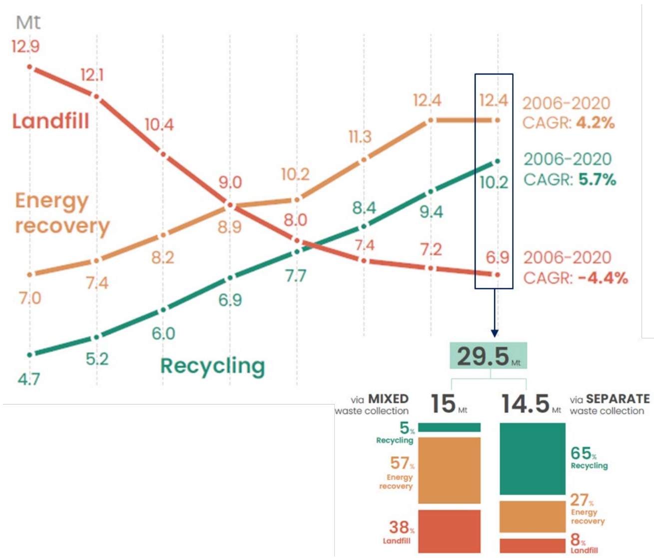

Figure 3: Plastic waste management in EU27+3 (Plastics Europe, Plastics The Fact 2022)

3. European Legislation

The important results of plastic waste management in Europe were achieved thanks to the definition of different legislative paths: already in 2014, the European Commission had included plastics among the priority sectors of intervention of the first "Action Plan for the circular economy". From this first text, the so-called “EU Plastics strategy” was defined, which sets the target that all plastic packaging placed on the single market must be reusable or recyclable by 2030. To this end, the Commission has introduced various measures, the most important of which is the Directive 2019/904, better known as Single Use Plastic directive, on reducing the impact of certain plastic products on the environment. The directive requires:

- measures to lead to the reduction of the consumption of certain plastic products (art.4)
- restrictions on placing specific single use products on the market (art.5)
- design and marking requirements (art. 6/7)
- separate waste collection target (art.9).

Additionally, plastics also contribute to achieve the objectives of climate neutrality by 2050 under the “EU Green Deal” and are part of “New action plan for the circular economy”, published in 2020.
In this context, EU has also foreseen a national contribution of 0.80 euro/kg of non-recycled plastic packaging waste starting from 1st January 2021, with different application among the Member States.
In France, Germany, Ireland, Luxembourg and Slovakia this levy is absorbed from the national budget. In Spain it is partially transferred to users for an amount of 0.45 euro/kg on non-reusable plastic packaging. In Belgium, its absorption in the final disposal costs (EPR extended producer responsibility) is under discussion.
Italy has introduced the "plastic tax" of 0.45 €/kg on single-use manufactured goods released for consumption, which however has not yet entered into force and it was postponed to 2024.
Due to the growing number of both national and international policy initiatives, it is important that the implementation of the European directives in each Member States is homogeneous, in order to avoid market imbalances and to jointly achieve the required targets.

4. Plastic value chain sustainability

The increase of global plastic demand expected in the following years, especially in the emerging countries, combined with rising attention to environmental issues, has led the plastics industry to embrace an important challenge: to increase production but in a more sustainable way, reducing both the consumption of new resources and the GHG emissions into the atmosphere associated with production.
The plastics sector involves several players with different roles and size, from companies involved in the production of raw materials, to highly specialized companies for the processing of finished products and finally local companies in charge for the collection and management of waste, as well as, for any recycling or energy recovery processes.
To make the entire business model more sustainable, two main objectives should be achieved:

- Reduction of CO_2 emissions along the entire value chain
- Reduction of waste disposal in landfills and/or its combustion.

There is not a silver-bullet to reach these targets, and all the players are called to give their contribution in a synergistic way. According with the principles of the circular economy, the main levers to increase the sustainability of the whole sector are:

- Use of alternative raw materials (e.g., organic waste materials and/or recycled materials)
- Application of eco-design principles (e.g., reducing the use of resource)
- Increase of the efficiency in the production process and logistic
- Use of renewable energy
- Reuse and repair of goods
- Improve waste collection and management
- Development of recycling technologies: mechanical, chemical and physical

Sustainability needs a rethinking of the entire life cycle of materials: from design, to use and repair, up to recycling at the end of their life.
Industries can reduce the emissions of the production phases by implementing efficient solutions and innovative technologies, such as renewable energies (e.g., green hydrogen), and Carbon Capture, Utilization and Storage (CCUS). All the possible actions need to be evaluated with a scientific and objective approach, through quantitative techniques that analyse the environmental impact on the entire life cycle (LCA - Life Cycle Assessment).

5. Emerging Technologies

In the last twenty years, many initiatives have been launched aiming to increase the sustainability of the entire plastics industry both in terms of reducing the carbon footprint of the production chain and in terms of improving the management of plastic materials at the end of their life.
In this context, two main technological developments have been carried on, both substantially aimed at replacing traditional fossil feedstocks: the use of raw materials from renewable sources (biological sources) to produce bioplastics and the valorisation of plastic waste into new raw materials through recycling technologies (*Figure 4*).
A recent study carried out by European Patent Office highlights that Europe and the United States are by far the leading innovators in terms of numbers of international patent family (IPF) filed between 2010 and 2019, with around 30% of patents regarding both bioplastic and plastic recycling technologies (European Patent Office, 2021).

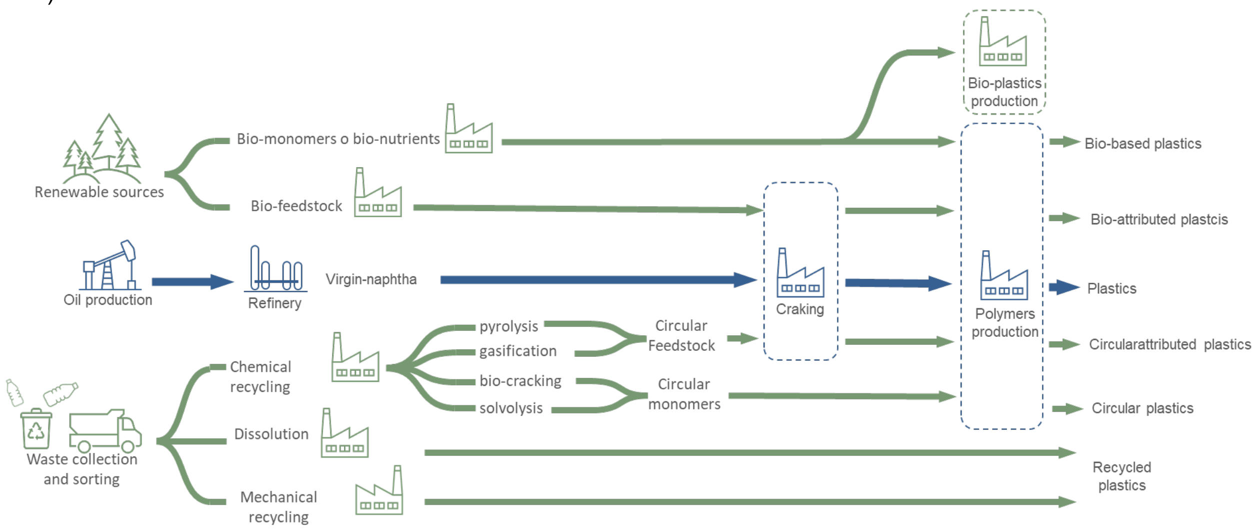

Figure 4: Traditional and new plastic production chains

5.1 Use of raw materials from renewable sources

Bioplastics represent a family of materials with different properties and application possibilities (Costa et al., 2023; Rosenboom et al., 2022). A plastic material can be defined as "bioplastic" if it is bio-based (i.e., produced at least in part from renewable sources) or biodegradable (i.e., if it can be degraded by microbial action into elements such as water, CO_2, CH_4, compost), or if it presents both characteristics (https://www.european-bioplastics.org/bioplastics/). The biodegradability of a material depends on its chemical structure and not on the source from which it is produced.
Bioplastics can be divided into three main groups:
1) Biobased, which are at least partially produced from biological sources and are not biodegradable, such as bio-based PE (made from bioethanol)
2) Biodegradable, which are produced from fossil sources but can be biodegraded, such as polycaprolactone (PCL) and polybutylene adipate terephthalate (PBAT)
3) Biobased and biodegradable, which are a particularly interesting group since are produced from renewable sources and are biodegradable, such as: polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), starch-based blends.
The global production of bioplastics is currently very low (1.5% of global plastic production), mainly due to the higher costs of production and (in some cases) reduced availability of raw materials. In spite of that, however, their market is rapidly growing and a significant increase in their production capacity is estimated in the coming years, raising from about 2.2 (in 2022) to 6.3 (in 2027) million tons. The different types of bioplastics can be used in several applications, among which the packaging sector represents the predominant sector, with 48% of the share in 2021 (https://www.european-bioplastics.org/market/). Currently, biobased bioplastics are mainly produced starting from plants rich in carbohydrates, such as corn and sugar cane, but there is a growing interest in the use of non-food crops, such as cellulose and algae, or residues / waste streams from the agri-food industry as well as from the organic fraction of municipal solid waste (OFMSW) (Moretto et al., 2020).

In this context, the technical feasibility to produce and recover commercial quality PHA from different organic wastes has been demonstrated at pilot scale (Lorini et al., 2021), and particularly studied with reference to OFMSW in a recent Horizon 2020 project entitled "RESources from URban BIo WaSte (RES URBIS)" (https://cordis.europa.eu/project/id/730349)

The choice of raw material is a key point for assessing the sustainability of bioplastics: the use of waste biomass, not in competition with the food chain, allows to reduce/eliminate the consumption of water and soil related to the production of the biological feedstock and allows to acquire the advantages of the circular economy also in this sector.

Biological raw materials can also be fed into traditional production chains together with fossil feedstocks to obtain bio-attributed products. With the 'mass balance' approach the quantity and sustainability characteristics of organic feedstock can be traced in the value chain and attributed to the final product on the basis of provable accounting.

5.2 Valorization of plastic waste through recycling

Among the main route to reduce the use of virgin raw material, recycling technologies certainly play a leading role in the plastics sector, by reprocessing waste into secondary raw material suitable to obtain new products. Currently the most widespread recycling technology is the mechanical one, which has allowed, especially in Europe, to achieve the important results described in section 2. Despite the prevalence of these technologies, mechanical recycling has some limits: it can treat only selected and limited fraction of plastics and usually cause a progressive drop in performance of plastic materials at each cycle. In order to reach the full circularity of all plastics, it is necessary to develop also other complementary technologies on industrial scale. In particular, chemical recycling technologies are suitable to transform those plastics materials that are not mechanical recyclable, for example mixed plastics waste, into a new feedstock for the production chain. With chemical recycling, plastic waste is transformed into a recycled oil, which can be fed at different points in the traditional production process to obtain new intermediates and plastics with characteristics and performance equivalent to virgin plastic (from fossil sources): theoretically, chemical recycling allows to recycle the material infinite times.

According to a LCA study conducted by Sphera for BASF, the chemical recycling of 'mixed plastic' waste (that cannot be mechanical recyclable) reduces overall CO_2 emissions by 50% compared to the combustion with energy recovery, that currently is the fate of such waste (*Figure 5*).

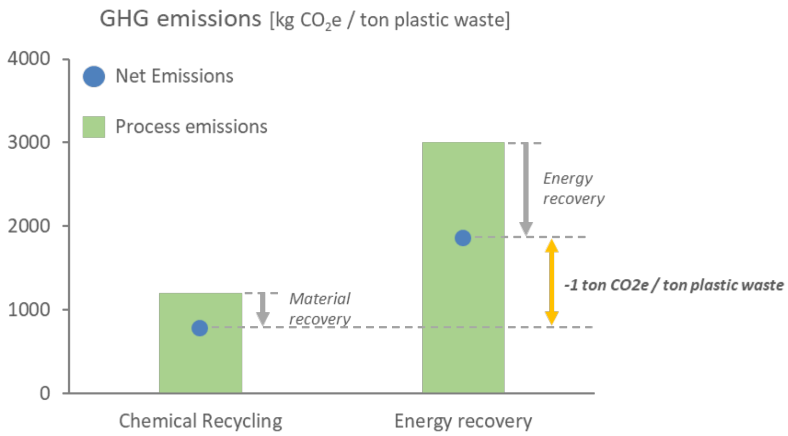

Figure 5: End-of-life processes comparison (adapted from ChemCyclingTM: Enviromental Evaluation by Life Cycle Assessment, BASF, 2020)

In addition to mechanical and chemical recycling, there is the physical recycling, also called dissolution: plastic waste is treated with solvents and other chemical agents, causing the polymers to dissolve and separate from the rest of the waste. The purpose of this operation is to separate the polymers, or even the additives, without causing the polymer chains to break. This allows to obtain separate materials which can then be directly reused as polymeric material.

The circular economy has defined a new industrial approach, based on collaboration and synergies, to achieve increasingly ambitious sustainability and decarbonisation objectives. To accelerate the development of new technologies and rapidly increase the sustainability of plastics sector, various associations and alliances have been created among chemical companies and stakeholders, such as "Circular Plastic Alliance", "Alliance to end plastic waste", "Styrenics circular solutions", "Polyolefin Circular Economy Platform", and many others.

6. Conclusions

Plastics include a wide range of materials, characterized by specific properties, such as, for example, lightness, resistance and cost-effectiveness. These properties make plastics irreplaceable in several applications and have contributed to making our lives easier, safer, healthier, more economical and more sustainable in many sectors. Plastic waste management is an important issue for the sustainability of the entire sector: institutions, industries, and associations have already started actions to increase the circularity of these materials and reduce the dispersion of plastic waste in the environment, with important results especially in Europe. However, further efforts are needed to reach the ambitioned targets. To increase the sustainability of plastic materials, there is not a unique solution: it is necessary to rethink the entire life cycle according to circular economy model, from the selection of materials, the design phase, to production and use, up to the virtuous management of product at their end of life. Using a scientific approach, all stakeholders at every step of the value chain are called to give their own contribution. Levering research and innovation, plastics sector can overcome the challenges which has ahead: renewable raw materials (including wastes) and advanced recycling technologies represent valid solutions, and their development can be accelerated thanks to the numerous alliances and platforms which have born in recent years.

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