Assessing techno-economic strategies to implement circular business models: the case of fiber-reinforced thermoset polymers

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Assessing techno-economic strategies to implement circular business models: the case of fiber-reinforced thermoset polymers[§]

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Abstract

We review the most recent techno-economic studies on the strategies for recycling Fiber-Reinforced Thermoset Polymers (FRPs) and we provide insights on the related issues which must be addressed in the assessment of the solutions to valorize them. We stress the need to adopt a demand-pull, entrepreneurial approach aimed to discover valuable industrial applications of the recovered materials on which to base appropriate techno-economic solutions, i.e. viable business models. We emphasize that, to start, public action is required to regulate the recycling process and, *rebus sic stantibus*, to change players' incentives and to coordinate their actions within the value chains involved.

1. Introduction

The need to develop viable techno-economic strategies to recycle Fiber-Reinforced Polymers (FRPs) and, in particular, thermoset-matrix composites is pressing for both environmental and economic reasons. In the near future, the quantity of end-of-life products to be managed is impressive and the efforts to develop viable strategies very rewarding. The most striking testimony of this is the picture of Tucson airport with thousands of parked aircrafts cannibalised for their spare parts but, most important, waiting for viable solutions for recycling their potentially valuable composite materials.

In this paper, we review the most recent studies on the strategies for recycling FRP, and we provide insights on the techno-economic issues which must be addressed. We argue that the technological and economic validation of the solutions for recycling FRP are strongly interlinked and that the variables involved, as well as the working hypotheses to be made, are highly context-dependent. This is mainly due to the number and heterogeneity of the economic actors potentially involved in the process of

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economic valorization. Moreover, so far most of the solutions have not been validated at wide industrial scale. Therefore, the recycling cost estimations resulting from the available assessments are not very reliable as a general benchmark.

In the assessment of the techno-economic recycling strategies, experiences made so far make a case for the adoption of a demand-pull, entrepreneurial approach aimed to discover high value-added industrial applications of the recovered material on which to base appropriate techno-economic solutions, i.e. viable business models. The preliminary step in this direction is the regulation of the recycling process by the public authority. *Rebus sic stantibus*, due to the high technological and market risks involved, the stakeholders' incentive to be the *first mover* is very low and public action is required to reduce uncertainty and to coordinate their actions within the value chains involved. We argue that, to this aim, a mix of market and non-market policy instruments should be implemented. Such a *Big Push* policy approach would also render credible the commitment of the government and, by so doing, change stakeholders' expectations.

The paper proceeds as follows. Section 2 reviews the recent techno-economic studies on recycling processes of FRP. Section 3 summarizes the main insights stemming from a critical assessment of the previous studies. Section 4 draws main conclusions and policy implications.

2. Review of techno-economic studies on recycling processes of fiber-reinforced thermoset polymers

To date, several technologies have been developed for recycling fiber-reinforced thermoset plastics, but only a few have been adopted on an industrial scale and integrated into waste management systems. Moreover, although the topic of recycling these materials is gaining increasing attention, only a limited amount of research up to now has been devoted to economic evaluations of the existing treatment modes – including recovery and recycling – of thermoset composite waste.

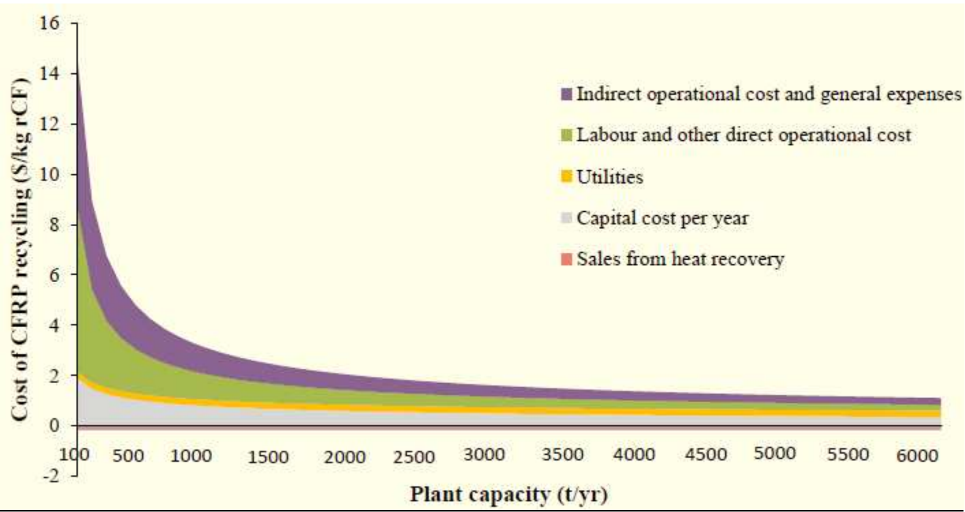
Hedlund-Ostrom (2005) carried out one of the very first studies on the subject, analysing the costs and environmental impact of end-of-life carbon fiber-reinforced polymers treatment processes by developing a model that encompasses different scenarios. Detailed cost estimates associated with mechanical recycling and incineration can be found in the study. The cost model has been designed so that factors defined as "internal" (endogenous) – which are closely dependent on the type of input waste and recycling process – can be considered in the assessment. The research results show that the recycling route is more desirable than incineration, both in terms of cost and environmental effects.

Even though their work does not include an assessment of the costs arising from each recycling alternative, Pimenta & Pinho (2011) have collected and commented on the main issues related to the recovery of thermoset composite waste, summarizing the characteristics of existing technologies (grinding, pyrolysis, fluidized bed, chemical process) and offering an overview of remanufacturing processes and potential markets or application sectors, based on the type of remanufactured product. A similar study was realized by Oliveux et al. (2015) who reserved a section to a brief analysis of the economic and environmental aspects of these processes along with reviewing the different recycling techniques and specifying for each of them the companies commercially active today. The authors point out that today the recovered products obtained by recycling end-of-life glass-fiber reinforced polymers (GFRP) are not as competitive as virgin products which are already low-priced. It is particularly true if the recovered products are realized with recycled GFRP coming from end-of-life components. Nevertheless, mechanical recycling is so far the less-costly way to recover glass fiber-reinforced polymers (GFRP). Recycling carbon fiber reinforced polymers (CFRP), instead, appears to be more cost-effective because of the higher value of the material, meanly related to the carbon fiber itself. However, recovered products from CFRP are mainly used in low-to-medium applications ("down-cycling") impeding a high economic return, even if recycling costs are on average equivalent to 70 % of the cost needed to produce virgin materials (Oliveux, Dandy, & Leeke, 2015).

Li et al. (2016) conducted an interesting Life Cycle Costing Analysis (LCCA) as well as an assessment of the environmental impact ("Life Cycle Assessment") of three treatment options for end-of-life carbon fiber-reinforced polymers, both in the EU and UK context: landfilling, incineration, and grinding. The authors show that, while there is a significant reduction in emissions compared to incineration, mechanical recycling of carbon fibers is not feasible on an industrial scale due to the high costs associated with the process. Moreover, the low material recovery rate does not allow to offset these costs by selling the recovered products. The study, however, provides a valid model for calculating the costs of such processes, especially mechanical recycling. For their estimation, the authors considered the operating costs resulting from the functioning of a hypothetical recycling plant and the costs associated with pre-treatment (dismantling and shredding) and transportation activities.

Meng (2017), instead, carried out a study on the techno-economic feasibility of using recovered carbon fibers for the production of automotive components. He financially assessed the closed loop of recycled carbon fibers by performing a life cycle cost analysis (LCCA), considering the carbon fiber recovery as one of the main phases within the cost model. Capital and operating costs associated with carbon fiber recycling were estimated for a fluidized bed plant with a hypothetical production capacity of 1,000 ton/year, based on the University of Nottingham's pilot plant experience. Among the most interesting results of the cost evaluation concerning the recovery step, Meng underlines that the weight of fixed and operating costs on the rCF final selling price is dependent upon the recycling plant capacity, as showed in the figure below (Fig.1). Operational costs appear to account for over the 50 % of the total cost. Consequently, smaller capacities make operation detrimental to the overall economic feasibility, confirming the existence of strong economies of scale. In fact, for example, for capacities exceeding 500 t/yr it is possible to achieve a minimum selling price of rCF equal to less than 5$/Kg. If it is considered a plant capacity equivalent to 100 t/yr, the minimum selling price of rCF would have a market value of up to 15$/yr, losing its competitiveness with, for example, low cost CF, with a price ranging between 4.5-7.5 €/Kg, or Virgin CF from lignin precursor, usually priced 6.6$/Kg ((Vo Dong, Azzaro-Pantel, & Cadene, 2018).

Figure 1-Minimum selling price of rCF and breakdown cost components for different plant capacities at constant feed rate (9 kg/hr-m2).



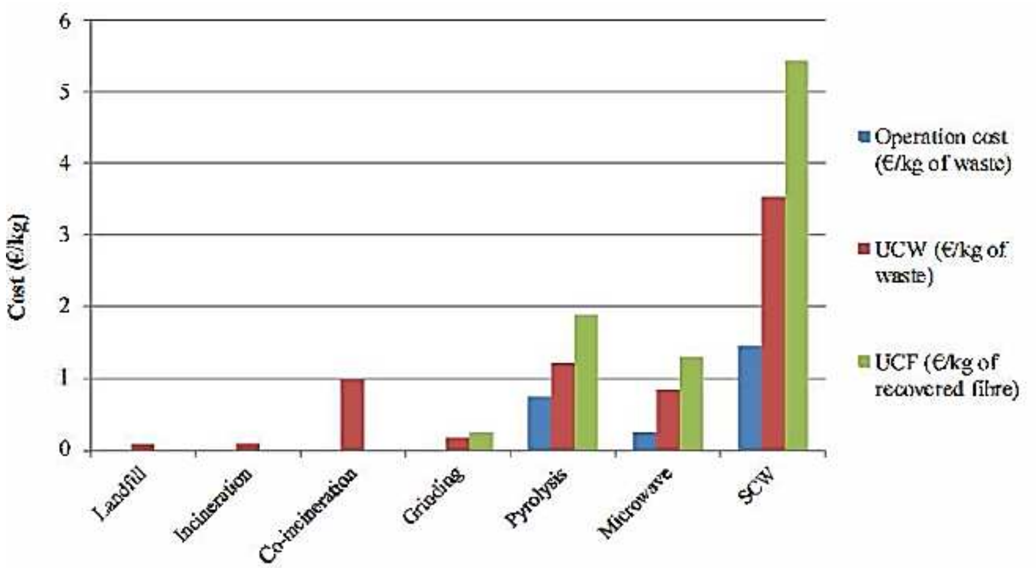
Source: (Meng, 2017)

However, the author has not included in its analysis the costs of sorting, dismantling and transport of CFRP waste, being potentially significant. In this regard, he stresses the need to make more accurate estimations by focusing the research on type, location and volume of CFRP wastes factors potentially affecting the whole financial viability of the recycling path (Meng, 2017).

Vo Dong et al. (2018) also contributed to the existing studies on the economic feasibility of different treatment alternatives for thermoset composite waste. Based on an approach that, like Meng (2017), combines an LCA ("Life Cycle Assessment") analysis with a Life Cycle Costing Analysis (LCCA), Vo Dong et al. (2018) compared through the use of environmental and economic indicators seven management options for end-of-life carbon fiber-reinforced polymers: landfilling, incineration, co-incineration, mechanical recycling, pyrolysis, microwave, and solvolysis with subcritical water. For doing this, the authors estimated three main parameters: operating cost (€/kg of waste), average unit cost per unit of waste (€/kg of waste), and average unit cost per unit mass of recovered fiber (€/kg of recovered fiber). First, they demonstrate that all recycling technologies are not competitive in comparison with conventional composite waste treatment methods (landfilling and incineration) by simply looking at the cost per unit of waste.

Figure 2 shows that the cost of landfilling is around 0.076-0.09 €/Kg, as average value calculated considering different EU countries (Fischer et al., 2012)[1], being the less-costly treatment method with respect to the other treatment methods.

Figure 2- Comparison of the cost (€/kg) of 7 treatment methods of CFRP waste



Source: (Vo Dong, Azzaro-Pantel, & Cadene, 2018)

Notwithstanding, when only considering recycling processes, grinding appears to be the alternative with the lowest cost[2] (nearly 0.2 €/Kg of waste) about the double of the cost of landfilling but, at the same time, four time less than the UCW of microwave (Fig. 2). The low unit cost of recovered fiber, however, should not be overlooked. It suggests poor potential returns from the sale of mechanically recovered materials (Vo Dong, Azzaro-Pantel, & Cadene, 2018). Instead, in contrast to grinding, solvolysis is the most expensive recycling technology at about 3.5€/kg (UCW), but it also has the highest Unit Cost of Fiber (over 5 €/kg), providing the most significant economic returns. It must be considered that, even if it is currently the most promising technology in terms of potential profits, solvolysis causes high negative environmental impacts and it is still at a low Technology Readiness Level (TRL).

Similar results were obtained by Wei & Hadigheh (2020) that realized, unlike Vo Dong et al. (2018), the evaluation through a Cost-Benefit Analysis whose reliability as a method of analysis, however, remains controversial (Vo Dong, Azzaro-Pantel, & Cadene, 2018). The two authors' study tries to show

[1] The fees charged in Northern Italy for landfilling composites are around 150-180€/tonne of waste.

[2] The price of virgin glass fiber for general applications is 1-3€/Kg. For applications in the high-tech sector, it is priced €3-30/Kg (Vo Dong, Azzaro-Pantel, & Cadene, 2018).

that pyrolysis, along with solvolysis, proves to be a cost-effective way of recycling thermoset composite materials.

Vo Dong and Azzaro-Pantel (2019), in collaboration with Boix, have also realised a study, the only one existing in the literature on the subject, that assesses the economic feasibility of recycled carbon fibres by evaluating the cost derived from the entire supply chain of FRP waste management. This work presents many innovative aspects that are still largely unexplored and not properly considered. In fact, employing a bi-criteria optimization approach that incorporates both a cost minimization objective and an environmental one, the authors try to investigate different cost scenarios for the optimal deployment of aerospace CFRP waste supply chain in France. The model used for cost estimation includes three main layers: type of waste treatment process, waste transportation from source to plant for recycling or recovery, transportation of recovered products output to the market and final use of recovered products. In this way, the authors were able to elaborate different strategy scenarios to optimize the set-up of a CFRP waste management supply chain considering the characteristics of each waste treatment process, the quality of the recovered products and target market, the existing recycling or recovery plants, their location and the potential position of new plants based on transportation distances, the growth rate of CFRP waste production and the level of Global Warming Potential (GWP) of the chain itself.

Mentioning some of their main findings, also Vo Dong, Azzaro-Pantel and Boix stress the existence of strong economies of scale, by demonstrating an inverse relationship between an "*Increase trend*" of input waste quantity and the cost price for recovered fibre (CUF, €/kg of fibre). Moreover, the authors report that the CUF is lower than 4.5 €/kg at a level of 99% of GWP minimization in all waste scenarios, making rCF competitive with low-cost carbon fibers. It must not be omitted that the authors also warn about the tendency of CUF to increase when the minimization of GWP increases, highlighting that, in a scenario where GWP is completely minimized, the Net Present Value would always be negative. Most importantly, in light of the many results obtained in the study, cooperation in the recovery system is seen as the only way to minimize cost and maximize profit (Vo Dong, Azzaro-Pantel, & Boix, 2019).

The study by Shehab et al. (2021) is the most recent study on the subject. The authors, on the basis of the existing literature, developed a cost model for recycling carbon fiber-reinforced polymers that can be used even by those who do not have in-depth knowledge of the various parameters required for estimating.

According to the literature analysis, some worthy studies have attempted to perform reliable estimates of the recycling costs of fiber-reinforced composites with the main intention of supporting decision-makers by focusing on the economic-environmental advantages and disadvantages – as well as the technical ones – of the different treatment methods. Despite this, the literature on the subject is still modest and mainly focused on the recycling phase of the supply chain. These models allow making economic assessments that, however, do not consider multiple factors simultaneously linked to each step of the whole value chain such as type of waste source, treatment process, waste and product transportation (dependent on territorial peculiarities), the quality of the recovered products and the related application market. This condition could be attributed to both the complexity of the material in terms of recycling potential and the absence of experiences of FRP waste management chains, whether in an open or closed-loop cycle, that could facilitate data collection for the development of a cost model more consistent with reality.

3. What have we learned so far?

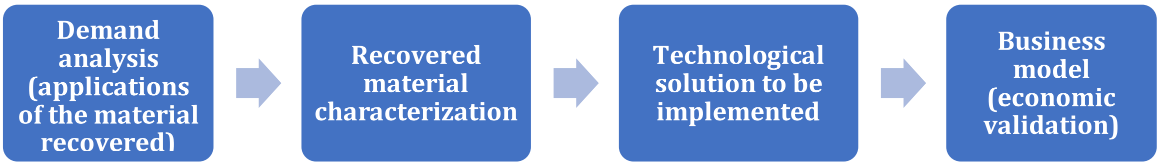
Our review shows that the technological and economic validation of the solutions for recycling thermoset fiber-reinforced polymers are strongly interlinked and that the variables involved, as well as the working hypotheses to be made, are highly context-dependent. This is mainly due to the number and heterogeneity of the economic actors potentially involved in the process of economic valorization. Moreover, so far most of the solutions have not been validated at wide industrial scale. Therefore, the recycling cost estimations resulting from these assessments are not very reliable as a general benchmark.

One of the most critical assumptions regards the scale of operation of the recycling system and plant that, in the presence of large economies of scale to be exploited, may strongly affect the cost estimations. In turn, the scale of operation is highly dependent on the business model adopted.

Another critical feature of the assessment process stems from the distinction of the recycling material between end-of-life products and waste. The estimated cost of dismantling end of life products, in particular in the case of aircrafts, ships or wind blades, can be substantial and may vary a lot depending on the scale of operation.

The main take home message of our review is that the selection of cost-effective techno-economic solutions calls for a demand-pull entrepreneurial approach based on the identification and analysis of the value-chains involved and on the choice of the most promising business model to implement these solutions. The later should be aimed to identify all the potential applications of the material recovered, the most promising ones in terms of market valorization and, on this ground, the most appropriate technological solutions. In short, the approach to follow should be based on the formula "*a market valorization looking for a techno-economic solution*" rather than on the formula "*a techno-economic solution looking for market valorization*", as shown in Fig.1. Demand-supply informative feedbacks may call for co-design solutions aimed at easing the pipeline of the recycling process, starting from the dismantling stage. A valuable contribution along these lines is provided by Shebab et al. (2021) and by an Italian project entitled "FiberEUse". the only one in Europe having adopted a holistic approach with the primary objective of enhancing profitability of FRP recycling and reuse.

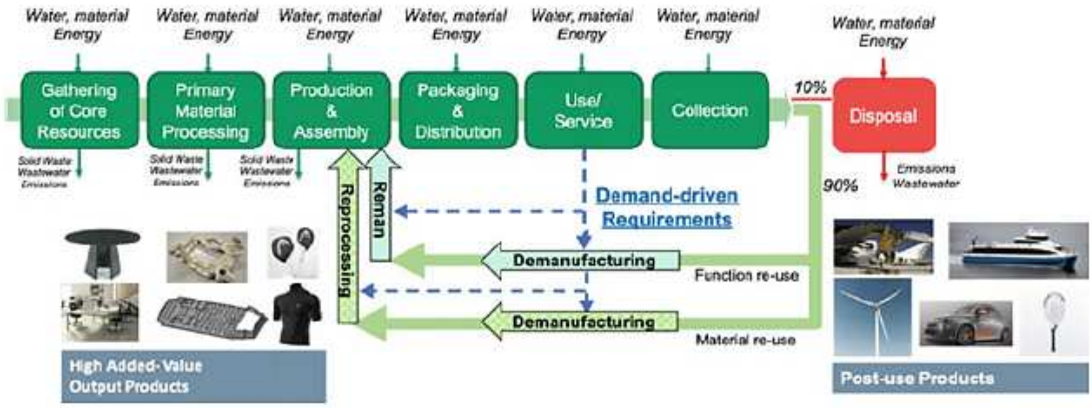
Figure 3- The demand-pull perspective



Source: Authors' own elaboration

The latter – through the involvement of a consortium of 21 partners from 7 EU countries representative of the targeted sectors – focused on the opportunities potentially arising from a demand-driven, cross-sectorial circular economy approach (Fig. 3) to create solid circular value-chains for End-of-Life composite materials. As Colledani, Turri and Diani (2022) affirm, they tried to overcome the traditional "push" approach that has led to put at a second level the search for potential value-added applications of recovered products, usually prioritizing the maximization of the recycling process efficiency in terms of quantity and quality of the recyclates. The "pull" approach has been exploited in the context of the project to develop the demonstrators adapting them to various demand needs and to hypothesize for them different process-chains solutions ("demo-cases") on the basis of sector of origin, typology, and final applications of End-of-Life FRP.

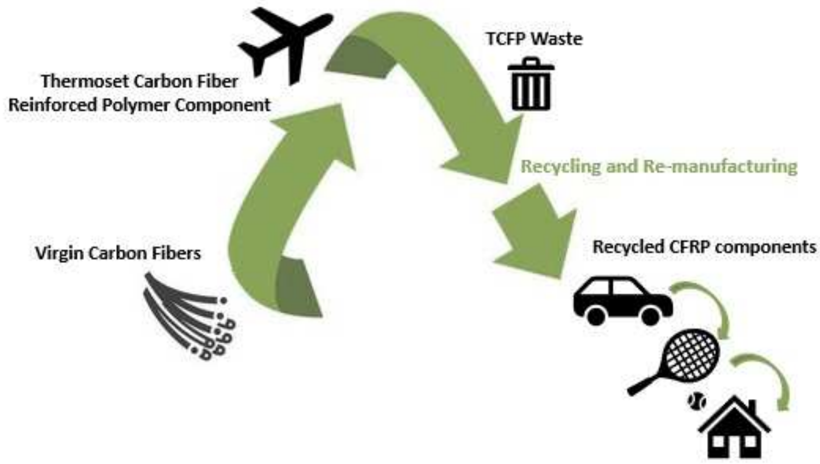
Figure 3- "Pull" demand- driven circular value-chains



Source: (Colledani et al., 2022)

Generally, the recovery of carbon fibers, mostly used by the aircraft industry, would be the most rewarding business also due to their increasing utilization in the new generations of aircrafts. After all, based on the state of arts and in the view of the above-cited demand-driven approach, up-cycling strategies for FRP are hardly implementable for carbon fibers due to the high cost of obtaining recovered materials with the required technical characteristics (mainly strength). Today, *cascade* down-cycling seems to be the second-best strategy (Fig. 4). The process would allow to maximize quantity and market value of recovered material. Carbon fibers recovered from aircrafts can be used at first, by the automotive industry, then after further recycling, by the sport apparel industry and, finally, by the construction industry. The critical point here is that, to set up a viable techno-economic solution, high levels of coordination is needed among the different players within the value chains concerned.

Figure 4 - *Cascade* downcycling of Thermoset Carbon Fiber Reinforced Polymers Components from the aviation industry



Source: Authors' own elaboration

A main factor affecting the viability of solutions at value chain level is the extent of fragmentation of the latter which may strongly affect the incentives of the players to start the process due to the high uncertainty of the final payoff. Not surprisingly, the attempts so far made to set up system solutions can be ascribed either to public action or to the presence of a *big player* in the position to coordinate the different stakeholders within the value chain.

In fact, the world's major civil aircraft original equipment manufacturers (OEMs), Boeing and Airbus, are the protagonists of the first efforts aimed at improving end-of-life aircraft management and finding alternative options for the treatment of composite waste, mostly coming from manufacturing processes. In 2006, Boeing has founded the AFRA (Aircraft Fleet Recycling Association), a non-profit organization, that brings together different actors involved in the aeronautic sector and interested in sharing expertise with respect to aircraft demolition and in promoting safe and environmentally-sound reuse and recovery of aerospace materials, including scrap composites (Boeing, 2007; Maaß, 2020). It could be considered as the only case where there is an attempt to face the problem engaging, through a collaborative design, the whole spectrum of potentially-involved stakeholders within the value chain, even if it actually does not consist in a functioning FRP waste management supply chain.

Recently, Boeing has also finalised a partnership with ELG Carbon Fibre for recycling excess carbon fibres from 11 production sites. It could be interpreted as the first noteworthy industry-wide FRP recycling supply chain. However, the loop is not closed because the recovered products, only suitable for low-value applications, cannot be re-introduced in the aviation industry, as a proper circular economy business model would be expected to be organised.

As Boeing, even Airbus has carried out an important consortium project with the purpose of better manage the end-of-life phase of aircrafts, called PAMELA (Project for Advanced Management of End-of-Life Aircraft), that led to the creation of a 3-step-divided process for handling end-of-life planes. It consisted in one preliminary action directed to foster the recycling of out-of-use aircrafts. Airbus has indeed planned that 95% of the CFRP waste that comes from its process will go to the recycling industry between 2020 and 2025 (Meng, Cui, Pickering, & McKechnie, 2020).

Nevertheless, none of these initiatives has yet been translated into an established and extended FRP waste management supply chain. As briefly mentioned before, the missing market for composite recyclates, along with the correlated absence of coordination among the potentially-involved actors of the supply chain, is one of the main factors – once the technology and the recycling process have been set – having impeded so far, and still impeding, the development of management solutions for recycling FRP waste (Pimenta & Pinho, 2011).

Another existing attempt aimed at setting up system solutions, as previously outlined, falls within the scope of public intervention. Since 2019, France has put into operation the first-ever existing European supply chain for the management and recycling of end-of-life vessels under an extended producer responsibility scheme. The system has guaranteed until now to coordinate at the national level the dismantling of end-of-life boats and the recycling of scrapped materials such as wood, metal and thermoplastics. Thermoset composites have been still an issue until recently. In fact, the APER ("Association pour la Plaisance Eco-Responsable"), the marine manufacturers organization commissioned by the government to manage the end-of-life boats supply chain, has recently signed a partnership with a Swiss FRP commercial recycler, Composites Recycling, planning to install 12 mobile pyrolysis units (containers) at the various waste treatment centers by the end of 2023 (APER, 2022). The recovered products are expected to be sent to the manufacturing sector, as done for the other materials. Also in this case, the problem of the establishment of a market for recyclates persists, potentially breaking the chain. Even so, it must be recognised the effectiveness of the whole public system as first step towards the establishment of a complete FRP waste management supply chain.

It is necessary to also report an upcoming Italian experience that, differently from the ones above described, has arisen from the collaboration among different actors of the private sector. It started as a pilot project initiated by the University of Bologna – that hosts a master course in Composite Materials in the Faenza branch – Curti Spa, an Italian company active in the business of machinery manufacturing, and Herambiente Spa, leading waste management company in Italy. The project has successfully ended with the ongoing construction of two recycling plants – the first located in Imola city of the Emilia Romagna region of Italy – that will mostly process end-of-life and scrap carbon fibers through pyro-gasification, a thermochemical technology (Aliplast, 2023). Herambiente Spa will be the key actor of the supply chain, being the owner of the recycling plants and, consequently, of the recovered products. The waste will mainly come from the production sites of the automotive companies located in the Motor Valley. The recovered carbon fibers will target different industrial uses, from sporting items to automotive components. The latter will be the most interesting application of recovered products, potentially closing the loop of the fibers coming from the automotive sector. In fact, the reclaimed carbon fibers will be used by the same automotive companies which have scrapped them. However, the dialogue among the different actors is still in progress as well as the construction of the two recycling facilities, that will be both working by 2024 (Aliplast, 2023).

Even if its success cannot be declared, this upcoming initiative is surely one to watch out for. This experience could be seen as the very first born at the European level from the need to commercially exploit a resource that otherwise would go to waste, according to an approach that is closer to the formula "*a market valorization looking for a techno-economic solution"* rather than "*a techno-economic solution looking for market valorization*". Exceptionally, it cannot be ascribed either to public action or to the incentive of a *big player,* following a spontaneous, as it is rare, collaborative design that entails the coordination of multiple actors involved in the FRP waste management value chain, as expected in the Italian and European contexts.

4. Policy implications

The need to develop viable techno-economic strategies to recycle composite fiber-reinforced material and, in particular, thermoset fiber-reinforced plastics is pressing for both environmental and economic reasons. In the near future, the quantity of end-of-life products to be managed is impressive and the efforts to develop viable strategies very rewarding.

The complex puzzle which comes out from our survey calls for system-level solutions which require strong public action. It should be seen as a typical scenario where the inertia of the economic agents to undertake the transition to circular economic business models arises from various information and coordination failures paired with high technological and market risks. For example, the several factors at play make any sort of cost discovery and related planning difficult. The lack of incentives to be first movers in the implementation of the available technical solutions is strongly linked to the presence of high levels of uncertainty about costs and benefits. Lack of coordination among players is also a barrier to the exploitation of the existing strategic complementarities (Redding, 1966).

As in the case of the conditions for the *take off* of subsistence economies, the transition towards a green economy, based on CE practices and business models, would call for the creation of the appropriate background conditions. Following the *Big Push* theory fundamentals (Rosenstein-Rodan 1943), an economy-wide public policy-effort would be essential to foster complementarities across sectors and industries and to support them in the development of CE solutions and business models (Murphy et al., 1989). Such a *Big Push* approach would be able both to “de-risk” the economic scenarios for risk-averse private actors and, beyond the “market failure” argument, give “directionality” to the investments themselves (Mazzucato, 2015). By so doing, the State would act as *first mover*, orientating the expectations of the stakeholders through its own commitment to the transition.

So, this calls for an integrated green industrial policy-mix that, like traditional industrial policies, aims to drive structural change by inducing large-scale investments in complementary fields and supporting industries to initiate the transition (Altenburg & Rodrik, 2017). This amounts to foster a process of *paradigm shift* in terms of technological solutions and business models (Dosi, 1988, 1982). The green industrial policy with a central role of the State is further motivated by enhanced uncertainty related to the unique nature of green transformations – longer time horizons and policy-driven objectives – that need to steer investment behavior to “good” technologies and business models for environmental purposes, even if they do not entail strong market-opportunities (Altenburg & Rodrik, 2017), at least in the initial stages of the process, when high levels of technological and market uncertainty are involved. The policy mix should be modulated according to the different scenarios faced by the policy makers in terms of technological and market uncertainty involved. The latter uncertainties are related to the technology and business readiness levels of the solutions to be implemented (Tab.1).

Table 1- Different scenarios of technological (Technological Readiness Level) and market uncertainty (Business Readiness Level) in the transition to the Circular Economy

Technology readiness level (TRL)	II- Low technological uncertainty High market uncertainty	IV- Low technological uncertainty Low market uncertainty

	I - High technological uncertainty High market uncertainty	III - Low technological uncertainty Low market uncertainty
	Business readiness level (BRL)	

Source: Authors' own elaboration

Wide ranging policy action through integrated policy mixes, including market and nonmarket instruments, is required to tackle high levels of technological and market uncertainty related to the joint presence of a low TRL and BRL. In the case of high technological uncertainty (low TRL) but low market uncertainty (high BRL), technology policy could be sufficient to change players' incentives. Conversely, in the case of high market uncertainty (low BRL) and low technological uncertainty (high TRL) policy action should aim to guarantee a market for the stakeholders involved in order to induce them to develop viable business models. Accordingly, this last scenario, highly-uncertain at the market level, would need major public authority intervention through its own commitment in supporting the demand for circular products. Government could directly stimulate the recyclates market integrating supply-side instruments with demand-side policies. For example, particularly "Green public procurement" could be an effective demand-side policy tool, spurring the diffusion of new eco-technologies through the purchase of recycled goods and circular services by the public sector (OECD, 2009). The latter can be a large consumer, potentially becoming a key source of demand for firms.

Therefore, to overcome the existing market failures and barriers to the adoption of CE business models in the composite industries, the government – as done in other sectors like the one of renewable energy production – is the only actor capable of dealing with uncertainty and missed strategic complementarities and shaping private incentives (Kirchherr, et al., 2017). The activation of the value chains and the creation of suitable organizational solutions must be driven by a wide integrated and mixed policy framework (Balke, et al. 2017) – supply and demand measures – that should, however, consider the context-dependence of the entrepreneurial landscape. The need for public action and the degree of State engagement may vary a lot depending on the demand for coordination and the structure of incentives. The extent to which the value chains concerned are fragmented is a major determinant of the need for public action. The mix of market and non-market instruments should be temporally modulated and reformulated to account for the changes in the background conditions induced by policy intervention. For instance, over time more reliable information about viable techno economic solutions should become available and, therefore, technological and market risks would be substantially reduced.

The interventions of a green industrial policy promoting CE transition are manyfold and could be ascribed to two main complementary strategies (Ellen MacArthur Foundation, 2015). On one hand, to directly fix market failures by redirecting producers' behavior, it would be ideal to combine market-oriented instruments with control-oriented ones**.** The former includes a mix of economic incentives, such as subsidies on recycled composite materials, and tax measures, like landfill levies on composite waste such that the cost of environmental externalities is internalized and the opportunity cost of recycling decreases. Moreover, the levies collected may be used as a revenue source to overcome the *first mover problem*, used to recycle systems at a scale of operation allowing to exploit economies of scale and to increase the payoff of the recycling activity. The second type of interventions mainly consists of mandatory targets to waste production levels or reusability and recyclability of products and the related sanctions in case of noncompliance (Enriquez, Sánchez-Triana, & Guerra López, 2021). Those instruments should be matched to investments aimed to stimulate and directly support market activity and innovation, i.e., public investment in R & D, regional recycling, recovery and transport infrastructures, initiatives for local stakeholders' networking to promote the establishment of clusters and industrial symbiosis through regional planning agencies or online collaboration platforms (European Commission, 2014; Ellen MacArthur Foundation, 2015).

However, many market failures are intertwined with regulatory failures that have proved to be a major barrier to composite circularity. So, on the other hand, the second complementary strategy implies a revision of the regulatory framework on composite waste management, usage and production at the EU, national and regional levels (Suschem, 2018; CSR Europe, Leonardo, Bax & Company, 2022). It is urgent to implement standardization measures to facilitate the different stages of the product life cycle. Standards must be set up to promote the interchangeability of components and products, for the enhancement of materials' repairability, reuse, separation, and recovery. In addition, it is necessary to introduce property and quality standards, particularly on recycled composite materials with the purpose of creating secondary markets (Suschem, 2018). Standardization of composite recyclates is crucial to enhance the trust among the different actors of the value chain, consequently leading to the wider application of recycled materials in the design and manufacturing of new products (CSR Europe, Leonardo, Bax & Company, 2022).

For this to occur, better regional and international legislation is needed (Balke, et al. 2017). For example, the European Union still lacks a uniform regulatory framework on the "End-of-Waste" to set standards on when composite waste should not be considered as such but rather an economic resource. Moreover, EU intervention is fundamental to harmonize and align policies across countries to avoid, for example, potential dumping phenomena.

5. Conclusions

The main take home message of our review is that the implementation of cost-effective techno-economic strategies to implement circular business models for thermoset fiber-reinforced polymers calls for a demand-pull entrepreneurial approach. This approach would allow to exploit demand-supply informative feedbacks and to implement co-design strategies aimed at optimizing the recycling pipeline, starting from the dismantling stage of end-of-life products.

Our assessment brings about more general insights on how to deal with the barriers to the implementation of circular business models in all those cases where high levels of technological and market uncertainty are involved and the incentive to be the first mover within the value chains interested is very low. In this scenario, the public sector's role could be essential both as facilitator and coordinator: strong public action, based on integrated policy mixes, is needed to coordinate the different actors and to change their incentives and expectations.

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