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Some of the challenges faced by the Composites Industry in its bid to become more sustainable

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The Composites Industry has evolved from simple beginnings to become a global multibillion dollar business with strong links to many aspects of everyday life. This growth has been possible due to the ability of the Composites Industry to respond to the needs and direction provided by its customer base. This article summarises some of the key challenges for the Composites Industry in light of the ongoing debate and discussion relating to the climate crisis, and the need to reduce the impact of operations and products on the environment. Some of the areas which would need to be addressed in order for the industry to continue to grow and thrive in the years ahead are also highlighted.

Sustainability spotlight

To play its part in the ambition of continued growth, and delivery of value to society in the form of innovative high performance solutions, the Composites Industry needs to increase participation in Circular Economies and increase the number of sustainable supply chains. This article identifies some of the challenges facing the Composites Industry in making the changes necessary to become a more active participant in future global and regional Circular or sustainable economies; and through advocacy for partnership and transparency, the article highlights possible opportunities for progress. In doing so, it is hoped that the agenda of the United Nations Sustainable Development goals SDG 8 (decent work and economic growth), SDG 9 (industry, innovation and infrastructure), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), SDG 13 (take urgent action to combat climate change and its impacts) and SDG 17 (partnerships for the goals) will be proportionally advanced by the Composites Industry.

Introduction

The Composites Industry is a multi-billion dollar business, with strong links to the Chemicals Industry. In a typical Composites Industry supply chain, small molecules are used to produce thermosetting and thermoplastic resin products, and reinforcement fibres. These resin products, and reinforcement fibres are then used to manufacture uncured, or partially cured, intermediate materials which are the feedstock for the processes used to create the composite structures used in the aerospace, automotive, marine, civil construction, renewable energy and defence industry applications. The importance of the Composites Industry to the global economy, and the leading role that it can play in shaping society has led to a lot of discussion and activity around the topic of sustainability.[1] This discussion is still evolving and, owing to the complexity and necessary reliance on an interdisciplinary approach, will likely continue to evolve for the foreseeable future. In this regard, the actions of the individuals, groups/associations, and companies within the Composites Industry should be to continue to adopt positions in debate, drive discussion forwards, reduce concepts to tangible realities and put forward opinion on a number of possible future states for the industry.

The changes required to evolve a more sustainable Composites Industry will likely be a series of small, cumulative steps which will occur across a number of years between many companies, rather than one or two single major changes. Therefore, with every conversation we hold, or when we read and write articles such as this, we have a chance to communicate, to better understand and to try to influence the popular opinion. We should, and need to talk and collaborate more. As individuals, whether we find ourselves in industry, academia, or elsewhere, we should be prepared to take intelligent risks and find ways to speak our minds. Our successes and failures should be communicated, and we simply should be prepared to try things out and start discussions to create the small changes required to steadily move the Composites Industry further down a sustainable path. To help us understand the significance of our outcomes, we need to use tools which can act as our Rosetta Stones and accumulate, package and disseminate data in understandable and useful formats to help identify the eventual agreements needed to create the impetus for true industrial change.

Much of the sustainability challenge facing the Composites Industry could be said to lie in the manufacturing, or the end of life stages of the intermediates and products which it creates. This perception is not incorrect, but is built on observations of predominantly linear supply chains and end of life options that imply a landfill site or incineration facility. As such there are

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plenty of other opportunities to make quantifiable changes and with an open mind, establish a new, more sustainable future for composite materials.

An unavoidable and simple truth is that if reinforced polymer materials disappeared overnight the world would wake up to a very much tougher reality than when it went to bed. Reinforced polymers deliver tremendous practical and economic value to the global economy and our societies. The Composites Industry should therefore promote a message built around the appropriate use of the correct material in the right application, and the benefits that composite materials bring to the use phases of the applications that rely on them. Effort should also be made to disentangle reinforced polymers from the types of 'bad plastic' applications where inappropriate materials are used for historical convenience, and are correctly highlighted as being appropriate causes for concern and improvement.

Understanding, defining and agreeing what 'sustainability' means to the Composites Industry

Arriving at a common understanding and set of definitions, which are widely accepted and practiced, is key to an industry progressing and growing in a unified way. In the case of the Composites Industry there seems to be a growing divergence in the way that our industry is communicating a message around 'sustainability' when it might mean 'Circular Economy' or *vice versa*.

Sustainability was defined by the United Nations Bruntland Commission[2] as being able to 'meet the needs of the present without compromising the ability of future generations to meet their own needs'. This definition is best viewed as a description of the desirable (lack of) impact of activities on the environment and available resources, or as a very loose goal for an operating framework rather than an operating model in its own right.

The Circular Economy[3] provides an example operating model for industry to follow, and is inspired by the study of natural systems. The biological origins of the Circular Economy are represented by the interaction of the Biosphere with the Technosphere in the form of a Butterfly Diagram; with the principles of renewable energy and waste minimisation driving processes in each half of the diagram. In a Circular Economy model, supply chains for 'consumable items' originate in, or do not harm, the Biosphere, and supply chains for 'durable items' originate from the Technosphere and integrate design for reuse principles. The economic consideration of the model ensures that every participant in a circular economy must be able to extract benefit/value/profit for the cycle to operate. This perhaps explains its attractiveness to industry but also highlights the greatest challenge to its adoption and progression in that 'value' has to be first recognised and then deemed worthy of investment in order that the cycle can be constructed and shown to be capable of turning indefinitely.

An aspirational and very high level closed loop Circular Economy is shown for the Composites Industry within the blue circle in Fig. 1. Under this model it is difficult to see a future where the Composites Industry can generate the business cases and capital required for the industry to recycle surplus or end of life material, and conduct the operations needed for the regeneration of resins, polymers, and reinforcements without relying on assistance from external industries and infrastructure.

By adopting an open loop Circular Economy model (the black circle in figure one) there is a much stronger case to be made for the Composites Industry continuing to take advantage of the essential assets and infrastructure already embedded in current supply chains which deliver into the Composites Industry. In an open model a series of 'bent linear' or related partially circular economies could be used to move material between composites applications and adjacent industries. In direct reference to the biological origins of the classic closed loop Circular Economy model, an open loop model also has interactions between the Biosphere and the Technosphere. Feedstock materials may originate in the Biosphere through sustainable supply chains and enter the Technosphere where they are further transformed into 'durable items'; with surplus (scrap or waste) material created by the Composites Industry during the transformation process or at the end of life phase of a 'durable item'. In an analogy to the way in which an ecosystem acts to break down surplus biological material, the surplus material in the Technosphere could be reused and/or repurposed externally through the same supply chains that supply the Composites Industry, or in some cases could become a premium feedstock for other industries by leaving the composites economy.

Adoption of this open loop model, and the associated philosophy of using the supply chains and infrastructure which are already readily available, avoids any difficult conversations around capital investment required for replication of infrastructure in the closed loop model. Additionally, as existing supply chains are more likely to be utilised, it creates a situation where existing relationships and trust can be used to enable each element in the open loop model to 'play to its strengths' and develop/encourage the innovations necessary to create less waste and find ways to reuse/repurpose or recycle more material.

Innovation and Technology in a more sustainable Composites Industry

During the assembly of a jigsaw, one does not need to have all the pieces slotted together to know the nature of the final design. The identification of corner and edge pieces helps frame the boundaries of the final image, and pieces with complimentary lugs and sockets and similar graphical features can often be assembled in groups and then brought together to form sections of the final image. A partially completed design can be used to aid with the selection and placement of the remaining pieces, and the Composites Industry is, in many ways, similar. Within academic and low TRL industrial research circles there is an abundance of awareness and useful technology which perhaps reduces the need for the Composites Industry to invent its way out of the problem.

• The mass balancing concept is developing in chemical supply chains and looking like an achievable way of reducing the need for injection of fresh fossil-based materials.

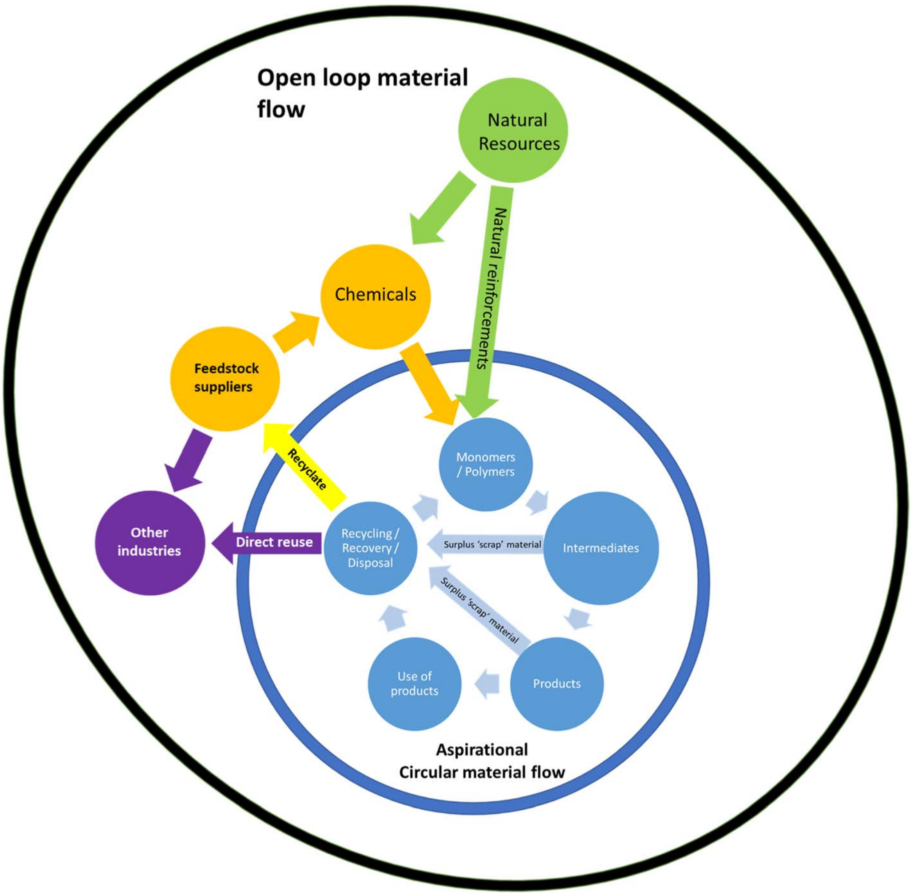

Fig. 1 Simplified example of material flow in the Composites Industry.

• Biotechnology and Chemistry are working together to deliver important starting materials for carbon fibres[4,5] and epoxy resins.[6]

• Recycling technologies[7] which emerged in, or were applied to the Composites Industry in the recent past are now demonstrating their role in keeping material circulating.

• Technologies have also been demonstrated to reduce the energy burden of the carbon fibre manufacturing process.[8]

Fig. 2 shows that through the application of the open loop model, and using existing technology, there is tremendous potential for a small number of supported concepts or technologies to open up key avenues which in turn create the desirable Circular outcomes or sustainable pathways. In this regard, it is logical to assume that time spent arranging available technologies into alternative supply chains and assessing the environmental and financial impact of those changes would be useful.

However, despite all this innovation, very few of the low TRL developments are likely to truly establish themselves at the appropriate scale within the Composites Industry as the means to create long term and positive sustainable change. The specific root cause(s) of this failure for everything technologically good to establish itself and thrive is complex, but one might expect that it could be reduced to two simple questions, 'what is the magnitude of the positive change, and what is the financial cost of that change to industry?'

Who is paying the bill, and with what are they paying?

There are two 'golden rules' when it comes to implementing new technologies and processes in industry.

The first relates to the financial benefit brought by a new technology and can be summarised as: new technologies need to generate more money than it costs to develop them, or that could be made by sticking with the incumbent technology until circumstances change.

The second rule relates to environmental impact and states that any new technology must make less of an environmental impact across the whole system than the incumbent technology.

If these rules are not satisfied, developments and projects in industry can be, and are, paused until circumstances cause a shift in the economic or technological landscape and the outlook changes.

Within this scope, it seems very hard to introduce anything new as most new technologies will likely have higher initial implementation costs relative to an incumbent technology by virtue of them not being able to take advantage of economies of scale. However, there is a nascent case developing around the proposal that with the correct investment in, and deployment

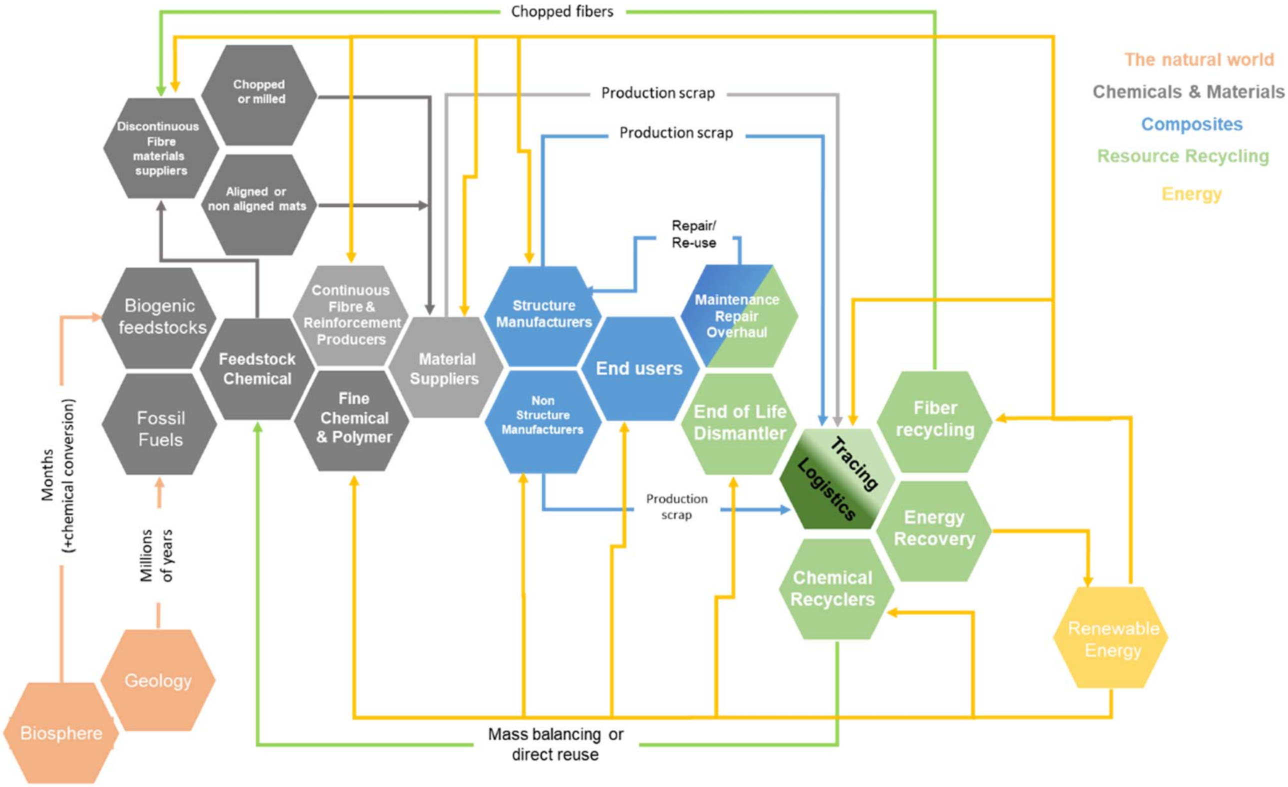

Fig. 2 An overview of the Composites Industry and its dependency on adjacent industries.

of, tools such as Life Cycle Assessment (LCA); it may be possible to calculate the 'real cost' of a process or technology as a function of its balance sheet plus the shadow price[9] for the total system.

Shadow price is a concept which allows for use of LCA to convert the environmental impact of the total system into a financial cost. This financial value, or shadow price, relates to the amount of money needed to offset the environmental impact of a particular technology or process. In theory this approach has been implemented since the ratification of the Kyoto Protocol,[10] but there are inconsistencies in some metrics as the financial value of a tonne of emitted CO_2 has been shown to vary between geographical regions[11] or be potentially underestimated in the first instance.[12]

Generally, a compromise to the total systems approach is used to perform LCA. This saves time and avoids the inconvenient truth that the robust, representative, and reliable data required to perform total systems LCA analyses are often not available. The risk in the compromised approach is that the consequence or magnitude of the change that is being measured can be overlooked, or underestimated. With a reliable and representative source of data to represent materials and processes the necessary LCA studies can be performed at the whole systems level, accurately determining the combined financial and environmental impacts of composite products and processes in order to create the best future state for the Composites Industry.

Simple is best

Post manufacturing steps such as recycling and recovery are highly likely to be rendered uneconomic by multiple low volume feedstock sources or by the production of variable quality recyclate. In the case of most composite materials, the integration of multiple materials at the micron or nanoscales makes the segregation and concentration of the material for recycling operations almost impossible and lowers the quality and value of the recycled material. This situation around manufacturing necessitates a discussion, and perhaps standardisation around the products arising from the act of recycling or recovery of composite materials.[13]

Drawing from the Biosphere in the Circular Economy model, an understanding of 'how to do more with less' may be gained from replicating the design models and physical mechanisms developed in nature.[14] Artificial Intelligence and/or computer modelling, could be useful in aiding the acceleration of the convergent evolution of current man-made materials and natural world concepts in relation to current design problems and recycling constraints. In doing so it might be possible to ultimately eliminate some of the supply chain complexity caused by the current proliferation of grades of molecules, polymers, and fillers into the Composites Industry.

There is also a parallel case for the development of materials which facilitate easier deconstruction and more selective recycling and recovery operations.[15]

In recent years there have been tremendous developments in recycling technologies which can aid in recovery of reinforcement fibres for use as fillers or in higher value reinforcement applications;[16] and more recently material originating from the resin matrix of reinforced composite materials.[17] Assuming that composite materials remain complex mixtures at the micron or ply scale for the foreseeable future, the adoption of recycling methods which are insensitive to differences in the material being recycled is very important. Of equal importance, is that the favoured recycling processes have the capability to provide feedstock materials which can be directly reused, or through low impact processes regenerated into simple molecules which can be rebuilt in the chemicals industry and then made available for use by the Composites Industry. Key to all the (re)use cases for fibre or resin recyclates is the stability, quantity, purity, and the supply of the recyclate itself. Viable industrial processes will not be built on variable quality and fluctuating volumes of feedstock.

The growing influence of policy

In today's world, politics and policies cannot be avoided and nor should they be. Through positive or negative incentives (the proverbial carrot or stick approach), policies help guide and shape the contributions of industry to society and ensure positive outcomes over relatively shorter timescales than if they were not applied. One good example of an environmentally positive policy is the Extended Producer Responsibility (EPR) policy. This has had the effect of making all material producers responsible for the post-consumer stage(s) of a product's lifespan. Since the implementation in the German plastic packaging industry, EPR has been adapted and applied to batteries, solar panels, and waste electronic and electrical equipment, and it continues to influence the global debate on sustainability and Circularity. Relevant and recent influence can be seen in the Wind Energy market and its commitment to enable full recycling of turbine blades rather than continuing with the practice of landfilling.[18]

The United Nations' Sustainable Development Goals have become the foundation blocks for participating nations to craft and implement collaborative regional and country level policies to address deprivation, improve health and education, grow the global economy, take coordinated steps to address climate change, and protect the natural environment. In support of these broad and easy communicable objectives, a number of parallel supporting efforts such as the Conference of the Parties (COP) framework and the Net Zero commitments have been drafted and implemented by a range of countries to lay the roadmaps for tackling climate change on global scale by changing the way that people, products, and industry interact with the environment.

These frameworks are clearly essential and effective components in bringing the world together to address important issues. The Composites Industry should ensure that it speaks with one voice, perhaps in alliance with the Chemicals Industry to ensure that scientific and industrial contributions, and the ability to collaborate within these framework agreements is strong and independent of geopolitics. If this independence is not maintained during a time when internationalism is seen to be in decline, the very ability of the frameworks to achieve the most suitable actions and positively change the world will be diminished.[19]

Concluding remarks

A more sustainable Composites Industry has to exist harmoniously within a more sustainable global future. This implies that collaboration, cooperation, trust, accountability, and the total systems LCA viewpoint are the lenses through which the Composites Industry needs to start to view possible future states.

The total systems LCA approach needs to be enabled *via* reliable, robust, and representative, open access datasets. Without the availability of reliable standardised data to base decisions on there is a real risk of actually ‘doing more bad’ whilst trying to ‘do more good’, or the opportunity for emotion, hunches, or the loudest voices to define the best course of action.

If the Composites Industry does not find a way to demonstrate that it is playing a part in a more sustainable global future, it may find that it’s future role is much diminished, and other industries with more compelling arguments and demonstrations of their sustainable contributions move to fill the space which it vacates. Regulation of the Composites Industry through restriction of its activities or access to materials must be avoided as the sole pathway for nations and sectors to comply with global framework agreements. The Composites Industry should find ways to work with and influence national and geographical policy discussions to enable participation in, and compliance with any future regulatory frameworks or legislations. This may require the formation of new industry led working groups and forums with specific charters to enable legally compliant alliances between companies and concentrate the influence of the Composites Industry to drive important discussions with adjacent industries on the best ways to recycle and repurpose composite materials or develop enabling legislations.

Thought needs to be given to the skills base within the Composites Industry. Prioritisation and development of people with the blended or balanced skill sets and the enablement of scientific and societally aware approaches to problems should be considered. For individuals already embedded in the industry, we need to perhaps stop seeing ourselves as Chemists, Engineers, Physicists or Materials Scientists. We should become confident in recognising that the old lines that defined our chosen educational pathways have become blurred or faded as we move forwards together to transition the Composites Industry into a more sustainable future.

A more sustainable Composites Industry should be a place with abundant opportunity to create the economies of the future and see the Composites Industry grow from the foundations built upon the tangible benefits already delivered to society. The global economy has become reliant on feedstock materials and the products that fuelled historical industrial revolutions. It will take time to wean industries from their dependency on familiar supply chains and favourable economics which are there by virtue of being the only available option at industrial scales, but we should all try to take the small steps available to us to enable the transition away from linear supply chains to ones which operate under more sustainable philosophies.

Conflicts of interest

Jon Meegan is a Research Fellow, employed by Solvay to provide advice and guidance to colleagues and collaborators in the area of polymer chemistry and sustainable composite materials. The views and opinions expressed in this article are held by the author and were accurate at the time of going to press and are not intended to malign or promote an organisation, company, individual or individual or other entity. Comment, discussion and corrections are welcomed.

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