Demystifying Low-Carbon Materials

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Abstract

Low-carbon materials (the ‘carbon’ is related to carbon dioxide emission potential and not elemental carbon) need to be developed and embraced ubiquitously for the sustainable development of human society and mitigate climate change. In the absence of clear consensus in the literature coupled with the presence of certain miss-information, this ‘discussion’ article seeks to define low-carbon materials as the materials that foster a healthy living environment and a circular economy via the elimination or reduction of associated greenhouse gas (GHG) emissions and resource depletion and wastage. Furthermore, the multidimensional facets of low-carbon products and services are described to promote widespread utilisation of low-carbon materials so as to transition to desired low-carbon or decarbonised economies. Several specific strategies for realising the aforementioned are illustrated, which include radical green chemistry and materials approach, efficient materials extraction and processing, utilising renewable feedstocks and energies, efficient product manufacturing, enhanced recycling rates, designing out wastes, circular flow of materials, and innovative business models. The information provided in this ‘discussion’ article strives to outline a variety of aspects and tools available and necessary to accelerate the growth of low-carbon materials and progress towards a sustainable future.

Highlights

- Low-carbon materials, products and services are explicitly defined
- Low-carbon materials reduce carbon footprint and promote circular economy model
- Low-carbon products have parts with low embedded GHG emissions and are recyclable
- Low-carbon services retain ownership of long-lasting materials/products by lending
- Strategies to develop low-carbon materials, products and services are provided

Keyword Low-carbon materials, Sustainability, Circular economy, GHG emission

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Introduction

The advent of the industrial revolution and the invention of internal combustion engines and numerous engineering materials propelled the development of human civilization exponentially (Alagumalai et al. 2021). Consequently, the mass production of materials or goods in factories and industries became the new normal. A linear economy model was adopted to manage the cradle-to-grave approach of materials: extraction–manufacture–use–dispose. This was bolstered by the pursuit of rapid economic growth founded on the economics of consumerism. However, humans realised the dangers associated with CO₂ emissions from fossil fuels, the finite nature of fossil fuels and the incapability of the environment to withstand the abuse in the form of excessive pollution. In light of the aforementioned, the inception of sustainable development occurred that aims to safeguard the well-being of current generations as well as the future generations to come. Sustainable development dictates that the present human generation should be able to meet the needs without compromising the ability of future generations to satisfy their needs (according to U.N. World Commission on Environment and Development 1987). This is possible through a transition to a low-carbon economy that prioritises the concept of ‘decarbonisation.’ In essence, a low-carbon economy in a particular society can be realised by embracing materials, products and services that inject minimal greenhouse gases (GHG) and waste into the Earth’s ecosystem (Shanmugam et al. 2021). Some advocate zero emissions and zero waste as the ultimate goals. Thus, the cornerstone for developing a sustainable future is to identify and utilise materials that would mitigate the ill effects of climate change and extreme weather. However, technological advancements have inadvertently led to the unbridled growth of the carbon footprint of materials and associated products (Zheng and Suh 2019). According to the estimates, the production of materials and waste treatment contribute to nearly 25% of total GHG emissions, globally. Over the period of 1995 to 2015, the materials’ share of the total GHG emissions increased from 15 to 23% (Hertwich 2021). In other words, there was an increase from 5 Gt CO₂e in 1995 to 11 Gt in 2015. An array of factors needs to be considered in the quest to attain material sustainability, which includes ozone depletion, eutrophication, eco/human toxicity, acidification, and land and water usage. More specifically, low-carbon materials directly affect climate change outcomes (by reducing GHG emissions), and hence is the most important factor, which is considered both in determining the carbon footprint and in conducting life cycle analysis (LCA) of materials. In other words, low-carbon materials are responsible for having an impact on climate change that is considered in a variety of sustainability assessments. On the other hand, currently

there is no ISO or other national standard that describes the developmental route for low-carbon materials. Thus, the growing interest in the design and development of low-carbon materials and utilising them in diverse products and services has been the focus of this ‘discussion’ article. It is to be kept in mind that the ‘carbon’ in low-carbon materials do not represent elemental carbon but is related to carbon dioxide emission potential.

The earliest materials used by humans are wood, stone, animal hides (leathers), and bones. They were mostly used for building shelters, tools, and protection from the adversities of nature. Only recently i.e. in the seventeenth century, thermochemistry was developed followed by electrochemistry in the eighteenth and nineteenth centuries. The beginning of the twentieth century was marked by the development of polymeric and ceramic materials, and the latter half was dominated by the creation of functional materials such as semiconductors and piezoelectricals (Ashby 2015). At present, the consumption of these engineering and functional materials rose to 10 billion tonnes annually, wherein each person utilises ca. 1.4 tonnes per year. Therefore, keeping in mind the notion of sustainable development, the aim is to procure and employ materials that simultaneously possess low embodied and operational carbon. Embodied carbon is associated with the emissions generated during the extraction, processing, transport, manufacturing and delivery of a material/product whereas the operational carbon is related to the emissions during the use/service of the material/product (Iddon and Firth 2013). The total carbon footprint of a material involves consideration of GHG emissions in all the phases i.e. from raw materials extraction through the manufacturing phase to the delivery, use, and end-of-life treatment of the product. Growing scientific literature, as well as diverse professional consultancies, that focus on sustainability labelling use these terminologies (e.g. low-carbon, embodied and operational carbon) interchangeably and thus are causing confusion with gross inaccuracies. Unintentionally, they are contributing to the lower confidence of businesses, governments and the public in these estimations, and thus dampening the much needed progress of low-carbon materials development. ‘Low-carbon’ materials are envisaged to be innocuous towards the earth’s ecosystems and beneficial for human health. A recent article by Kai Liu et al. (2020) introduces the concept of such low-carbon materials and also extended the historical timeline for material development to include low-carbon materials and intelligent materials (Fig. 1). In the current article, a novel periodic table is formulated containing some common materials with their approximate environmental data (Fig. 2). The number on the top left corner of the material denotes its embodied energy while the number of the bottom right indicates CO₂, eq (i.e. global warming potential).

Impetus and Confusion

The two main impetus for the development of low-carbon future and associated low-carbon economic development are the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and the Paris agreement of 2016, with 189 countries being parties to it. Nations are urged to adopt policies that would stabilise the atmospheric concentration of greenhouse gases (GHGs) so that the harmful effects of climate change are nullified. Although having different responsibilities towards lowering emissions, both developed and developing countries are obliged to hinder

pernicious anthropogenic activities tampering with the earth's climate. However, anthropogenic actions have been the main cause of altering the composition of the earth's atmosphere, which have led to harmful climate change. The greatest threat comes from increasing levels of CO₂ (and also N₂O) generated from fossil fuel combustions and materials engineering that will continue to be prevalent in the atmosphere for the foreseeable future. Even though GHG emissions are produced by biotic activities too, it is the human action through fuel combustion and materials engineering that is the greatest contributor for CO₂ and NO₂ (Fig. 3). In fact, materials engineering in the service of humankind involves significant amounts of fossil fuel-derived energy,

Fig. 1 The timeline for major materials (reproduced with permission from Liu et al. 2020)

	I	II	III	IV	V	VI	VII
1	120 MJ/kg Butyl Rubber 6.6 kg/kg						52 MJ/kg Alumina 2.8 kg/kg
2	64 MJ/kg Polychloroprene 1.7 kg/kg						5 MJ/kg Bamboo 0.31 kg/kg
3	100 MJ/kg Polyisoprene Rubber 5.4 kg/kg						3.3 MJ/kg Brick 0.22 kg/kg
4	120 MJ/kg Silicone Elastomers 7.9 kg/kg						5.7 MJ/kg Cement 0.95 kg/kg
	Index: Polymers= C- I:VI; R- 1:8 Biodegradables= C-I; R- 5:8 Elastomers= Blue Thermoplastics= Orange Can be both Thermoplastics and Thermosetting= Green Thermosetting= Yellow Materials= C-VII						
5	90 MJ/kg Cellulose Polymers 3.8 kg/kg	95 MJ/kg ABS 3.8 kg/kg	79 MJ/kg EVA 2.1 kg/kg	120 MJ/kg Polyamides 8 kg/kg	110 MJ/kg PC 6 kg/kg	300 MJ/kg PEEK 23 kg/kg	1.1 MJ/kg Concrete 95e-3 kg/kg
6	85 MJ/kg Polyhydroxyalkanoates 4.4 kg/kg	81 MJ/kg PE 2.8 kg/kg	85 MJ/kg PET 4 kg/kg	110 MJ/kg Polymethyl Methacrylate 6.8 kg/kg	90 MJ/kg Polyoxymethylene 4 kg/kg	58 MJ/kg PVC 2.5 kg/kg	51 MJ/kg Paper & Cardboard 1.2 kg/kg
7	52 MJ/kg Poly lactides 3.6 kg/kg	97 MJ/kg PS 3.8 kg/kg	110 MJ/kg PTFE 6 kg/kg	79 MJ/kg Phenolics 3.6 kg/kg	87 MJ/kg Polyurethane 3.7 kg/kg	40e6 MJ/kg Polyester 3 kg/kg	9.2 MJ/kg Softwood 0.38 kg/kg
8	25 MJ/kg Starch-Based Thermoplastics 1.1 kg/kg	80 MJ/kg PP 3.1 kg/kg			130 MJ/kg Epoxies 7.2 kg/kg	110 MJ/kg Ionomer 4.2 kg/kg	11 MJ/kg Soda-Lime Glass 0.76 kg/kg

Fig. 2 Periodic table of some common materials with their embodied energies (top left) and global warming potentials (bottom right)

thus indirectly and directly causing GHG emissions and climate change. Despite the international climatic conventions, worldwide emissions have continued to increase and enormous efforts are underway to find and extract fossil fuel resources across the globe. At this rate of emissions, irreversible global warming is imminent and it is important to understand that the warming is a consequence of the aggregate of carbon emissions throughout the human history and not of a particular phase of emissions at a certain point of time (Hansen et al. 2013).

In light of the increasing GHG emissions and undesirable climate change, the Earth is going to witness numerous devastating consequences. These negative impacts of climate change include but are not limited to sea-level rise (Foster and Rohling 2013); an increased occurrence of hurricanes (Jones et al. 2012) and abnormal heat waves (Stott et al. 2004); increase in the frequency of floods in Southeast Asia, Peninsular India, eastern African continent and northern region of the Andes mountains (Hirabayashi et al. 2013); Ocean acidification; shifting climate zones that threaten indigenous populations (Parry et al. 2007); human-induced species extinction that can induce food shortages (due to lack of pollination-causing species); and deteriorating human health due to polluted land and water (Parry et al. 2007). It, therefore, becomes imperative to avert climate-related disasters to safeguard human lives, avoid economic loss and ensure a sustainable future.

The accelerating GHG emissions can be curtailed by the development of a low-carbon economy. As such, research and development (R&D) programmes are given prime importance as a means to decarbonise products and

processes to establish a low-carbon economy (Urban and Nordensvard 2013). There is an urgent need for a massive scale R&D on low-carbon materials worldwide. Nevertheless, the governments of most nations still do not prioritise the adoption of low-carbon materials and associated technologies thereby creating a bottleneck for the implementation of environmental policies (Urban and Nordensvard 2013). This problem is further aggravated by a lack of understanding regarding the multidimensional facets of low-carbon materials and incomplete definitions that do not explain the holistic nature of such materials. Currently, the concept of low-carbon materials is mostly confined to the sphere of construction and building materials. One study explains low-carbon materials as, “*The use of modern building materials should be carried out paying attention to the energy intensity of materials; the natural resources and raw materials consumed; the recycling and safe disposal; and the impact on the environment* (Cabeza et al. 2013)” However, the development of low-carbon materials should also ensure that the performance properties of the materials/products are enhanced or at least conserved. One Click LCA (<https://www.oneclicklca.com/low-carbon-refurbishment/>) lists the attributes of low-carbon materials as i. *Natural products or those with low energy manufacturing processes*; ii. *Materials with recycled content*; and iii. *Reuse materials*. However, the extent of operational carbon is also important to determine if a material is “low-carbon.” Only a handful of elements from the periodic table is incorporated in construction materials thereby making the definition of low-carbon materials narrow. Furthermore, there exists a limited understanding of the true nature of low-carbon materials in the construction

Fig. 3 Anthropogenic actions, in the form of materials engineering in the service of humankind, contribute significantly towards GHG emissions, including CO₂ that is extremely persistent in the atmosphere (the thickness of the arrows shows relative extent of the contribution)

community. The concept of low-carbon materials, at present, is not translated to all other elements that are in the periodic table and, as such, the broader materials community should be made aware. The dearth of a proper definition of low-carbon materials, products and associated services in an encompassing manner is the source of inspiration for this article. Hence, in the following sections, low-carbon materials, products and services are explicitly explained, which can be applied not only to the construction sector but to virtually any sphere of human activity.

Low-Carbon Materials and Products

Due to the dearth of literature consensus on low-carbon materials, herein the discussion is built on a working definition (Liu et al. 2020). “*Low-carbon materials* are the ones that simultaneously lower embodied and operational carbon emissions, reduce carbon footprint and enhance materials’ circularity, compared to the conventional material choices without compromising the end product’s functional requirements and performance properties.” The carbon footprint is the culmination of direct and indirect GHG emissions produced throughout all the stages of the life cycle of a product or material. An intended core purpose of low-carbon materials is to enhance the healthy living environment and create a more equitable society via a low-carbon circular economy while sustaining the Earth’s resources and ecology for the future generations. Examples of low-carbon materials are waste biomass resources (sawdust from logging and paper mills, agricultural residue) that sequester CO₂ during their growth as plants and possess a negative CO₂ footprint. An understanding of low-carbon material is only the tip of the sustainability iceberg. This is because materials are the fundamental constituents for products, which in turn form the basis for various services. Therefore, in the following sections, the definition and meaning of ‘*low-carbon product*’ and ‘*low-carbon services*’ are provided that will give a holistic comprehension of the concept of low-carbon technologies.

Since products are the consequence of assembly of various parts/materials, the GHG emission of a product will depend on the individual GHG emissions of the constituent parts. Furthermore, the assessment of GHG emission of the product must take into account the entire life cycle of the product from its cradle to its grave. The basic design process for a product includes the planning of the product, conceptual design, embodiment design, manufacturing of prototype and finally mass production of the product (Ulrich and Eppinger 2008). For a product to be labelled ‘low-carbon’ the materials or parts that can contribute to high GHG emission should be identified and replaced with alternative parts having lower emission potential. The first

step towards the development of a low-carbon product is to identify the GHG emission target followed by the embodiment design step where materials/parts are chosen (i.e. the bill of materials) that can satisfy the required performance properties of the product as well as the price considerations. Then, the embedded GHG emission data regarding each of these materials should be calculated and integrated with the various other part information in the bill of materials. It is to be kept in mind that the embedded GHG data of an individual part is a combination of two factors. The first being the emissions resulting from the procurement of feedstock, manufacturing and logistics involved with the individual part (i.e. embodied carbon) and the second is the emissions from the processing, use, distribution and end-of-life treatment of the parts integrated as the product (i.e. operational carbon) (Song and Lee 2010, Khosravi et al. 2020). This is followed by the actual manufacturing of the product and subsequent determination of the GHG emissions. In case the GHG emission has surpassed the initial target, a retrospective design step will be undertaken to identify parts having higher embedded GHG emissions and replace them with lower value substitutes. These parts having lower embedded GHG emissions will be utilised to manufacture the new product followed by an estimation of the GHG emission. This cycle can be repeated until the target GHG emission is reached. Figure 4 shows the flow of the aforementioned design system. In light of the aforementioned, *low-carbon products* can be defined as, “A product whose GHG emissions can be rapidly estimated and tailored according to a particular set of environmental protocols involving only those parts/materials that possess low embedded GHG emissions while as a bulk producing low GHGs during its operation (i.e. low operational carbon) and having the foundation for easy disassembly and recycling.”

Strategies for Low-Carbon Materials/Products Development

Figure 5 portrays the various strategies, which can be adopted to develop low-carbon materials and products. Specific examples of some important strategies, as depicted in Fig. 4, are as follows.

Example 1 — Designing at Atomic and Molecular Scales to Yield Low-Carbon Material

A green chemistry route must be adopted to create materials whose utilisation does not cause any perturbation of the biogeochemical cycles (Anastas and Zimmerman 2019). In a 2018 study by Major et al. (2018), *Miscanthus* grass was catalytically [through combined application of Fe(NO₃)₃

Fig. 4 The designing process of a low-carbon product. Commercial and market feasibility include (i) does the substitute part satisfy customer requirements? and (ii) is the cost difference acceptable? The

test for technical workability is the modification of process engineering. (modified from Song and Lee 2010)

Fig. 5 A framework that can be implemented to develop a low-carbon material. Some strategies for low-carbon materials/products development include: (a) Designing materials at atomic and molecular scales to facilitate higher circularity. (b) Technologies for efficient material processing. (c) Procuring local materials that are renewable in nature. (d) The use of recyclable materials that enhance circularity and sustainability. (e) Material/product design for longer life and without generation of wastes. (f) Ensuring the functional properties are conserved. (g) Increasing energy efficiency

and $\text{Co}(\text{NO}_3)_2$] converted to graphite directly without the formation of an amorphous carbon intermediate. The produced graphitic carbon has the potential to be applied in a variety of applications ranging from catalysis, electronics and composites. This study reveals that thermo-chemical conversion of biomass can be manipulated at an atomic scale to create high-value materials without the generation of intermediates.

Another biomass resource, in the form of Kraft lignin, was used by Leng et al. (2016) to develop metal encapsulated graphene at much lower temperature i.e. at 500 °C compared to other reported studies. The catalyst used was copper sulphate pentahydrate and three carbonisation temperatures were investigated by the authors, which were 300, 400 and 500 °C. At just 400 and 500 °C, the authors observed the formation of 2D carbon sheets over the metal nanoparticle. The authors reported the d-spacing of the graphene layer to be 0.34 corresponding to the number of layers to be less than five. The low-carbonisation temperature is particularly interesting that makes this process an environmentally friendly way to create low-carbon materials.

In a recent study by Mi et al. (2020), transparent wood was prepared from Douglas fir by the means of delignification followed by epoxy impregnation. The developed transparent wood had optical transmittance of ca. 80% and haze of ca. 93% while inheriting the wood patterns from the untreated sample. Additionally, the authors reported that the transparent wood exhibited acceptable UV shielding ability and low thermal conductivity of $0.25 \text{ W m}^{-1} \text{ K}^{-1}$. Owing to the transparent wood having longitudinal tensile strength and toughness of 92 MPa and 2.8 MJm^{-3} , respectively, the authors speculated that the material was suitable for scale up to be used in developing green-construction materials.

Example 2 — Efficient Materials Processing

ceEntek Pte. Ltd (<https://ceentek.com/>) in Singapore developed a novel ultra-high performance concrete that is added with carbon nanofibre (CNF). Waste emissions in the form of CO_2 are being used as the feedstock. The company developed a catalyst from which the CNF was produced in a modified reactor and then dispersed into a paste. Finally, sand, cement and water were utilised to develop the CNF reinforced concrete. According to the company, the new product has low permeability and high chemical, freeze–thaw and corrosion resistance apart from enhanced mechanical properties. Additionally, the expected life span is over a hundred years and the production cost is lower than the conventional processes. The innovative material processing reduced the carbon footprint of the concrete by a factor of 8–10 over hundred years, and the product is fully recyclable thereby

satisfying the circular materials economy model. Thus, the capture of carbon emissions and subsequent utilisation to produce carbon fibres can be performed to develop strong, lightweight and durable concretes.

Example 3 — Materials Selection and Substitution

In recent studies by Das et al., wheat gluten was converted into biochar through pyrolysis and the same was added to the gluten bioplastic to create a self-reinforcing “all-gluten biocomposite” (Das et al. 2019a, 2020). The developed biocomposite was made from constituents that were concurrently locally sourced and renewable in nature, thus upholding the circular economy concept (Das et al. 2018). Furthermore, gluten has a lower carbon footprint than other bioplastics e.g. poly (lactic acid)/PLA (Das et al. 2020). The biocomposite also exhibited improved indenter modulus and reduced water-uptake. This was the first study to demonstrate that it is possible to obtain composites products where both the filler and the matrix are naturally sourced from the same material.

Example 4 — Using Recycled Materials

Rahimizadeh et al. obtained glass fibres from decommissioned turbine blades through size reduction and incorporated them in thermoplastic i.e. PLA filaments for 3D printing (Rahimizadeh et al. 2019). The study reported that the glass fibre reinforced filament had an increase in the value of tensile strength and modulus by 10% and 16%, respectively as compared to the neat PLA filament. Hence, this study is important as it reveals the potential salvaging of turbine wastes, which otherwise could have been disposed of in landfills creating environmental pollution, in creating products with superior material properties (Shanmugam et al. 2020b).

Recently, in Singapore, a start-up company by the name of Green Li-ion developed a new process to efficiently recover precious metals from discarded lithium-ion batteries by co-precipitation method (www.eco-business.com/news/singapore-startup-claims-breakthrough-in-lithium-ion-battery-recycling). This process can potentially increase the recycling efficiency of waste batteries by 200% and consequently reduce the carbon footprint (as opposed to mining of the raw materials).

Example 5 — Designing Out Waste

Apple Inc. is making conscious efforts in achieving materials circularity and supply chain efficiency. In particular, the company has developed a new recycling process for polyethylene terephthalate (PET) films, which are usually used as protective covers for iPhones. PET is recycled into trays that

transport the manufactured parts down the assembly line. The company claims to eliminate 200 metric tons of plastic wastes annually through the recycling and reuse of the PET liners (<https://www.edie.net/>). Furthermore, according to Apple's 2020 Environmental Progress Report, the company has taken huge strides in incorporating low-carbon materials in their product manufacturing. They are shifting their focus on materials having low-carbon energy and higher recycled content. For example, the company is using aluminium that was smelted using clean hydroenergy rather than fossil fuels. The company is using aluminium scraps generated from the manufacturing of previous Apple products in making the enclosure of MacBook Air. Apple claims that by using 100% recycled aluminium, the carbon footprint of the current MacBook Air is 50% less than that of the 2017 counterpart.

Another example for designing out waste is the American commercial flooring company called Interface, Inc. (www.interface.com) that initiated a "Net-Works" programme. The programme facilitates the collection of waste fishing nets from poor communities across the globe and uses them to create carpet tiles. This process has led to a reduction in the number of virgin materials along with the creation of an income source for the poor fishing villages.

Viewing the aforementioned discussions in a commercial aspect, the development of low-carbon materials depends on embracing a circular supply chain for products and

capitalising on the recovery and recycling of products. The acceptance of the circular supply chain of products depends on abstaining from utilising resources that are environmentally damaging and rare while indulging in making renewable, recyclable and degradable resources the crux of the production process (Fig. 6a). The recovery and recycling model encourages companies to establish end-of-life products as the starting feedstock for further production processes (Das et al. 2019b). These end-of-life products could be generated by the company itself or gathered from other neighbouring companies, thereby fostering an industrial symbiosis (Fig. 6b). Recovering and reusing energy is another facet of this concept.

Low-Carbon Services

To comprehend low-carbon services, it is critical to first gain an insight into the linear and circular economy models. Figure 7 shows the basic difference between the two aforementioned models. A linear economy has unidirectional flow, where resources are converted into materials/products by an array of processing steps to add value. The final product is sold to the customer who inherits the ownership and becomes responsible for the related risks and waste generation. In this model, the end-of-life management of a product is completely decided by the consumer. The linear

Fig. 6 Conceptual models for a. circular supply chain and b. recovery and recycling in commercial platforms (the thickness of the arrows shows relative importance of the subsequent steps)

Fig. 7 The portrayal of the life cycle of a material in the present linear economy and the incipient circular economy (modified with permission from Shanmugam et al. 2020a)

economy model is adept in the business of abundance, which can be detrimental as resources are exploited to their fullest extent in a market domain that is currently bounteous. The circular economy, on the other hand, considers materials/products as resources that need perpetuation rather than rampant consumption. The basis of the circular economy is focused on the reprocessing, recycling, and reuse of

materials and products that will, in turn, minimise waste generation, energy consumption and resource depletion along with providing new avenues of creation of jobs. The circular economy aims to optimise the value of the material/product at every stage of its life cycle. The advantages of the circular economy were revealed by a study that reported a transition away from the linear economy in the European

Fig. 8 The concept of low-carbon materials, products and services. Various strategies for the development of the low-carbon materials encourage the genesis of low-carbon products, which in turn creates an impetus for providing low-carbon services within a circular economy framework

nations will reduce GHG emissions by a significant 70% and also enhance the workforce by 4% (Stahel 2016).

Owing to ineffective materials technologies that utilise energy throughout the life cycle of the material/product and lack of recycling, the linear economy is plagued with higher embodied carbon and carbon footprint. On the other hand, the circular economy model utilises efficient material technology by designing at an atomic or molecular level to render them recyclable, possess longer life, generate less waste and cause reduced pollution (Shanmugam et al. 2020b). Additionally, the circular economy concept encourages the inception of state-of-the-art business models and lifestyle choices that are centred on the consumption of less material and products i.e. the adoption of environmentally conscious existence.

One of the cornerstones for the successful propagation of a circular economy is ‘*low-carbon services*.’ This pertains to the sale of materials and products as services in the form of renting, leasing, and sharing (Stahel 2006). Basically, low-carbon services follow the mantra, “sharing is caring” (in this case, caring for the environment) and “quality over quantity.” Contrary to the linear economy model, the manufacturer develops durable materials/products and maintains the ownership along with the responsibility for the generation of wastes and bearing the associated risks. Low-carbon services endeavour to create solutions for the needs of the consumers instead of producing products with a potentially short life. The profits in this type of service are cultivated from the avoidance of dealing with large-scale waste management and performing frequent end-of-life treatments for products. Low-carbon services are particularly beneficial for climate change mitigation since the sharing of products minimises the volume of materials constructed and as such reduces the associated GHG emissions mainly in the embodied form. The operational carbon, however, might remain unaltered from the current high-carbon services because the emissions related to two products used by two individuals might be similar to a single product being used by two individuals. Nevertheless, low-carbon services provide freedom and flexibility to the consumers as they can waive the maintenance costs associated with owning a product. There are many examples of low-carbon services. Nudie Jeans, a Sweden-based denim brand provides free garment repairing services for life aimed at all their customers. Neutron Holdings, Inc. (Lime) operates a fleet of sharable electronic scooters and bicycles across Asia, the Middle East, Europe, Oceania and the USA, many of which are charged by renewable energy thus reducing GHG emissions. eBay is an online platform for buying and re-selling of virtually any commercial product, which is mostly second hand in

nature. Furthermore, shared products can be serviced out as garment and jewellery rentals (e.g. The Folly Boutique and SwapMamas), hired temporary workspaces (e.g. The Business Exchange), carpooling (e.g. BlaBla Car), etc. Based on the aforementioned, *low-carbon services* can be defined as “services that cause business models to retain ownership of long-lasting materials and products, which themselves exhibit low embodied and operational carbon, throughout their life cycle by temporarily lending them to the customers thereby providing a continual solution and causing the remission of GHG emissions instead of manufacturing materials and products having a short lifetime.” Implementation of low-carbon services could become challenging since the lack of ownership of a product by a customer may cause its ill-treatment, which can rapidly reduce its service life.

Conclusions

This ‘discussion’ article provides definitions for low-carbon materials, products and services in a circular economy perspective necessary for creating a sustainable future. The core essence of low-carbon materials and associated products is that they are developed with the least environmental impact without compromising their performance properties. The central concept of the article is summarised in Fig. 8, indicating strategies for the development of low-carbon materials, which include design at atomic/molecular scales, effective feedstock processing, usage of renewables and recycled products and design alteration to minimise wastes. The low-carbon materials can then be integrated within a product design scheme that is flexible enough to replace parts having high GHG emissions with the low-emission counterparts. Finally, the low-carbon products can be interweaved within a new business model that retains the ownership while providing solutions to customers in a cyclical manner. Therefore, the attainment of a sustainable future will only be possible through the development and implementation of low-carbon materials, products and services through the juxtaposition of advanced technologies with societal, policy, and ethical aspects in the entire biogeochemical sphere. It is time to invest more resources into the research and development of low-carbon materials and creating a trained human capital.

Author contribution OD, MSH and SR involved in Conceptualisation. AR and VS involved in writing, review and editing. GS and MF involved in data validation and reviewing. QX and LJ performed data analysis, review and editing. All authors read and approved the final manuscript.

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Declarations

Competing interests The first author, Oisik Das is an Editorial Board Member of Materials Circular Economy and the last author Seeram Ramakrishna, is the Editor-in-Chief of Materials Circular Economy.

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