Ecological Indicators 72 (2017) 833–847

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Review

Identification of Key Sustainability Performance Indicators and related assessment methods for the carbon fiber recycling sector

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ARTICLE INFO

Article history:
Received 15 April 2016
Received in revised form 28 July 2016
Accepted 31 August 2016
Available online 22 September 2016

Keywords:
Carbon fiber
Recycling
Key Sustainability Performance Indicators
Sustainability assessment
Criticality assessment

ABSTRACT

The need for the extensive use of sustainability assessment as a standalone tool to evaluate the environmental, economic and social aspects of an activity be it at project, product, company or region level has resulted in the development of various methods and standards. There are several indicator issues to address each aspect of sustainability and it is not easy for decision makers to understand the result due to the use of multiple indicators. In this regard, the paper aims at the identification and combination of indicators allowing to assess the sustainability which is applicable to a carbon fiber recycling sector. Indicators selection were carried out by performing an extensive literature review on existing publications dealing with the different pillars of sustainability and setting a number of selection criteria to prioritize indicators that are relevant to the sector. For the environmental aspect global warming, acidification and human toxicity seem to be the most relevant. The social-economic aspect can be addressed through considering the resource impact assessment by considering the supply risk due to the geological scarcity of a resource and the potential supply disruption due to geopolitical and other social factors. The finding shows that three indicators have been identified enabling the assessment of the environmental pillar. Then the necessity to use extra resources indicators was shown and justified by the need of providing a shorter timeframe perspective as well as to consider the amount of fiber to be recycled in the future and also to determine the potential benefit provided by the creation of this sector to the resource strategy point of view. This will be made possible by using such method as the criticality assessment that enable the consideration of geological and geopolitical supply risk as well as the characterization of the system dependence to a specific resource.

Finally, these results lead to the expression of the need to the development of a novel indicator assessing the criticality of carbon fibers as well as the expression of the necessity for further research on the socio-economic perspectives.

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http://dx.doi.org/10.1016/j.ecolind.2016.08.056
1470-160X/

1. Introduction

The consumption of carbon fiber reinforced polymers is increasing enormously, which can be explained by the rising demand combined with a considerable reduction in their prices over the past decades (Kraus et al., 2014; Walsh, 2001; Witten et al., 2012). Since the end of 2009–2013, the demand for carbon fibers has increased from 49 to 72 kilotons and it is expected to reach 146 kilotons by 2020 (Kraus et al., 2014). Carbon fibers are known for their outstanding physical and chemical properties such as high tensile strength, low densities, excellent thermal and chemical stabilities, high electrical and thermal conductivities (Lavin, 2001; Walsh, 2001). These properties are in fact dependent on the type of precursors used in the production processes. The most widely used precursor is polyacrylonitrile (PAN) but others such as rayon or pitch and from bio-based precursor cellulose and lignin can also be used despite they have limited strength and modulus compared with PAN based fibers (Ogale et al., 2016; Walsh, 2001; Wangxi et al., 2003). Carbon fibers are usually produced by bonding carbon atoms (90–95% by weight) in crystals, which are parallel aligned along the axis. Each fiber may have a diameter that ranges between 5 and 15 μm. The fiber may also contain a very small amount of residual atoms from the manufacturing process, mostly nitrogen (Griffing and Overcash, 2010). Thousands of carbon fibers (from 1000 to 24000 fibers or more) are twisted together to form the so called tow (Campbell Jr, 2003; Chung, 2001). Carbon fibers are mostly used to manufacture composites as reinforcement for thermoset and thermoplastic matrices, which represents 64% of their global revenues. They are also used for carbon, ceramic and metal matrices (Kraus et al., 2014).

The increasing carbon fiber consumption could lead to the generation of a large amount of wastes in the near future. The exact evolution of the amounts over time depends on the varying lifetime of the different products. Therefore, end of life solutions for carbon fibers need to be developed based on adequate technologies, thus allowing to reduce the overall life cycle impacts of carbon fibers. This can be done by reuse options, actually extending the lifetime, or by material recycling options, either providing the same function or delivering material for new applications. Different studies have reported on the recyclability of carbon fibers. For example, Pimenta and Pinho (2011) provide an extensive study on the recyclability of carbon fibers and existing recycling processes. The properties of recycled carbon fibers are dependent on the type of the recycling process that influences the resin removal and the damage to the fibers. This may result in reducing its overall properties for the next applications. The remanufacturing process and the type of resin thermoset or thermoplastic used to align and to produce the new composites for intended applications in the next life cycle could also effect the properties of recycled fibers. Non-structural use as thermal and acoustic insulation (e.g. electromagnetic shield), or air and liquid filtration are the examples of foreseen application areas for the recycled carbon fibers (Asmatulu et al., 2013), however, there are ongoing recycling process modifications that enhance their efficiency so that recycled carbon fibers may be used in the building and construction sectors for structural applications and also in the automotive sector as cars panels or seats (Pimenta and Pinho, 2014). In addition to the environmental benefits, recycling of carbon fibers could also be considered as a way to support socio-economic development. By establishing a new carbon fiber recycling sector, local communities can benefit from the direct development opportunities the sector offers such as the creation of new jobs, the provision of valued added and the revenue generation. In this context, this paper aims at looking at important sustainability indicators to assess both the socio-economic and the environmental benefits from reusing and recycling carbon fibers in a newly created sector.

Still most existing literature sources on carbon fiber recycling have been focusing only on the environmental benefits through comparison with other end of life waste treatment options such as landfilling and incineration with energy recovery (Witik et al., 2013). In addition, life cycle assessment of products using carbon fibers for lightweight design has shown that the environmental benefit provided by the carbon fiber during the use phase could be dramatically reduced if not recycled (Raugei et al., 2015). Moreover the recycling stage is primordially considered by the end of life vehicle directive (2000/53/EC, European, 2000) requiring to recycle at least 85% in mass of each cars. Regulation that could be extended to other sectors using carbon fibers. Thus, despite the fact that stakeholders still have time to build this recycling sector, its implementation will have to occur rather sooner than later. Otherwise it could be a serious obstacle to the use of carbon fibers in general or even forbidden in regulated sectors. However, to the best of our knowledge, there is no single study that evaluates their benefits in a broader context, which includes not only the environmental impacts but also the economic and social considerations to assess their sustainability (UNEP, 2011). The selection of the right indicators to assess social and economic aspects is a key element for the stakeholders, in addition to the potential environmental benefits and technical feasibility, to make well informed decisions (Singh et al., 2012) on the way how to implement a new recycling sector. In this regard, the paper focuses on broadening the scope of evaluating the carbon fiber recycling from a purely environmental to a wider sustainability perspective, including the social and economic feasibility. It is foreseen to do so within the context of the life cycle sustainability assessment framework (LCSA). Therefore, the paper aims at providing a compressive list of Key Sustainability Performance Indicators (KPSIs) and related assessment methods for the carbon fiber recycling sector.

The study is mainly based on the conceptual framework recently proposed by Sonnemann et al. (2015) that integrates resource criticality assessment into the LCSA framework. This is done to better address impacts related to the area of protection (AoP) 'natural resources' that according to Sonnemann et al. (2015) remains a controversial AoP. Though there are several existing methods, all of them are principally focusing only on the geological availability and fail to address other socio-economic aspects such as the geopolitical and social constraints that limit their accessibilities in a short and mid-term time horizon. Such aspects are highly relevant for resources that are key to modern technology applications. Sonnemann et al. (2015) brought the concept of resource criticality assessment into the LCA context so that both the environmental and socio-economic aspects can be meaningfully addressed. According to several recent publications, such as Schneider et al., 2013; Dewulf et al., 2015 and Sonnemann et al., (2015), the life cycle sustainability of a resource can be assessed in two ways: On one hand, this can be done by addressing the damage on the AoPs 'human health' and on 'ecosystem health' of the energy and material requirements in all the life cycle stages of the resource. On the other hand, the direct impact from the use of the resource, which is a damage on the AoP 'natural resources', and can be addressed through consid-