Journal of Cleaner Production 137 (2016) 910–921

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Environmental impacts of substituting tempered glass with polycarbonate in construction – An attributional and consequential life cycle perspective

Harn Wei Kua, Yujie Lu*

Department of Building, School of Design and Environment, National University of Singapore, 4 Architecture Drive, S117566, Singapore

ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form
26 June 2016
Accepted 25 July 2016
Available online 28 July 2016

Keywords:
Attributional life cycle assessment
Consequential life cycle assessment
Tempered glass
Annealed glass
Polycarbonate

ABSTRACT

Attributional and consequential life cycle assessments were conducted for tempered glass and its possible replacement materials, polycarbonate. A cradle-to-cradle approach was adopted for evaluating the global warming potential, human toxicity potential, freshwater aquatic ecotoxicity potential, marine ecotoxicity potential, eutrophication potential, acidification potential and terrestrial ecotoxicity potential of both materials. The attributional approach found that replacing tempered glass with polycarbonate will result in net decrease in acidification, human toxicity, terrestrial ecotoxicity and freshwater aquatic ecotoxicity, but net increase in eutrophication; the results for global warming potential and marine ecotoxicity are inconclusive. When polycarbonate replaces tempered glass and short term consequences were considered, only the results for human toxicity and freshwater aquatic ecotoxicity are the same as those from the attributional approach. Over longer term, when the import of both materials respond correspondingly to the change in demand in Singapore – that is, for every 1 kg of change in demand, there is a corresponding change in import of 1 kg – it was found that replacing tempered glass by polycarbonate will increase global warming potential and eutrophication, while decreasing human toxicity, freshwater aquatic ecotoxicity, and marine ecotoxicity. This combined attributional and consequential studies illustrate the strengths of both approaches, as well as highlight the importance to consider longer term effects in policies aimed at replacing one material with another, to improve environmental sustainability.

1. Introduction – the need to compare tempered glass with polycarbonate

Tempered glass (TG) is a type of safety glass processed by controlled thermal or chemical treatments to increase its strength. As a result of this additional treatment, it is usually four to five times stronger than normal annealed glass (Bell and Rand, 2006; Fernandez, 2012). It is widely used in the building envelope (for example, in windows and façade) and interior systems (for example, as doors) of buildings, due to its high stress resistance (Bonenfant, 2004). Unfortunately, TG may undergo spontaneous fracture on rare occasions due to the expansion of impurity particles, which may be caused by the expansion of nickel sulfide particles or the thermal expansion of silicon particles present in the glass. This spontaneous breakage had led to more stringent guidelines on safety glass around the world, and the need to seek for alternative materials.

Polycarbonate (PC) is one of the materials being increasingly used to replace traditional glass (Agarwal and Gupta, 2011) due to their light weight, light-transmitting capabilities, and insulation potential (Brownell, 2013; Montella, 1985). PCs are a particular group of thermoplastics consisting of polymers having functional groups linked together by carbonate groups (–O–CO–O–) in a long molecular chain. Besides for windows, PC is frequently used to make translucent sheeting for facades and roofs, ranging from corrugated roofing for garden sheds and multi-wall extrusion sheeting for industrial building to internally illuminated cladding for facades and internal walls. Furthermore, PC costs less than glass and is easier to install (Albertine, 2011).

Since PC is increasing deemed as a possible replacement for glass in architectural applications (Bell and Rand, 2006), and the building industry is likely to increase the market share of PC in the

* Corresponding author.
E-mail address: luy@nus.edu.sg (Y. Lu).

http://dx.doi.org/10.1016/j.jclepro.2016.07.171

future, it is necessary to conduct a comparative life cycle environmental assessment of TG and PC to provide a more holistic idea of the likely environmental consequences when PC replaces TG. Specifically, we aim to answer these questions:

- When PC replaces TG, the local market distributions of PC and TG will change; how will these changes affect the net environmental impacts of both materials?
- Over long term, due to an increase in the market share of PC, the import of raw materials for PC and TG will change accordingly; how will these changes affect the net environmental impacts of both materials?
- To answer the two questions above more completely, a combination of attributional and consequential life cycle approaches can be adopted. Are there any differences between the results of these two life cycle approaches? What are the key lessons from the comparisons of these results?

A review that explains and justifies applying the said two life cycle approaches is provided in the next section. Existing gaps in applying LCA to study TG and PC are also highlighted. Although this study was done for Singapore, the overall approach is certainly relevant to other geographical areas of interest.

2. Literature review on related attributional life cycle assessment (ALCA) and consequential life cycle assessment (CLCA) studies

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, including during the raw material acquisition, manufacturing, use and waste management (ISO, 2006). An LCA of building and construction materials can follow either an attributional or consequential modeling approach. ALCA focuses on describing the environmentally relevant physical flows to and from a life cycle and its sub-systems. Its key feature is to allocate environmental impacts to co-products.

Majority of existing LCA studies on building materials are ALCA in nature, including those done for the glass aspect of windows; but even these studies are limited in number. For example, Weir and Muneer (1998) performed a comparative ALCA of window systems containing various types of inert gases. They concluded that the xenon-filled insulated glass unit (IGU) consumed the most embodied energy, followed by the argon- and krypton-filled IGUs. In contrast, Citherlet et al. (2000) studied the energy efficiency of eight different window systems with IGUs, as a function of building type, orientation and site location. They concluded that the high performance windows (hard coating with an argon gas-filled cavity) consume more energy during the extraction to production stages, but their overall embodied energy was less than a typical window system (without coating and argon gas). More recently, Kim (2011) conducted a comparison of life cycle energy and carbon dioxide (CO_2) emissions of a transparent composite façade system (TCFS) and a glass curtain wall system (GCWS). It was found that TCFS′ total life cycle energy is about 93% of that of the uncoated GCWS, whereas the former's total greenhouse gas emissions is about 89% of the uncoated GCWS. Similar studies were conducted by Ng et al. (2013) and Ng and Mithraratne (2014).

Most of the existing studies on plastic are also ALCA in nature. Duval and MacLean (2007) found that PC has the highest GHG emission in the list of plastic that includes polyester and polypropylene. However, this study was done on plastic resin instead of plastic products. In their study of the life cycle impacts of building-integrated solar thermal collector, Lamnatou et al. (2015) included PC in their scope but only as the main material for the blades in the collector unit and not as a transparent light-transmitting material.

ALCA has also been applied to expand products' system boundaries to consider co-products, co-processes and marginal changes. These include works by Schmidt et al. (2004) and Kua and Wong (2012). However, such system boundary expansion in ALCA allows the identification of environmental impacts of the selected system but does not assess the *changes* generated *outside* the system (Cederberg and Stadig, 2003). In cases where there is a need to assess such *external* changes – say, by changes in the demand, supply or flows of a product (for example, TG) in responses to changes to a *competing* product (for example, PC) – then we need the consequential LCA (CLCA) approach. In CLCA, the system boundary defined in ALCA is expanded so that the new boundary also describes any marginal changes in environmental flows and impacts (Curran et al., 2005; Sandén and Karlström, 2007); this makes CLCA relevant to our study.

Compared to ALCA, applications of CLCA on building materials are even less common, with the few existing studies focusing on materials other than glass and plastic. For example, using CLCA, Mladenovič et al. (2015) found that replacing asphalt-based courses with carbon steel slag aggregates could lead to an increase in the use of binder in the mixture, and consequently reduce acidification, eutrophication, photochemical ozone creation, and human toxicity by as much as 80%. Kua (2013a,b) applied CLCA to show that the benefit of substituting cement with used copper slag could be achieved only if the copper slag replaces at least 10% (by volume) of cement in concrete mixture and the excess cement in the national stockpile is either re-exported or diverted to another construction sectors. Kua and Kamath (2014) found that replacing concrete with bricks might actually increase the net environmental impacts based on ALCA; however, based on CLCA, such replacement might result in small reductions in GWP. Another combined ACLA and CLCA study on the replacement of sand with steel slag also suggested that such a replacement may result in a net reduction in environmental impacts (Kua, 2015; Kua and Maghimai, 2016).

In summary, this study contributes to the current literature as one of the first few environmental assessments of the use of TG and PC for windows; furthermore, it is also the first life cycle study of the consequences of replacing TG with PC, using a combined ALCA and CLCA approach.

3. Research methodology

Seven types of environmental impact categories were considered in this study – global warming potential (GWP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine ecotoxicity potential (MEP), acidification potential (AP), eutrophication potential (EP) and terrestrial ecotoxicity potential (TEP). These impact categories were chosen because they are commonly included in LCA and data on them are available for many building materials. Data was obtained from extensive literature review on life cycle inventories of the different life cycle stages, interviews with key industry professionals on the quantities of materials and resources required for certain key life cycle stages, reference to equipment catalogues (which were used in the various life cycle stages of TG and PC), and databases that are relevant to the local geographical scope. The sources and the uncertainties inherent in these sources were stated and we considered how results may vary according to the uncertainties of calculated LCIs. Specific aspects of our methodology are described in the following sections.