Environmental Life Cycle Assessment for a Carbon Nanotube-Based Printed Electronic Sensor Platform.

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ABSTRACT

This paper describes research to characterize the potential environmental impact associated with the manufacture of a newly developed printed electronic temperature sensor composed of specialized carbon nanotube (CNT) formulation (called CNTRENE® 1030 material) using gate-to-gate environmental life cycle assessment (Eco-LCA). The Life-Cycle Inventory (LCI) was constructed using data collected from samples pulled directly off the production line. Modeling estimated limited environmental impacts from CNTRENE® 1030 material manufacturing process, with the relative impact largely attributed to fossil fuels and resource depletion due to the required high-temperature incineration of wastes. Brewer Science's optimization of the CNTRENE® 1030 material manufacturing process reduced the environmental impacts by approximately one order of magnitude. For the temperature sensor, modeling results showed indicated limited environmental impacts given the very small quantities of CNTs and other materials used in its production. Relative impacts were emphasized by greenhouse gas emissions and natural resource depletion associated with expending of fossil fuels used for gas compressors and electrical power requirements.

Keywords: carbon nanotubes, environmental life cycle assessment, electronic sensor manufacturing.

1 INTRODUCTION

Here, we describe efforts to characterize the potential environmental impact associated with the manufacture of a newly developed printed electronic temperature sensor (Fig. 1) using environmental life cycle assessment (Eco-LCA). The sensor is composed of a specialized carbon nanotube (CNT) formulation called CNTRENE® 1030 material, which was developed by Brewer Science.

2 METHODS

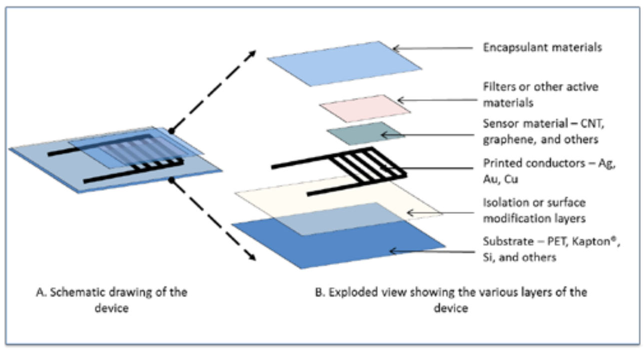

Figure 1. Generic structure of a fully printed sensor device.

Environmental emissions were calculated based on the construction of a representative Life-Cycle Inventory (LCI). The LCI contains a record of all inputs and outputs associated with the manufacture of the CNTRENE® 1030 material, including raw materials, chemicals, electricity, wastes, as well as any energy associated with the transport of materials. A questionnaire was prepared and submitted to Brewer Science. All data included in the questionnaire were obtained by directly sampling technosphere inputs as well as the actual manufacturing process, as well as (such as materials and power) outputs or emissions during the manufacturing and waste incineration.

The life cycle inventory (LCI) was carefully constructed by sampling the actual manufacturing process for technosphere inputs. The LCI was computationally constructed in SimaPro 7.3.3 (PRé Consultants, Netherlands) to include sub-processes associated with the manufacture of the CNTRENE® 1030 material and the conductive nanosilver ink, and the general encapsulation procedure for constructing the printed electronic temperature sensor. We created a gate-to-gate Eco-LCA model with a theoretical functional unit representing 2400 sensors/day. Total emissions for the gate-to-gate assessment were calculated from the mass balance of the inventory components as represented through the Eco-Invent 2.2 database [1] and environmental impacts were assessed using commonly available impact assessment models. For this paper, we focus only on impacts calculated from the IMPACT 2002+ [2] model.

3 RESULTS AND DISCUSSION

3.1 Eco-LCA results for the CNTRENE® 1030 CNT material

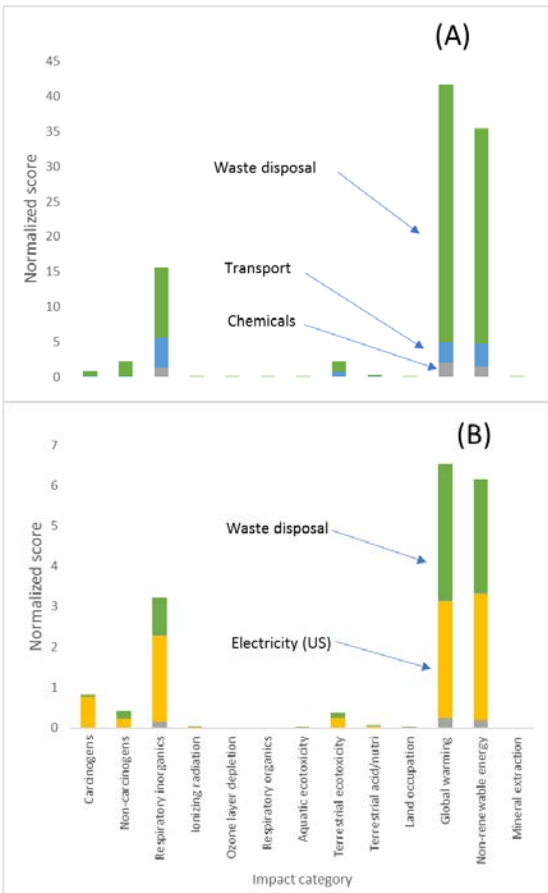

Figure 2. Calculated environmental impacts for (A) original and (B) optimized CNTRENE® 1030 material.

While the Eco-LCA study was limited to the portions of CNTRENE® 1030 material development directly under Brewer Science's control, hypothetically including the manufacture of the raw CNT materials (a process controlled and performed by outside producers) produced a negligible difference in the outcome of the Eco-LCA due to the overall small quantity of CNTRENE® 1030 material produced annually. Given that often the exact CNT synthesis technique is proprietary, we considered the equivalent representation of CNT synthesis as carbon black powder a conservative estimate of the associated environmental impacts.

Computed characterization factors and damages for all midpoint impact categories for CNTRENE® 1030 material production were dominated (74%) by the production of the derivatized CNT suspension. Fig. 2A shows the majority of impacts for the original CNTRENE® 1030 material, developed in 2014, arose from the disposal CNT wastes. As required by local regulatory guidelines, Brewer Science incinerates all residual waste CNT suspensions as hazardous waste. Our calculations estimated that the environmental impacts originated from the fossil fuels and other energy resources (Fig. 3) required to power such high-temperature incineration, as well as the release of greenhouse-type combustion products to the atmosphere. The environmental impact of synthesizing the CNT powder, as emphasized by Eckelman et al. [3], was negligible relative to incineration of the CNT wastes.

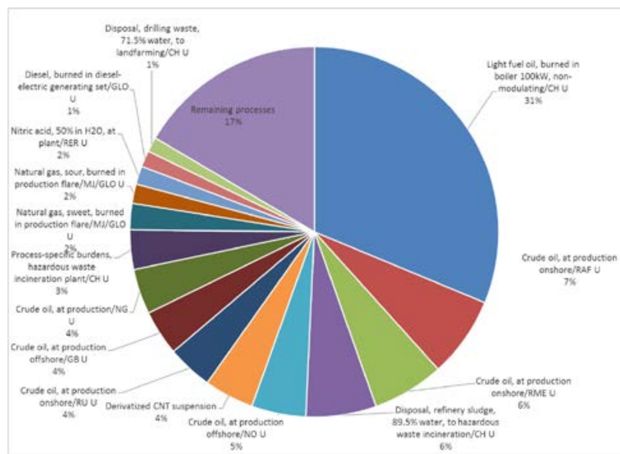

Figure 3. Pie chart representing the calculated process contributions to the environmental impacts for CNTRENE® 1030 material.

In light of these impacts, Brewer Science improved the efficiency of manufacturing the CNTRENE® 1030 material by reducing water usage, and consequently, waste generation by over 95%. Thus, Eco-LCA modeling (Fig. 2B) showed optimizing CNTRENE® 1030 material production resulted in substantial absolute reductions in climate change and resource depletion-associated impacts, by approx. one order of magnitude, based on the normalized impact score. Furthermore, optimization of the CTNRENE® 1030 material shifted the relative environmental burden from the energy consumption associated with hazardous waste incineration to electricity used in the manufacture process.

3.2 Eco-LCA results for the CNTRENE® 1030 material-based temperature sensor

Given the very small quantities of materials used in constructing the sensor, as well as the fact that Brewer Science had completely sealed all systems (to eliminate occupational exposures) associated with handling the raw and formulated CNT products and wastes, the absolute environmental impacts calculated from the Eco-LCA model related to the sensor's manufacture were very low in magnitude (Fig. 4). Greenhouse gas emissions and natural resource depletions associated with the use of compressed gas and electrical power requirements for creating the temperature sensor represented the bulk of the relative environmental impacts, reflecting the inherent challenges in adapting conventional manufacturing processes to next-generation materials.

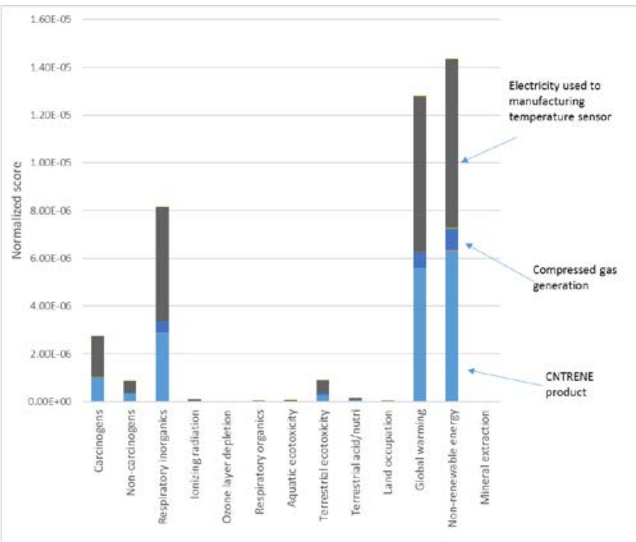

Figure 4. Calculated environmental impacts for the CNTRENE® 1030-based temperature sensor.

Particular processes contributing to these impacts (Fig. 5) are similar to those calculated for the CNTRENE® 1030 material. Thus, the Eco-LCA approach identified the opportunities to improve energy and cost efficiencies for this particular process.

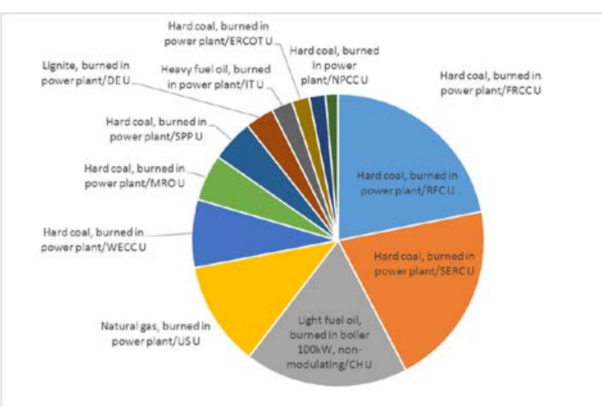

Figure 5. Pie chart representing the calculated process contributions to the environmental impacts for the production of the CNTRENE® 1030 material-based temperature sensor.

4 CONCLUSIONS

From this simple study, we concluded that the majority of environmental impacts in production of the CNTRENE® 1030 material arose from the high-temperature incineration of the dilute CNT suspension, and not from the production of the CNT materials. Enhancing the efficiency of the CNTRENE® 1030 material manufacturing process substantially reduced the computed environmental impacts. This benefit is expected to carry over in the production of the temperature sensor. This study shows, however, that the quantity of CNTs as well as other materials used in the production of the temperature sensor were so small in magnitude that the overall environmental impact was limited for the theoretical functional unit.

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