Advancing Sustainable Manufacturing of Carbon Nanomaterials and Devices through Life Cycle Assessment

Wu-Sheng Shih[†*], Mark A. Chappell[‡], Alan J. Kennedy[‡], John K. Bledsoe[†], Brooke N. Stevens[‡], Lesley F. Miller[‡], Qihua Wu[†], Chris Cox[†], William Stone[†], Dan Janzen[†], Stephen Gibbons[†], Christopher Landorf[†], Rishi Patel[#], Jonathon Brame[‡], Taylor Rycroft[‡], Matthew Wood[‡], Stephen A. Diamond[%], Doyle Edwards[†], Jeffery A. Steevens[‡]

*Corresponding author: wshih@brewerscience.com
[†]Brewer Science, Inc., Rolla, MO
[‡]U.S. Army Engineer Research and Development Center, Vicksburg, MS
[#]Missouri State University, Jordan Valley Innovation Center, Springfield, MO
[%]NanoSafe, Inc., Duluth, MN

ABSTRACT

Nanotechnology-related environmental, health, and safety (NanoEHS) decision-making tools, such as Nano NAV-PAL and NanoGRID, and the life cycle assessment (LCA) methodology have been successfully deployed to guide the research, development, engineering, and manufacturing of carbon nanomaterials (in this work, carbon nanotubes) and printed thermistors and moisture sensors to reduce the EHS impact and risk through improved manufacturing efficencies and material and device performance. Through the iterative LCA process and multiple cycles of improvements in R&D, engineering, and manufacturing processes, the projected EHS impact was significantly reduced by as much as 95% in certain categories. In addition, manufacturing productivity and performance were greatly improved by as much as one order of magnitude. This project was accomplished using NanoEHS decision-making tools and LCA to guide the development, manufacturing, and commercialization of nanomaterials, nanotechnology, and nanotechnology-enabled products in a rapid and socially responsible manner.

Keywords: carbon nanotubes, printed sensors, environmental health and safety, life cycle assessment, LCA

1 INTRODUCTION

Responsibly developing nanotechnology and fostering its use in products for commercial and public benefit are two of the four long-standing National Nanotechnology Initiative (NNI) goals [1]. To achieve these goals, nanotechnology-related environmental, health, and safety (NanoEHS) efforts need to consider the very early stages of research and development, captured within a "cradle-to-grave" life cycle assessment (LCA), Figure 1, to guide technology development and to accomplish sustainable manufacturing of nanomaterials and nanotechnology-enabled commercial products.

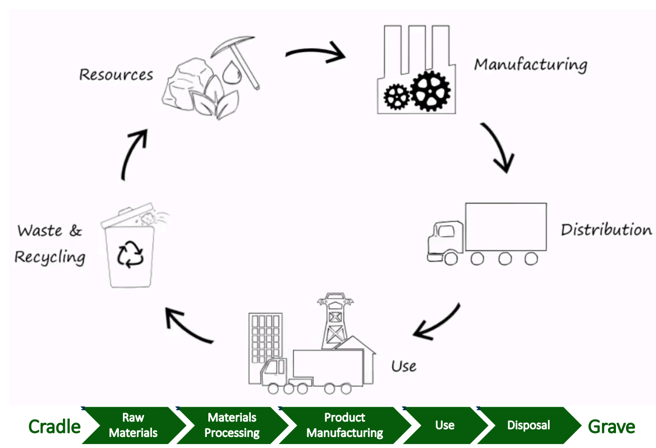

Figure 1. "Cradle-to-grave" life cycle assessment (LCA). A life cycle inventory (LCI) identifies and quantifies the energy and resources used along with the environmental releases throughout the life of a given product. LCI data are then entered into an analytical tool for LCA.

Through a public-private partnership, Brewer Science has been taking a proactive and systematic approach using NanoEHS and LCA methodologies to guide the development, manufacturing, and commercialization of carbon nanomaterials and devices. The NanoEHS assessment was conducted using a series of environmental risk assessments and decision-making tools developed at the U.S. Army Engineer Research Development Center (ERDC) – Environmental Laboratory, such as Nano NAV-PAL (nano-enabled navigation for product acquisition and liability) and NanoGRID (nanomaterials guidance for risk-informed deployment) [2. 3]. These tools facilitate and accelerate informed decision making for the product development and commercialization pathway with a systematic approach. The LCA methodology is deployed to guide the development and manufacturing of the carbon nanomaterials (in this case, carbon nanotubes, or CNTs) and devices (printed thermistors and moisture sensors) to improve productivity while reducing the environmental impacts and mitigating the health and safety risks to workers and the general public [4]. The basic concept of this study is illustrated in Figure 2, with the anticipated outcome of increasing the overall product manufacturing efficiency and performance while reducing the EHS impacts and costs throughout the life cycle of the materials, devices, and technology; see Figure 3. The project mission, objective, and detailed scope of this research have been described elsewhere [5].

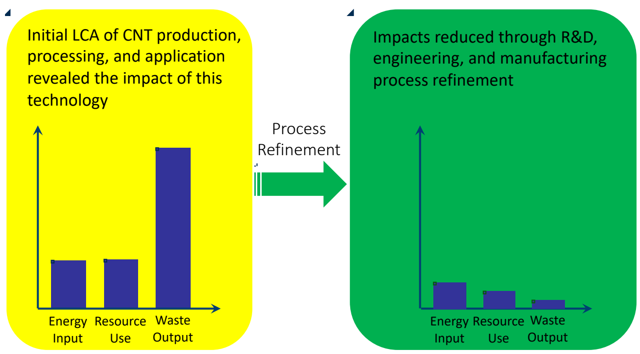

Figure 2. Concept of advancing carbon nanomaterials and devices while reducing EHS impacts through LCA.

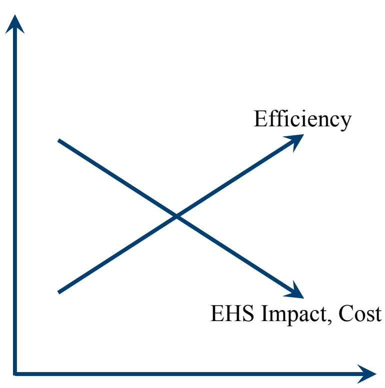

Figure 3. Anticipated outcome of this study: increasing the overall product manufacturing efficiency and performance while reducing the EHS impact and cost throughout the life cycle of the materials, devices, and technology.

2 METHODS

NanoEHS decision tools, such as Nano NAV-PAL and NanoGRID, were deployed to assist with decision making during materials, devices, and technology development. The LCA methology was used to identify the most critical EHS impact/risk categories and to guide the research, development, engineering, and manufacturing efforts to mitigate the identified risk. The details of the NanoEHS decision tools and LCA methology have been described elsewhere [2, 3, 4].

An iterative approach was taken using the LCA methodology to identify critical areas for improvement and to quantitatively validate the reduction of the EHS impact, Figure 2. During the development of the CNT material and device manufacturing processes, detailed technical process LCI data were collected and populated into an LCA model developed at ERDC to identify the initial impacts and risks and the major contributors to such risks. A mitigation plan was implemented to reduce or eliminate the major contributors, which in turn reduced the EHS impacts/risks.

To establish a reference point based on the starting manufacturing processes, an LCI was carefully constructed by thoroughly sampling the actual initial manufacturing processes for producing carbon nanomaterials and printed sensors (thermistors and moisture sensors). The LCI data were then fed into the gate-to-gate LCA model to identify major EHS impacts and risks and their contributing categories and factors ("Product Iteration 1" in the following figures). Subsequently, a mitigation plan with R&D and engineering efforts having specific engineering design criteria reducing impacts and risks in the identified categories and factors was planned and carried out.

Through multiple cycles of R&D, engineering, and manufacturing efforts, the LCI data were collected and LCA modeling conducted to determine the improvement in the manufacturing processes as well as the final EHS impact and risk ("Product Iteration 2" in the following figures) and its comparison with that of the reference point.

While reducing the EHS impact and risk, the overall performance and cost of the manufactured materials and devices should at least remain the same or be improved.

3 RESULTS AND DISCUSSION

The initial NanoEHS and LCA analysis first identified wastewater generated during the carbon nanomaterials manufacturing process as the major contributor to potential EHS impacts. The three primary potential EHS impacts identified were global warming, non-renewable energy consumption, and respiratory inorganics. After wastewater generation had been reduced by over 90% through multiple cycles of improvement, energy consumption was identified to be the next major EHS impact contributor. Through the iterative process, the overall manufacturing process was carefully examined and characterized, including the raw materials, chemistry, processing parameters, and process control (statistical process control (SPC) methodology deployed). For the printed sensor manufacturing process, the major EHS impact contributors were the materials and energy consumption. The sensor printing methodology and processing parameters were carefully evaluated, modified, engineered, and characterized to accomplish improved sensor performance while significantly reducing the potential for EHS impact.

Through the NanoEHS and iterative LCA approaches, efforts were made to reduce wastewater generation, energy comsumption, materials emission, etc., from the entire manufacturing process. As a result of these efforts, wastewater was reduced by an order of magnitude, major EHS identified impact categories were reduced by as much as 95%. Furthermore, carbon nanomaterial manufacturing throughput increased by nearly threefold without any additional capital investment, and device manufacturing throughput increased by an order of magnitude.

3.1 Carbon Nanomaterials and Printed Sensors Manufacturing Processes Improvement

Figure 4 shows that the R&D and engineering efforts have resulted in a nearly threefold increase in carbon nanomaterial (CNT) batch production yield without additional capital investment. The total metal ion impurity (14 metals identified and characterized using ICP-MS, mainly from the production of raw CNTs) in the final CNT formulation was reduced by 80%. Shelf life improved from 3 months to more than 12 months. The printed sensors (thermistors and moisture sensors) throughput was increased by nearly ten times, and performance consistency was improved.

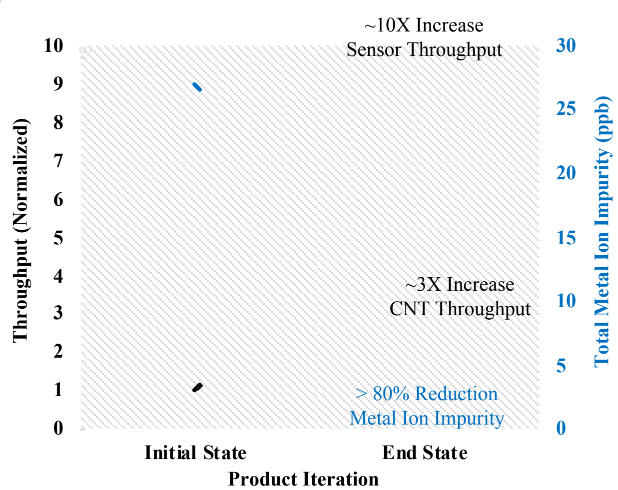

Figure 4. Improvements in manufacturing the CNT material and the printed sensors from the beginning (Product Iteration 1) to the conclusion (Product Iteration 2) of this project through multiple LCA iterations.

3.2 EHS Impact for the Carbon Nanomaterials and Printed Sensors

The initial LCA analysis of the carbon nanomaterial and printed sensors provided a reference point and identified the major EHS impact and risk contributors. Multiple cycles of LCA and mitigation plan were carried out through research, development, engineering, and manufacturing efforts to reduce the EHS impact and risk.

As shown in Figures 5 through 7, the three major EHS impacts, global warming, non-renewable energy consumption, and respiratory inorganics, were significantly reduced, by as much as 95%, through multiple cycles of LCA-guided research, development, engineering, and manufacturing efforts.

Figure 5. EHS impact/risk reduction of CNT material before (Product Iteration 1) and after (Product Iteration 2) multiple LCA iterations.

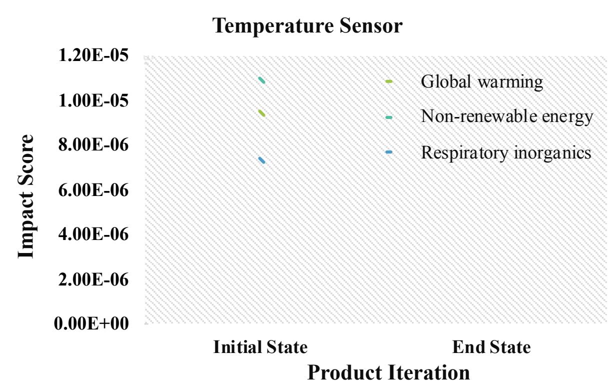

Figure 6. EHS impact/risk reduction of printed thermistor before (Product Iteration 1) and after (Product Iteration 2) multiple LCA iterations.

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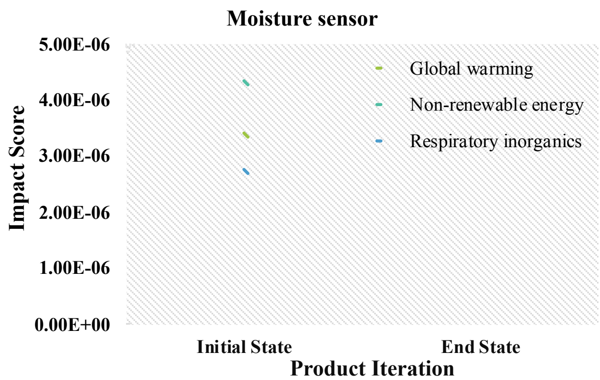

Figure 7. EHS impact/risk reduction of the printed moisture sensors before (Product Iteration 1) and after (Product Iteration 2) multiple LCA iterations.

The NanoEHS decision-making tools and LCA methodology have clearly guided development and manufacturing of the carbon nanomaterial and printed sensors to reduce the EHS impact and risk while increasing productivity and improving performance. The efficiency of the research, development, engineering, and manufacturing of carbon nanomaterials and printed sensors was significantly improved, as were the production throughput, quality, and performance. The EHS impacts on global warming, non-renewable energy consumption, and respiratory inorganics have been dramatically reduced, by as much as 95%. Consequently, the overall economic and social cost of ownership, from research to disposal of the carbon nanomaterials and printed sensors, has been reduced, and the benefit has been substantially increased.

4 CONCLUSIONS

Through the development, application, and guidance of the NanoEHS decision-making tools and LCA methodology, significant increases in productivity and performance of the carbon nanomaterials and printed sensors have been achieved with dramatic decreases in EHS impacts and risks. This project has accomplished the following goals:

1. Socially responsible development and commercialization of CNT materials and printed sensors with much reduced EHS impact and risk.
2. Use data-driven NanoEHS decision-making tools and LCA process to guide nanomaterial, nanotechnology, and nanotechnology-enabled product development and manufacturing.
3. Facilitate and improve performance while significantly reducing EHS impact and risk.

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