Screening Level Cradle to Grave Life Cycle Assessment of Conceptual 15 Inch Carbon Nanotube (CNT)-Field Emission Display(FED) Device

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ABSTRACT

Commercialization of carbon nanotube field emission displays (CNT-FEDs) is highly encouraged because of their conceptually proven features that offer multiple benefits to consumers. However, considering they are nanomaterial-enabled (CNT) products, large-scale deployment of CNT-FEDs must be approached cautiously because of their potential to adversely impact human health. To better understand of the holistic human health and environmental impacts related to CNT-enabled products, life cycle assessment (LCA) can be used to evaluate the environmental performance of a CNT-FED. In this study, we report and discuss the results obtained from a screening-level, cradle-to-grave LCA of a conceptual 15-inch CNT-FED which is assumed to be produced, used for its effective life and disposed of without recycling in the US. Results show the manufacturing stage dominates the life cycle impacts. However, the environmental performance of a CNT-FED is still much better than cathode ray tube (CRTs) and liquid crystal displays (LCDs).

Keywords: Life cycle assessment, CNT-FED, CRT, LCD.

1 INTRODUCTION

Carbon nanotubes (CNTs) are expected to improve the performance and longevity of a variety of consumer products. Additionally, CNT-enabled products have the potential to reduce the environmental burden associated with conventional products. Although knowledge of the commercial use of these products is lacking, conceptual designs for such products suggest the following environmental benefits are possible: (a) decreased depletion rates of nonrenewable natural resources; (b) reduced use of hazardous and/or toxic materials during product manufacturing; (c) increased energy efficiency during use; and (d) reduced quantities of product waste for disposal at the end of their life [1].

As promising as these benefits sound, large-scale commercialization of CNT products should proceed cautiously with an understanding that unforeseen impacts to human health and the environment could occur. For example, the CNT manufacturing process has been associated with increased global warming [2] and elevated ecotoxicity impacts [3]. Similarly, CNTs released during the product life cycle can have multiple effects on human health (e.g. hemolysis & mesothelioma) [4] and ecosystems (e.g. rise in mortality rates of several aquatic species and cause disruption in food chains) [5]. To better understand these tradeoffs, there is an urgent need to critically evaluate CNT-enabled products during the developmental stage of product deployment. For this purpose, a holistic assessment tool such as life cycle assessment [6] can be applied to quantify the potential environmental impacts associated with the CNT products. The replacement of conventional products with CNT-enabled products has to be rationally justified based on the fact the latter would offer a superior environmental performance compared to the throughout the life cycle to avoid burden shifting.

This paper presents the results of a comparative assessment of a CNT-enabled product to conventional technologies. We selected a conceptual CNT-field emission display (FED) device as our model product and performed a screening level cradle-to-grave LCA to identify potential hot spots in the life cycle. We then compared the results to a cathode ray tube (CRT) display and liquid crystal display (LCD) assuming the three display devices have similar specifications and the same effective life. Initial prototypes of CNT-FEDs are considered to be efficienct as compared to state-of-the-art (e.g. LCD) and emerging (e.g. LEDs) display types because of their superior image quality and low size-to-weight ratio [7]. Furthermore, CNT-FEDs have been designed to operate with a greater energy efficiency when compared to the others [8]. However, the assumption this improved performance will make CNT-FEDs the superior product environmentally will depend on how much this benefit outweighs the impacts attributed to other stages in the life cycle of the product as determined using LCA.

2 DETAILS OF SCREENING LEVEL LCA OF CNT-FED

LCA is a modeling technique for characterizing and quantifying environmental impacts associated with a product by considering all the life cycle stages of a product from cradle (raw material acquistion) to grave (end of life which may or may not include recycling and reuse stages). The CNT-FED study approach followed the LCA methodology described by the ISO 14040 &14044 standards [9].

2.1 Goal and Scope of the Study

The goal of this assessment is to perform a screening level LCA of one CNT-FED that is manufactured, used for its effective life, and disposed of in the US. Remanufacturing, recycle or reuse at end of life of the product was not included. The effective life is defined as the "life time operating hours" that a CNT-FED is used by single or multiple users before being disposed because it no longer functions properly [10]. Effective life is an important parameter needed to compute the total use-phase power consumption of an electronic display panel based on its operating pattern [10].

2.2 Life Cycle Inventory Data for CNT-FED

A block diagram representing the major life cycle stages of a CNT-FED is shown in Figure 1.

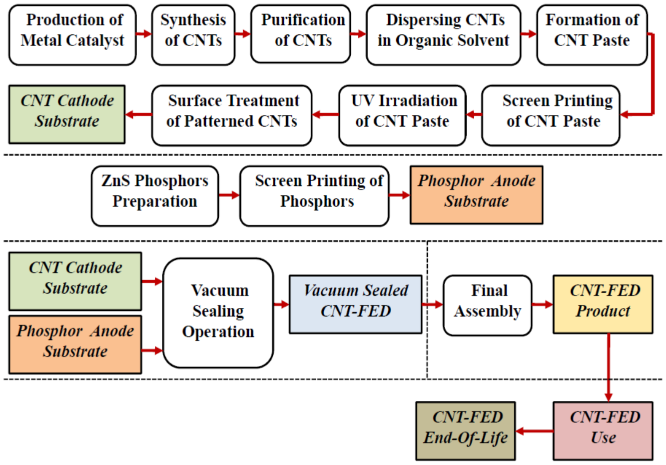

Figure 1. Life Cycle of a CNT-FED Product

The manufacturing process of CNT-FED consists of four steps: 1. fabrication of the CNT cathode substrate, 2. fabrication of the phosphor anode substrate, 3. vacuum sealing the field emission assembly containing the anode and cathode, and 4. final assembly. Fabrication of the CNT cathode substrate begins with the uniform dispersion of acid purified CNTs in organic solvents such as isopropanol (IPA) in the presence of small amounts of a dispersing agent (e.g. polyvinyl pyrolidone (PVI) or sodium dodecyl benzene sulfonate (SDBS)) using ultrasonication to obtain a homogenous mixture. The CNT solution is heated to maximize the evaporation of IPA solvent while maintaining the dispersivity of CNTs in the remaining solvent. Glass frit, metal powder, and organic binder are then added to the mixture followed by intense milling in a 3-roll ball mill for 2 hours [11]. The metal powder enhances the conductivity of the paste [12], whereas the frit improves cohesion of the CNTs on the substrate after screen printing. Finally, a photosensitive vehicle is added to the above mixture and the milling is continued for another 2-3 hrs [11].

The CNT paste is screen printed onto an indium tin oxide (ITO) coated glass substrate and subsequently patterned to a predetermined shape using a UV hardening method [11, 12]. The patterned CNT-coated glass substrate is baked at a temperature of 400-500°C in a nitrogen rich atmosphere to remove the organic binder from the CNT paste [11]. However the baking process might result in the loss of field emission activity of CNTs as they tend to bury themselves underneath the organic contents of the paste [11]. Therefore, the baked CNT-coated glass substrate is treated with a liquid phase surface treating material, as described by Jin et al [11], to complete fabrication of the CNT cathode.

Preparation of the phosphor anode substrate in step 2 involves deposition of phosphors onto an ITO-coated glass substrate [13]. In this study we assumed the use of zinc sulfide (ZnS) phosphors activated with trace amounts of Cu and Ag metals, as decribed by Poss [13].

In step 3, the CNT cathode and phosphor anode substrates are vacuum sealed according to flat panel display protocol given by Dunham et al. [14]. Finally, in step 4, the vacuum sealed CNT-FED is assembled with electronic components such as cables and printed wiring board (PWB) and encased in a housing assembly to obtain the finished CNT-FED product. The downstream side of manufacturing of CNT-FED consists of use and end-of-life to complete the life cycle.

In addition, the energy consumption of processes associated with CNT-FED manufacturing is calculated either based on the equipment data specification sheets or literature data. The energy is assumed to be supplied from the US energy grid. The LCI data were built using SimaPro LCA software. The primary data needed for manufacturing of CNTs and CNT-FED unit was obtained from academic & scientific literature, whereas the secondary data which are inclusive of LCI data of other raw materials, e.g. Zn for production of ZnS, metal catalyst material for production of CNTs, and organic solvents, acids and CNT paste constituents etc were obtained by ERG [15], and from the USLCI [16] and Ecoinvent [17] databases. ERG is an externally acquired database whereas the latter two are inbuilt within SimaPro. Based on the assumptions listed in Table 1, LCI data for a CNT-FED are given in Table 2.

Table 1. Major Assumptions Made in Collecting LCI Data

Step	Major Assumptions
Pre Manufacturing	
Metal catalyst prodn.	• Ni: Fe: Al_2O_3 catalyst system with (20:20:60) wt% is used [18]
CNT synthesis	• C_2H_2 is used as carbon precursor with CNT synthesis occuring in a catalytic chemical vapor deposition reactor [19] • Synthesis reaction yield & and carbon deposition yields assumed as 30% [18, 20]
CNT Purifn.	• 50 ml of Conc. H_2SO_4:HNO_3 @ 3:1 v/v needed to purify 0.5g CNTs
Phosphors Prodn.	• Cu & Ag activated ZnS phosphors are used
CNT-FED Manufacturing	
Dispersion of CNTs in IPA	• 500 ml IPA & 125 mg dispersing agent needed for 0.5 g CNTs [21]
Formation of CNT paste	• CNT paste is comprised of 30 wt % CNTs; 5 wt % each of frit & Ag powder; 40 wt% epoxy resin; 20 wt% photosensitive vehicle (MMA) [11]
Fabrication of CNT cathode	• Amnt of glass is similar to LCD • Post screen printing protocol is based on patent literarure [11]
Fabrication of phosphor anode	• Amnt of glass is similar to LCD
Vac. Sealing of CNT-FED	• Material & energy data is calculated based on patent literature [14]
Final assembly of CNT-FED	• Amnts of cables, housing etc are 5.5 times less than LCD because of low weight to size ratio of CNT-FED [8]
CNT-FED Use	
Effective life of usage of CNT-FED	• Operating patterns (65% office & 35% home) similar to LCDs • 1st life = 4 yrs; 2nd life = 2.5 yrs. The definition of 1st & 2nd lives provided by Socolof et al [10] • Power consumption = 12 W [8]
CNT-FED End Of Life	
End of Life of CNT-FED	• No disposition data is yet available. Thus, it is assumed that 55% of CNT-FED is land filled & 45% incinerated.

Table 2. LCI Data for CNT-FED (Only Major Materials &Energy Inputs are Shown)

Material/Energy Inputs	Amount Needed (kg)
Stage 1: Synthesis of 100 grams of CNT Paste	
Acid-Purified CNTs	0.03
Isopropanol (IPA)	11.789
Epoxy Resin	0.04
Methyl Methacrylate	0.02
Glass frit	0.005
Ag metal powder	0.005
Stage II. CNT Cathode Substrate Fabrication	
CNT paste from stage 1	0.1
Cr-coated flat glass	0.590
ITO powder	5E-04
Stage III. Phosphor Anode Substrate Fabrication	
ZnS	0.0188
Flat glass uncoated	0.59
ITO Powder	5E-04
Stage IV. Vacuum sealing of CNT-FED Module	
CNT cathode substrate	0.6905
Phosphor anode substrate	0.6092
Stage V. Final assembly of CNT-FED Unit	
Vacuum sealed CNT-FED	1.2997
Printing wiring board	0.185
Cables	0.23
Galvanized steel	0.9
Aluminum	0.06
Polystyrene	0.36
Polycarbonate	0.52
Total Mfg. Energy	65-70
Use Phase Energy/ Eff. Life	82 kWH
End of Life Allocations	50% to landfill; & 45% incineration.

The impacts of a CNT-FED are compared with the impacts of a 15-Inch CRT display and an LCD display. Complete LCI data modules for these displays are available in the Ecoinvent database of SimaPro [17].

2.3 Life Cycle Impact Assessment Method

The impacts of the CNT-FED were calculated by applying the U.S. Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) [22]. The calculated mid-point impacts for this method are global warming (kg CO2 equiv), acidification (H^+ moles equiv), carcinogenics (kg benzene equiv), non-carcenogenics (kg toluene equiv), respiratory effects (kg PM2.5 equiv), eutrophication (kg N equiv), ozone depletion (kg CFC-11 equiv), ecotoxicity (kg 2,4-D equiv), and smog (kg NOx equiv).

The impact scores for CNT-FED are given in Table 3.

Table 3. Impact Assessment Results for CNT-FED

Impact	Eq. Units	MFG	USE	EOL
Global Warming	kg CO_2	150.69	63.63	1.04
Acidification	H^+ moles	59.56	28.69	0.033
Carcinogens	kg benzene	1.08	0.047	0.29
Non carcinogens	kg toluene	13,415.1	111.33	9348.96
Resp. Inorganics	$PM_{2.5}$	0.24	0.10	8.7E-05
Eutrophication	kg N	1.05	0.0075	0.0097

Ozone Depletion	kg CFC-11	4.4E-06	4.8E-10	6.9E-09
Ecotoxicity	kg 2-4 D	692.59	2.266	78.53
Smog	g NO_x	0.56	0.22	7E-04

2.4 Interpretation of Results

As seen in Table 3, manufacturing dominated the total impacts compared to the other stages of the product life cycle. A comparison of the environmental performance of a CNT-FED display, the impacts are compared with those of an LCD and a CRT display is, shown in Table 4.

Table 4. Impact Assessment Results for CNT-FED, LCD & CRT

Impact	Eq. Units	FED	LCD	CRT
Global Warming	kg CO_2	**215.37**	525.15	**625.79**
Acidification	H^+ moles	**88.29**	200.64	**568.26**
Carcinogens	kg benzene	**1.425**	6.593	**7.140**
Non carcinogens	kg toluene	**22,875.4**	88,141.4	**122,343**
Resp. Inorganics	$PM_{2.5}$	**0.351**	0.826	**1.147**
Eutrophication	kg N	**1.076**	**4.945**	1.177
Ozone Depletion	kg CFC-11	**4.4E-06**	**2E-05**	1.2E-05
Ecotoxicity	kg 2-4 D	**773.39**	**3616.65**	1909.06
Smog	g NO_x	**0.793**	1.541	**2.060**

The maximum impact values are highlighted in red and minimum values in green for all three displays. Of the three display types, the CNT-FED has the least amount of impact in all nine categories compared to LCD and CRT.

3 CONCLUSION

This streamlined LCA demonstrates the environmental performance of a CNT-FED can be better than CRT and LCD displays. Although this is encouraging with respect to commercialization, these results are preliminary and depend on refinements to the LCA process to better evaluate nanoproducts. For example, impact characterization factors have not been developed specifically for nanomaterials like CNTs. More accurate values might lead to larger impacts associated with CNT products. On the other hand, continuing impact scores for CNT-FED might change greatly as they are made available. Furthermore, improvements in CNT-FED manufacturing (e.g. alternate methods to make CNT paste) could lead to more reductions in the overall environmental impacts of displays. Ultimately, a rigorous, iterative LCA is needed to maximize the benefits associated with CNT-FED technology.

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