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Life Cycle Impacts and Benefits of a Carbon Nanotube-Enabled Chemical Gas Sensor

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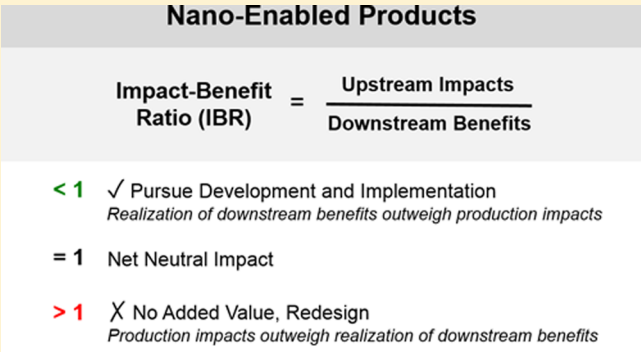
Supporting Information

ABSTRACT: As for any emerging technology, it is critical to assess potential life cycle impacts prior to widespread adoption to prevent future unintended consequences. The subject of this life cycle study is a carbon nanotube-enabled chemical gas sensor, which is a highly complex, low nanomaterial-concentration application with the potential to impart significant human health benefits upon implementation. Thus, the net lifecycle trade-offs are quantified using an impact-benefit ratio (IBR) approach proposed herein, where an IBR < 1 indicates that the downstream benefits outweigh the upstream impacts. The cradle-to-gate assessment results indicate that the midpoint impacts associated with producing CNTs are marginal compared with those associated with the other manufacturing stages. The cumulative upstream impacts are further aggregated to units of disability-adjusted life years (DALYs) using ReCiPe end point analysis method and quantitatively compared with the potential downstream DALY benefits, as lives saved, during the use phase. The approach presented in this study provides a guiding framework and quantitative method intended to encourage the development of nanoenabled products that have the potential to realize a net environmental, health, or societal benefit.



INTRODUCTION

Chemical gas sensors are used in a range of industrial applications as well as to prevent environmental and human health consequences caused by exposure to harmful gaseous chemicals.[1−4] Development of chemical sensor technology began around 1970 to enable detection of odorants and combustible gases.[5−7] Since then, concern over permissible limits and impacts of exposure to certain air pollutants has driven the development of improved sensing technologies.[8] Semiconducting metal oxides (e.g., ZnO, SnO_2, and TiO_2) are commonly used in electrochemical sensors.[7,9] Recently, the incorporation of nanomaterials has been realized as a way to facilitate improved sensor performance since their length scale offers increased surface area to volume ratio providing high adsorption capacity and increased reactivity.[2] Single-walled carbon nanotubes (SWNTs) are a specific class of nanomaterial that offer a promising alternative to semiconducting metal oxides. Their 1D structure is composed entirely of surface atoms making SWNTs incredibly sensitive to minute changes in the chemical environment.[3,4] Furthermore, SWNTs have distinct electronic properties dependent on the diameter and helicity.[10,11] SWNTs can be functionalized or doped to improve selectivity and sensitivity further enhancing their performance in a chemical sensor application.[1,4,12,13]

There are several shortcomings of conventional (non SWNT-enabled) gas sensing technology, including high cross sensitivity to multiple gaseous substances, long break-in time, unreliability under variable power availability, sensitivity to environmental conditions, and decreased performance over time due to high operation temperature requirements.[3,7,9] The next generation of SWNT-enabled chemical gas sensors offers numerous benefits over the conventional alternatives, including small size, fast response time, high sensitivity, high selectivity, low sensitivity to environmental conditions, room temperature operation, low power consumption, and quick recovery time.[1,3,4] Many of these performance parameters have been empirically demonstrated and are summarized in recent reviews.[1,14]

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The subject of this study is a SWNT-enabled chemical sensor currently under laboratory development to detect hydrogen sulfide (H_2S).[13,15,16] H_2S is a colorless flammable gas that can be extremely harmful to human health depending on the acute or chronic exposure concentration.[8,17−20] H_2S arises from both natural and anthropogenic sources. Natural sources of H_2S include volcanic gases, crude petroleum, natural gas, and hot springs.[17,18] Anthropogenic sources of H_2S are associated with natural gas drilling and refining, kraft pulp and paper manufacturing, sewage treatment, tanning, and mining processes.[17,18] Exposure to H_2S can result in a range of human health effects, including death.[18] Therefore, a use-phase extension of the life cycle assessment (LCA) is presented here to evaluate the potential realization of downstream human health benefits upon implementation of the SWNT-enabled sensor with enhanced performance abilities. Advantages of the sensor studied here include remote sensing capabilities, increased detection range, decreased measurement time, low cross sensitivity to other gases, and reliable performance under O_2-free, high pressure, high temperature, and high humidity environments (performance metric comparison between the H_2S sensor under development and three conventional alternatives is provided in Supporting Information (SI) Table S1).[13,21,22]

While SWNT-enabled chemical sensors offer promising performance enhancements to guard against exposures and protect human health, it is important to consider the implications associated with production and implementation of the improved technology. A comprehensive evaluation of potential risks and impacts associated with SWNTs and SWNT-enabled products takes into consideration the entire life cycle. The majority of CNT life cycle assessment (LCA) studies to date have focused primarily on the nanotube synthesis or product manufacturing impacts (cradle-to-gate), including material demand, energy requirements and amount of waste generation.[23−25] Realization of these associated implications has motivated improvements in nanomanufacturing techniques, focusing on low-cost, high-rate, and resource-efficient methods that have resulted in reduced energy and waste generation.[26] Other studies focus specifically on potential CNT release and ecotoxicity impacts.[27,28] Only recently have both CNT production and CNT exposure been incorporated and considered together in a LCA.[29]

Several studies have highlighted the significant upstream resource requirements for semiconductor and nano device manufacturing.[30−32] The manufacturing steps required for the next generation sensor are largely the same as for conventional sensors currently in use. The primary difference is the replacement of the sensing source, typically a semiconducting metal oxide, with SWNTs. While the synthesis of pure SWNTs is resource-intensive, their contribution to the cradle-to-gate impacts of nano enabled devices depends on SWNT loading and any required changes in manufacturing. Dahlben et al. showed that SWNTs used in an electronic switch for flash memory applications contribute less than one billionth of a percent to overall resource use and environmental impacts.[33] Even at low concentrations, however, SWNTs can impart significant improvements to device or material performance, with energy, environmental, or health benefits that may far outweigh any negative impacts associated with nanomaterial synthesis and device manufacturing.

LCA models are specifically designed to analyze trade-offs among different life cycle stages, for example between device production and use, and among several categories of environmental and health impacts. A common obstacle to implementing and interpreting LCA results for novel materials or emerging technologies, however, is that often they have not yet been commercialized, so their specific applications and end-of-life disposition are unknown.[34] For nanomaterials, only a handful of LCA studies have considered trade-offs between production and use stages, including for vehicle lightweighting,[35] antimicrobial treatments for textiles,[36] and electronics.[33] Use−phase benefits to human health can be particularly difficult to quantify in a life cycle framework as they cannot be measured or deterministically modeled.

Several alternate methods exist, particularly in risk assessment, that consider impact and benefit trade-offs associated with emerging nanotechnologies, and these have been applied to nanomaterials and carbon nanotubes specifically.[37,38] Most recently, Canis et al. and Linkov proposed two approaches for evaluating risk associated with nanomaterial synthesis, (1) a stochastic multiattribute analysis and (2) a combined multi-criteria decision analysis (MCDA) risk assessment method, respectively.[37,38] These approaches can use LCA results as model inputs, but as with LCA, the accuracy of results obtained using these approaches is frequently limited by the lack of comprehensive data surrounding the use, fate, exposures, and effects associated with emerging technologies such as nanomaterials. The strengths and weaknesses of these combined approaches are comprehensively outlined by Linkov.[38]

The benefit of such approaches is that they provide early evaluation and identification of key aspects of the life cycle that are of primary concern to a given stakeholder (e.g., manufacturer or regulator). Decision frameworks built on MCDA methods are adaptable to specific stakeholder concerns, where quantitative life cycle impacts are normalized, integrated with qualitative measures of benefits, and then combined based on subjective but transparent weighting sets.[37,38] A recent publication by Prado-Lopez et al. presents a stochastic multiattribute analysis for life cycle impact assessment (SMAA-LCIA) that combines MCDA approaches with LCA methods.[39]

The present study uses LCA to evaluate the potential environmental and human health impacts associated with the synthesis and incorporation of SWNTs into these next generation H_2S gas sensors, in order to quantify the relative contribution of SWNTs to the cradle-to-gate impacts of the overall device. The analysis also extends to potential reductions in human mortality related to the sensor's enhanced capabilities and performance, using a hypothetical scenario to illustrate the balance between production and use implications. The cradle-to-gate analysis delivers results across multiple categories of environmental and health impacts, while the discussion of use-phase benefits focuses only on the single end point of disability-adjusted life years (DALYs), because reducing human exposure is the primary purpose of the H_2S sensor being evaluated.

The integrated life cycle assessment and impact-benefit approach presented in this study intends to provide a quantitative evaluation of the product manufacturing impacts and potential use-phase benefits of a developing nano-enabled product in units that are physically meaningful. Rather than a comparative decision making analysis, the method presented here is intended to quantify both the indirect impacts and direct benefits of a single nano-enabled device to inform future research and development.

METHODS

Goal and Scope. The goal of this study in to perform a cradle-to-gate LCA of a SWNT-enabled chemical gas sensor currently under development. The study is designed to identify (1) which inputs and manufacturing processes are most impactful, (2) the impacts of SWNT production relative to the entire sensor device, and (3) the potential impacts of large-scale deployment of these sensors relative to their potential benefits to public health and safety. For this particular SWNT-enabled product, the probability of exposure to SWNTs is of minimal concern. The SWNTs used during sensor manufacture are in suspension, minimizing the probability of inhalation exposure. Furthermore, the SWNTs in the sensor are embedded at low concentrations (~7 mg/chip, 0.17% of the total mass) making exposure during the use phase highly unlikely. For these reasons and the lack of consensual empirical data regarding the life cycle environmental implication of carbon nanotubes, releases and end-of-life processes are not considered here. Rather, the focus is on the SWNT material and manufacturing impacts relative to the impacts of other sensor material and manufacturing processes. In addition, a performance assessment comparison of a conventional and SWNT-enabled sensor will enable realization of the benefits and trade-offs associated with adopting next generation sensor technology.

Reference Flow and System Boundary. The chosen reference flow for the cradle-to-gate LCA is one chip; this is the basis on which all of the inputs and results are scaled. One chip contains 16 sensors and there are 36 chips per silicon wafer. The functional service provided by each sensor is H_2S detection, down to a limit of 1 ppm, but the number of sensors required to prevent one occupational fatality is unknown. Thus, to enable comparison of the sensor production impacts and potential realization of downstream human health benefits, the functional unit of DALYs preserved is used and will be discussed in later sections. DALYs is a metric established by the World Bank and the World Health Organization to quantify the burden associated with premature death, disease, and injury.[40] DALYs are used here to enable comparison between the human health impacts of sensor production and the human health benefits associated with the improved performance of the nanoenabled sensors over the conventional sensor alternative. The assessment includes all upstream production, transportation, and infrastructure components for each of the chemical, material, and energy inputs into chip fabrication and manufacturing. This includes production and high-purity refining of standard silicon wafers used in electronics applications (4 g, 45 cm^2, >8N purity) as well as SWNT manufacturing via the most commonly used CVD process. The SWNT synthesis inventory was compiled from Healy et al.[25] The sensor manufacture requires 11 processing stages discussed in detail elsewhere and summarized in Table 1.[13,15,16]

Energy associated with the use of laboratory equipment was determined using specific power requirements and the length of time used. Facility-level inputs, such as lighting and HVAC operation for laboratory clean rooms, are not included in this study as they are assumed to be similar to those used to manufacture conventional sensors.[1,13] Figure 1 outlines the system boundaries of the study.

Inventory and Impact Assessment Method. Inventory data were directly measured during bench-scale device fabrication, or estimated based on equipment specifications (Table 2). Each material and energy input and output was matched with corresponding unit processes taken from the US-EI 2.2 and Ecoinvent 2.2 LCI databases. All modeling and calculations were performed using SimaPro 7.3.3 software platform (PRé Consultants, Amersfoort). Environmental and public health burdens resulting from this resource use and associated emissions were evaluated using the U.S. EPA's TRACI 2 impact assessment method including the impact categories of global warming (green house gas emissions), acidification, eutrophication, ozone depletion, smog formation, human health impacts from carcinogenic, noncarcinogenic, and respiratory disease, and ecotoxicity. In addition, ReCiPe, an end point impact assessment method (v1.08, World H/H), was used to evaluate the resulting damage to human health in equivalents of DALYs.[41] The associated characterization table of the relative contribution of each processing stage to the DALY impacts is provided in the SI (Table S2).

Assumptions. Certain chemical inputs were not included in any current LCI databases, in which case synthesis of these chemicals were modeled based on known reactions using existing chemical unit processes in stoichiometric quantities. Table 2 includes the compiled inputs and outputs for the sensor manufacturing process, references utilized, and all assumptions of modeled inputs. The SWNT mass is the most uncertain input parameter in the study and increased resource

Table 1. Sensor Manufacturing Processing Stages

stage no.	description
1	PMMA deposition and baking (including Si chip processing)
2	dicing wafer into chips
3	cleaning and removal of PMMA protecting layer
4	plasma etch
5	lithography for trenches
6	dip coating for SWNT assembly in trenches (analysis completed both including and excluding SWNT manufacture by CVD process)
7	cleaning and removal of PMMA layer
8	lithography for contact leads
9	metal deposition for contacts
10	lift off
11	functionalization

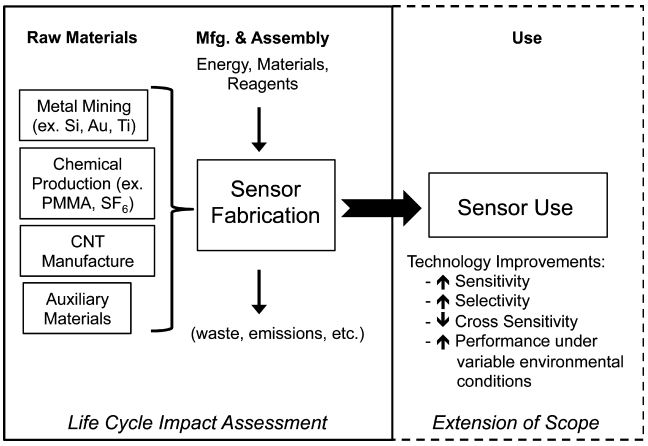

Figure 1. Scope and system boundary of this life cycle assessment of a next generation SWNT-enabled chemical gas sensor. The solid line boundary encloses those processes included in the impact assessment. The dashed line indicates the boundary of the impact extension.

Table 2. Input Materials, Outputs and Energy Associated with the Fabrication of One Functional Unit (F.U. = 1 Chip, 16 Sensors/Chip, 36 Chips/Wafer) Including, Relevant Processing Stages, Simapro Specific Inputs, and References for Assumptions Made to Specific Inventory Items

chemical/ material inputs	g/chip	relevant stage(s)	SimaPro unit process input
silicon	0.11	1	single-Si wafer, electronics, at plant (629g/m^2)/US-EI
poly(methyl methacrylate)	20	1, 5, 8	poly(methyl methacrylate), beads, at Plant/US-EI
titanium	0.00010	9	titanium dioxide, production mix, at plant/US-EI (contained Ti basis)
gold	0.013	9	gold at regional storage/US-EI
pyridine compound	0.21	10	pyridine-compounds at regional storehouse/US-EI (proxy for TEMPO)
carbon nanotubes	0.0069	6	existing LCI data for CVD manufacturing process[25]
plastic film	0.083	2	extrusion, plastic film/US-EI
paper towels	55	1, 3, 5, 8	Kraft paper, unbleached, at plant/ US-EI
solvent inputs			
acetone	1980	3, 7, 9	acetone, liquid, at plant/US-EI
isopropanol	4560	3, 5, 8	isopropanol, at plant/US-EI
4-methyl-2-pentanone	600	5, 8	4-methyl-2-pentanone, at plant/ US-EI
gas inputs			
nitrogen	1.7	3, 7, 9	nitrogen, liquid, at plant/US-EI
sulfur hexafluoride	6.3	4	sulfur hexafluoride, liquid, at plant/US-EI
argon	0.46	4	argon, liquid, at plant/US-EI
oxygen	1.4	4	oxygen, liquid, at plant/US-EI
total water & energy input			
tap water (L)	0.53	2	tap water, at user/US-EI
deionized water (L)	2.1	2, 3, 5, 6, 8	water, deionized, at plant/US-EI
energy (kWh)	119	1, 2, 4, 5, 6, 8, 9	medium voltage, consumer mix, at grid,/US-EI

efficiency is likely upon commercial scale up.[42] As such, a sensitivity analysis was performed around the SWNT mass loading. Labor inputs are expected to be minimal for commercial scale production and are not included.

LCA model uncertainty was not considered here, due to the lack of robust information on the probability distributions for each input at this early stage of development. As such, this should be considered a screening-level analysis.

■ RESULTS AND DISCUSSION

Cradle-to-Gate Life Cycle Impacts and Interpretation. Figure 2 presents the compiled results from the impact assessment organized by manufacturing stage (Figure 2a,b) as well as by material and energy inputs (Figure 2c,d). Figure 2a,c includes the compiled midpoint assessment results from the TRACI 2 analysis method while Figure 2b,d include compiled end point assessment results from the ReCiPe World H/H analysis method (in units of DALYs). SWNTs are utilized in Stage 6 (dip coating for SWNT assembly in trenches), but SWNT manufacturing inputs and outputs are compiled separately to illustrate the associated impacts relative to other processing stages.

Consistent with previous studies, there are notable impacts associated with SWNT manufacturing via chemical vapor deposition (CVD), yet they are marginal compared to the impacts associated with the overall fabrication stages (Figure 2a,b).[23−25,29] It is important to note that the concentration of SWNTs utilized in the fabrication of this sensor is very low (9.5×10^{-5} % of the total input mass). The results should not suggest that SWNT manufacturing is impact-free, merely that they are not the driver of total life cycle impacts of this chemical sensor. There is room for continued improvement and further reduction of deleterious CNT manufacturing impacts.[43,44] Given the uncertainty in SWNT mass loading and likely increase in resource efficiency, a 50% decrease from the given mass was evaluated. The relative contribution of CVD synthesis to the overall impacts ranged from ∼0.3% to ∼0.7% and the impacts scaled linearly with the change in mass loading.

The stages with the greatest overall impact include Stages 5 (lithography for trenches, blue), 8 (lithography for contact leads, purple), and 9 (metal deposition, light green), and the relative impacts are consistent in both the midpoint and end point assessment results. Lithography for contact leads (Stage 8), results in the greatest environmental and human health impacts, while lithography for trenches (Stage 5) and metal deposition (Stage 9) are the next most impactful manufacturing stages. The processes involved in developing the contact leads (Stage 8) account for over 40% of each impact category, while metal deposition (Stage 9) contributes most significantly to noncarcinogenic (34%) and ecotoxicity (21%) midpoint impact categories and the human toxicity (38%) end point impact category. Stage 5, lithography for trenches, accounts for 30% of the eutrophication potential and approximately 20% of smog, acidification, and respiratory effects (Figure 2a), while contributing 26% of photochemical oxidant formation and approximately 20% of particulate matter formation and climate change human health (Figure 2b). These high impact processes of stages 8, 5, and 9 are ubiquitous in semiconducting device manufacturing and are not unique to the SWNT-enabled device.

The material and energy inputs associated with the manufacture of one chip are evaluated and are compiled in Table 2. Figures 2c,d present the relative midpoint and end point impacts, respectively, associated with specific inputs. Energy requirements, in the form of electricity, have the greatest environmental and human health impact accounting for 87% of the total ozone depletion and greater than 55% of carcinogenics, noncarcinogenics, respiratory effects, and acidification potential (Figure 2c), while contributing over 50% to ozone depletion, human toxicity, particulate matter formation, and ionizing radiation end point categories (Figure 2d). Stage 8 (lithography for contact leads) requires nearly seven times the amount of electricity than that of any other stage and over half of the total energy required to manufacture one chip. Electron beam (e-beam) lithography, used in Stage 8 to develop the contact leads, is an incredibly energy intensive process.[45,46] E-beam lithography is also used in Stage 5 to construct trenches, though accounts for only 5.5% of the total energy demand. The dip coating process, used in Stage 6 to optimally deposit the SWNTs on the sensors, accounts for 9% of the total manufacturing energy demand.[15,16]

The chemicals category, including isopropanol, acetone, and 4-methyl-2-pentanone, is the second most impactful input category. The combined solvents account for approximately 97% of the total mass input per chip and it is therefore not surprising that they contribute significantly to the overall manufacturing impacts. Gold, used to construct sensor contact

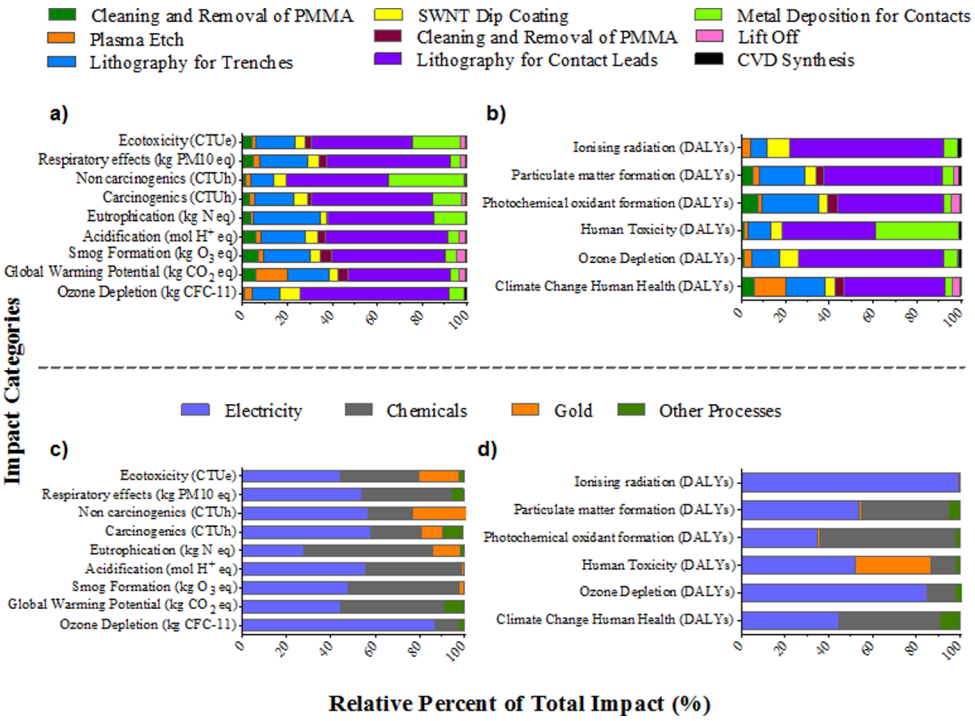

Figure 2. Horizontal stacked plots of the life cycle impacts associated with the manufacturing processes organized by manufacturing stage, (a) and (b), and by material and energy inputs (c) and (d). Plots (a) and (c) include midpoint results using TRACI 2 method while plots (b) and (d) include end point results, in units of DALYs, using ReCiPe World H/H method. All values are normalized by the total impact to obtain a relative percent contribution of each stage/input. Only those stages and inputs that contribute significantly enough to be viewed in the stacked plot are included. (CTU: Comparative Toxic Unit, h: for humans, e: for ecosystems, eq: equivalents.).

points, also accounts for a significant portion of the impact categories. Unlike the solvents, gold is used solely in Stage 9 and is 0.0002% of the total input mass, yet contributes significantly to the ecotoxicity, noncarcinogenics, carcinogenics, and eutrophication impacts. This is due to the very low ore grade of gold, meaning that large quantities of ore must be excavated, milled, processed, and refined per unit of metal, collectively resulting in a relatively large environmental burdens.[33,47,48]

The material and energy inputs that are major contributors to the life cycle impacts are associated with processes standard to all semiconducting device manufacturing. Therefore, when considering the potential differences in impacts between a conventional metal oxide sensor and the next generation CNT-enabled sensor, the processes with the greatest impact are universal to both sensors. While this study is based on laboratory scale manufacturing, nominal fabrication costs are assumed for scale-up considering that the CMOS micro-fabrication techniques and associated infrastructure are already well established.[1] Given this result, the benefits from increased performance achieved through the incorporation of SWNTs are likely to significantly outweigh the incremental environmental and human health impacts associated with their production.

Extension of Scope: Downstream Human Health and Economic Benefits. Due to its distinctive unpleasant odor, H_2S is often detected well before it reaches debilitating concentrations (odor threshold 0.01−1.5 ppm).[18] Yet, chronic exposure to low concentrations as well as unexpected acute exposure to high concentrations (>100 ppm) cause olfactory paralysis, eliminating detection by odor and resulting in increased vulnerability to inhalation of lethal H_2S doses (≥502 ppm).[17−19] While occupational exposure limits are set at 10−20 ppm, which vary by industry, NIOSH's recommended exposure limit (REL) is 10 ppm with a 10 min ceiling time and consider 100 ppm to be immediately dangerous to life and health (IDLH).[17,18,49]

Current H_2S sensors require manual operation. When high concentrations are suspected, appropriate personal protective equipment is worn to monitor a specific location. Yet, the most common source of H_2S-induced incidents is unexpected exposure to concentrations above the REL or IDLH demonstrating the shortcomings of the current system.[18,50−52] According to the Bureau of Labor Statistics, accidental exposure to high concentrations of H_2S was the cause of 61 occupational fatalities between 2003−2012 in the United States.[53] In such cases, remote sensing of H_2S and enhanced sensor performance would offer the benefit of detecting and identifying the source of dangerously high concentrations as well as prevent fatal encounters. In addition to occupational hazards, residents living near industrial sources of H_2S would benefit from enhanced sensing capabilities as they are at risk of chronic exposure health implications, including respiratory, neurological, cardiovascular, and reproductive effects.[18,20,54−56]

While there are numerous estimates of the economic impact that nanotechnologies may have, there are currently no studies that quantify the environmental and health benefits associated with nanoenabled product implementation. The benefits and potential negative impacts are typically discussed separately, with different metrics, boundaries, and estimation methods. As a result, LCA work on nanoenabled products has not been able to evaluate life cycle trade-offs that include the enhanced technological capabilities that nanotechnologies can provide. Integrated methods would offer clear delineation between products that have potential to positively impact human and

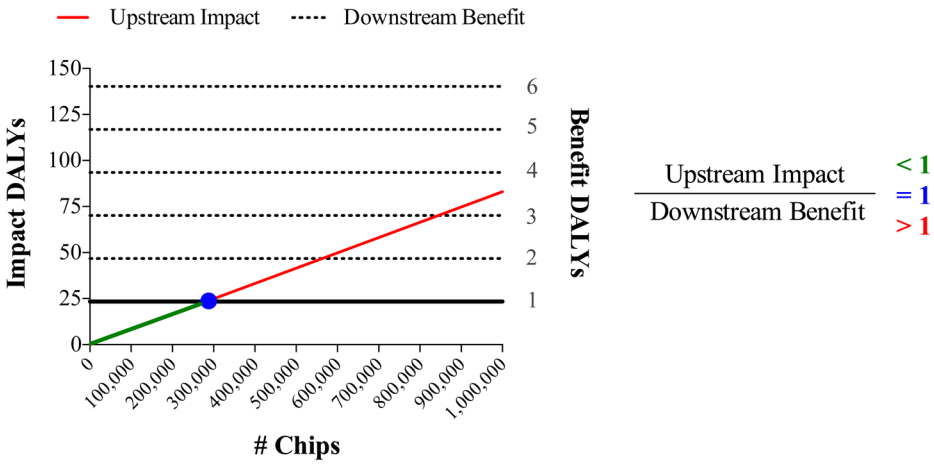

Figure 3. Plot showing the impact−benefit analysis for a SWNT-enabled H_2S gas sensor. The solid line represents upstream impacts, in DALYs, from the manufacture of the associated number of chips (16 sensors per chip). The dotted horizontal lines represent the realized benefits, in DALYs, associated with the prevention of fatalities based on the average annual occupational fatalities caused by H_2S exposure.[53] The solid horizontal line represents the breakeven point where IBR = 1 for the scenario of a single prevented fatality.

environmental health from those products with environmental and human health impacts that outweigh the realized benefits. Similar to the hazard quotient (HQ) utilized in risk assessment to estimate whether harmful effects from a given contaminant are likely or not,[57] the proposed impact-benefit ratio (IBR) would quantify the relative human health and environmental upstream impacts of a given nanoenabled product as well as the implementation benefits. Like the HQ, the goal of IBR is to achieve a value less than 1 indicating a net realized benefit.

IBR requires a common unit for comparison. DALYs, or disability-adjusted life years, is a metric established in 1993 from a collaboration between the World Bank and the World Health Organization to quantify the burden associated with premature death, disease and injury.[40] A DALY is equivalent to one healthy life year and is the sum of the years of life lost (YLL) and the years lived with a disability (YLD).[58] In addition to its application to public health, DALY is commonly used in LCA as an end point category indicator used to evaluate human health impacts from emissions or changes in environmental quality.[59] End point indicators aggregate the environmental and human health mid point impacts into a single unit relevant to human health (DALYs), ecosystems (species•year), and resources (surplus cost).[59] Since the SWNT-enabled H_2S sensor has the potential to impart human health benefits, as lives saved, during the use-phase, DALYs serves as a convenient unit for the IBR in the study.

While disabilities from exposure to H_2S, excluding mortality, range from eye irritation to respiratory effects, the compiled number of incidents is not reported and the average duration of the disabilities are either on the order of several days or unknown. Combined, this makes it difficult to accurately estimate YLD from H_2S exposure from existing statistical sources and minimizes the contribution of YLD to DALY. Therefore, YLL is conservatively considered the primary contribution to DALY in this study, which includes a discount rate reflecting the preference of a healthy year now rather than in the future:

$$\mathrm{DALY} = \frac{N}{r}(1 - e^{-rL}) \tag{1}$$

where N represents the number of fatalities, L the standard life expectancy at the age of death, and r is the discount rate (3%, established by the WHO).[58]

Figure 3 includes a graphical representation of the environmental and human health impacts and benefits associated with widespread implementation of SWNT-enabled H_2S gas sensors. The DALY impacts associated with production of the sensors are evaluated using the ReCiPe end point World H/H assessment method (solid line) and the DALY benefits realized from the prevention of annual occupational fatalities are calculated using eq 1 (dashed lines). The DALY values associated with the prevention of 1−6 annual occupational fatalities were determined based on the 61 occupational fatalities that occurred from 2003−2012.[53] The average age at death and standard life expectancy values used in the calculations were determined from the International Labour Organization's labor force participation rates and the Social Security's actuarial life table (average of male and female), respectively.[60,61]

The DALYs associated with the production of the sensors can be sensitive to perturbations in the material and energy inputs as well as process efficiencies. Since this study is based on lab scale production of the H_2S sensors, the cumulative impacts are expected to decrease as scale up estimations are applied.[1] Relevant information on the long-term environmental and human health impacts of SWNTs is not currently available for convenient inclusion in LCA, and are thus not included in this study. Still, the amount of SWNT used in the sensor application is minimal and the likelihood of SWNT release from the sensor is also minimal given the proposed integrated sensor platform.[22] Furthermore, a recent LCA completed by Eckelman et al. elucidate that the ecotoxicity impacts associated with nanomaterial production processes significantly outweigh the ecotoxocity associated with the realistic release scenario.[29]

While it is impossible to determine an exact number of sensors required to save one life, we are able to directly compare the DALYs associated with the production of one sensor (8.3×10^{-5} DALYs) and those associated with the prevention of one occupational fatality (23.4 DALYs). This provides the opportunity to quantitatively compare the production impacts and potential implementation benefits. To illustrate the utility of the IBR, the following scenario is

carried out and illustrated in Figure 3. It seems reasonable that the introduction of 50 000 chips (800 000 sensors) has the potential to prevent one of the average annual fatalities. Following this assumption, the associated IBR is 0.18 (DALYs associated with the production of 50 000 = 4.15, DALYs associated with prevention of one occupational fatality = 23.4). In the best-case scenario, all six of the average annual fatalities are prevented and the IBR is 0.03. The scenarios in which there is a net DALY benefit are identified by the portion of the curve below the intersection point (in green, Figure 3). The point at which the two curves intersect represents the neutral impact–benefit scenario, IBR = 1 (blue circle, Figure 3), which in this scenario occurs upon the implementation of 280 000 chips (4.48 million sensors). The scenario described here is intended to demonstrate the utility of IBR as a decision making tool to differentiate nanoenabled products that have the potential to offer use-phase human health benefits that exceed the potential health risks associated with other life cycle stages. While IBR is designed to evaluate nanotechnologies that have a direct impact on human health, the framework highlights the importance of developing methods to quantifying additional positive trade-offs realized in the product use-phase (e.g., environmental benefits such as reduced CO_2 equivalents). In this way, quantitative support is provided for the development of only those products where upstream impacts are recovered by downstream environmental and human health benefits, and provides guidance for necessary improvements to those products that do not currently meet this threshold.

Previous studies have established an associated economic value of DALYs lost to a given disease or illness as the product of those DALYs and the average annual per capita GDP.[53,62] Thus, an equivalent estimation of the associated human health economic value can be carried out here. Given the average annual per capita GDP for 2012 is \$51 749,[63] the economic value associated with the equivalent DALY impacts of producing 50 000 chips is approximately \$215 000, while the DALY economic value associated with the average annual loss of life to H_2S (1–6) ranges from approximately \$1.2–\$7.3 million. As such, there is a greater than 5-fold economic benefit realized from the prevention of just one occupational fatality over the economic damages associated with the production of 50 000 chips. This comparison excludes significant additional economic benefits realized from the potential application of SWNT-enabled H_2S sensors for corrosion prevention and remote sensing capabilities.[64–67]

Implications. LCA coupled with an impact–benefit ratio (IBR) extension was utilized in this study to quantify the life cycle impact and benefit trade-offs associated with the production and use phases of a developing SWNT-enabled chemical sensor. The study highlights the positive attributes of a next generation nanoenabled technology that are often neglected in life cycle and risk assessment studies. The results indicate that the impacts associated with the incorporation of SWNTs are minimal compared with those associated with other material and processing stages. When evaluating cumulative life cycle impacts, downstream benefits of improved occupational health and economic savings realized from prevention of harmful H_2S exposure are equally important considerations as the upstream manufacturing impacts. In particular, the quantitative method presented in this study normalizes these impacts and benefits to the unit of disability-adjusted life years (DALYs) because there is a tangible health benefit associated with product implementation. The equivalent DALY impact from the manufacture of the SWNT-enabled H_2S sensors is negligible compared with the potential DALY gain from the prevention of occupational fatalities. The IBR utilized here provides a guiding framework and quantitative method of screening that encourages the development of only those nanoenabled products having the potential to realize a net environmental, health or societal benefit.

■ ASSOCIATED CONTENT

Supporting Information

Additional tables including sensor performance metrics (Table S1) and itemized inventory impact results (Table S2). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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