



Increasing the lifetime of products by nanomaterial inclusions—life cycle energy implications

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Abstract

Purpose Typically, the high energy required to manufacture nanomaterials is weighed against the benefits transferred to a product. Adequately establishing the environmental characteristics of a product that contains nanomaterials requires a complete methodology. The objectives of this study are to draw attentions on life cycle information and to demonstrate the methodology for the scientific assessment of the environmental benefits of using a nanomaterial in a product to extend the product life and to provide a real example for the calculations of the approach.

Methods About 1317 products with nanomaterials in the market were analyzed to identify the outcomes of lifetime extension by the nanomaterial additions. Five life cycle elements were quantified to establish the cradle-to-gate (CTG) life cycle footprint of a product comprised of a nanomaterial. These are the following: the life cycle of the conventional product with the usual construction and without added nanomaterial, the life cycle of the nanomaterial manufactured from CTG per kilogram of nanomaterial, the amount of nanomaterial incorporated into the product, the quantitative improvement in the product performance due to the presence of the nanomaterial (such as increased lifespan), and the incremental energy and auxiliary materials (often negligible) involved in the incorporation of the nanomaterial into the conventional product

Results and discussion The primary challenge here is to have all five of the informational pieces in order to ensure that the environmental footprint of using a nanomaterial is complete. The results can be seen for the range of products with life extension via nanomaterials, ranging from 130 to 3100%. In these cases, the higher energy to manufacture the nanomaterial is more than offset by the avoidance of manufacturing non-nanoproducts multiple times over the life extension period.

Conclusions It was found that several nanoscale inclusions in the products greatly increased many properties of the final product along with the lifetime. Increasing the lifetime of products by adding nanoscale inclusions will thus reduce environmental and health concerns, as well as the use of virgin materials, energy consumption, landfill allocations in the long term, and product marketability.

Keywords Nanomaterials · Life cycle energy saving · Product life extension

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1 Introduction

All marketed products have useful and specified life spans with efficiency, which is referred to as the product life. There are many ways to expand a product life span, including (but not limited to) adding different micro- and nanomaterials to the products, applying a coating to the materials, blending the products with preservatives, packaging and storing, changing the environmental conditions (e.g., UV light, moisture, emissions/pollutants, pH, ozone/oxygen), controlling the hygienic conditions, shipping, and handling (Steeman 2011; Subramanian et al. 2018).

Nanomaterials are mainly related to various forms of particles, films, wires, fibers, tubes, and composites at nanoscale

(where one of the dimensions is between 1 and 100 nm), which exhibit unusual physical, chemical, physicochemical, and biological properties that are not present in the corresponding bulk materials. These properties mainly come from the specific surface area; surface-to-volume ratio; and lesser imperfections of the nanostructured materials of any type, size, shape, and structure (Khan et al. 2012).

Some applications of nanomaterials are energy storage and production, information technology, medical devices, manufacturing, food and water purification, instrumentation, and environmental uses (Asmatulu et al. 2012). According to the Woodrow Wilson Center's Project on Emerging Nanotechnologies (PEN) (PEN 2012), 1317 nanomaterial-based products are currently available on the market (Consumer Products Inventory, CPI). It is believed that the PEN CPI-based catalog is a convenient and trusted inventory that documents the diversity and magnitude of nanoproducts used in various fields. This inventory list primarily covers both primary consumer products and industrial products. Nevertheless, the criticism is that the PEN CPI list might not perfectly identify all categories of nanomaterials and use, which means it is referred to as a fuzzy image of nanoproduct classification (BéruBé et al. 2010).

One of the claims for the use of nanomaterials is potentially improving the lifetime or efficiency of a new product in certain areas, significantly reducing energy consumption, enhancing the efficient use of electronic and computer devices, providing advances in smart and strong lightweight materials for aircraft and other industries, affecting clean energy and manufacturing, saving resources/raw materials, and mitigating environmental contamination (Gavankar et al. 2012). Batteries are one example of consumer products that show how nanoscale inclusions increase a product lifetime (Wallner et al. 2010). For example, Altair Nano, Inc. is one of the lead manufacturers of nanomaterials for alternative energy systems. This company recently developed a nanomaterial-based rechargeable battery (called NanoSafe battery) that has a distinct advantage compared with lithium-ion batteries. Titanium dioxide (TiO₂) nanoparticles are used as a negative electrode to provide a high-capacity battery, which is also thermally stable and essentially safe. This offers a unique ability to charge and discharge the new battery several times without losing the charging capacity and mechanical strength (e.g., fatigue, thermal stress, corrosion, and degradation) for a longer period of time. For instance, Li-ion batteries can be charged about 750 times prior to the end of life, while NanoSafe batteries have achieved more than 9000 charge and discharge cycles without losing performance. This is basically a 12 times higher lifetime and 25 years of useful life (AltairNano Inc. 2012; Saner et al. 2012).

However, there is no methodology nor examples of using life cycle information and extended product life to evaluate the overall energy savings of such additions. Here the tradeoff is

the use of nanomaterials usually requiring high energy for manufacture against extending the life of a product, thus reducing the manufacturing of more products. The objective of this paper is to demonstrate the level of information needed to establish that a nanomaterial addition that extends product life is a net-positive choice for the environment.

The goal of this research is to use life cycle inventory data on energy at the gate-to-gate level to assess the larger benefit of nanomaterials in products to extend product life. Thus, traditional methods for generating life cycle data are not needed. Our intent is to show the comprehensive life cycle pieces of information that are necessary to make a scientific evaluation of the net benefits from nanomaterials extending product life. This scope extends to offer a default concept for life cycle data on nanomaterials that have not been studied by linking nanomaterial manufacturing energy to the conventional same material manufacturing energy.

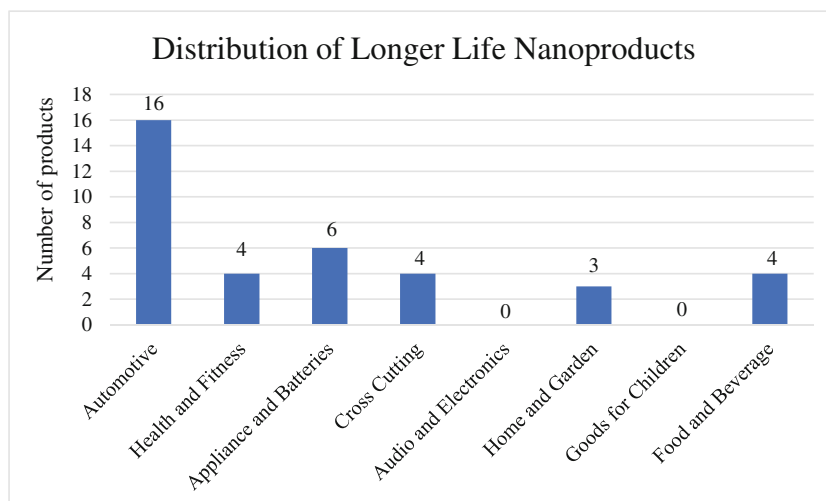
2 Methodology

This study uses primarily the complete PEN CPI list of 1317 nanoproducts (PEN 2012). This PEN list is considered to be the leading catalog presently available for nanoproducts. PEN CPI has categorized nanoproducts into eight different application areas: automotive, appliances, cross-cutting, food and beverage, electronics and computer, goods for children, health and fitness, and home and garden. This study utilized all of the PEN CPI categories in detail. We searched for all products that indicated a longer life as the result of nanomaterial inclusions. These products show better performances compared with regular products without any nanomaterial inclusions. During these studies, we utilized the PEN list, published articles, consumer surveys, and companies' product web pages.

As a first step, we focused only on those products that provided quantitative lifetime extensions (6 months, 1 year, etc.) (Appendix 1). These fall in the eight product categories used in PEN (Fig. 1). For example, a truck battery made of ceramic nanomaterials offers a longer lifetime (12 years or more) than a regular battery life (4–7 years). Also, different companies produce the same type of products with the same material (e.g., nanosilver particles), such as a hair iron (Hicks and Theis 2017). Since all the family of selected products have similar properties and offer comparable advantages, these are all grouped together. In Appendix 1, we viewed the company information, grouped by the six PEN categories that described extended life (Fig. 1). Data were extracted on the product type; nanomaterial that was used; company claim; increased life amount; and, if available, the amount of nanomaterial added.

Based on the above steps, we then defined the number of products that offer a quantitative lifetime extension with the addition of nanomaterials. At this stage, only 28 groups containing 37 products showed increased lifetimes (Appendix 1).

Fig. 1 Number of nanoproducts in PEN-marketed product groups with extended life



The number of longer life products under the PEN categories is shown in Fig. 1. Without any doubt, adding nanomaterials appears to be advancing the value of regular products.

In the next step, we focused on the 27 products with sufficient information for the environmental assessment, so that we could calculate the quantitative longer life data on the specific type and amount of nanomaterials in the product (Appendix 2). Similar headings are used to organize these data, and these data were used in the calculations found in Table 2. As a note to readers, we have also included an Appendix 3 in which we catalogued products that are made more efficient by the nanomaterials. A similar analysis of the magnitude of the energy improvement of these efficiency increases could be undertaken with these references.

3 Results and discussion

In Table 1, energy requirements for production of nanoproducts as well as the non-nano counterparts are shown. The influence of using nanomaterials to extend product service life must include the five components of a full methodology,

- The life cycle of the conventional product with the usual construction and without added nanomaterial
- The life cycle of the nanomaterial manufactured from CTG per kilogram of nanomaterial
- The amount of nanomaterial incorporated into the product
- The quantitative improvement in the product performance due to the presence of the nanomaterial (such as increased lifespan)
- The incremental energy and auxiliary materials (often negligible) involved in the incorporation of the nanomaterial into the conventional product

A single example for a nanoprotectant is used in this paper to illustrate the scientific basis for evaluating nanoproducts environmental footprints. Here the example nanoprotectant is a long-lasting product and improves the surface penetration using tiny nano-sized particles for better cleaning, conditioning, and UV protection for both vinyl and leathers in the car.

3.1 Life cycle inventory analysis of conventional products

As a starting point, the life cycles of conventional products must be completed as the basis of quantifying change by introducing a nanomaterial. The life cycle is conducted with the usual ISO standards to produce a life cycle inventory (LCI), which quantifies the process energy and material inputs in order to construct the product. These data are then converted to the full energy needed to produce the process energy, such as steam or electricity, referred to as natural resource energy (NRE). In addition, the LCI provides the mass loss or emissions and waste from manufacturing the product. Then, the input chemicals and materials to construct the full product are identified, and the full supply chain LCIs are used to provide the full cradle-to-gate energy and mass losses. The full cradle-to-gate (CTG) values are changed by adding the energy for the amounts of nanomaterials used in each product.

3.2 Energy requirements of nanomaterials and nanoproducts

Although nanomaterials can increase the lifetime of many products currently available in the market, manufacturing of some of these nanomaterials is an energy-intensive process, requiring more energy than the counterparts at bulk scales. As shown in Appendix 1, a number of different nanomaterials are consumed to increase a product lifetime

Table 1 Ratio of nanomaterial metal with conventional metal

Product name	Production of nanomaterial metal (MJ/kg)	Production of conventional metal (MJ/kg)	Energy ratio of nanomaterial/conventional metal
Gold lotion	Assumption: gold nanoparticle—435,736 MJ/kg	Gold (raw material): mining process—265,000 MJ/kg (Recreational Equipment Inc. Co-Op. 2012)	1.6
Nanoprotectant	TiO ₂ manufacturing: 19 MJ/kg	Titania (raw material):	2.0–3.2
Rain repellent	(dry chloride)—40 MJ/kg	6 MJ/kg (dry chloride)—20 MJ/kg (wet sulfate)	2.0–3.2
Hydrophobic car wash	(wet sulfate) (Osterwalder et al. 2006)	(Osterwalder et al. 2006)	2.0–3.2
Lip protection crème and sunblock crème	ZnO nanoparticle—267 MJ/kg (Hattori et al. 2011)	Zinc (raw material): 36 MJ/kg (electrolytic process)—48 MJ/kg (imperial process) (Norgate et al. 2007)	5.6–7.4
Anti-graffiti paint	Silver nanoparticle: 11,480 MJ/kg (micro reactor)—37,290 MJ/kg	Silver (raw material): mining process—1550 MJ/kg	7.4–24
Jacket	(batch reactor) (Kück et al. 2011)	(Recreational Equipment Inc. Co-Op. 2012)	7.4–24
Antimicrobial paint supplement			7.4–24
Plastic bottle	Nanoclay—142 MJ/kg (Roes et al. 2007)	Clay—3 MJ/kg (general baked clay)	47
Li-ion battery	LiFePO ₄ nanoparticle: 96 MJ/kg—Li ₄ Ti ₅ O ₁₂ nanoparticle: 242 MJ/kg (Ishihara et al. 2002)	Lithium (raw material)—0.853 MJ/Kg (Gaines et al. 2011)	113–284

and efficiency (Appendix 2). These nanomaterials are mainly titanium dioxide, gold, silver, zinc oxide, lithium, and clay.

Table 1 provides a comparison of the nanomaterial life cycle inventory results compared with the bulk life cycle inventory results. Table 1 appears to be the first attempt to compare the production energy of nano- to non-nanomaterials across a range of materials. The ratios of production energy for nanomaterial to non-nanomaterial are listed from the lowest to the highest. Those versed in the science of manufacturing nanomaterials may be able to offer explanation for the ratio order based on other metal or chemical properties. If the life cycle of a nanomaterial is not known, Table 1 would suggest the median ratio of about 2.5:1 might be used as an initial default.

The following section provides a brief description of nanomaterial production methods and energy consumption during the production phase.

It is evaluated that the wet and dry processes to understand the cost and energy requirements of TiO₂ nanoparticle manufacturing techniques (Osterwalder et al. 2006). The energy consumption of TiO₂ manufacturing consists of electricity, steam, gas, and coal energy used during the synthesis of TiO₂. As shown in Table 1, the wet sulfate process requires 40 MJ/kg of TiO₂, while the dry chloride process requires 19 MJ/kg of TiO₂; however, the wet sulfate process provides more uniform and defect-free nanomaterials (Osterwalder et al. 2006).

The green production of silver nanoparticles analyzed using a micro reactor technology (Osterwalder et al. 2006). In order to evaluate this method, it is compared with the batch reactor process. Producing 1 kg of silver nanoparticle with the batch reactor requires 37,290 MJ/kg of energy (Table 1), which involves a pump, stirrer, thermostat, and further stirring energy. However, producing the same amount of silver nanoparticles with the micro reactor process requires 11,480 MJ/kg energy from a solid dosing feeder, pump, thermostat, and PC control. Comparatively, the batch reactor process is nearly 3.5 times more energy-intensive than the micro reactor process, thus indicating that larger-scale productions will likely make the nanotechnology products more affordable on the market (Kück et al. 2011).

CTG energy requirements of nanomaterials LiFePO₄ and Li₄Ti₅O₁₂ employed in cathode and anode of lithium batteries. Fabricating these nanoscale materials requires 96 and 242 MJ/kg of energy for the hydrothermal and spray pyrolysis methods, respectively, while approximately 80 MJ/kg for the dry sintering method. Changing manufacturing processes and types of materials change the lifetime and capacity of lithium batteries. The authors estimated that batteries utilizing nanoscale materials could improve the total life cycle energy efficiency by 3–8 times (Ishihara et al. 1999).

Next, the conventional product (non-nanomaterial) life cycle previously completed plus the addition of the nanomaterial is established. The nanoproduction energy is simplified as the conventional product plus the energy for the amount of

Table 2 Life cycle inventory of non-nano products and products with nanomaterials

Product name	Energy for conventional product (MJ/kg)	Production of nanomaterial (MJ/kg)	Average amount of nanomaterial used	Energy of conventional product with added nanomaterial	Life extension factor	Energy savings (%)
Jacket	312.78 MJ/kg (Steinberger et al. 2009)	Silver nanoparticle: 11,480 MJ/kg (micro reactor)–37,290 MJ/kg (batch reactor) (Kück et al. 2011)	20 mg silver/kg	313.01–313.53	31	3100
Hydrophobic car wash	24.8 MJ/kg (European Commission 2007)	TiO ₂ Manufacturing: 19 MJ/kg (dry chloride)–40 MJ/kg (wet sulfate) (Sullivan and Gaines 2010)	TiO ₂ ≈ 33.825 g nanomaterial for 452 g car wash (7.5%) (Ashland EHS Dept. 2008)	25.44–26.16	16	1500–1600
Rain Repellent	24.8 MJ/kg (European Commission 2007)	TiO ₂ Manufacturing: 19 MJ/kg (dry chloride)–40 MJ/kg (wet sulfate) (Sullivan and Gaines 2010)	TiO ₂ ≈ 6.2 g nanomaterial for 85 g rain repellent (7.5%) (Ashland EHS Dept. 2008)	24.92–25.06	7	690–700
Li-ion battery	Li-ion: photovoltaic energy—0.432 MJ/kg (Gaines et al. 2011)	LiFePO ₄ nanoparticle: 96 MJ/kg–Li ₄ Ti ₅ O ₁₂ nanoparticle: 242 MJ/kg (Ishihara et al. 2002)	Lithium content: 4.5 g for 25 g Li-ion battery (Daniel 2008)	0.86 LiFePO ₄ –1.52 Li ₄ Ti ₅ O ₁₂	11	310 for Li ₄ Ti ₅ O ₁₂ –550 for LiFePO ₄
Nanoprotectant	Li-ion: electric vehicle—0.27 MJ/kg (Gaines et al. 2011)	LiFePO ₄ nanoparticle: 96 MJ/kg–Li ₄ Ti ₅ O ₁₂ nanoparticle: 242 MJ/kg (Ishihara et al. 2002)	Lithium content: 4.5 g for 25 g Li-ion battery (Daniel 2008)	0.70 LiFePO ₄ –1.36 Li ₄ Ti ₅ O ₁₂	11	220 for Li ₄ Ti ₅ O ₁₂ –420 for LiFePO ₄
Antimicrobial paint supplement	24.8 MJ/kg (European Commission. 2007 August)	TiO ₂ manufacturing: 19 MJ/kg (dry chloride)–40 MJ/kg (wet sulfate) (Osterwalder et al. 2006)	TiO ₂ ≈ 39 g nanomaterial for 510 g protectant (7.5%) (Ashland EHS Dept. 2008)	25.53–26.33	2	190
	Solvent-borne paint 155.2 MJ/kg (Greenspec 2012)	Silver nanoparticle: 11,480 MJ/kg (micro reactor)–37,290 MJ/kg (batch reactor) (Kück et al. 2011)	Nanosilver content: 3000 ppm–0.3% (PEN 2008)	189.64–267.07	2	120–160
	Water-borne paint: 94.4 MJ/kg (Greenspec 2012)	Silver nanoparticle: 11,480 MJ/kg (micro reactor)–37,290 MJ/kg (batch reactor) (Kück et al. 2011)	Nanosilver content: 3000 ppm–0.3% (PEN 2008)	128.84–206.27	2	92–150
Plastic bottle	PET bottle—25.276 MJ/kg (100 units) (Ashby et al. 2012)	Nanoclay—142 MJ/kg (Roes et al. 2007)	Nanoclay content: 10 g for a 200-g bottle	26.70	1.3	130
Anti-graffiti paint	Solvent-borne paint: 155.2 MJ/kg (Greenspec 2012)	Silver nanoparticle: 11,480 MJ/kg (micro reactor)–37,290 MJ/kg (batch reactor) (Kück et al. 2011)	Nano silver content: 100 ppm–0.01% (chemical of the day, squarespace 2019)	270–528.1	2	59–110
	Water-borne paint: 94.4 MJ/kg (Greenspec 2012)	Silver nanoparticle: 11,480 MJ/kg (micro reactor)–37,290 MJ/kg (batch reactor) (Kück et al. 2011)	Nano Silver Content: 100 ppm – 0.01% (chemical of the day, squarespace 2019)	209.2–467.3	2	40–90

nanomaterial added (Table 2). So now we have the full life cycle energy of the conventional product with current life expectancy, and since the nanoproduct that replaces this has a longer life, we multiply the conventional product energy by the life extension factor, which is the ratio of extended life to conventional product life (Table 2). Manufacturers do not provide the mechanistic details of why product life is extended, and so, we simply stated the magnitude of the life extension (Table 2). These extensions were not verified, but used as quoted because the product suppliers are accountable in the

market, if performance is not as advertised. Where available, some explanation of the reason a product extends life have been included in Appendix 1.

The following Eq. 1 was developed to calculate the percentage of increased energy impact from selecting the non-nanoproduct when compared with the products using nanomaterials. This is the benefit impact of using the nanomaterial, depending on the values of the five parameters that need to be assembled.

Energy impact of selecting the non-nano product with conventional life expectancy versus the same

$$\text{product with nanomaterials and an extended life, (\%)} = \frac{(\text{life cycle of conventional product}) * (\text{life extension factor})}{\text{life cycle of product with nanomaterials}} * 100 \quad (1)$$

According to Eq. 1, the numerator is the number of conventional products that must be made over the expanded life of the product with nanomaterial added times the energy to make one conventional product. Based on Eq. 1, an example problem is provided for the calculation of the percentage of energy savings of the nanoproduct as follows:

As an example, the nanoprotectant is one of the products listed in Table 2. This gel product has a weight of 510 g (0.51 kg) and a life of 1 year. The life extension factor is 2 (doubling the lifetime of 1 year). The energy production of the conventional product, which equals the life cycle of the conventional product (nanoprotectant) is 24.8 MJ/kg. Therefore, the lifecycle of the conventional product multiplied by the life extension factor is $24.8 * 2 = 49.6$. This 0.51 kg of product with nanomaterials contains 38.25 g of TiO_2 nanomaterials, which can then be used for 2 years. The life cycle of the product with nanomaterial is $24.8 \text{ MJ/kg} + 0.03825 \text{ kg nano TiO}_2 * 19 \text{ MJ/kg nano TiO}_2 = 25.53 \text{ MJ/kg product with nanomaterial}$. The conventional product if selected thus increases the environmental energy impact by 190%.

The energy improvement results for the products with life extension using nanomaterials (Table 2), ranging from 60–110% up to 3100%. In these cases, the higher energy to manufacture the nanomaterial is more than offset by the avoidance of manufacturing non-nanoproducts multiple times over the life extension period.

4 Conclusion

Nanomaterials in the forms of nanoparticles, nanotubes, nanofilms, nanowires, nanofibers, and nanocomposites have outstanding properties (e.g., mechanical, electrical, optical, magnetic, and thermal) because of the larger surface area,

surface-to-volume ratio, and reduced structural imperfections. These nanoscale materials are used in a number of different consumer and industrial products to increase the lifetime or efficiency. Even though the research and development of nanomaterials has been growing very rapidly, the lifetime expansion or efficiency of products incorporated with nanomaterials have not yet been studied on a comparative basis. It was found that several nanoscale inclusions in the products greatly increased many properties of the final product along with the lifetime. This can be explained as follows: a manufacturer would have to produce two non-nano/conventional products versus one of the same product with nanomaterials added to extend the life from 1 to 2 years, thus reducing the manufacturing of a second product after year 1. Increasing the lifetime of products by adding nanoscale inclusions will thus reduce environmental and health concerns, as well as the use of virgin materials, energy consumption, land-fill allocations in the long term, and product marketability. As a result, increasing the life expectancy and efficiency of these products will open up new possibilities for sustainable manufacturing. Further research is also needed to quantify energy-saving production methodologies for nanomaterials used in consumer and industrial products.

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