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Review

Green and Clean: Reviewing the Justification of Claims for Nanomaterials from a Sustainability Point of View

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Abstract: Nanotechnology is an emerging technology with the potential to contribute towards sustainability. However, there are growing concerns about the potential environmental and human health impacts of nanomaterials. Clearly, nanomaterials have advantages and disadvantages, and a balanced view is needed to assess the overall benefit. The current "green and clean" claims of proponents of nanomaterials across different sectors of the economy are evaluated in this review study. Focusing on carbon emissions and energy use, we have reviewed 18 life cycle assessment studies on nanomaterials in the solar, energy, polymer, medical and food sectors. We find that the "green and clean" claims are not supported for the majority of the reviewed studies in the energy sector. In the solar sector, only specific technologies tend to support the "green and clean" claims. In the polymer sector, only some applications support the "green and clean" claims. The main findings show that nanomaterials have high cradle-to-gate energy demand that result in high carbon emissions. Synthesis of nanomaterials is the main contributor of carbon emissions in the majority of the studies. Future improvements in reducing parameter uncertainties and in the energy efficiency of the synthesis processes of nanomaterials might improve the environmental performance of nanotechnologies.

Keywords: nanomaterials; sustainability; quantitative assessment; life cycle assessment; industrial ecology

1. Introduction

Nanotechnology is an emerging technology, often cited as a key enabling technology [1–3], used more and more in society. It is estimated that 300–400 thousand employees in Europe work in the nanotechnology sector and that nano-technological products in 2015 had an estimated global volume of 2 trillion euros [4]. The increasing importance of nanotechnology can also be identified from the number of published articles. While in the 1950's only a few articles were published in the area of nanomaterials, in 2009 more than 80,000 papers were committed to the nanotechnology area [5].

Europe has identified nanotechnology as one of the key technology sectors in the research and innovation program Horizon 2020, having an important role within global challenges. The next generation of products with high added value in a big variety of strategic technological sectors such as transport, health and bio-medical, construction, mechatronics, catalysis, packaging, and textiles are the basis for European technological development, innovation, and competitiveness [6].

In addition to the role of nanomaterials in technological competitiveness and innovation, there are many books and reports, including innovation and research programs such as EU Horizon 2020, which state that nanotechnologies will have a significant contribution to the transition to sustainability. Examples include applications towards more efficient energy systems, high-performance batteries, smart technologies, as well as a significant contribution towards resource efficiency and waste reduction [3,6,7]. This potential of nanomaterials of moving towards sustainable technological development is defined in this article as the "green and clean" claims of proponents of nanomaterials.

Despite the high potential of nanomaterials, there is a growing concern that researchers on engineered nanomaterials thus far have given insufficient attention to the negative sides of these technologies, in terms of potential environmental and human health impacts. At the heart of the concerns is that the release of nanomaterials to the environment might impose unpredictable behavior and little research has been done until now in evaluating the fate, toxicity, and transport of nanomaterials [7–10]. Furthermore, the production methods of nanomaterials might have a significant environmental and human health impact that does not stem from the nanomaterials themselves, but from related processes involved in the manufacturing of the nanomaterials and the related material and energy inputs and outputs [7,11,12]. In other words, the deployment of nanomaterials may either decrease or increase the environmental performance of the products and services that society consumes.

In order to evaluate the "green and clean" claims of the sustainability potential of nanomaterials, comprehensive environmental impact assessment studies have to be considered. Such comprehensive studies necessarily address more than the use phase: they should also include production and end-of-life impacts. The system thus analyzed is variously known as the value chain, the supply chain, or the life cycle. Here we will use the term life cycle and introduce the life cycle assessment (LCA) approach as the key tool that can be used to better understand and address the challenges related to the environment and human health due to the development of nano-based products/technologies [7,13–15]. LCA is used to map the environmental impact throughout the whole life cycle of a product or technology, from extraction of raw materials, manufacturing, use and end-of-life treatment [16]. Moreover, life cycle assessment can be used to compare the environmental performance of nano-based technologies with that of their conventional equivalents. In providing such a comprehensive analysis, LCA is capable of including different types of impacts, such as climate change, toxicity, and resource depletion. This multi-impact scope is important for understanding the risks and benefits of a trade-off of, for instance, a lower energy use and a higher toxicity level. Only by considering the entire life cycle and multiple impacts is it possible to make a verdict on the "green and clean" claims.

In this paper, we will identify whether or not these "green and clean" claims on nanomaterials are defensible when we use LCA as a benchmark. We review published scientific studies in LCA of nanomaterials for seven technological sectors:

- Solar/photovoltaic (PV);
- Medical technology;
- Energy;
- Food;
- Biomolecules;
- Polymers;
- Photo (-electro) chemistry.

At the outset, we must mention a limitation. Of the reviewed LCA studies, quite a few are restricted to one of just a few environmental impact categories, and the overlap among studies in impact categories considered is restricted to climate change only. Therefore, the "green and clean" claims are only assessed on the basis of the climate change impact. This of course limits the validity of our conclusions, but we still fill an important gap by making a seminal step in synthesizing the literature on environmental costs and benefits in a life-cycle perspective. Where available, conclusions on other impact categories will be highlighted.

This paper is structured as follows. Section 2 discusses the method of searching the literature. Section 3 presents the overall environmental performance of the meta-analysis on the performance of nano-based technologies compared to existing commercial alternatives. Section 4 presents the potential environmental burdens and/or benefits of nanotechnologies and the results from the comparison among nano-based technologies and existing commercial technologies. A particular focus is to identify and explain the most important parameters and activities that contribute to the environmental impact of nanomaterial development. Limitations and uncertainties related to nano-specific data and assessment methods are also discussed. Section 5 presents a synthesis of the main findings on the "green and clean" claims of nanomaterials.

2. Methods

The criteria of the literature search are the following. The literature research was conducted using ISI Web of Knowledge for all studies that were published until December 2017. Publications on Life Cycle Assessment of nanotechnologies for solar, energy, polymers, food, biomolecules, medical and photo (-electro) chemistry sectors were considered. For each of these sectors keywords were defined (see the Appendix A). The energy sector was further subdivided into coal, oil, lignite, natural gas, diesel, nuclear, wind, and hydropower in order for the keyword selection to give more accurate results. A series of step-wise search strategies were conducted to find the most relevant articles for each of the sections selected.

- Only studies that had 5 or more citations at the time of our search were included in our analysis.
- Next, we excluded studies that only mention LCA without actually performing an LCA.
- For the articles selected, a one by one screening was conducted, because not all of them are relevant to a comprehensive life cycle analysis of nanotechnologies. The number of studies that actually perform life cycle assessment of nanomaterials for the different sectors and have more than 5 citations, they are 18 in total. 8 studies for the solar sector, 5 studies for the polymer sector, 3 studies for the energy sector, 1 study for the food sector and 1 study for the medical sector. No relevant studies that have performed life cycle assessment of nanomaterials were found for the biomolecules and photo (electro) chemistry sector.

3. Results

The reviewed studies on nanomaterials used in the different sectors are presented and evaluated in Tables 1–3. These tables include the specific nanomaterials used and the overall assessment of how the nano-based technologies environmentally perform in terms of carbon emissions over their life cycle compared to alternatives. In the supplementary information, the carbon emissions and energy demand and the main key drivers that contribute to global warming and/or energy consumption are shown. For the solar sector the comparison is presented in terms of carbon emissions and/or energy payback time (EPBT) of the PV systems, while for the other sectors the comparison is presented in terms of carbon emissions and/or energy demand (Tables S1–S5).

Table 1. Summary of LCA studies on nanomaterials in the solar sector. See Table S1 for a more detailed analysis.

Nanomaterial	Overall Assessment	Reference
Nanoscale layers on polymer PVs with glass and flexible substrate	Polymer PVs on glass substrate: 48% lower carbon emissions than mc-Si [1]. Lower carbon emissions than CdTe [2], CIS [3], a-Si [4]. Higher carbon emissions than DSC [5]. Polymer PVs on flexible substrate: 90% lower carbon emissions than mc-Si. Lower carbon emissions than CdTe, CIS, a-Si, DSC. **Green and clean claims:** Supported	[17]
Quantum dot photovoltaics (QDPV)	About 72% to 81% lower carbon emissions than silicon PVs (ribbon mc-Si, mc-Si, mono-Si [6]). About 67% to 93% lower carbon emissions than thin film PVs (CdTe, CIS). About 91% lower carbon emissions than other nano PVs (DSC). **Green and clean claims:** Supported	[18]
Nanocrystalline dye sensitized solar cells (ncDSC)	• Comparable carbon emissions to amorphous solar cell system. 90% lower carbon emissions than a natural gas power plant. **Green and clean claims:** Comparable	[19]
Organic PV (OPV) using fullerene derivative phenyl-C61-butyric ester (PCBM)	• About 70% lower carbon emissions compared to a-Si solar cells. • About 90% lower carbon emissions compared to mc-Si cells. **Green and clean claims:** Supported	[20]
Amorphous silicon/nano-crystalline silicon (a-Si/nc-Si) solar cell	• About 25% higher carbon emissions than multi-silicon PVs. **Green and clean claims:** Not supported	[21]
a-Si/nc-Si solar cell	• About 29% to 46% higher carbon emissions than a-Si (most likely scenario). • About 31% to 33% higher energy requirements than a-Si (most likely scenario). **Green and clean claims:** Not supported	[22]
a-Si/nc-Si solar cell	• About 40% higher energy requirements than a-Si PVs. Green and clean claims: Not supported	[23]
TiO_2 nanotube (TNTs) perovskite solar cell	• About 25% higher carbon emissions than CdTe solar cells. • Comparable carbon emissions to a-Si and DSC solar cells. • About 22% and 50% better performance compared to mc-Si and mono-Si solar cells respectively in terms of carbon emissions. **Green and clean claims:** Not supported and Comparable	[24]

[1] mc-Si: multi-crystalline silicon, [2] CdTe: cadmium telluride, [3] CIS: copper, indium, selenide or sulfide, [4] a-Si: amorphous silicon, [5] DSC: dye-sensitized, [6] mono-Si: mono-crystalline silicon.

Table 2. Summary of LCA studies on nanomaterials in the polymer sector. See Table S2 for a more detailed analysis.

Nanomaterial	Overall Assessment	Reference
Carbon nanofiber (CNF) reinforced polymer nanocomposite (PNC)-based vehicle panels	Production phase: • CNF PNCs: 1.6 to 12 times higher energy demand compared to steel.	[25]
	Production and use phase (application to vehicle body panels): • CNF PNCs: 1.4% to 10% fuel gasoline savings for vehicles compared to steel. That leads to offset and net energy savings of the different CNF-PNCs relative to steel for car applications.	
	Green and clean claims: Not supported for the production of CNF PNCs; Supported for application to car panels	
Nanofibrillated cellulose (NFC) reinforced epoxy composite vehicle part	Carbon emissions in production phase: • Bacterial cellulose (BC) reinforced epoxy: about 194% higher compared to neat PLA. • NFC reinforced epoxy: about 83% higher carbon emissions compared to neat polylactide (PLA).	[26]
	Carbon emissions in production, use and EOL phase (vehicle application): • BC and NFC epoxy composites almost balance off compared to neat PLA and glass fiber-reinforced polypropylene (GF/PP) composites.	
	Green and clean claims: Not supported for NFC production; Comparable for car applications	
Nano organophilic montmorillonite (OMMT) used as PHB (poly 3-hydroxybutyrate) filler in monitors and car panels	Carbon emissions of cathode ray tube (CRT) monitors: • PHB1—5OMMT: almost 30% better compared to HIPS. • PHB1—10SCB: 150% better compared to HIPS.	[27]
	Carbon emissions of internal car panels: • PHB1—10OMMT: 9% worse compared to PP-GF. • PHB1—20SCB: 3% better compared to PP-GF.	
	Green and clean claims: Supported for CRT applications; Not supported for car applications	
Nanoclays LDH (layered double hydroxides) and MMT (montmorillonite) in mulching films	Carbon emissions of nanoclays: • Best case: LDH (based on MgO + $Al(OH)_3$ + Stearate)—about 6% better than MMT.	[28]
	Carbon emissions of mulching films: • Best case: LDPE [7]-based films with recycling and energy recovery from incineration—about 40% better compared to PBAT [8] (LDH/ZnAl-stearate).	
	Green and clean claims: Not supported for mulching film applications	
Multiwalled carbon nanotube (MWCNT) HT-PEM-FCs [9] in μ-CHP [10] and vehicles	HT-PEM-FCs—overall performance [11]: • PEM FCs with MWCNT: 20% better than PEM-FCs with carbon black	[29]
	μ-CHP plants—overall performance: • HT-PEM-FC powered plants: about 20% better than Stirling engine.	
	Carbon emissions for vehicle types: • Renewable energy mix: FCEV [12] has comparable emissions to BEV [13], and performs more than 50% better than ICV [14]. • EU energy mix: FCEV has about 50% higher emissions than BEV, and about 25% higher emissions than ICV.	
	Green and clean claims: Supported for MWCNT PEM FC production and μ-CHP plants; Not supported and comparable for car applications	

[7] LDPE: low density polyethylene, [8] PBAT: poly(butylene adipate-co-terephthalate), [9] HT-PEM-FC: high temperature polymer electrolyte membrane fuel cell, [10] μ-CHP: micro-combined heat and power plant, [11] Overall environmental performance (single score for 17 impact categories), [12] FCEV: fuel cell electric vehicle, [13] BEV: battery electric vehicle, [14] ICV: internal combustion vehicle.

Table 3. Summary of LCA studies on nanomaterials in the energy, medical and food sectors. See Tables S3–S5 for a more detailed analysis.

Sector	Nanomaterial	Overall Assessment	Reference
Energy	Silicon nanowires (SiNWs) in lithium ion batteries (LIB)	LIB packs with SiNWs: • About 18% higher carbon emissions than the alternative LIB pack with graphite anode. **Green and clean claims:** Not supported	[30]
Energy	Single-walled carbon nanotube (SWCNT) anode and multi-walled carbon nanotube cathode (MWCNT) LIB in vehicles	Production and Use phase (Application on LIB on vehicles): • Negative net energy benefits for SWCNT anode LIB on vehicles throughout vehicle lifetime compared to graphite anode LIB on vehicles: −14,716 MJ. • Positive net energy benefits for MWCNT cathode LIB on vehicles throughout lifetime compared to carbon black cathode LIB on vehicles: 2775 MJ. **Green and clean claims:** Not supported for SWCNT anode; Supported for MWCNT cathode	[12]
Energy	Carbon coated $LiFePO_4$ and lithium titanate nanoparticle $Li_4Ti_5O_{12}$ in batteries	Level 1: Production phase: • Production of nano-based battery systems: 40–300% more cumulative energy demand (CED) per KWh compared to alternatives. Level 2: Use phase: • Nanomaterials increase battery lifetime and thus, the lifecycle energy efficiency increases. Level 3: Implication of background energy system: • Improvements in quality of batteries due to nanomaterials may improve the transportation system efficiency at higher level, in which the energy flows are much larger in magnitude, i.e., introduction of competitive electric vehicles. **Green and clean claims:** Not supported	[31]
Medical	Silver nanoparticle (AgNP) enabled bandage	AgNp: • Carbon emissions for AgNp synthesis dominate the life cycle impacts of the bandage. • Carbon emissions from AgNp and bandage production are several times higher compared to carbon emissions from bandage EOL treatment. **Green and clean claims:** Not determined	[32]
Food	Cellulose nanofibers produced from carrot waste	Cellulose nanofibers: • Carrot waste process performs 17.8 to 2.0 times better than unripe coconut and cotton processes in terms of carbon emissions. • Carrot waste process performs better compared to tempo oxidation homogenization (TOHO) process (about 27% lower carbon emissions). **Green and clean claims:** Supported	[33]

4. Discussion

4.1. Carbon Emissions and Energy Use

4.1.1. Solar Sector

"Green and clean" claims are not supported by the findings of the reviewed studies of Kim and Fthenakis [23], Mohr et al. [21] and van der Meulen and Alsema [22], that assess a-Si/nc-Si solar cells. In terms of carbon emissions, three studies have concluded that nano-based photovoltaic cells perform better to alternatives. These studies are from Roes et al. [17], Sengul and Theis [18] and Tsang et al. [20], for the environmental assessment of glass/flexible polymer photovoltaics, quantum dot photovoltaics and organic photovoltaics respectively. Greijer et al. [19] found that nanocrystalline dye sensitized solar cells have comparable emissions as amorphous silicon solar cells. In two studies, nanobased solutions were reported to perform worse compared to alternatives in terms of carbon emissions. Roof integrated a-Si/nc-Si [21], and a-Si/nc-Si [22] have a significant climate change impact. Lastly, one study shows that TiO_2 nanotube based perovskite solar cells have either comparable or worse carbon impacts compared to alternatives [24].

In the studies of Roes et al. [17] and Tsang et al. [20] the performance of polymer PVs and organic PVs are on a per watt-peak basis. In the case of Roes et al. [17], the reason that watt-peak has been chosen as a functional unit is that at the time the study was performed, the lifetime of polymer PVs was much lower compared to multicrystalline silicon PVs. Thus, for 25 years of electricity generation, in order for the different technologies to break even in terms of climate change impact, polymer PVs with glass substrate require a minimum lifetime of 13 years and polymer PVs with flexible substrate require a minimum lifetime of 2.6 years. At the time of the study, lifetimes of more than one year had been reported. This indicates that results were more promising for polymer PVs on flexible substrate. In the case of Tsang et al. [20], the minimum required lifetime for the OPVs to compete a-Si PVs in terms of climate change potential is 4.8 years. At the time the study was performed the maximum lifetime of OPVs was 7 years. Details of the relevant studies are summarized in Table S6.

4.1.2. Polymer Sector

Nanocomposites used in polymers can improve the properties of the polymers such as thermal and mechanical, gas permeability, strength-to-weight ratios, improved corrosion resistance and other functionalities. Bio-based or biodegradable polymers have the potential to replace conventional petrochemical plastics [27], high-strength polymer nanocomposites can replace steel, aluminum, or other metals in industrial applications [25,26] and also, they can be used in the production of alternative fuel cells [29]. Results obtained from the reviewed studies vary in terms of carbon emissions of nanomaterial-based polymers compared to alternative technologies. The production of nanomaterial-based polymers resulted in higher carbon emissions in two of the studies [25,26]. However, when the nano-based polymers are applied to car body panels the results are different. In the study of Khanna and Bakshi [25] the application of carbon nanofiber reinforced polymer composites in vehicle body panels resulted in net energy savings and subsequently to lower carbon emissions compared to steel alternatives. In the study of Hervy et al. [26], application of nanofibrillated cellulose reinforced epoxy composites as applied in vehicle body panels resulted in almost breakeven of carbon emissions compared to neat polylactide (PLA) and glass fiber/polypropylene (GF/PP) alternatives. In the study of Pietrini et al. [27] the use of nanoscaled organophilic montmorillonite PHBs (poly3-hydroxybutyrate) resulted in a better carbon impact in the case of CRT monitors (using HIPS) and in a comparable carbon impact in the case of car body panels (using GF-PP). In the study of Notter et al. [29], multiwalled carbon nanotubes are used in the production of polymer electrolyte membrane fuel cells (PEM FCs). PEM FCs used in vehicles result in comparable carbon emissions with battery electric vehicles when the energy mix is renewable-based, and they perform worse when the EU energy mix is used. In the same study the PEM FCs with multiwalled carbon nanotubes were found to have better overall environmental performance compared to PEM FCs using carbon black. Moreover, in the same study the PEM FCs used in μ-CHP power plants result in better overall environmental performance compared to μ-CHPs (micro-combined heat and power plant) using a Stirling engine. On the other hand, in the study of Schrijvers et al. [28] the use of nano-based polymers in mulching films for the agriculture sector results in worse performance in terms of carbon emissions. The use of nanoclays in PBAT (poly-butylene adipate-co-terephthalate) results in higher carbon emissions compared to LDPE (low-density polyethylene) alternatives.

In the study of Pietrini et al. [27], the use of nanoscaled organophilic montmorillonite poly(3-hydroxybutyrate) in CRT monitors results in better performance in terms of carbon emissions compared to conventionally produced CRT monitors from high-impact polystyrene. The reason for this finding is that the production of PHB from sugar cane results in negative non-renewable energy use. That is the main driver for a better performance compared to the alternative. In the study of Notter et al. [29], the use of multiwalled carbon nanotubes reduces the platinum use in fuel cells (FCs). The MWCNT PEM (polymer electrolyte membrane) FCs perform better compared the alternative carbon black in terms of overall environmental performance and the key driver for that are the benefits from platinum savings. Moreover, the use of PEM FCs in μ-CHP plants results in better overall environmental performance compared to the alternative Stirling engine, due to higher electricity production of the former.

The "green and clean" claims are mostly not supported for the production of nanomaterials. When nanomaterials are used in specific application, the "green and clean" claims are supported only in half of the applications assessed. Improvements in nanomaterial synthesis need to be achieved in order to reduce the high energy demand of this process. Details of the relevant studies are summarized in Table S7.

4.1.3. Energy Sector

All of the three studies reviewed for the energy sector are related to the use of nanomaterials in lithium ion batteries [12,30,31]. The use of nanomaterials in batteries has the potential to improve various performance limitations, for example they can increase the capacity and the lifetime of the lithium ion batteries. In two of the studies [30,31] the "green and clean" claims are not met. The production of nano-based lithium ion batteries results in higher carbon emissions compared to their alternatives. Also, in the study of Zhai et al. [12] the "green and clean" claims are not supported for SWCNT anode production compared to graphite anode production in terms of energy requirements, but they are supported for MWCNT cathode compared to carbon black cathode for Li-ion batteries. Moreover, in the study of Zhai et al. [12] the application of Li-ion batteries in vehicles using SWCNT anode and MWCNT cathode is assessed. The battery weight reduces with the use of nanomaterials and that results in energy benefits during the use phase of the vehicle. However, even when the use phase of a car is considered the "green and clean" claims are not supported for the SWCNT anode in Li-ion batteries. In the case of the MWCNT cathode Li-ion batteries in which results are positive, the net energy benefits are even bigger when the use phase of a car is considered. We should also mention here that in the study of Kushnir and Sanden [31] is supported that improvements in the lifetime of the battery might open the way of competitive electric vehicles and thus they may improve the efficiency of the energy transport system in which the energy flows are of much higher magnitude than the production of the batteries. The studies are summarized in Table S8.

4.1.4. Medical Sector

Only one study [32] has performed a comprehensive impact assessment of nanomaterial use in the medical sector. The use of silver nanoparticles provides bandages with antimicrobial properties that prevent infection of a wound and promote healing. The study does not address comparable conventional technologies and it focuses on identifying the contribution of the related processes of the production, use and end-of-life treatment of the nanosilver enabled bandages to climate change, including end-of-life treatment of nanosilver released to the environment. The study clearly shows that nanomaterial production is the biggest contributor of carbon emissions despite of its very small portion in the total mass of the medical application. It is not possible to draw a conclusion about the "green and clean" claims, since the study does not compare different technologies.

4.1.5. Food Sector

Piccinno et al. [33] have performed a life cycle assessment of cellulose nanofiber production from vegetable food waste. Nanocellulose that is produced from renewable sources has the potential of achieving exceptional properties and at the same time the product is biodegradable when it comes to the end of its life cycle. The findings of the reviewed article showed that cellulose nanofiber production from carrot waste performs better in terms of carbon emissions compared to alternative methods of cotton and unripe coconuts and wood pulp. The "green and clean" claims are supported from the results of this study.

4.2. Assumptions and Scenarios

4.2.1. Solar Sector

All authors in the reviewed articles—except one [22]—have studied nano-based solar technologies that exist in the research and development phase at a lab scale. All studies emphasize the importance of uncertainties regarding the future commercialization of the technologies. Seven of these studies applied different scenarios to deal with uncertainties. Scenarios for conversion efficiency of the different solar cell technologies is the most widespread among the studies. The parameters and processes of the systems to which different scenarios have been applied are the following:

- Lifetime of solar cell [19,24];
- Conversion efficiency of solar cell [17,19,21,22,24];
- Process energy demand [19,21,22];
- Deposition rate [23];
- SF_6 release and recycling [22];
- NF_3 release and thermal abatement [22];
- Thickness of solar cell layer [22];
- Overall performance of the PV system [21];
- Material and energy input data [21];
- Insolation [24];
- Alternative manufacturing options [20].

These are important parameters that affect the successful implementation of nano-based photovoltaic systems. In other words, the performance of the future commercial nano-based PV systems depends strongly on the assumed improvement of the parameters summarized. For instance, conversion efficiency measures the fraction of the energy coming from the sunlight that is converted into electricity. Improvements in cell efficiency result in smaller energy payback time and thus, it is an important indicator for successful deployment of nano-based solar cells. It has to be noted here that the study from van der Meulen and Alsema [22] analyzes the life cycle greenhouse gas emissions of an amorphous silicon solar cell with nanocrystalline layers that already exists in a commercial production.

4.2.2. Other Sectors

All the reviewed studies for the polymer sector have applied life cycle assessment for nanomaterials that are in an early stage of research and development. Uncertainties regarding future development of the technologies have been identified from the reviewed studies and are summarized here:

- Weight reduction due to material substitution [25,29];
- Mechanical properties of materials [25,27,28];
- Nanomaterial fraction usage [26];
- Energy requirements of processes [27];
- Process efficiencies [28];
- Tensile strength of nano-based material [28];
- End-of-life (EOL) treatment [28];
- Release rates [28];
- Energy mix [29];
- Material requirements [29].

The mechanical properties of materials are one source of uncertainty that have been identified in most reviewed studies. Changes in these parameters will affect the environmental performance of the technologies assessed. For instance, achieving specific mechanical properties of materials (e.g., high strength to weight ratios) directly affects the material requirements and thus the upstream flows of the system.

Furthermore, several uncertainties regarding future development of the technologies have been identified from the reviewed studies for the energy sector. The lifespan of the batteries has been included in all three studies. Again, changes in the parameters affect the environmental performance of the technologies assessed. For example, if the energy mix for charging the batteries is produced from renewable sources, then an improvement of the environmental performance of the use phase of the technologies assessed, is obtained. A summary of the parameters that have been identified from the reviewed studies, in which uncertainties exist, is as follows:

- Battery capacity [30];
- Cycling performance of battery [30];
- Material selection and processing [30,31];
- Battery lifetime [12,30,31];
- Energy mix [30,31];
- Operating geographic region [30];
- Relationship between energy use and weight of vehicle [12].

Moreover, because all studies reviewed have performed life cycle assessments only at an early stage of research and development, future improvements in process efficiencies and end-of-life treatment of the technologies should be expected.

For the medical sector, the study from Pourzahedi and Eckelman [32], which is the only one that includes nanowaste treatment, has identified uncertainties related to nanomaterial size, shape, and surface chemistry. It is mentioned that particle production with different techniques will result in different environmental impacts. Moreover, the authors mention that results reported in this study should be considered as an upper bound of impacts from the production of nanomaterials. That is because data used are bench-scale and future industrial scale processes should be considered more efficient. Thus, life cycle impacts are likely to decrease.

Finally, the data used for the food sector study of Piccinno et al. [33] were from the lab scale and uncertainties are related to scaling up to a future industrial production of nanocellulose from vegetable food waste.

4.3. Limitations on Current LCA Studies of Nanomaterials

In current life cycle impact assessment methodologies, databases and software, no information related to nano-emissions have been developed yet. Several of the studies reviewed for the solar, polymer and energy sectors, have included toxicity impacts in their impact analysis:

- Solar sector [21,24];
- Polymer sector [26,28,29];
- Energy sector [30].

However, these toxicity impacts are related to upstream and downstream flows of extraction, manufacturing, and end-of-life treatment of the technologies and not to the potential human health risks of the nanomaterials themselves. The only exception is the study of Pourzahedi and Eckelman [32] for the medical sector, in which data related to toxicity, fate and transport of nanomaterials and end-of-life treatment was included. Thus, even though an unpredictable release of nanomaterials to the environment is an important concern, the studies reviewed do not address this issue due to the lack of data.

Li et al. [30] has reported the mass, shape, particle size and particle number of nanowastes from silicon nanowires, all properties of which toxicity may be assessed. However, these authors have not included the toxicity of the nanowastes in their assessment as no suitable methods were available in the conventional impact assessment methods. Finally, the only study that includes releases and end-of-life treatment of nanowastes is the study of Pourzahedi and Eckelman [32] for the medical sector. The release of silver nanoparticles has been modelled and it has been included in the life cycle impact analysis.

4.4. Main Contributors of Climate Change and Energy Demand

In the solar sector, the deposition process, which is the synthesis of nanomaterials in layers, has been recorded in most reviewed studies, except of the studies of Roes et al. [17] and Tsang et al. [20], as one of the most important contributors for both primary energy consumption and climate change impact. Different deposition methods have been included in the reviewed studies. The characteristics related to them are high energy consumption and use of gases with high global warming potential during the deposition. The addition of extra nanolayers onto substrates increases the deposition time and thus the material and energy usage. Furthermore, the low deposition rates extend further the deposition time and subsequently, the energy consumption and carbon emissions. Five studies have included balance-of-system (BOS) equipment, which is all the related equipment that is needed to allow the functioning of the photovoltaics, cables, inventers, switches and more, in their system boundaries [17,19,21,22,24]. All the studies have shown that BOS is also a very important contributor for both climate change impact and primary energy consumption. Moreover, the integration of roof mounted solar cells, frame and laminate has a significant contribution to both carbon emissions and energy demand.

In the reviewed studies in the polymer sector, the synthesis of nanomaterials appears to be one of the most significant contributors to carbon emissions and energy consumption [25–27]. The application of nano-based polymers to vehicle body panels reduces the weight of the vehicle compared to the alternatives. This results in fuel savings during vehicle's operation and thus, reduction of carbon emissions according to the studies of Hervy et al. [26] and Khanna and Bakshi [25]. However, in the study of Pietrini et al. [27] the application of nano-based polymers to vehicle body panels significantly increases the weight of the vehicle compared to the alternatives and thus, it increases the emissions. In the study of Schrijvers et al. [28] for the mulching films application, the nanoclay-based PBAT results in worse performance in terms of carbon emissions compared to the alternative LDPE. The reason is that energy credits are given to LDPE due to the incineration process.

For the energy sector the production of nanomaterials is identified in the studies of Kushnir and Sanden [31] and Li et al. [30] as the main contributor of environmental impact due to the high energy demand. In addition, the electricity use in batteries (renewable or non-renewable source) also appears to be an important factor of environmental impact in both studies. In the study of Zhai et al. [12] the energy requirements for the production of SWCNT anodes and MWCNT cathodes dominate the energy demand for Li-ion battery manufacturing.

For the food sector, Piccinno et al. [33] have identified the liberation of MFC (microfibrillated cellulose) used in the wet-spinning process route for nanocellulose production as the main contributor of environmental impact.

Finally, for the medical sector the production of nanomaterials is also the most important contributor of carbon emissions. In addition, for the bandage production the nanomaterial used has the biggest contribution of carbon emissions.

4.5. Other Impact Categories

Other impact categories have been analyzed in five of the reviewed studies in the solar sector [17,18,20,21,24]. The study from Zhang et al. [24] calculates the environmental impacts of TNT perovskite solar cells from cradle to gate, for different impact categories, but the comparison among other type of solar cell technologies is based only on greenhouse gas emissions. The remaining four studies have included different impact categories. An noticeable example is the study from Mohr et al. [21] where the comparison between the different solar technologies is based on a large number of impact categories (terrestrial acidification, freshwater ecotoxicity, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, human toxicity, ionizing radiation, climate change, ozone layer depletion, photochemical oxidant formation, particulate matter formation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion and fossil depletion). Among these impact categories, the amorphous-silicon/nanocrystalline-silicon solar cells perform better only in terrestrial ecotoxicity and photochemical oxidant formation compared to multicrystalline-silicon solar cell technologies. For the rest of the impact categories the nano-based technology performs worse. In some cases, such as ozone layer depletion, the a-Si/nc-Si solar cells score 46 times higher compared to the multicrystalline-silicon solar cells. It is interesting to mention here the study of Sengul and Theis [18] in which they have assessed the carbon emissions, sulfur and nitrogen oxide emissions and heavy metal emissions. Quantum-dot photovoltaic (QDPV) modules perform far better in terms of carbon emissions and they also perform better in terms of sulfur and nitrogen emissions than other types of PV technologies. In terms of heavy metal emissions, QDPV modules perform worse compared to other PV technologies.

For the polymer sector, non-renewable energy use has been included in the impact assessment in the studies of [27,28], abiotic depletion has been included in the study from Hervy et al. [26] and an overall impact indicator (through the subjective aggregation of 17 impact categories) in the study of Notter et al. [29]. In all these studies the results of these impact categories follow the same trend as carbon emissions. In the energy sector, the study from Li et al. [30] has included many different impact categories in the comparison between the nano-based technologies and their alternatives. The result from the study of Li et al. [30] is that lithium-ion battery packs with silicon-nanowire anode perform worse in terms of the impact results of abiotic depletion potential, acidification potential, eutrophication potential, ozone depletion potential, photochemical oxidation potential, ecological toxicity potential, and human toxicity potential compared to lithium-ion battery packs with graphite anode. Lastly, for the food sector the study from Piccinno et al. [33] has also included human toxicity and overall environmental performance in the impact assessment. The results follow a similar trend as in case of consideration of carbon emissions.

4.6. LCA Methodologies

The application of life cycle assessment is well described in the ISO 14040 and ISO 14044 standards. The ISO standards provide the requirements and guidelines for the LCA phases. The LCA phases include the goal and scope definition, inventory analysis, impact assessment and interpretation. In 9 of the studies reviewed, the ISO standards are followed and described in their methods section [17,19,20,22,26–30]. The other studies describe aspects that are common to ISO-LCA (such as inventory data and impact assessment methods), but do not specifically refer to the ISO standards. The benefits of applying the ISO standards in the life cycle assessment is an increased transparency and reliability of the results by providing a structured and reproducible evaluation of the environmental performance of the different nano-based technologies. It should be noted that the reviewed studies show differences in the life cycle assessment methodologies they use. The differences that have been identified include: functional unit, system boundaries, geographical characteristics, data quality and data sources, impact assessment methods, up-scaling uncertainties, and interpretation of results.

4.7. Future Perspective

Since most of the studies reviewed assess technologies that are at an early stage of research and development, a future up-scaling of these technologies might reduce carbon emissions. Ex-ante or prospective LCA studies have shown that emerging technologies can benefit from better design choices and efficient industrial processes [34,35]. Furthermore, the environmental performance of technologies can benefit from economies of scale. Louwen et al. [36] showed a significant downward trend in both cumulative energy demand and greenhouse gas emissions of photovoltaic technologies the last 40 years, by showing a correlation between growing installed photovoltaic capacity and better environmental performance. Since production processes of nanomaterials are still immature we might expect better environmental performance in the future. On the other hand, further research should be done in order to deal with uncertainties related to nanomaterial release and treatment.

5. Conclusions

A synthesis of the main findings from the reviewed studies shows that nanomaterials have high cradle-to-gate energy demand that result in high carbon emissions. The "green and clean" claims, in terms of carbon emissions and energy use, are not supported from the findings of the reviewed studies for the energy sector with the exception of MWCNT cathode for Li-ion batteries. For the solar sector the "green and clean" claims are not supported for the a-Si/nc-Si solar technologies, they are comparable for nanocrystalline dye sensitized solar cells and TiO_2 nanotube perovskite solar cells and they are supported for polymer PVs, organic PVs and quantum dot PVs composed of CdTe. For the polymer sector the "green and clean" claims are supported only in a few applications. For the food sector, the "green and clean" claims are supported from the findings. The claim could not be verified for the medical sector.

Life cycle assessment of nanomaterials most often are performed in an early stage of research and development using laboratory and experimental data (17 out of 18 studies). It is clear from the reviewed studies that in most sectors—solar, polymer, energy, and medical sector—improvements in the carbon emissions and energy efficiency of nanomaterial production need to be considered in order for the nanomaterials to achieve their "green and clean" claims.

None of the reviewed studies has included the release and subsequent effects of nanomaterials to the environment in their impact assessments. This important omission is due to the lack of impact data on the toxicity, fate, and exposure of nanomaterials. Exposure to nanomaterials can cause severe damage to human health. Thus, impact models need to be developed and included in the future LCA studies of nanomaterials, as they might significantly change the environmental impact assessment results of the nanomaterials.

Despite uncertainties, the application of LCA at the early stage of research and development of the technologies reviewed has displayed environmental burdens. Design of the technologies can be adjusted on the basis of results provided by the LCA. The application of LCA to nanomaterials should be further developed with emphasis given in data collection, scenario development for scaling up to industrial level and development of impact models and data for nanomaterials.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/10/3/689/s1, Table S1: LCA studies on nanomaterials in the solar sector, Table S2: LCA studies on nanomaterials in the polymer sector, Table S3: LCA studies on nanomaterials in the energy sector, Table S4: LCA studies on nanomaterials in the medical sector, Table S5: LCA studies on nanomaterials in the food sector, Table S6: Summary of performance of nanomaterial use in the solar sector compared to alternatives, Table S7: Summary of performance of nanomaterial use in the polymer sector compared to alternatives, Table S8: Summary of the performance of nanomaterial use in the energy sector compared to alternatives.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Keyword selection:
Nanos:

- Nano *
- ENM

AND
Assessment:

- Life Cycle Assessment
- Life Cycle Analysis
- Life Cycle Impact
- Life Cycle Sustainability
- Life Cycle Energy
- Life Cycle Inventory

AND
Sector specific keywords

Keywords search for nanotechnologies and life cycle assessment

((“Nano*” OR “ENM”) AND (“life cycle assessment” OR “life cycle analysis” OR “life cycle impact” OR “life cycle sustainability” OR “lifecycle assessment” OR “lifecycle analysis” OR “lifecycle impact” OR “lifecycle sustainability” OR “life cycle energy” OR “lifecycle energy” OR “life cycle inventory” OR “lifecycle inventory”))
Using the above keywords in the Web of Science database we get 335 hits.

Keyword search for photovoltaic/solar energy sector

((“Nano*” OR “ENM”) AND (“life cycle assessment” OR “life cycle analysis” OR “life cycle impact” OR “life cycle sustainability” OR “lifecycle assessment” OR “lifecycle analysis” OR “lifecycle impact” OR “lifecycle sustainability” OR “life cycle energy” OR “lifecycle energy” OR “life cycle inventory” OR “lifecycle inventory”) AND (“photovoltaic*” OR “solar”))
We get down to 43 hits. For these articles a one by one screening was conducted, and the result is that not all of them are relevant to a comprehensive life cycle analysis of nanotechnologies in the solar sector. 8 of them are applying life cycle assessment and have more than 5 citations.

Keyword search for food sector

((“Nano*” OR “ENM”) AND (“life cycle assessment” OR “life cycle analysis” OR “life cycle impact” OR “life cycle sustainability” OR “lifecycle assessment” OR “lifecycle analysis” OR “lifecycle impact” OR “lifecycle sustainability” OR “life cycle energy” OR “lifecycle energy” OR “life cycle inventory” OR “lifecycle inventory”) AND (“food”))
19 articles in total. 1 article is related to life cycle assessment and food sector (food waste) and has more than 5 citations.

Keyword search for polymers

((“Nano*” OR “ENM”) AND (“life cycle assessment” OR “life cycle analysis” OR “life cycle impact” OR “life cycle sustainability” OR “lifecycle assessment” OR “lifecycle analysis” OR “lifecycle impact” OR “lifecycle sustainability” OR “life cycle energy” OR “lifecycle energy” OR “life cycle inventory” OR “lifecycle inventory”) AND (“polymer”))

The keyword search gives us 35 articles. 5 of them are related to life cycle assessment of polymers and have more than 5 citations.

Keyword search for biomolecules

((“Nano*” OR “ENM”) AND (“life cycle assessment” OR “life cycle analysis” OR “life cycle impact” OR “life cycle sustainability” OR “lifecycle assessment” OR “lifecycle analysis” OR “lifecycle impact” OR “lifecycle sustainability” OR “life cycle energy” OR “lifecycle energy” OR “life cycle inventory” OR “lifecycle inventory”) AND (biomolecule*))

2 studies are found. No study is related to life cycle assessment and biomolecules.

Keyword for energy sector

((“Nano*” OR “ENM”) AND (“life cycle assessment” OR “life cycle analysis” OR “life cycle impact” OR “life cycle sustainability” OR “lifecycle assessment” OR “lifecycle analysis” OR “lifecycle impact” OR “lifecycle sustainability” OR “life cycle energy” OR “lifecycle energy” OR “life cycle inventory” OR “lifecycle inventory”) AND (“wind” OR “nuclear” OR “hydro” OR “diesel” OR “gas” OR “batter*” OR “lignite”))

By applying this keyword search on the web of science database I get 44 hits. Only 3 of them are related to life cycle assessment that have more than 5 citations and all three of them are in batteries.

Keyword for photo (electro) chemistry

((“nano*” OR “ENM”) AND (“life cycle assessment” OR “life cycle analysis” OR “life cycle impact” OR “life cycle sustainability” OR “lifecycle assessment” OR “lifecycle analysis” OR “lifecycle impact” OR “lifecycle sustainability” OR “life cycle energy” OR “lifecycle energy” OR “life cycle inventory” OR “lifecycle inventory”) AND ((“photo” OR “electro”) AND (“chemistry”)))

1 study found. No study is related to life cycle assessment and photo-electro chemistry.

Keywords for medical technology

((“nano*” OR “ENM”) AND (“life cycle assessment” OR “life cycle analysis” OR “life cycle impact” OR “life cycle sustainability” OR “lifecycle assessment” OR “lifecycle analysis” OR “lifecycle impact” OR “lifecycle sustainability” OR “life cycle energy” OR “lifecycle energy” OR “life cycle inventory” OR “lifecycle inventory”) AND (“medical” OR “medicine”))

7 articles. 1 of them related to LCA in medical sector and has more than 5 citations.

References

1. Savolainen, K.; Backman, U.; Brouwer, D.; Fadeel, B.; Fernandes, T.; Kuhlbusch, T.; Landsiedel, R.; Lynch, I.; Pylkkänen, L. *Nanosafety in Europe 2015–2025: Towards Safe and Sustainable Nanomaterials and Nanotechnology Innovations*; Finnish Institute of Occupational Health: Helsinki, Finland, 2013.
2. European Commission KETs. *Time to Act. High-Level Expert Group on Key Enabling Technologies*; European Commission: Brussels, Belgium, 2015.
3. European Commission. *Towards a European Strategy for Nanotechnology*; Office for Official Publications of the European Communities: Luxemburg, 2004; ISBN 92-894-7686-9.
4. European Commission CORDIS Express: The nanotech revolution. Available online: http://cordis.europa.eu/news/rcn/36656_en.html (accessed on 15 March 2017).

5. Peralta-Videa, J.R.; Zhao, L.; Lopez-Moreno, M.L.; de la Rosa, G.; Hong, J.; Gardea-Torresdey, J.L. Nanomaterials and the environment: A review for the biennium 2008–2010. *J. Hazard. Mater.* **2011**, *186*, 1–15. [CrossRef] [PubMed]
6. European Commission Horizon 2020 Work Programme 2016–2017. 5.ii. In *Nanotechnologies, Advanced Materials, Biotechnology and Advanced Manufacturing and Processing*; European Commission: Brussels, Belgium, 2015.
7. Klöpffer, W.; Curran, M.A.; Frankl, P.; Heijungs, R.; Köhler, A.; Olsen, S.I. Nanotechnology and Life Cycle Assessment: A systems approach to Nanotechnology and the environment. In Proceedings of the European Commission, DG Research, jointly with the Woodrow Wilson International Center for Scholars, Washington, DC, USA, 2–3 October 2006.
8. Dowling, A.; Clift, R.; Grobert, N.; Hutton, D.; Oliver, R.; O'neill, O.; Pethica, J.; Pidgeon, N.; Porritt, J.; Ryan, J. *Nanoscience and Nanotechnologies: Opportunities and Uncertainties*; Royal Society: London, UK, 2004; pp. 61–64.
9. Colvin, V.L. The potential environmental impact of engineered nanomaterials. *Nat. Biotechnol.* **2003**, *21*, 1166–1170. [CrossRef] [PubMed]
10. DG Environment; Science Communication Unit; UWE; Bristol; European Commission; Science for Environment Policy. *Assessing the Environmental Safety of Manufactured Nanomaterials*; The Publications Office of the European Union: Luxembourg, 2017; ISBN 978-92-79-45732-6.
11. Healy, M.L.; Dahlben, L.J.; Isaacs, J.A. Environmental assessment of single-walled carbon nanotube processes. *J. Ind. Ecol.* **2008**, *12*, 376–393. [CrossRef]
12. Zhai, P.; Isaacs, J.A.; Eckelman, M.J. Net energy benefits of carbon nanotube applications. *Appl. Energy* **2016**, *173*, 624–634. [CrossRef]
13. Bauer, C.; Buchgeister, J.; Hischier, R.; Poganietz, W.R.; Schebek, L.; Warsen, J. Towards a framework for life cycle thinking in the assessment of nanotechnology. *J. Clean. Prod.* **2008**, *16*, 910–926. [CrossRef]
14. Som, C.; Berges, M.; Chaudhry, Q.; Dusinska, M.; Fernandes, T.F.; Olsen, S.I.; Nowack, B. The importance of life cycle concepts for the development of safe nanoproducts. *Toxicology* **2010**, *269*, 160–169. [CrossRef] [PubMed]
15. Guineé, J.B.; Heijungs, R.; Vijver, M.G.; Peijnenburg, W.J.G.M. Setting the stage for debating the roles of risk assessment and life-cycle assessment of engineered nanomaterials. *Nat. Nanotechnol.* **2017**, *12*, 727–733. [CrossRef] [PubMed]
16. Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; de Koning, A.; van Oers, L.; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; et al. *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards*; Springer Science & Business Media: Berlin, Germany, 2002; p. 692.
17. Roes, A.L.; Alsema, E.A.; Blok, K.; Patel, M.K. Ex-ante environmental and economic evaluation of polymer photovoltaics. *Prog. Photovolt. Res. Appl.* **2009**, *17*, 372–393. [CrossRef]
18. Şengül, H.; Theis, T.L. An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use. *J. Clean. Prod.* **2011**, *19*, 21–31. [CrossRef]
19. Greijer, H.; Karlson, L.; Lindquist, S.-E. Environmental aspects of electricity generation from a nanocrystalline dye sensitized solar cell system. *Renew. Energy* **2001**, *23*, 27–39. [CrossRef]
20. Tsang, M.P.; Sonnemann, G.W.; Bassani, D.M. A comparative human health, ecotoxicity, and product environmental assessment on the production of organic and silicon solar cells. *Prog. Photovolt. Res. Appl.* **2016**, *24*, 645–655. [CrossRef]
21. Mohr, N.J.; Meijer, A.; Huijbregts, M.A.J.; Reijnders, L. Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate. *Prog. Photovolt. Res. Appl.* **2013**, *21*, 802–815. [CrossRef]
22. Van der Meulen, R.; Alsema, E. Life-cycle greenhouse gas effects of introducing nano-crystalline materials in thin-film silicon solar cells. *Prog. Photovolt. Res. Appl.* **2011**, *19*, 453–463. [CrossRef]
23. Kim, H.C.; Fthenakis, V.M. Comparative life-cycle energy payback analysis of multi-junction a-SiGe and nanocrystalline/a-Si modules. *Prog. Photovolt. Res. Appl.* **2011**, *19*, 228–239. [CrossRef]
24. Zhang, J.; Gao, X.; Deng, Y.; Li, B.; Yuan, C. Life Cycle Assessment of Titania Perovskite Solar Cell Technology for Sustainable Design and Manufacturing. *ChemSusChem* **2015**, *8*, 3882–3891. [CrossRef] [PubMed]
25. Khanna, V.; Bakshi, B.R. Carbon nanofiber polymer composites: Evaluation of life cycle energy use. *Environ. Sci. Technol.* **2009**, *43*, 2078–2084. [CrossRef] [PubMed]

26. Hervy, M.; Evangelisti, S.; Lettieri, P.; Lee, K.-Y. Life cycle assessment of nanocellulose-reinforced advanced fibre composites. *Compos. Sci. Technol.* **2015**, *118*, 154–162. [CrossRef]
27. Pietrini, M.; Roes, L.; Patel, M.K.; Chiellini, E. Comparative life cycle studies on poly(3-hydroxybutyrate)-based composites as potential replacement for conventional petrochemical plastics. *Biomacromolecules* **2007**, *8*, 2210–2218. [CrossRef] [PubMed]
28. Schrijvers, D.L.; Leroux, F.; Verney, V.; Patel, M.K. Ex-ante life cycle assessment of polymer nanocomposites using organo-modified layered double hydroxides for potential application in agricultural films. *Green Chem.* **2014**, *16*, 4969–4984. [CrossRef]
29. Notter, D.A.; Kouravelou, K.; Karachalios, T.; Daletou, M.K.; Haberland, N.T. Life cycle assessment of PEM FC applications: Electric mobility and μ-CHP. *Energy Environ. Sci.* **2015**, *8*, 1969–1985. [CrossRef]
30. Li, B.; Gao, X.; Li, J.; Yuan, C. Life cycle environmental impact of high-capacity lithium ion battery with silicon nanowires anode for electric vehicles. *Environ. Sci. Technol.* **2014**, *48*, 3047–3055. [CrossRef] [PubMed]
31. Kushnir, D.; Sandén, B.A. Multi-level energy analysis of emerging technologies: A case study in new materials for lithium ion batteries. *J. Clean. Prod.* **2011**, *19*, 1405–1416. [CrossRef]
32. Pourzahedi, L.; Eckelman, M.J. Environmental life cycle assessment of nanosilver-enabled bandages. *Environ. Sci. Technol.* **2014**, *49*, 361–368. [CrossRef] [PubMed]
33. Piccinno, F.; Hischier, R.; Seeger, S.; Som, C. Life cycle assessment of a new technology to extract, functionalize and orient cellulose nanofibers from food waste. *ACS Sustain. Chem. Eng.* **2015**, *3*, 1047–1055. [CrossRef]
34. Louwen, A.; Sark, W.; Schropp, R.E.I.; Turkenburg, W.C.; Faaij, A.P.C. Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. *Prog. Photovolt. Res. Appl.* **2015**, *23*, 1406–1428. [CrossRef]
35. Villares, M.; Işildar, A.; Mendoza Beltran, A.; Guinee, J. Applying an ex-ante life cycle perspective to metal recovery from e-waste using bioleaching. *J. Clean. Prod.* **2016**, *129*, 315–328. [CrossRef]
36. Louwen, A.; van Sark, W.G.; Faaij, A.P.C.; Schropp, R.E.I. Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. *Nat. Commun.* **2016**, *7*, 13728. [CrossRef] [PubMed]