Supplementary Information

Table S1. LCA studies on nanomaterials in the solar sector.

Reference	Nanomaterial	Carbon emissions, energy payback time	Compare to alternative	Key drivers for carbon emissions and energy	Overall assessment
(Roes et al., 2009)	Nanoscale layers on polymer PVs with glass and flexible substrate	Carbon emissions per watt-peak Polymer PV on glass substrate results in 819 gCO2-eq. mc-silicon PV results in 1559 gCO2-eq. Minimum lifetime for the two systems to break even for global warming potential is 13 years. Polymer PV on flexible substrate results in 132gCO2-eq. mc-silicon PV results in 1293 gCO2-eq. Minimum lifetime for the two systems to break even for global warming potential is 2.4 years. Energy payback time (EPBT) per watt-peak 1.26 years for glass-based polymer PVs. 2.33 years for mc-silicon PVs. 0.19 years for flexible-based polymer PVs. 1.95 years for mc-silicon PVs	Polymer PVs on glass or flexible substrate are compared to multi-crystalline silicon PVs, CdTe (cadmium telluride), CIS (copper, indium, selenide or sulphide), silicon and DSC (dye-sensitized)	Carbon emissions For Polymer PV on glass substrate: Production of glass, sputtering of ITO (indium, tin, oxide) on the top of glass, lamination, framing and balance-of-system (BOS) For Polymer PV on flexible substrate: Sputtering and lamination	Carbon emissions per watt-peak: For Polymer PV on glass substrate: 48% less emissions than mc-silicon Also less emissions than CdTe, CIS, silicon Higher emissions than DSC For Polymer PV on flexible substrate: 90% less emissions than mc-silicon Also less emissions than CdTe, CIS, silicon, DSC
(Greijer et al., 2001)	Nanocrystalline dye sensitized solar cells (ncDSC)	Carbon emissions Nanocrystalline dye sensitized solar cell system: 19 to 47 gCO2-eq/KWh Amorphous silicon solar cell system: 42gCO2-eq/KWh Natural gas power plant: 450gCO2-eq/KWh	Nanocrystalline dye sensitized solar cell system is compared to amorphous silicon solar cell system and a natural gas power plant	Carbon emissions Production of solar cell module (deposition and sintering of the porous layers on the top of the substrate), substrate glass, frame and junction box	Carbon emissions Nanocrystalline dye sensitized solar cell system: Comparable emissions to amorphous solar cell system. 90% less emissions than natural gas power plant.
(Tsang et al., 2016)	Organic PV (OPV) using fullerene	Carbon emissions: OPV: 52.2 gCO_2eq. per watt-peak.	Compared to multi-crystalline silicon and	The biggest contributor in carbon emissions is the production of the fluorine-doped tin	Carbon emissions per watt-peak

	derivative phenyl-C61-butyric ester (PCBM)	a-Si, mc-silicon: n.d.[1] EPBT per watt-peak: OPV: 0.21 years a-Si: 2.18 years mc-silicon: 2.72 years	amorphous silicon (a-Si) solar cells	oxide (FTO) film used as a transparent front electrode. It is followed by annealing and the PCBM production.	OPV: about 70% lower emissions compared to a-Si solar cells about 90% lower emissions compared to mc-silicon cells
(Mohr et al., 2013)	Amorphous-silicon/nanocrystalline-silicon	Carbon emissions Energy Payback time (EPBT) 2.3 years for a-Si/nc-Si solar cell system 3.4 years for multi-silicon solar cell system Cumulative Energy Demand 1.4MJ/KWh for both systems	Amorphous-silicon/nanocrystalline-silicon solar cell systems are compared to multi-silicon solar cell systems	Carbon emissions Encapsulation (emissions of chlorofluoro in production of encapsulated foil). Integrated roof construction (production of aluminum). Plasma enhanced chemical vapor deposition (PECVD). Removal of aluminum temporary carrier. Balance-of-system (BOS) components. Energy demand Integrated slanted roof construction (production of aluminum). Deposition of silicon (PECVD). Removal of aluminum temporary carrier (wet etching). BOS integration (mainly from the inventers)	Carbon emissions a-Si/nc-Si: About 25% higher emissions than multi-silicon PVs
(van der Meulen and Alsema, 2011)	Amorphous-silicon/nanocrystalline-silicon	Most likely scenario: Carbon emissions a-Si/nc-Si: about 42 to 55 gCO2-eq/KWh a-Si: about 30 gCO2-eq/KWh Energy demand a-Si/nc-Si: 1219 to 1242 MJ/m2 module area a-Si: 836 to 838 MJ/m2 module area	Amorphous silicon/nano-crystalline silicon (micromorph) are compared to amorphous silicon PV systems	Carbon emissions a-Si/nc-Si: Increase in material (SF6, NF3, H2, SiH4, O2). Increase in energy (module processing, capital equipment, feedstock material) requirements. Increased Fluor-gases usage in deposition process Energy demand Module processing. Fabrication of the thin-film (extended deposition time due to energy intensive	Most likely scenario: Carbon emissions a-Si/nc-Si: About 29% to 46% higher emissions than a-Si Energy demand About 31 to 33% higher energy requirements than a-Si

[1] n.d.: not determined

				plasma enhanced chemical vapor deposition process)	
(Kim and Fthenakis, 2011)	Amorphous-silicon/nanocrystalline-silicon	<u>Energy Payback time (EPBT)</u> a-Si/nc-Si: 0.7 to 0.9 years a-Si: 0.8 years <u>Energy demand</u> a-Si/nc-Si: 1300 MJ/m2 a-Si: 930 MJ/m2	Amorphous-silicon/nanocrystalline-silicon PVs are compared with triple-junction amorphous silicon PVs	<u>Energy demand</u> <u>a-Si/nc-Si:</u> Prolonged deposition time. Increased use of precursor gases.	<u>Energy demand</u> <u>a-Si/nc-Si:</u> About 40% higher energy requirements than a-Si PVs
(Şengül and Theis, 2011)	quantum dot photovoltaics (QDPV)	<u>Carbon emissions</u> <u>quantum dot photovoltaics (QDPV):</u> 25 gCO2-eq/m2 or 5 gCO2-eq/KWh <u>silicon PVs:</u> about 18 to 27 gCO2-eq/KWh <u>thin film PVs</u> about 15 to 68 gCO2-eq/KWh <u>other nano PVs</u> about 58 gCO2-eq/KWh	Quantum dot photovoltaics (QDPV) are compared with other types of PVs: silicon PVs (ribbon multi-crystalline silicon, multi-crystalline silicon and mono-crystalline silicon), thin film PVs (cadmium telluride and copper-indium-selenide) and Nano PVs (dye sensitized). They are also compared to other type of energy sources coal, oil, lignite, natural gas, diesel, nuclear, wind and hydropower	<u>Carbon emissions</u> <u>QDPV:</u> Production of the quantum dot solar cells (electricity, aluminum foil and methanol). Production of the module.	<u>Carbon emissions</u> <u>QDPV:</u> about 72 to 81% less emissions than silicon PVs about 67 to 93% less emissions than thin film PVs about 91% less emissions than other nano PVs

Table S2. LCA studies on nanomaterials in the polymer sector.

Reference	Nanomaterial	Carbon emissions and energy	Compare to alternative	Key drivers for carbon emissions and energy	Overall Assessment
(Khanna and Bakshi, 2009)	Carbon nanofiber (CNF) reinforced polymer nanocomposites (PNC)	Carbon emissions 1st level - production phase: Polypropylene - CNF (15% Vol) results in about 45 Giga Joules per component Polypropylene - Glass Fiber - CNF (0.6% Vol) results in about 6 Giga Joules per component Steel results in about 3 Giga Joules per component	Polypropylene (PP) and unsaturated polyester resin (UPR) carbon nanofibers(CNFs) with and without glass-fiber (GF) are compared to steel for production phase (1st level) and for production and use phase with an application to vehicle body panels (2nd level)	Energy demand Synthesis of carbon nanofibers (CNFs) requires enormous energy input. In the case of application in body panels for vehicles, CNF-PNCs contribute to weight reduction and thus fuel gasoline savings	1st level - production phase CNF polymer nanocomposites result in 1.6 to 12 times higher energy demand compared to steel 2nd level - production and use phase (application to vehicle body panels) CNF polymer nanocomposites result in 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
(Hervy et al., 2015)	Nanofifibrillated cellulose (NFC) reinforced epoxy composites	Carbon emissions Production phase: BC reinforced epoxy composites results in 13.8 Kg CO2 eq. NFC reinforced epoxy composites results in 8.6 Kg Co2 eq. Production, use and EOL treatment phase (application to composite automotive part): BC reinforced epoxy composites results in about 27 Kg CO2 eq. NFC reinforced epoxy composites results in about 18 Kg Co2 eq.	Bacterial cellulose (BC) and nanofifibrillated cellulose (NFC) reinforced epoxy composites are compared to two benchmark materials: 30wt.-% randomly oriented glass fibre-reinforced polypropylene (GF/PP) composites and neat polylactide (PLA). Firstly the production phase and secondly the production, use and EOL treatment phase with an application to composite automotive part	Carbon emissions Production phase Reinforcement production (NFC from wood pulp and BC biosynthesis from low molecular weight sugars), VARI (porous flow medium production) and polymer matrix production Production, use and EOL treatment phase (application to composite automotive part) The application of NFC and BC reinforced epoxy composites to vehicles contribute to weight reduction and thus fuel savings	Carbon emissions Production phase BC reinforced epoxy result in about 194% higher carbon emissions compared to neat PLA NFC reinforced epoxy result in about 83% higher carbon emissions compared to neat PLA Production, use and EOL treatment phase (application to vehicles) BC and NFC epoxy composites almost balance of compared to neat PLA and GF/PP composites

(Pietrini et al., 2007)	Nanoscaled organophilic montmorillonite (OMMT) used as poly(3-hydroxybutyrate) (PHB) filler	<u>Carbon emissions</u> <u>Cathode ray tube (CRT) monitor - housing</u> best case: PHB1 – 5OMMT results 0.5 Kg CO2 eq. per FU best case: PHB1 - 10SCB results 0.1 Kg CO2 eq. per FU HIPS results 15.1 Kg CO2 eq. per FU <u>Internal car panels</u> best case: PHB1 – 10OMMT results 627.2 Kg CO2 eq. per FU best case: PHB1 - 20SCB results 552.1 Kg CO2 eq. per FU PP-GF results 569.9 Kg CO2 eq. per FU	Nanoscaled organophilic montmorillonite (OMMT) and sugar cane bagasse (SCB) used as poly(3-hydroxybutyrate) (PHB) fillers are compared to high-impact polystyrene (HIPS) used in cathode ray tube (CRT) monitor housing and glass-fibers-filled polypropylene (GF-PP) used in internal panels of vehicles	NREU contribution - Analogous considerations can be made for carbon emissions <u>CRT monitor housing</u> Injection molding, extrusion and filler production are the highest contributors for PHB-MMT composites <u>Internal car panels</u> Use phase is the highest contributor for PHB-MMT due to higher weight that leads to higher fuel consumption. PHB produced from sugar cane (PHB1). PHB produced from corn starch (PHB2).	<u>Carbon emissions</u> <u>Cathode ray tube (CRT) monitor - housing</u> PHB1 – 5OMMT performs almost 30% better compared to HIPS in terms of carbon emissions PHB1 - 10SCB performs 150% better compared to HIPS in terms of carbon emissions <u>Internal car panels</u> PHB1 – 10OMMT performs 9% worse compared to PP-GF in terms of carbon emissions PHB1 - 20SCB performs 3% better compared to PP-GF in terms of carbon emissions
(Schrijvers et al., 2014)	Nanoclays LDH (layered double hydroxides) and MMT (montmorillonite)	n.d.	Different compositions of nanoclays LDH and MMT with surfactants (dodecyl sulfate and stearate) are compared. Biodegradable polymer PBAT, with and without nanoclay, is compared to LDPE that is recycled and incinerated with energy recovery for mulching film application (in agriculture sector). Irganox 1010 or p-hydroxy-cinnamic acid are used as UV stabilizers.	<u>NREU contribution</u> <u>Nanoclays:</u> LDH: Surfactants and drying of the clay are the highest contributors MMT: Organic modification and surfactants are the highest contributors <u>Carbon emissions</u> <u>Mulching films:</u> LDPE: Waste incineration is the highest contributor in carbon emissions PBAT: PBAT production is the highest contributor in carbon emissions	<u>Carbon emissions</u> <u>Nanoclays:</u> best case: LDH (based on MgO+Al(OH)3+Stearate) performs about 6% better than MMT in terms of carbon emissions <u>Mulching films:</u> best case: LDPE based films with recycling and energy recovery from incineration perform about 40% better compared to PBAT (LDH/ZnAl-stearate) in terms of carbon emissions

(Notter et al., 2015)	Multiwalled carbon nanotubes (MWCNTs)	n.d.	High temperature (HT) polymer electrolyte membrane fuel cells (PEM FCs) with MWCNTs as support materials for platinum compared to PEM FCs with CB (carbon black). Fuel cell electric vehicles (FCEV) that use PEM FC are compared with battery electric vehicles (BEV) and internal combustion vehicles (ICV). Micro-combined heat and power plants (μ-CHP) that use PEM FC are compared to μ-CHP plants with Stirling engine.	Carbon emissions HT PEM FCs Energy intensive processes of platinum mining and refining processes contribute more to carbon emissions FCEV EU energy mix: Operation of vehicle due to hydrogen production is the biggest contributor Renewable energy mix: Operation of vehicle and PEF FC (production, maintenance and disposal) Environmental performance μ-CHP plants natural gas production, operation of the plant are and quality of energy produced the biggest contributors	Overall environmental performance HT PEM FCs PEM FCs with MWCNT have 20% better performance than PEM FCs with CB. μ-CHP plants HT PEM FC powered plants perform about 20% better than Stirling engine device Carbon emissions for vehicle types Renewable energy mix: FCEV has comparable emissions to BEV, and performs more than 50% better than ICV EU energy mix: FCEV have about 50% higher emissions than BEV, and about 25% higher emissions than ICV

Table S3. LCA studies on nanomaterials in the energy sector.

Reference	Nanomaterial	Carbon emissions and energy	Compare to alternative	Key drivers for carbon emissions and energy	Overall Assessment
(Li et al., 2014)	Silicon nanowires (SiNWs)	Carbon emissions LIB packs with SiNW anode result in about 0.188 kg CO2eq. per km of EV driving LIB packs with graphite anode result in 0.155 Kg CO2eq. per km of EV driving.	High capacity lithium ion batteries (LIB) with silicon nanowires (SiNW) anode are compared to conventional LIB with graphite anode and applied to electric vehicles (EV) driving	Carbon emissions Battery use mainly from primary energy consumption is the highest contributor to carbon emissions. It is followed by battery production and specifically SiNW anode production due to large energy demand and toxic chemicals. SiNW fabrication is energy intensive.	Carbon emissions LIB packs with SiNW result in about 18% higher carbon emissions than the alternative LIB pack with graphite anode.
(Zhai et al., 2016)	Single-walled carbon nanotube (SWCNT)	Energy demand Manufacturing phase: SWCNT anode: Requires additional energy of 21425	Conventional graphite anode is compared to SWCNT anode and conventional carbon black cathode is compared to MWCNT cathode in	Energy demand Manufacturing of SWCNT anode requires very large amount of energy.	Production and Use phase (Application on Li-ion batteries on vehicles) Negative net energy benefits for

	anode and multi-walled carbon nanotube cathode (MWCNT)	MJ compared to conventional graphite anode. MWCNT cathode: Avoids energy of 444 MJ compared to conventional carbon black cathode.	Li-ion batteries.		SWCNT anode Li-on batteries on vehicles throughout vehicle lifetime compared to graphite anode Li-on on vehicles: -14716 MJ Positive net energy benefits for MWCNT cathode Li-on batteries on vehicles throughout lifetime compared to carbon black cathode Li-on on vehicles: 2775 MJ
(Kushnir and Sandén, 2011)	Carbon coated $LiFePO_4$ and lithium titanate nanoparticle $Li_4Ti_5O_{12}$	n.d.	Level 1 Carbon coated $LiFePO_4$ as cathode and lithium titanate nanoparticle $Li_4Ti_5O_{12}$ as anode for lithium ion batteries are compared to alternatives $LiCoO_2$ and $LiNi_{0.8}Co_{0.2}O_2$ as cathodes and carbon as anodes for lithium ion batteries. Level 2 This level includes the use phase of the lithium ion batteries. Level 3 This level includes the implication of background energy systems	Level 1 Energy intensive material processing of production of nano-based lithium ion batteries and lowered voltages of cells which result in larger material use per unit of energy storage are the most important drivers. Level 2 Battery lifetime Level 3 Energy mix	Level 1 Cumulative energy demand (CED) Production of nanomaterial based battery systems results in 40-300% more CED per KWh compared to alternatives. Level 2 Nanomaterials increase battery lifetime and thus, the lifecycle energy efficiency increases. Level 3 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

Table S4. LCA studies on nanomaterials in the medical sector.

Reference	Nanomaterial	Carbon emissions and energy	Compare to alternative	Key drivers for carbon emissions and energy	Overall Assessment
(Pourzahedi and Eckelman, 2014)	Silver nanoparticles (AgNPs)	AgNP synthesis results in 1.3E+02 Kg CO2 eq. for the production of 1 Kg of AgNP	n.d.	AgNp synthesis: Combustion related processes: hard coal, natural gas, lignite and diesel for power generation Bandage production: Silver nanoparticles are the biggest contributor for carbon emissions even though they cover just 6% of the bandage mass	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

Table S5. LCA studies on nanomaterials in the food sector.

Reference	Nanomaterial	Carbon emissions and energy	Compare to alternative	Key drivers	Overall Assessment
(Piccinno et al., 2015)	Cellulose nanofibers	<u>Carbon emissions</u> <u>Brazilian electricity mix</u> Carrot waste process for the production of 1g of MFC results in about 0.1 kg CO2eq Cotton and unripe coconuts for the production of 1g of MFC results in about 0.1 and 1.1 kg CO2eq. respectively <u>US electricity mix</u> Carrot waste process for the production of 1g of MFC results in about 1.5 kg CO2eq TOHO process for the production of 1g of MFC results in about 1.9 kg CO2eq	Production of cellulose nanofibers from vegetable food waste (carrot waste) is compared to the existing alternatives of the production of cellulose nanofibers from cotton and unripe coconuts, and from wood pulp	Liberation of MFC (microfibrillated cellulose) used in the wet-spinning process route for cellulose production from waste carrot is the main contributor of environmental impact	<u>Carbon emissions</u> 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 TOHO process (about 27% lower carbon emissions)

Table S6. Summary of performance of nanomaterial use in the solar sector compared to alternatives.

Nanomaterial	Performance of nanos compared to alternative	Comparison of nanomaterial to alternative in terms of carbon emissions	Reference
Nanoscale layers on polymer PVs	Better	Both polymer PVs on glass substrate and polymer PVs on flexible substrate perform better compared to mc-Si PV systems.	[17]
Quantum dot PVs	Better	Quantum dot PVs perform better compared to ribbon multi-Si, multi-Si, mono-Si, CdTe, CIS, DSPV.	[18]
C60 fullerene OPVs	Better	OPVs perform better compared to a-Si and mc-Si PVs.	[20]
Nanocrystalline DSC solar cells	Comparable	nc-DSC have comparable carbon emissions with a-Si cell systems	[19]
a-Si/nc-Si solar cell	Worse	a-Si/nc-Si solar cell performs worse compared to mc-Si solar cells in terms of carbon emissions	[21]
a-Si/nc-Si solar cell	Worse	a-Si/nc-Si solar cell performs worse compared to a-Si technology in terms of carbon emissions	[22]
a-Si/nc-Si solar cell	Worse	a-Si/nc-Si solar cell has higher energy demand than a-Si solar cell	[23]
TNT perovskite solar cell	Worse and Comparable	TNT perovskite solar cells perform worse compared to CdTe solar cells; they are comparable to a-Si, multi-Si and DSC solar cells; they perform better than mono-Si solar cells in terms of carbon emissions.	[24]

Table S7. Summary of performance of nanomaterial use in the polymer sector compared to alternatives.

Nanomaterial	Performance of nanos compared to alternative	Comparison of nanomaterial to alternative	Reference
CNF reinforced polymer nanocomposites	Production of CNF PNCs: **Worse** Application to car panels: **Better**	Production of CNF PNCs results in higher carbon emissions compared to steel production. Application of CNF PNCs to body panels for vehicles results in fuel savings and net energy savings compared to steel alternative.	[25]
Nanofifibrillated cellulose (NFC) reinforced epoxy composites	Production NFCs: **Worse** Application to car panels: **Comparable**	Production of NFC epoxy composites results in higher carbon emissions compared to neat PLA. Application of NFC epoxy composites to body panels for vehicles balance of carbon emissions compared to GF/PP composite alternatives.	[26]
Nanoscaled organophilic montmorillonite (OMMT) used as poly(3-hydroxybutyrate) (PHB) filler	Application to CRTs: **Better** Application to car panels: **Worse**	PHB1 - 5OMMT and PHB1 - 10SCB perform better compared to HIPS in terms of carbon emissions in CRT monitor - housing. PHB1 - 10OMMT and PHB1 - 20SCB have worse and comparable carbon emissions respectively compared to PP-GF in internal car panel	[27]

		applications.	
Nanoclays LDH and MMT used in polymer nanocomposites	Application to mulching films: **Worse**	Nanoclay LDH production performs better than nanoclay MMT production in terms of carbon emissions. Nanoclay based PBAT perform worse compared to LDPE alternative, for mulching film application in agriculture sector.	[28]
Multiwalled carbon nanotubes	Production of MWCNT PEM FCs: **Better** Application to μ-CHP: **Better** Application to vehicles: **Worse and Comparable**	PEM FCs with MWCNTs perform better compared to PEM FCs with CB in terms of overall environmental performance. HT PEM FCs powered μ-CHP plants perform better compared to alternative Stirling engine μ-CHP plants in terms of overall environmental performance. FCE vehicles perform worse in terms of carbon emissions compared to BEVs and ICVs when EU energy mixed is applied. FCE vehicles have comparable carbon emissions to BEVs when renewable energy mix is applied.	[29]

Table S8. Summary of the performance of nanomaterial use in the energy sector compared to alternatives.

Nanomaterial	Performance of nanos compared to alternatives	Comparison of nanomaterial to alternative	Reference
Silicon nanowires (SiNWs)	Worse	LIB packs with SiNW result in higher carbon emissions than the alternative LIB pack with graphite anode.	[30]
Carbon coated LiFePO4 and lithium titanate nanoparticle Li4Ti5O12	Worse	Production of nanomaterial-based battery systems results higher energy demand compared to alternatives.	[31]
SWCNT anode and MWCNT cathode	Worse for SWCNT Better for MWCNT	SWCNT anode performs worse compared to graphite anode. MWCNT performs better compared to carbon black cathode. Application of SWCNT Li-on batteries in vehicles results in negative net energy benefit. Application of MWCNT Li-on batteries in vehicles results in positive net energy benefit.	[12]