

# Nanotechnology for environmentally sustainable electromobility

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**Electric vehicles (EVs) powered by lithium-ion batteries (LIBs) or proton exchange membrane hydrogen fuel cells (PEMFCs) offer important potential climate change mitigation effects when combined with clean energy sources. The development of novel nanomaterials may bring about the next wave of technical improvements for LIBs and PEMFCs. If the next generation of EVs is to lead to not only reduced emissions during use but also environmentally sustainable production chains, the research on nanomaterials for LIBs and PEMFCs should be guided by a life-cycle perspective. In this Analysis, we describe an environmental life-cycle screening framework tailored to assess nanomaterials for electromobility. By applying this framework, we offer an early evaluation of the most promising nanomaterials for LIBs and PEMFCs and their potential contributions to the environmental sustainability of EV life cycles. Potential environmental trade-offs and gaps in nanomaterials research are identified to provide guidance for future nanomaterial developments for electromobility.**

Anthropogenic greenhouse gas emission rates increased by more than 80% from 1970 to 2010<sup>1</sup>, and emissions from the transport sector increased at a faster rate than any other energy end-use sector<sup>2</sup>. In 2010, transportation was responsible for 23% of total energy-related CO<sub>2</sub> emissions<sup>2</sup>, with total energy consumption reaching 27% of the total end-use energy, of which about half was consumed by light-duty vehicles<sup>2</sup>. There is currently an estimated one billion light-duty vehicles worldwide, and as a result of increasing standards of living and economic activity, this number is expected to double by 2035<sup>3</sup>, with obvious repercussions for energy security, climate change and urban air quality.

Vehicles with electric powertrains are seen as attractive alternatives to conventional internal combustion engine vehicles<sup>2</sup>, and many governments have introduced policies promoting market uptake of EVs<sup>4,5</sup>. With the increasing market for EVs, most major automobile manufacturers now have one or more EVs in their production line. The significant drop in the cost of LIBs over the past decade will further accelerate the adoption of EVs<sup>6</sup>.

When combined with clean energy sources, EVs can offer a range of advantages over conventional vehicles, such as reduced greenhouse gas emissions and local air pollution<sup>7,8</sup> and improved energy efficiency<sup>9</sup>. However, a shift in drivetrain technology to LIBs and PEMFCs leads to changes in supply chains, introducing more environmentally intensive materials and production processes in exchange for potentially lower operating emissions<sup>10</sup>. To understand the environmental implications arising from transport electrification therefore requires a systems perspective, such as that provided by life-cycle assessment (LCA). LCA offers a way to quantify environmental impacts associated with the production, use and waste handling of goods and services<sup>11</sup> (Box 1).

Due to the unique electrical and mechanical properties only attainable at the nanoscale, nanostructured materials developed for LIBs and PEMFCs may significantly improve their performance. Nanomaterials can notably offer advantages over bulk-structured materials through reduced diffusion lengths of ions and electrons,

and in some cases, through changes in the phase diagram resulting in changes in the reaction mechanism. However, the synthesis of nanomaterials may be more energy demanding<sup>12</sup> than that of their bulk counterparts, which in turn may have significant bearings on the life-cycle environmental impact of EVs<sup>13</sup>, particularly with respect to greenhouse gas emissions. For EVs to offer environmental benefits over conventional vehicles, any technical improvements introduced by nanomaterials must result in environmental advantages outweighing the potentially increased production impacts.

In this Analysis, we investigate how nanomaterials can contribute to more environmentally sustainable electromobility and compare different candidates for development in this direction. For the purpose of this study, the term EVs includes vehicles with a fully electric drivetrain using LIBs or PEMFCs. First, we briefly review the LCA literature of EVs to identify potential trade-offs and sources of environmental impacts of the current state of EV technology. This serves to identify areas in which the development of novel materials may bring about the greatest improvements from a systems perspective. These identified challenges are grouped into three life-cycle attributes that we use to evaluate and compare different nanotechnological developments for environmentally sustainable batteries and fuel cells for electric transport. Finally, we distil the overarching evaluations and provide insights into the contribution of nanotechnologies for more environmentally sustainable mobility.

## Life-cycle assessment of EVs

Several academic studies have assessed the environmental impact of EVs<sup>7,10,14–22</sup>. Studies assessing EVs and relevant components have assumed LIBs for battery electric vehicles<sup>22–25</sup> and PEMFCs for fuel cell vehicles<sup>10,15,20,21</sup>. Compared with conventional vehicles, a larger share of EVs' life cycle impacts occur in the material processing and vehicle production phase, notably because of their reliance on relatively scarce materials and on production processes with high energy requirements<sup>10,14,15,19</sup>. Consequently, studies have found up to 40–90% higher greenhouse gas production-phase emissions for EVs compared

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**Box 1 | Life-cycle assessment.**

Life-cycle assessment is an analytic method for estimating the environmental impacts associated with the production and consumption of products and services. This method first strives to inventory all exchanges with the environment necessary to deliver a function, considering the material and energetic inputs required at all stages, from raw material extraction, through processing and manufacturing, to product use, recycling and final disposal. The total emissions and resource use associated with the delivery of a functional unit (for example, transporting one person over one kilometre) are thus compiled in a life-cycle inventory. Examples of such emissions include carbon dioxide, methane, particulate matter and volatile organic carbons. These inventoried emissions are then linked to potential environmental impacts, such as climate change, eutrophication, acidification and ecotoxicity, using characterization factors determined by modelling, experimental results or physical properties. These potential environmental impacts, also referred to as midpoint indicators, may be further characterized based on their negative effects on key areas of protection, or endpoint indicators, as valued by humanity: damage to human health, damage to ecosystems and damage to resource availability. Unfortunately, current characterization methods do not provide characterization factors for quantifying the impact of emissions of different nanomaterials on the environment. Nevertheless, despite data limitations and important sources of uncertainty, life-cycle assessment provides a useful 'whole system' perspective over entire supply chains. This perspective helps identify environmental 'hot-spots' and the processes where efficiency measures would have greatest effect.

with conventional vehicles. Whether or not EVs can compensate for their higher up-front environmental impact depends on the emission intensity of electricity sources and hydrogen for charging LIBs and fuelling PEMFCs, respectively. A life-cycle perspective is therefore required when evaluating their environmental performance<sup>7,10,14,19</sup>.

Studies assessing impact categories beyond climate change find that EVs can offer substantial improvement during its use phase, such as reductions in photochemical smog and fossil resource depletion<sup>8,19</sup>. However, EVs can also have a negative impact in other categories (for example, human toxicity, freshwater ecotoxicity, metal depletion), mostly arising from material extraction in the production chain<sup>14,19,20,26</sup>.

Due to the relatively high environmental impacts associated with the production of LIBs and PEMFCs, the lifetime expectancy and the recyclability of these energy devices are key parameters in determining their life-cycle environmental performance. Several studies have pointed to challenges with PEMFC durability due to degradation in the membrane and catalyst layer during long-term operation<sup>27–29</sup>. Battery EVs, on the other hand, generally suffer from limited driving ranges, and while larger batteries allow for longer driving ranges, they also cause more production-phase impacts and add weight to the vehicle, thereby increasing electricity consumption during EV operation<sup>30</sup>.

As many excellent reviews already cover the contribution of nanomaterials to overcoming technological and commercialization challenges of LIBs and PEMFCs<sup>31–36</sup>, this Analysis rather screens the environmental effects arising from the use of nanomaterials in these devices. For example, while the battery literature indicates that increasing volumetric energy density is an important factor for LIB adoption in battery EVs due to the limited space available<sup>37–40</sup>, the LCA literature rather focuses on the need for higher gravimetric energy density to avoid the additional material production and use-phase energy consumption associated with the transport of heavier batteries<sup>7,18,19,23,25</sup>.

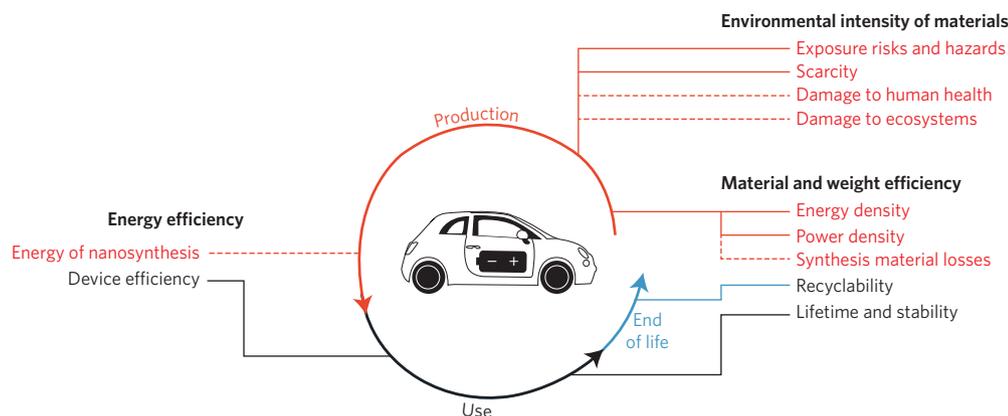
**Life-cycle approach for environmental screening**

LCAs strive to guide product development by quantifying all environmental impacts associated with each product, but such a comprehensive assessment is typically limited by data quality and quantity. Multiple simplified, or streamlined, LCA methods have been proposed as a first iteration toward complete LCAs<sup>41–43</sup> to provide life-cycle guidance as early as possible in product design, that is, before the design is decided and improvement options restricted. In contrast to full LCAs, there is no standard method to guide the performance of these scoping approaches. In this Analysis, we develop a framework that draws elements from streamlined LCA methods, the qualitative environmentally responsible product matrix scoping approach<sup>41–43</sup> and key principles of green chemistry<sup>44,45</sup> (see Supplementary Figs S1 and S2). These elements are adapted, combined and updated to address the parameters that both can be influenced by nanotechnological research and determine the environmental impacts of EVs. The development of the framework is made all the more pertinent by the fast pace of nanotechnology research, the great diversity of competing nanomaterials and their differing technological readiness levels, which ranges from laboratory-scale proof of concept to commercialization.

The framework used here appraises nanomaterial candidates with respect to three life-cycle attributes: environmental intensity of materials, material and weight efficiency, and energy efficiency, which are described in detail below and illustrated in Fig. 1 and Supplementary Fig S3. Together, these life-cycle attributes cover all life-cycle phases of the material: production, use and end of life. To guide action, we distinguish between intrinsic parameters that are attributed to the material itself, and value-chain parameters that are characteristic not of the material but of the activities involved in its production. The evaluation of materials is adapted to the special nature of electromobility. Section 3 in the Supplementary Information describes the criteria and basis of comparison and provides further details in Supplementary Tables S1–S5 and Supplementary Figs S4–S9.

**Environmental intensity of materials.** The environmental intensity of a material describes the extent to which producing and using a given mass of a given material causes damages to the life-cycle areas of protection: human health, ecosystems and resource availability (Box 1). For example, energy-intensive extraction or production processes can result in high greenhouse gas emissions, which in turn can lead to damages to human health and ecosystems. This life-cycle attribute is highly relevant since, on the one hand, LCA studies on EVs find that materials used in LIBs and PEMFCs have environmentally intensive extraction and refining processes<sup>10,14,15,19</sup>, while on the other hand, nanotechnological developments are likely to alter the materials used in LIB and PEMFC productions. Some materials can themselves cause damages through exposure risks and hazards. The use of non-renewable materials can exacerbate resource scarcity, while material extraction and processing activities throughout the production chain result in embodied damage to human health and damage to ecosystems. Reducing the particle size from bulk material to the nanoscale can change both the material properties (for example, increased reactivity) and lead to differing environmental intensity (for example, damage to human health).

**Material and weight efficiency.** The material efficiency characteristic is a metric of the functionality that a material can achieve per unit of mass. Because the environmental aspects of materials as described in the previous section scale directly with the amount of material used, we should strive to attain the same functionality with less material. Given the relatively high environmental impacts associated with material processing in the production of LIBs<sup>22,24,46</sup> and PEMFCs<sup>10,15,21</sup> for EVs, optimizing the utilization of the materials in these devices



**Figure 1 | Early life-cycle environmental screening of lithium-ion batteries and proton exchange membrane hydrogen fuel cells for electric vehicles.**

Solid lines denote intrinsic aspects of the material itself. Dotted lines denote properties that are attributes of the value-chain aspects or embodied activities related to the material's production. Red lines denote production aspects, black lines use-phase aspects and the blue line end-of-life aspects.

is important. Increasing gravimetric energy density in LIBs or power density increases the material efficiency as less material can be used for the same energetic output. Improvements in material lifetime and stability allow for devices that last longer and in turn can reduce the need for replacement, thereby avoiding the use of additional materials. Energy density, power density, and lifetime and stability of nanomaterials were compared with the performance of a commercial 'baseline' material. Reducing material losses during synthesis and increasing the recyclability both improve material efficiency by minimizing waste. The use of nanomaterials in LIBs and PEMFCs may affect the material efficiency (for example, change in energy or power density) due to large surface areas, but it may also result in unwanted side reactions (for example, influence lifetime and stability). Material efficiency considerations such as energy and power density allow for lighter batteries and PEMFCs; these lightweighting effects also provide side benefits in the form of gains in energy efficiency.

**Energy efficiency.** Energy efficiency is a measure of how much functionality a given energy input can provide; here we consider energy losses during operation and energy use in the synthesis of nanomaterials. Depending on the energy sources used for producing electricity or hydrogen, the energy losses in LIBs and PEMFCs during operation can contribute to a substantial share of the device's life-cycle greenhouse gas emissions and other environmental impacts<sup>9,19,24,25</sup>. Here, we consider the device efficiency to measure how well nanomaterials enable the device to transform and deliver energy. LCA studies find that energy consumption in the value chains of LIBs can also contribute significantly to their greenhouse gas emissions and production impact<sup>24,25,46</sup>. Energy of nanosynthesis measures how energy efficient the manufacturing processes of nano-enabled LIB and PEMFC materials are. While using nanomaterials instead of bulk materials may improve the device efficiency due to increased reactivity, the differing methods to synthesize these nanomaterials require varying amounts of energy. As energy is often produced from carbon-intensive sources, energy use often translates to greenhouse gas emissions.

In the following sections, qualitative and semi-quantitative comparisons will be performed in terms of the three life-cycle attributes for various nanomaterials. Figures 2–5 use colour coding to illustrate the perceived relative strengths of different nanostructure materials with respect to the above life-cycle attributes. Green denotes relative strength, red relative weakness, yellow intermediate characteristics and white a lack of data. Nanostructures are given by circles, whereas the paler background indicates the characteristics

of the material in bulk form. Absence of a circle indicates a lack of data relevant to nanostructures. The grey background denotes the 'baseline' material. Although many of these life-cycle attributes pertain to the device as a whole (for example, energy density, power density and lifetime), we will consider the materials in isolation for greater ease of analysis. Thus, a cathode with high specific capacity and operating voltage will be described as a 'high energy density cathode'<sup>38</sup> because its combination with an appropriate anode allows for a high energy density LIB.

### Nanotechnologies in battery developments

Battery cells are composed of several key components: anode, cathode, separator, electrolyte and current collectors. However, their energy density and environmental footprint are mainly determined by the properties of the electrode materials<sup>39</sup>. We therefore focus on the environmental performance of different nanostructured anode and cathode materials.

**Anode materials.** The use of pure lithium anodes is precluded in rechargeable LIBs with liquid electrolytes because of the formation of lithium dendrites on charging, which short the cell, leading to thermal runaway and fires<sup>36</sup>. Due to this increased reactivity and the associated safety issues, pure lithium anodes in nanoform are, so far, unsuitable for LIBs. Most current LIBs rely on the intercalation of lithium ions in anodes predominantly composed of graphite<sup>47–49</sup>. More recently, the use of nanosized lithium titanium oxide spinel ( $\text{Li}_4\text{Ti}_5\text{O}_{12}$ , LTO) has also been adopted. In addition to these commercial anode materials, multiple alloys and conversion anode materials are currently under research. Figure 2 presents the material life-cycle attributes of reviewed anode nanomaterials, as well as graphite, which is considered to be the 'baseline' anode material.

Graphite is an abundant material<sup>47</sup>, and its extraction or synthesis has relatively low environmental impact<sup>50,51</sup>. Today, it also requires little energy during its production<sup>22</sup> and allows for batteries with good cyclability<sup>47</sup> and high energy efficiency<sup>52,53</sup>. The main weakness of this chemistry from a sustainability standpoint relates to its low material efficiency; its limited energy density leads to heavier, larger batteries<sup>54</sup>.

Alternative carbon nanostructures with higher theoretical energy densities are under investigation<sup>34</sup>, but neither carbon nanotubes nor graphene have been found to be technically feasible because they have too many side reactions<sup>55</sup>. Carbon nanotubes and graphene also exhibit more environmentally intensive<sup>50,51</sup> profiles and, like other carbon nanostructures, their handling requires more precaution<sup>56</sup>

Material type:			Intercalation			Alloying			Conversion					
Material:			Graphite	Carbon nanotubes	LTO	Si	Sn or SnO <sub>2</sub>	Ge	Fe oxides	Co or Cr oxides	Cu oxides	Mo or Ru oxides	Ni oxides	Mn oxides
Environmental intensity of material	Intrinsic	Exposure risks and hazards		●	●	●	●	●	●	●	●	●	●	●
		Scarcity												
	Value chain	Damages to human health												
		Damages to ecosystems												
Material and weight efficiency	Intrinsic	Energy density		●	●	●	●	●	●	●	●	●	●	●
		Power density			●	●	●	●	●	●	●	●	●	●
		Lifetime and stability		●	●	●	●	●	●	●	●	●	●	●
		Recyclability	N/A			N/A			●	●	●		●	●
	Value chain	Synthesis material losses		●	●	●●	●	●	●	●●	●			●
Energy efficiency	Intrinsic	Device efficiency		●	●	●	●	●	●	●	●	●	●	●
	Value chain	Energy of nanosynthesis	N/A	●	●	●●	●	●	●	●●	●	●	●	●

**Figure 2 | Anode materials for lithium-ion batteries.** Nanoarchitected materials are given by a circle. Background colours reflect characteristics of bulk materials. Green denotes relative strength, red relative weakness, yellow intermediate characteristics and white no data. Absence of circle indicates no data for the nanomaterial. The grey background denotes the 'baseline' material. LTO, lithium titanium oxide. See Supplementary Information for the sources of the data in this figure.

than graphite<sup>57</sup>. The current carbon nanotube synthesis routes are energy intensive<sup>58–60</sup>. Even when potential economies of scale are taken into account, energy requirements for the synthesis of carbon nanotubes through chemical vapour deposition, arc discharge or laser-assisted methods remain significant<sup>61</sup>, which in turn result in high greenhouse gas emissions<sup>62</sup>. Furthermore, carbon nanotube anodes have lower charge–discharge energy efficiencies<sup>34,52</sup>. Increasing evidence points to toxicity effects of carbon nanotubes similar to those of asbestos fibres<sup>63,64</sup>, which may affect production and end-of-life processing and recycling of the batteries<sup>65</sup>.

LTO is obtained from relatively abundant resources<sup>47,66</sup> and has moderate production impacts<sup>50,51</sup>. It intercalates lithium in a safer manner than carbon because it is 1.5 V away from lithium metal deposition<sup>33</sup>, but must be nanostructured to reach acceptable power densities due to its low conductivity<sup>34</sup>. Contrary to carbon nanotubes, LTO can be synthesized with moderate amounts of energy and low reagent losses, especially if a hydrothermal synthesis route is used<sup>13,67</sup>. The resulting nanostructured anodic material offers high cycling energy efficiency<sup>47,68</sup>, increased safety<sup>34</sup>, high power density<sup>69</sup> and extended lifetimes<sup>52</sup>. Although LTO is already used in small commercially available EVs<sup>70</sup>, the 1.5 V operating potential of LTO leads to inherently low energy densities<sup>33</sup>, which reduces its material and weight efficiency and thus its environmental desirability for EVs.

LTO nanoparticles also pose a high exposure risk<sup>71</sup>. The positive properties of LTO, however, potentially make it an environmentally sustainable candidate for static and high power applications.

Even more abundant than carbon<sup>47</sup>, silicon presents the highest theoretical capacity to store lithium of all studied anode materials<sup>52</sup>, potentially allowing for high energy density anodes. Refining silicon to metallurgical grade for use in the chemical industry causes moderate damage to human health and ecosystems<sup>50,51</sup>. Regarding electrochemical performances, bulk silicon anodes suffer from poor power density<sup>72</sup> and extreme volume changes (up to 320%)<sup>73</sup> that lead to rapid structural degradation of the electrode<sup>33</sup>, resulting in poor lifetime. The material must therefore be nanostructured to ensure that voids can buffer such swelling<sup>34,74</sup>. Silicon nanoparticles in carbon-based nanocomposites and silicon nanowires have been shown to improve electrochemical performance and lifetime with cycle life of 1,000–2,000 cycles<sup>73,75</sup>. Nanostructured silicon anodes thus open the possibility for high material efficiency in the LIB life cycle, particularly with respect to lifetime<sup>76</sup> and energy and power density<sup>73,77</sup>. However, handling silicon nanoparticles in carbon nanostructures<sup>56,78</sup> and silicon nanowires<sup>79</sup> requires some precaution. The most popular technique used to grow silicon nanowires is chemical vapour deposition<sup>75</sup>, which has moderate to high energy requirements<sup>60,75</sup>. As a result, the synthesis of nanostructured silicon may

Material type:			Intercalation					Conversion			
			Layered				Olivine	Spinel	Chalcogenide		
Material:			NCA	NMC	LCO	LMR	LFP	LVP	LMO	Sulfur	Lithium sulfide
Environmental intensity of material	Intrinsic	Exposure risks and hazards	●	●	●	●	●	●	●	●	●
		Scarcity			●						
	Value chain	Damages to human health									
		Damages to ecosystems									
Material and weight efficiency	Intrinsic	Energy density		●	●	●	●	●	●	●	●
		Power density		●	●	●	●	●	●	●	●
		Lifetime and stability		●	●	●	●	●	●	●	●
		Recyclability		●	●	●	●	●	●	N/A	●
	Value chain	Synthesis material losses	N/A	●	●		●	●	●	●	●
Energy efficiency	Intrinsic	Device efficiency		●		●	●	●	●	●	●
	Value chain	Energy of nanosynthesis	N/A	●	●	●	●	●	●	●	●

**Figure 3 | Cathode materials for lithium-ion batteries.** Circles and colour coding are as defined in Fig. 2. NCA, lithium nickel cobalt aluminium oxide; NMC, lithium nickel manganese cobalt oxide; LCO, lithium cobalt oxide; LMR, lithium/manganese rich transition metal oxide; LFP, lithium iron phosphate; LVP, lithium vanadyl phosphate; LMO, lithium manganese oxide. See Supplementary Information for the sources of the data in this figure.

result in high greenhouse gas emissions<sup>72</sup>. Furthermore, during the use phase, silicon anodes also suffer from higher voltage hysteresis<sup>47</sup> and thereby lower cycling energy efficiencies than graphite or LTO.

Tin and germanium can also reversibly alloy lithium. Nanostructured tin-based anodes cycle with a higher Coulombic efficiency than silicon<sup>47</sup>, and germanium-based anodes allow for exceptional power densities<sup>34</sup>. However, given the greater scarcity<sup>47,66</sup> of these metals and the environmental impacts of their extraction and refining<sup>50,51</sup>, their life-cycle environmental sustainability performance remains unremarkable<sup>57,80,81</sup>. Tin may nonetheless prove attractive because of its superior performance when combined with other elements, such as abundant and low-impact iron (for example, Sn<sub>2</sub>Fe nanoparticles)<sup>82–84</sup>.

Many nanostructured transition metal oxides can enter in a conversion reaction with lithium, which in principle offers more options as potential anode materials. Among these, iron oxides, such as haematite (α-Fe<sub>2</sub>O<sub>3</sub>) and magnetite (Fe<sub>3</sub>O<sub>4</sub>)<sup>34</sup>, are by far the most abundant<sup>47,66</sup> and the least environmentally intensive<sup>50,51,85,86</sup>, in contrast to more scarce elements<sup>47,66</sup> such as chromium, molybdenum, ruthenium and cobalt<sup>87–89</sup>. Green synthesis routes for iron oxide nanoparticles should lead to relatively lean use of reagents and energy<sup>54,90</sup>. Though high specific capacities have been demonstrated<sup>54,90</sup>, their relatively high voltages during delithiation<sup>34</sup>

substantially reduces the overall cell voltage and consequently, energy and power density. High voltage hysteresis<sup>68,91</sup> makes all these issues worse and also leads to low cycling energy efficiencies, typically less than 60%. Such low energy efficiencies constitute a major handicap for an otherwise environmentally attractive material.

**Cathode materials.** The energy density of LIBs is largely determined by the cathode, as its practically achievable energy is greatly inferior to that of the anode<sup>92,93</sup>. There are two broad categories of cathode materials: intercalation and conversion. Intercalation materials are the most widely investigated and are already used as bulk materials in commercial LIBs<sup>47</sup>. Of the conversion-type cathode materials, none have reached commercialization<sup>47,94</sup>. Figure 3 presents the material life-cycle attributes of reviewed cathode nanomaterials. LiNi<sub>0.8</sub>Co<sub>0.15</sub>Al<sub>0.05</sub>O<sub>2</sub> (NCA) is considered to be the ‘baseline’ cathode material.

By far the most commonly used cathodes today are the layered oxides, such as LiCoO<sub>2</sub> (LCO). Due to the use of the relatively scarce cobalt<sup>47,66</sup>, commercially available LCO causes moderate direct exposure risks<sup>86,95</sup> and embodied damages to human health and ecosystems<sup>50,51</sup>. In addition, cobalt’s high cost has led a drive to replace most of it in many applications<sup>96</sup>, resulting in the adoption of materials with lower cobalt content such as LiNi<sub>1/3</sub>Mn<sub>1/3</sub>Co<sub>1/3</sub>O<sub>2</sub> (NMC) and

NCA. The popular NMC and NCA pose exposure risks and hazards because they, as with many nickel-containing compounds, are suspected of being human carcinogens<sup>57,97–99</sup>. Their high energy and power densities have nevertheless made them attractive as bulk materials, and these materials are already used in EVs<sup>47</sup>. As nanostructures, however, the decomposition of the electrolyte and formation of surface films result in unsatisfactory lifetime for EV applications. Even though these layered oxides are not used in nanoform, alternative materials must have equal or superior energy density while demonstrating better lifetime and stability than bulk NMC and NCA to displace them from the EV market.

A promising layered oxide is the lithium/manganese-rich material (LMR)<sup>100</sup>, often written as  $\text{Li}_2\text{MnO}_3 \cdot n\text{LiMO}_2$  (where M is Mn, Co, Ni, and so on). LMR contains more than one lithium atom per transition metal and has more manganese than other metals. Here, we focus on  $0.5\text{Li}_2\text{MnO}_3 \cdot 0.5\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$ . Due to its higher content of manganese relative to NMC, LMR is slightly less environmentally intensive than NMC<sup>50,51,98,101</sup>. Furthermore, LMR also has a high voltage and specific capacity that allows for a significant increase in energy density over current commercially available cathode materials<sup>102</sup>. Despite these advantages, poor rate capability<sup>103</sup> results in low power density, while thermal safety issues<sup>37</sup> and voltage fade<sup>104</sup> result in poor lifetime and stability, all of which complicate its commercial introduction for EVs.

Lithium iron phosphate (LFP) is found in nature as the mineral triphylite<sup>105</sup> and has low exposure risks and hazards<sup>86</sup>. Furthermore, environmental impacts associated with its production value chain are lower than most other cathode materials<sup>16,50,51</sup>. As a bulk material, LFP has moderate electric potential<sup>47</sup>, outstanding thermal stability<sup>52</sup> and excellent cycling performance<sup>106</sup>, but its two-phase reaction mechanism, with low ion diffusion rate and very low electronic conductivity<sup>107</sup>, makes it difficult to reach capacities close to the theoretical limit<sup>52</sup>. However, research found that in nanoparticle form, the material could produce stable cycling much closer to its theoretical capacity because the phase diagram is changed and the reaction proceeds via a metastable single-phase mechanism<sup>37</sup>. This development increased the material's energy<sup>52</sup> and power<sup>33</sup> densities, but its energy density remained inferior to that of other commercially available cathode materials such as NMC<sup>47,48</sup>. The lower energy density<sup>47</sup> and the claimed lower charge–discharge energy efficiency of LFP<sup>106</sup> can result in higher electricity use per kilometre driven compared with other cathode materials, which in turn would lead to higher indirect greenhouse gas emissions in the use phase. LFP can be produced through several nanosynthesis methods<sup>108</sup>, which particularly influences the energy use, and consequently greenhouse gas emissions, associated with its production. The superior electrochemical and safety properties of nano-LFP have spurred interest in finding other phosphates that might have much higher energy densities. One approach is to use materials that can incorporate up to two lithium ions. One such material is  $\text{VOPO}_4$ , which must be nanosized and carbon coated to be operative<sup>109</sup>, but has the advantage of being made of relatively abundant materials<sup>47,66</sup>. This material forms  $\text{Li}_2\text{VOPO}_4$  (LVP) on discharge and has a capacity of  $305 \text{ Ah kg}^{-1}$  compared with the  $170 \text{ Ah kg}^{-1}$  of LFP. However, the lifetime and stability are inadequate for EV use and much work is still needed to make LVP commercially viable.

Spinel  $\text{LiMn}_2\text{O}_4$  (LMO) is made of abundant manganese<sup>47,66</sup>, is relatively safe to handle<sup>86,110</sup> and has relatively low damages associated with its production<sup>50,51</sup>. Nanosized spinel LMO has been synthesized in various morphologies. Studies have found increased power densities<sup>47</sup>, and although increased energy densities have also been obtained<sup>107</sup>, these are not as high as those of bulk NMC and NCA<sup>47,106</sup>. In the case of LMO, nanoparticles tend to increase the undesirable dissolution of manganese to the electrolyte<sup>32,107</sup>, leading to lifetime issues. Porous nanorods, however, have been found to have remarkable lifetime<sup>111</sup>.

As one of very few viable options to the intercalation materials, the conversion material sulfur has received intense interest in the past decade due to exceptionally high theoretical energy density<sup>112–115</sup>. Supply of sulfur is unlikely to become an issue as it is an abundant element in the Earth's crust<sup>47</sup>. In batteries, the insulating nature of sulfur results in poor power density and creates large internal resistance and polarization of the battery<sup>116</sup>, resulting in poor device efficiency. Furthermore, volume expansion (~80%) and dissolution of intermediate reaction products (polysulfides) in the electrolyte result in poor lifetime<sup>47,113</sup>. The most promising approach to mitigate poor conductivity and lifetime is the encapsulation of sulfur within conductive additives to form sulfur–carbon and sulfur–polymer nanocomposites<sup>47,117</sup>. Sulfur–carbon nanocomposites pose higher exposure risks and hazards<sup>56,118</sup> than sulfur nanocomposites with polymers such as polyacrylonitrile, polyvinylpyrrolidone, polydimethylsiloxane<sup>118,119</sup> and polyaniline<sup>118,120</sup>. Even if the issue of lifetime is overcome, the sulfur cathode must be paired with a lithium metal or a lightweight lithiated anode for high energy density<sup>47,114,121,122</sup>. In contrast, lithium sulfide ( $\text{Li}_2\text{S}$ ) can be paired with lithium-free anodes, which avoids safety concerns and short lifetime<sup>122</sup>. Although the  $\text{Li}_2\text{S}$  cathode has a high theoretical capacity, it is both electronically and ionically insulating<sup>47</sup>, which has led to various efforts using conductive additives, such as metals and carbon<sup>114</sup>. Earlier studies tended to focus on  $\text{Li}_2\text{S}$ –metal composites, but the inherent disadvantages of  $\text{Li}_2\text{S}$ –metal composites have prompted extensive interest in the development and use of  $\text{Li}_2\text{S}$ –carbon composites in the past five years<sup>116</sup>. Due to a high content of lithium and carbon nanostructures, care should be taken when handling nanostructured  $\text{Li}_2\text{S}$ –carbon composites<sup>56,86</sup>. Studies have reported different nanostructures, synthesis methods and carbon content in  $\text{Li}_2\text{S}$ –carbon nanocomposites. This can lead to significant differences in material losses and energy use, which in turn influence greenhouse gas emissions and damages to human health and ecosystems. Further improvement on lifetime is required for  $\text{Li}_2\text{S}$  cathode materials to replace the layered oxides on the EV market.

**Recycling of LIBs.** There are several competing industrial LIB recycling processes<sup>123</sup>. LIB recycling is typically a combination of two or more of the following processes: mechanical separation, pyrometallurgical treatment and hydrometallurgical treatment. The various industrial recycling pathways offer different yields depending on the recycling route and electrode materials. As the metal value in batteries is mainly driven by prices of cobalt and nickel metals, current recycling processes still focus on the recovery of these metals<sup>97,124,125</sup>. Other transition metals, such as copper and iron, are also typically recovered in the current industrial LIB recycling processes. In only a few recycling routes are aluminium, lithium and manganese recovered<sup>97,123,125</sup>. According to relevant literature<sup>97,123,126</sup> and two European recycling companies (Accurec, personal communication, 2016; Umicore, personal communication, 2015), phosphate and graphite are normally not recycled in current industrial processes. Nanostructured LFP is currently recycled successfully (Accurec, personal communication, 2016), which suggests that nanostructuring electrode materials does not affect recycling yields compared with bulk materials. During recycling, however, nanomaterials may become airborne, which can pose exposure risks and hazards to workers<sup>127</sup>.

### Nanotechnologies in fuel cell developments

While there are multiple fuel cell types, we focus here on PEMFCs, which demonstrate the most potential within the transport sector<sup>10,15,21</sup>. High cost, durability and lifetime challenges are all barriers to the mainstream adoption of fuel cell EVs<sup>27</sup>; in contrast to battery EVs, commercial sale of fuel cell EVs has only very recently become reality (for example, Honda Clarity and Toyota Mirai). In contrast to LIBs, the 'baseline' materials are already in nanoform;

Material type:			Platinum and PGM-based				Metal			Carbon	
Material:			Pt nanoparticles	Pt nanostructures	Pt alloys (with Pd, Ni, PdAu, AuCu, Cu, Co, Fe, W, P)	Pd, PdAu	Fe	Nb, Ta, Zr	CoMo, CoS*	N-doped	N-, F-, S-, B-, P-, I-, Se-multi-doped
Environmental intensity of material	Intrinsic	Exposure risks and hazards	●	●	●	●	●	●	●	●	●
		Scarcity	■	■	■	■	■	■	■	■	■
	Value chain	Damages to human health	■	■	■	■	■	■	■	■	■
		Damages to ecosystems	■	■	■	■	■	■	■	■	■
Material and weight efficiency	Intrinsic	Power density	●	●●	●	●	●●	●	●	●	●
		Lifetime and stability	●	●●	●●	●	●●	●	●	●●	●●
		Recyclability	●	●	●	●	●			N/A	N/A
	Value chain	Synthesis material losses	●	●●	●●	●	●			●	●
Energy efficiency	Value chain	Energy of nanosynthesis	●	●●	●●	●	●	●●	●	●●	

**Figure 4 | Cathode catalyst materials for polymer electrolyte membrane fuel cells.** Circles and colour coding are as defined in Fig. 2. PGM, platinum group metals; \*, material on non-carbon black support. See Supplementary Information for the sources of the data in this figure.

rather, we review here alternative nanostructures and nanomaterials that have the potential to replace current state-of-the-art materials. These advances in nanotechnology have shown promising opportunities to improve the technical and environmental performance of PEMFCs in EVs and thus encourage their widespread commercial adoption.

Figures 4 and 5 summarize the life-cycle attributes of some of the most promising nanostructured materials for cathode catalyst and catalyst support, respectively. Although the electrocatalyst often refers to the catalyst and support together (Pt/C), they are considered as two components independent of each other in this study. Electrolyte membranes, being a bulk material, are discussed in section 4 of the Supplementary Information while nanotechnological improvements to these bulk materials are discussed in the text.

**Cathode catalysts.** The oxygen reduction reaction occurring at the cathode is enabled by the cathode catalyst; a well-performing catalyst is therefore a determinant of the device's overall power output. At present, both PEMFC anodes and cathodes rely on platinum catalysts supported on high surface area carbon (Pt/C), which are costly, scarce<sup>47</sup> and have extremely high environmental implications from platinum extraction<sup>50,51</sup>. In terms of efficient use of this high-impact, non-renewable material, the cathode is the key technological bottleneck as the oxygen reduction reaction occurs five to six orders of magnitude slower than the hydrogen oxidation reaction occurring at the anode<sup>28</sup>, thus greatly limiting the cell power density. Furthermore, the pure platinum catalysts suffer from poisoning from impurities in the hydrogen fuel as well as dissolution and agglomeration, which can drastically shorten the fuel cell lifetime<sup>29,128,129</sup>. A shorter lifetime

demands more frequent replacement of PEMFC stacks in EVs, and may ultimately require more platinum extraction per kilometre driven.

Current research therefore focuses on reducing or eliminating platinum use in the catalyst<sup>130-132</sup>. Several solutions are being explored, including the use of ultra-low platinum loading, platinum alloys and platinum-free catalysts to reduce material costs while maintaining or improving catalytic activity over current Pt/C catalysts. Compared with the commercial Pt/C catalyst, most of these platinum-containing alternatives yield enhanced durability and demonstrate similar or superior oxygen reduction reaction catalytic ability.

Alternative platinum nanomorphologies and nanostructured platinum alloys can maintain or even increase the catalytic activity relative to conventional Pt/C catalysts. Increasing the specific catalytic activity allows for a reduction in the amount of platinum used, thus improving material efficiency over the conventional catalyst. In addition to the various nanomorphologies, research using different assembly methods, such as electrospraying, improve catalytic activity by influencing the hierarchical structure of the electrode<sup>133,134</sup>. Similarly, platinum alloys with nickel<sup>135-137</sup>, cobalt<sup>136,138</sup> and copper<sup>139,140</sup> have also demonstrated good performance while decreasing platinum use.

While platinum reduction is a desirable goal for PEMFC development, the complete elimination of platinum use in PEMFCs would be an even greater improvement of the material environmental impacts<sup>56,141</sup>. Non-precious metal catalysts using more abundant metals such as iron have been tested, but present severely depressed technical performance and stability in acidic operating conditions<sup>142</sup>. Other metal catalysts based on niobium, tantalum and zirconium have improved lifetime over Pt/C, but do not meet power density expectations, and are more scarce<sup>47,66</sup> and environmentally intensive

Material type:		Carbon based					Titanium based			
Material:		Carbon black	Carbon nanostructures	Carbon-polymer composites	N-, P-, S-doped carbon nanostructures	Carbon-SnO <sub>2</sub> , -TiO <sub>2</sub> composites	Carbon black-TiO <sub>2</sub>	TiO <sub>2</sub>	Nb-TiO <sub>2</sub> , RuO <sub>2</sub> -TiO <sub>2</sub>	Ti <sub>3</sub> AlC <sub>2</sub>
Environmental intensity of material	Intrinsic	Exposure risks and hazards	●	●	●	●	●	●	●	●
		Scarcity	■	■	■	■	■	■	■	■
	Value chain	Damages to human health	■	■	■	■	■	■	■	■
		Damages to ecosystems	■	■	■	■	■	■	■	■
Material and weight efficiency	Intrinsic	Power density	●	●	●	●	●	●	●	●
		Lifetime and stability	●	●	●	●	●	●	●	●
		Recyclability	N/A	N/A	N/A	N/A	●	●	●	●
	Value chain	Synthesis material losses	●	●	■	■	●	■	●	●
Energy efficiency	Intrinsic	Device efficiency	●	●	●	●	■	●	●	●
	Value chain	Energy of nanosynthesis	●	●	●	●	●	●	●	●

**Figure 5 | Catalyst support materials for polymer electrolyte membrane fuel cells.** Circles and colour coding are as defined in Fig. 2. See Supplementary Information for the sources of the data in this figure.

to produce than iron<sup>50,51</sup>, although they still represent an improvement over platinum. Metal-free catalysts using functionalized carbon nanostructures, particularly nitrogen-doped carbon nanotubes and graphene materials, are promising candidates for platinum-free catalysts that capitalize on abundant precursor materials, though they require further research to improve the energy efficiency of their synthesis and to provide adequate catalytic ability in acidic environments<sup>143–145</sup>. A clear trend, however, is that platinum-free catalysts continue to struggle in catalytic activity and lifetime compared with low-platinum and platinum-alloy catalysts<sup>143</sup>.

In addition to the morphological and material nature of the catalyst, the hierarchical organization of the nanostructured materials in the device also affects catalyst performance. While such organization may increase material efficiency by increasing catalytic activity, it may also present consequential side issues such as water flooding, which in turn cancels out or exceeds the gains in performance, or causes unstable cell performance<sup>146</sup>.

If the goal is to reduce the amount of platinum used in fuel cell EVs to the amount used in the catalytic converters of conventional internal combustion engine vehicles, the device lifetime must be accounted for. Since fuel cell EVs currently have a shorter lifetime than conventional vehicles, the amount of platinum required to drive an equal distance increases, that is, several fuel cell stacks will be required. Furthermore, the growing light-duty vehicle market

represents an unsustainable demand for further platinum extraction into the future. Rather, focus should be placed on robust, low- or non-platinum catalysts with long lifetime.

**Cathode catalyst supports.** Effective support materials enhance catalytic catalyst utilization and thus increase material efficiency by allowing for smaller quantities of catalyst while maintaining similar levels of catalytic activity. A catalyst support would ideally maximize the catalyst surface area available for reactions and maintain high electric conductivity for high energy efficiency. Supports made of carbon black, our ‘baseline’ material, are currently used in commercial PEMFC catalysts. These supports are vulnerable to corrosion, which causes catalyst sintering and decreases the amount of conductive material in the electrode, thereby decreasing power density and PEMFC lifetime<sup>29,147</sup>. Carbon black-based support materials also suffer from deep micropores that physically block reagent access to the catalyst and thus decrease catalyst efficiency<sup>148</sup>.

Nanostructured materials can provide the characteristics needed for an effective catalyst support, including a high surface area with a mesoporous structure that does not inhibit catalytic activity<sup>149</sup>. Catalyst support materials must also be sufficiently electrically conductive to reduce internal resistance, thereby enhancing charge transport within the cell, and be stable at higher temperatures and in the acidic environment of a PEMFC.

Carbon nanostructures and titanium dioxide are two promising catalyst support materials that demonstrate improved technical performance. In their bulk form, these materials have low environmental intensity<sup>50,51</sup>. The synthesis methods for the nanomorphologies, however, may potentially have high energy demand<sup>60</sup>, and thereby be detrimental to the overall climate change performance of the manufacturing process. The graphitized carbon-based nanomaterials have enhanced durability under fuel cell operating conditions<sup>29</sup>, which improves the climate change performance of the PEMFC over the lifetime as a counterpoint for the increased synthesis energy. Doping the carbon with heteroatoms, such as nitrogen, phosphorus or sulfur, functionalizes the otherwise inert carbon to allow catalyst deposition<sup>148</sup>. In some cases, functionalization, such as with nitrogen-doped carbon nanotubes, also allows the otherwise catalytically inert carbon supports to become catalytically active, thereby increasing power density of the PEMFC<sup>150</sup>. Some carbon-polymer nanocomposites have shown improved material efficiency via power density, but in some cases this is in exchange for reduced lifetime.

Carbon-free, transition metal oxide-based supports such as titanium dioxide in mesoporous or nanofibre morphologies, while relatively robust, have not yet achieved the same performance level as the baseline carbon black catalyst support. Composite titanium dioxide catalyst supports may also be more sensitive to scarcity<sup>47,66</sup> and material production impacts<sup>50,51</sup> than carbon-based supports, as are supports of niobium- and ruthenium oxide-doped titanium dioxide.

**Electrolyte membrane.** The PEMFC membrane, with its high cost<sup>151</sup>, poor durability<sup>29</sup> and intolerance to fuel impurities<sup>152</sup>, represents another obstacle to the widespread commercialization of transport PEMFCs. The current commercial standard, Nafion, is a perfluorinated membrane that performs poorly in temperatures beyond 80 °C and in low-humidity environments, and is not stable with impure feed gases<sup>153,154</sup>. An ideal membrane for transport PEMFCs must therefore have satisfactory performance and stability at these conditions. Research has been directed towards more robust membranes, which would allow for thinner membranes that represent an improvement in material efficiency (less membrane material used) and device efficiency (for example, superior ion exchange/proton conductivity performances). While membrane polymers conduct protons at the nanoscale, the membrane material itself does not constitute a nanomaterial. A brief review of the main membrane polymer groups may be found in Section 4 of the Supplementary Information. Nanotechnology offers several options for improving these bulk membranes. Such options include the use of nanofillers to enhance the membrane, or the use of nanosynthesis methods to provide a superior hierarchical structure to the membrane.

One attractive strategy of generating an optimum balance between ion conduction and physicochemical stability in electrolyte membranes is to create a 'microphase separated' morphology in polymers made of highly ordered ion-nanochannels and a hydrophobic phase. An example is the fabrication of ion-conductive polymer nanofibres. These demonstrate distinctive electrochemical, physicochemical and thermal properties owing to their high specific surface area and polymer orientation along the nanofibre direction<sup>155,156</sup>. The use of a reinforcing, mechanically strong nanofibre morphology can minimize in-plane swelling changes during wet(on)/dry(off) fuel cell operation and thus extend the device lifetime<sup>157</sup>. Some success has been achieved with a dual electrospun composite of poly(phenyl sulfone) and Nafion<sup>158</sup>, where the poly(phenyl sulfone) polymer provides mechanical stability to the Nafion membrane, thus improving lifetime while maintaining device efficiency (cell power output). Similarly, improved proton conductivity, leading to increased power density, was achieved with electrospun acid-doped

polybenzimidazole in a sulfonated polymer matrix compared with a similar composite membrane without nanofibre morphology<sup>156</sup>.

In one type of composite membrane, a polymer membrane matrix may have embedded nanostructures of inorganic materials to improve membrane characteristics. Such materials may be metal oxides or synthetic clays to improve mechanical stability<sup>159</sup> and water uptake, or nanocarbons or nanofibres to provide ionic channels and thus improve device efficiency of the PEMFC. Heteropolyacids such as phosphotungstic acid are used as fillers to improve proton conductivity (device efficiency), but decrease mechanical stability and therefore have a shorter lifetime. Phosphotungstic acid also has significant exposure risks<sup>160</sup>. However, while hygroscopic particles are intended to increase the device efficiency by improving proton conductivity via increased water retention, these particles decrease device efficiency by diluting the concentration of the proton-conducting ionomer when made of material less conductive than that the ionomer membrane<sup>161-164</sup>. Nanofillers may also increase the mechanical strength of the polymer, as in the case of zwitterionic structured SiO<sub>2</sub> in polybenzimidazole<sup>159,165</sup>. In addition, the heterogeneous hybrid membranes also experience phase separation due to differing water uptake and thermal expansion coefficients of the nanofillers and the polymer matrix, causing stresses and strains in the membrane and thereby shortening the lifetime and decreasing material efficiency<sup>166</sup>.

Hierarchical ordering in these nanocomposites is also a promising strategy to improve membrane performance; in particular, the alignment of one-dimensional (nanotubes, nanofibres or nanorods) and two-dimensional nanomaterials (nanoflakes, nanosheets or nanoplates) in the membrane have a two-fold benefit. In the direction parallel to the membrane, proton conductivity is improved, while across the membrane, mechanical properties, chemical stability and fuel permeability characteristics are improved. Graphene oxide<sup>167</sup> and electrospun<sup>156,158</sup> nanofibres are particularly emphasized due to the creation of long-range ordered ionic nanochannels for proton conduction and excellent physicochemical stability.

**Recycling of PEMFCs.** In terms of both cost and environmental intensity, platinum catalyst and fluorinated membranes are of greatest interest for recycling and recovery processes. The most common platinum recovery approaches include selective chlorination or gas phase volatilization, hydrometallurgical and pyrometallurgical processes<sup>168</sup>. Selective chlorination or gas phase volatilization, however, require carbon monoxide and chlorine gases or aggressive solvents such as aqua regia or cyanide. Many of these compounds pose considerable risks to workers<sup>169-171</sup>. Many hydrometallurgical approaches also require high operating temperatures and pressures, making them energy-intensive processes. Pyrometallurgical processes for PEMFCs containing fluorinated membranes such as Nafion would result in the emission of highly toxic hydrogen fluoride<sup>172,173</sup>. The Pt/C catalyst can also be recovered using a chemical recovery process after carbon-based supports are incinerated<sup>172,173</sup>. In general, alloying and non-combustible elements consisting of 10% or less of the total recoverable materials will not detrimentally affect recoverability or reusability of precious metal catalysts (Umicore, personal communication, 2015).

Mechanical separation of membranes from the catalyst layers is difficult, as these components are generally hot-pressed together<sup>172</sup>. Re-use of the membrane is also unlikely as performance drops in fuel cells are usually caused by membrane degradation or failure due to dehydration and pin-holing, which makes recycling a more likely end-of-life fate for membranes<sup>172</sup>. Nafion membranes are generally recovered using chemical extraction<sup>172-174</sup>, after which a new membrane may be re-cast, although possibly with some loss of quality<sup>174</sup>. As for the catalyst, it is unknown whether the adoption of novel multi-element catalysts and alternative catalyst support materials in

PEMFCs will affect the yield or quality of recovered precious metals given the current PEMFC recycling techniques.

### The road ahead

Nanomaterials are opening a broad range of opportunities to improve the technical and life-cycle environmental performance of EVs. Identifying the alternative material candidates with the most promising opportunities for enhancing overall environmental performance of LIBs and PEMFCs in EVs at an early stage is therefore important. To this end, we performed an early stage life-cycle environmental screening of the material candidates and mapped their potential strengths and weaknesses with respect to key life-cycle attributes (Figs 2–5). We found that no single nanomaterial seems poised to outcompete its rivals in terms of all reviewed sustainability criteria for any of the reviewed LIB and PEMFC materials. Rather, the current research frontier presents multiple promising candidates for continued development, each subject to non-trivial environmental trade-offs that should be addressed.

To maximize climate change mitigation benefits offered by EVs, we must improve both the electrochemical and environmental performance of LIBs and PEMFCs. Nanomaterials show great promise in providing the necessary technical breakthrough in these devices, but their ability to be a part of the mitigation solution for transport-related greenhouse gas emissions depends on several life-cycle attributes spanning extraction, refinement, synthesis, operational performance, durability and recyclability. As such, the next generation of LIBs and PEMFCs should ideally be based on abundant resources that can be extracted and refined with low energy consumption and environmental impacts. It should be resource and material efficient, achieved through improvements in synthesis yields, lightweighting, durability and, ultimately, recyclability. Finally, it should be energy efficient, both in the production and use phase. In practice though, we are likely to have to make some trade-offs.

Our analysis of the current situation clearly outlines the challenge: the materials with the best potential environmental profiles during the material extraction and production phase (less environmentally intensive materials, lower nanosynthesis energy use and facile synthesis) often present environmental disadvantages during their use phase (lower energy efficiency, heavier battery or shorter lifetimes), and vice versa.

Meeting this challenge will require concerted efforts and a new focus within the nanotechnology community. Throughout this Analysis, we found that publications on novel nanomaterials rarely explicitly communicate synthesis yields, solvent use and energy consumption during production. These are all key parameters that significantly influence the environmental performance and that can largely be improved through the choice of alternative synthesis protocols and foreseeable economies of scale. Increased, systematic and consistent reporting of these attributes would remove a very avoidable source of uncertainty. Improved flow of information would be of mutual benefit to both the LCA and nanotechnology communities; through joint efforts, both communities would be able to direct research efforts towards the materials and synthesis protocols with the best environmental sustainability potential. An extension of the above aspect is the current lack of data regarding potential toxic effects, which unfortunately remains a challenge for nearly all of the investigated nanomaterials. Similarly, we also found little literature on how the physicochemical properties of novel nanomaterials affect existing recycling and disposal processes. Addressing these issues would allow us to efficiently manoeuvre towards the most environmentally superior options. As more detailed and consistent information becomes available, one can move from screening studies to detailed LCAs to refine our understanding and ultimately make the right design trade-offs that optimize LIB and PEMFC nanomaterials for EV usage towards mitigating climate change.

This will require a cross-disciplinary collaboration between material scientists and LCA practitioners to reap — and maximize — the benefits offered by simultaneously incorporating nanotechnology, nanotoxicology, eco-design and green chemistry considerations. If we succeed, nanotechnology can be a key contributor to climate change mitigation in the transport sector.

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### References

- Gabriel, B. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) 351–412 (IPCC, Cambridge Univ. Press, 2014).
- Sims, R. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) 1–115 (IPCC, Cambridge Univ. Press, 2014).
- Shepard, S. & Jerram, L. *Executive Summary: Transportation Forecast: Light Duty Vehicles* (Navigant Consulting, 2015).
- Global EV Outlook 2016: Beyond One Million Electric Cars* (International Energy Agency, 2016).
- European Automobile Manufacturers' Association *Overview of Purchase and Tax Incentives for Electric Vehicles in the EU 1–7* (European Automobile Manufacturers' Association, 2016).
- Crabtree, G., Kócs, E. & Trahey, L. The energy-storage frontier: lithium-ion batteries and beyond. *MRS Bull.* **40**, 1067–1078 (2015).
- Samaras, C. & Meisterling, K. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. *Environ. Sci. Technol.* **42**, 3170–3176 (2008).
- Szczecowicz, E., Dederichs, T. & Schnettler, A. Regional assessment of local emissions of electric vehicles using traffic simulations for a use case in Germany. *Int. J. Life Cycle Assess.* **17**, 1131–1141 (2012).
- Helmers, E. & Marx, P. Electric cars: technical characteristics and environmental impacts. *Environ. Sci. Eur.* **24**, 1–15 (2012).
- Simons, A. & Bauer, C. A life-cycle perspective on automotive fuel cells. *Appl. Energy* **157**, 884–896 (2015).
- Hellweg, S. & Milà i Canals, L. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* **344**, 1109–1113 (2014).
- Kushnir, D. & Sandén, B. a. Energy requirements of carbon nanoparticle production. *J. Ind. Ecol.* **12**, 360–375 (2008).
- 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.* **19**, 1405–1416 (2011).
- Bartolozzi, I., Rizzi, F. & Frey, M. Comparison between hydrogen and electric vehicles by life cycle assessment: a case study in Tuscany, Italy. *Appl. Energy* **101**, 103–111 (2013).
- Bauer, C., Hofer, J., Althaus, H.-J., Del Duce, A. & Simons, A. The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework. *Appl. Energy* **157**, 871–883 (2015).
- Dunn, J. B., Gaines, L., Kelly, J. C., James, C. & Gallagher, K. G. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy Environ. Sci.* **8**, 158–168 (2015).
- Faria, R., Moura, P., Delgado, J. & de Almeida, A. T. A sustainability assessment of electric vehicles as a personal mobility system. *Energy Convers. Manag.* **61**, 19–30 (2012).
- Ellingsen, L. A.-W., Singh, B. & Strømman, A. H. The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. *Environ. Res. Lett.* **11**, 054010 (2016).
- Hawkins, T. R., Singh, B., Majeau-Bettez, G. & Strømman, A. H. Comparative environmental life cycle assessment of conventional and electric vehicles. *J. Ind. Ecol.* **17**, 53–64 (2012).
- Miotti, M., Hofer, J. & Bauer, C. Integrated environmental and economic assessment of current and future fuel cell vehicles. *Int. J. Life Cycle Assess.* <http://dx.doi.org/10.1007/s11367-015-0986-4> (2015).
- Notter, D. A., Kouravelou, K., Karachalios, T., Daletou, M. K. & Haberland, N. T. Life cycle assessment of PEM FC applications: electric mobility and  $\mu$ -CHP. *Energy Environ. Sci.* **8**, 1969–1985 (2015).
- Notter, D. A. *et al.* Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environ. Sci. Technol.* **44**, 6550–6556 (2010).
- 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.* **48**, 3047–3055 (2014).

24. Majeau-Bettez, G., Hawkins, T. R. & Strømman, A. H. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environ. Sci. Technol.* **45**, 4548–4554 (2011).
25. Zackrisson, M., Avellan, L. & Orlenius, J. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles — critical issues. *J. Clean. Prod.* **18**, 1519–1529 (2010).
26. Singh, B., Guest, G., Bright, R. M. & Strømman, A. H. Life cycle assessment of electric and fuel cell vehicle transport based on forest biomass. *J. Ind. Ecol.* **18**, 176–186 (2014).
27. Othman, R., Dicks, A. L. & Zhu, Z. Non precious metal catalysts for the PEM fuel cell cathode. *Int. J. Hydrogen Energy* **37**, 357–372 (2012).
28. Debe, M. K. Electrocatalyst approaches and challenges for automotive fuel cells. *Nature* **486**, 43–51 (2012).
29. Wu, J. *et al.* A review of PEM fuel cell durability: degradation mechanisms and mitigation strategies. *J. Power Sources* **184**, 104–119 (2008).
30. Shiau, C.-S. N., Samaras, C., Haufler, R. & Michalek, J. J. Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles. *Energy Policy* **37**, 2653–2663 (2009).
31. Iwan, A., Malinowski, M. & Pasciak, G. Polymer fuel cell components modified by graphene: electrodes, electrolytes and bipolar plates. *Renew. Sustain. Energy Rev.* **49**, 954–967 (2015).
32. Aricó, A. S., Bruce, P., Scrosati, B., Tarascon, J.-M. & van Schalkwijk, W. Nanostructured materials for advanced energy conversion and storage devices. *Nat. Mater.* **4**, 366–377 (2005).
33. Bruce, P. G., Scrosati, B. & Tarascon, J.-M. Nanomaterials for rechargeable lithium batteries. *Angew. Chem. Int. Ed.* **47**, 2930–2946 (2008).
34. Goriparti, S. *et al.* Review on recent progress of nanostructured anode materials for Li-ion batteries. *J. Power Sources* **257**, 421–443 (2014).
35. Nie, Y., Li, L. & Wei, Z. Recent advancements in Pt and Pt-free catalysts for oxygen reduction reaction. *Chem. Soc. Rev.* **44**, 2168–201 (2015).
36. Whittingham, M. S. Inorganic nanomaterials for batteries. *Dalton Trans.* **2008**, 5424–5431 (2008).
37. Whittingham, M. S. Ultimate limits to intercalation reactions for lithium batteries. *Chem. Rev.* **114**, 11414–11443 (2014).
38. Obrovac, M. N. & Chevrier, V. L. Alloy negative electrodes for Li-ion batteries. *Chem. Rev.* **114**, 11444–11502 (2014).
39. Liu, C., Li, F., Ma, L.-P. & Cheng, H.-M. Advanced materials for energy storage. *Adv. Mater.* **22**, E28–E62 (2010).
40. Gallagher, K. G. *et al.* Quantifying the promise of lithium–air batteries for electric vehicles. *Energy Environ. Sci.* **7**, 1555–1563 (2014).
41. Graedel, T. E., Allenby, B. R. & Comrie, P. R. Matrix approaches to abridged life cycle assessment. *Environ. Sci. Technol.* **29**, 134A–139A (1995).
42. Graedel, T. E. *Streamlined Life-Cycle Assessment* (Prentice Hall, 1998).
43. Todd, J. A. *et al.* *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup* (Society of Environmental Toxicology and Chemistry, 1999).
44. Anastas, P. T. & Warner, J. C. *Green Chemistry: Theory and Practice* (Oxford Univ. Press, 1998).
45. Anastas, P. T. & Eghbali, N. Green chemistry: principles and practice. *Chem. Soc. Rev.* **39**, 301–312 (2010).
46. Ellingsen, L. A.-W. *et al.* Life cycle assessment of a lithium-ion battery vehicle pack. *J. Ind. Ecol.* **18**, 113–124 (2014).
47. Nitta, N., Wu, F., Lee, J. T. & Yushin, G. Li-ion battery materials: present and future. *Mater. Today* **18**, 252–264 (2015).
48. Whittingham, M. S. History, evolution, and future status of energy storage. *Proc. IEEE* **100**, 1518–1534 (2012).
49. Yoshino, A. in *Lithium-Ion Batteries: Advances and Applications* (ed. Pistoia, G.) 1–20 (Elsevier, 2014).
50. ReCiPe Mid/Endpoint Method, version 1.11 (ReCiPe, 2015).
51. *Ecoinvent Data and Reports 3.2* (Ecoinvent Centre, 2015).
52. Hudak, N. S. in *Lithium-Ion Batteries: Advances and Applications* (ed. Pistoia, G.) 57–82 (Elsevier, 2014).
53. Ohta, N., Nagaoka, K., Hoshi, K., Bitoh, S. & Inagaki, M. Carbon-coated graphite for anode of lithium ion rechargeable batteries: graphite substrates for carbon coating. *J. Power Sources* **194**, 985–990 (2009).
54. Latorre-Sanchez, M., Primo, A. & Garcia, H. Green synthesis of Fe<sub>3</sub>O<sub>4</sub> nanoparticles embedded in a porous carbon matrix and its use as anode material in Li-ion batteries. *J. Mater. Chem.* **22**, 21373–21375 (2012).
55. Lahiri, I. & Choi, W. Carbon nanostructures in lithium ion batteries: past, present, and future. *Crit. Rev. Solid State Mater. Sci.* **38**, 128–166 (2013).
56. *Safety Data Sheet – Carbon Nanostructures* (US Research Nanomaterials, 2015).
57. *Material Safety Data Sheets* (ESPI Metals, accessed 22 April 2016); [www.espimetals.com/index.php/msds](http://www.espimetals.com/index.php/msds)
58. Kim, H. C. & Fthenakis, V. Life cycle energy and climate change implications of nanotechnologies. *J. Ind. Ecol.* **17**, 528–541 (2013).
59. Gutowski, T. G. *et al.* Thermodynamic analysis of resources used in manufacturing processes. *Environ. Sci. Technol.* **43**, 1584–1590 (2009).
60. Şengül, H., Theis, T. L. & Ghosh, S. Toward sustainable nanoproducts. *J. Ind. Ecol.* **12**, 329–359 (2008).
61. De Volder, M. F. L., Tawfik, S. H., Baughman, R. H. & Hart, A. J. Carbon nanotubes: present and future commercial applications. *Science* **339**, 535–539 (2013).
62. Charitidis, C. A., Georgiou, P., Koklioti, M. A., Trompeta, A.-F. & Markakakis, V. Manufacturing nanomaterials: from research to industry. *Manuf. Rev.* **1**, 11 (2014).
63. Sharifi, S. *et al.* Toxicity of nanomaterials. *Chem. Soc. Rev.* **41**, 2323–2343 (2012).
64. Bystrzejewska-Piotrowska, G., Golimowski, J. & Urban, P. L. Nanoparticles: their potential toxicity, waste and environmental management. *Waste Manag.* **29**, 2587–2595 (2009).
65. Köhler, A. R., Som, C., Helland, A. & Gottschalk, F. Studying the potential release of carbon nanotubes throughout the application life cycle. *J. Clean. Prod.* **16**, 927–937 (2008).
66. Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P. & Reck, B. K. Criticality of metals and metalloids. *Proc. Natl Acad. Sci. USA* **112**, 4257–4262 (2015).
67. Lee, W. W. & Lee, J.-M. Novel synthesis of high performance anode materials for lithium-ion batteries (LIBs). *J. Mater. Chem. A* **2**, 1589–1626 (2014).
68. Reddy, M. V., Subba Rao, G. V. & Chowdari, B. V. Metal oxides and oxysalts as anode materials for Li ion batteries. *Chem. Rev.* **113**, 5364–5457 (2013).
69. Ma, Y., Ding, B., Ji, G. & Lee, J. Y. Carbon-encapsulated F-doped Li<sub>7</sub>Ti<sub>5</sub>O<sub>12</sub> as a high rate anode material for Li+ batteries. *ACS Nano* **7**, 10870–10878 (2013).
70. Anderman, M. *The Tesla Battery Report* (Total Battery Consulting, 2016).
71. *Safety Data Sheet – Lithium Titanium Oxide 1–6* (NEI Corporation, 2014).
72. Gan, L. *et al.* A facile synthesis of graphite/silicon/graphene spherical composite anode for lithium-ion batteries. *Electrochim. Acta* **104**, 117–123 (2013).
73. Zamfir, M. R., Nguyen, H. T., Moyon, E., Lee, Y. H. & Pribat, D. Silicon nanowires for Li-based battery anodes: a review. *J. Mater. Chem. A* **1**, 9566–9586 (2013).
74. Scrosati, B. & Garche, J. Lithium batteries: status, prospects and future. *J. Power Sources* **195**, 2419–2430 (2010).
75. Su, X. *et al.* Silicon-based nanomaterials for lithium-ion batteries: a review. *Adv. Energy Mater.* **4**, 1–23 (2014).
76. Ge, M., Rong, J., Fang, X. & Zhou, C. Porous doped silicon nanowires for lithium ion battery anode with long cycle life. *Nano Lett.* **12**, 2318–2323 (2012).
77. Jia, H. *et al.* Novel three-dimensional mesoporous silicon for high power lithium-ion battery anode material. *Adv. Energy Mater.* **1**, 1036–1039 (2011).
78. *Safety Data Sheet – Silicon Nanopowder/Nanoparticles* (US Research Nanomaterials, 2016).
79. *Material Safety Data Sheet – Monodispersed silicon nanowires* (Sigma Aldrich, 2010).
80. *Safety Data Sheet – Tin Oxide Nanopowder* (American Elements, 2015).
81. *Material Safety Data Sheet – Germanium Nanoparticles* (US Research Nanomaterials, accessed 22 April 2016).
82. Dong, Z. *et al.* The anode challenge for lithium-ion batteries: a mechanochemically synthesized Sn-Fe-C composite anode surpasses graphitic carbon. *Adv. Sci.* **3**, 1–8 (2016).
83. Sony's new nexelion hybrid lithium ion batteries to have thirty-percent more capacity than conventional offering. *Sony* (15 February 2005); <http://www.sony.net/SonyInfo/News/Press/200502/05-006E/>
84. Fan, Q., Chupas, P. J. & Whittingham, M. S. Characterization of amorphous and crystalline tin–cobalt anodes. *Electrochem. Solid State Lett.* **10**, A274–A278 (2007).
85. *Safety Data Sheet – Iron(II, III) Oxide Nanopowder* (American Elements, 2015).
86. *SDS | LTS* (LTS Chemical, accessed 22 April 2016); <https://www.ltschem.com/msds/>
87. *Material Safety Data Sheet – Cobalt (II) Oxide Nanoparticles (CoO)* (US Research Nanomaterials, accessed 22 April 2016).
88. *Safety Data Sheet – Chromium Oxide Nanopowder* (American Elements, 2015).
89. *Safety Data Sheet – Molybdenum Oxide Nanopowder* (American Elements, 2015).
90. Wang, B., Chen, J. S., Wu, H. B., Wang, Z. & Lou, X. W. Quasiemulsion-templated formation of alpha-Fe<sub>2</sub>O<sub>3</sub> hollow spheres with enhanced lithium storage properties. *J. Am. Chem. Soc.* **133**, 17146–17148 (2011).
91. Etacheri, V., Marom, R., Elazari, R., Salitra, G. & Aurbach, D. Challenges in the development of advanced Li-ion batteries: a review. *Energy Environ. Sci.* **4**, 3243–3262 (2011).
92. Li, Q. *et al.* Balancing stability and specific energy in Li-rich cathodes for lithium ion batteries: a case study of a novel Li–Mn–Ni–Co oxide. *J. Mater. Chem. A* **3**, 10592–10602 (2015).

93. Rosenman, A. *et al.* Review on Li-sulfur battery systems: an integral perspective. *Adv. Energy Mater.* **5**, 1–21 (2015).
94. Bruce, P. G., Freunberger, S. A., Hardwick, L. J. & Tarascon, J.-M. Li–O<sub>2</sub> and Li–S batteries with high energy storage. *Nat. Mater.* **11**, 19–29 (2012).
95. *Safety Data Sheet — Lithium Cobalt Oxide Nanopowder* (American Elements, 2015).
96. Whittingham, M. S. Lithium batteries and cathode materials. *Chem. Rev.* **104**, 4271–4301 (2004).
97. Hanisch, C., Diekmann, J., Stieger, A., Haselrieder, W. & Kwade, A. in *Handbook of Clean Energy Systems* <http://dx.doi.org/10.1002/9781118991978.hces221> (2015).
98. *Material Safety Data Sheet — Lithium Manganese Nickel Cobalt Oxide Powder* (NEI Corporation, 2014).
99. *Safety Data Sheet — Lithium Nickel Cobalt Aluminum Oxide* (NEI Corporation, 2014).
100. Liu, J., Wang, R. & Xia, Y. Degradation and structural evolution of  $x\text{Li}_2\text{MnO}_3\cdot(1-x)\text{LiMn}_{1/3}\text{Ni}_{1/3}\text{Co}_{1/3}\text{O}_2$  during cycling. *J. Electrochem. Soc.* **161**, A160–A167 (2013).
101. *Safety Data Sheet — LMR* (Pfaltz & Bauer, 2013).
102. Yu, H. & Zhou, H. High-energy cathode materials (Li<sub>2</sub>MnO<sub>3</sub>–LiMO<sub>2</sub>) for lithium-ion batteries. *J. Phys. Chem. Lett.* **4**, 1268–1280 (2013).
103. Liu, J. *et al.* General synthesis of  $x\text{Li}_2\text{MnO}_3\cdot(1-x)\text{LiMn}_{1/3}\text{Ni}_{1/3}\text{Co}_{1/3}\text{O}_2$  nanomaterials by a molten-salt method: towards a high capacity and high power cathode for rechargeable lithium batteries. *J. Mater. Chem.* **22**, 25380–25387 (2012).
104. Croy, J. R., Balasubramanian, M., Gallagher, K. G. & Burrell, A. K. Review of the US Department of Energy's 'deep dive' effort to understand voltage fade in Li- and Mn-rich cathodes. *Acc. Chem. Res.* **48**, 2813–2821 (2015).
105. Ellis, B. L., Lee, K. T. & Nazar, L. F. Positive electrode materials for Li-ion and Li-batteries. *Chem. Mater.* **22**, 691–714 (2010).
106. Pampal, E. S., Stojanovska, E., Simon, B. & Kilic, A. A review of nanofibrous structures in lithium ion batteries. *J. Power Sources* **300**, 199–215 (2015).
107. Song, M. K., Park, S., Alamgir, F. M., Cho, J. & Liu, M. Nanostructured electrodes for lithium-ion and lithium-air batteries: the latest developments, challenges, and perspectives. *Mater. Sci. Eng. R Rep.* **72**, 203–252 (2011).
108. Satyavani, T. V. S. L., Srinivas Kumar, A. & Subba Rao, P. S. V. Methods of synthesis and performance improvement of lithium iron phosphate for high rate Li-ion batteries: a review. *Eng. Sci. Technol. Int. J.* **19**, 178–188 (2015).
109. Lin, Y.-C. *et al.* Thermodynamics, kinetics and structural evolution of  $\epsilon\text{-LiVOPO}_4$  over multiple lithium intercalation. *Chem. Mater.* **28**, 1794–1805 (2015).
110. *Safety Data Sheet — Lithium Manganese Oxide Nanoparticles* (American Elements, 2015).
111. Cheng, F. *et al.* Porous LiMn<sub>2</sub>O<sub>4</sub> nanorods with durable high-rate capability for rechargeable Li-ion batteries. *Energy Environ. Sci.* **4**, 3668–3675 (2011).
112. Li, W. *et al.* A sulfur cathode with pomegranate-like cluster structure. *Adv. Energy Mater.* **5**, 1500211 (2015).
113. Xu, R., Lu, J. & Amine, K. Progress in mechanistic understanding and characterization techniques of Li-S batteries. *Adv. Energy Mater.* **5**, 1–22 (2015).
114. Cai, K., Song, M.-K., Cairns, E. J. & Zhang, Y. Nanostructured Li<sub>2</sub>S–C composites as cathode material for high-energy lithium/sulfur batteries. *Nano Lett.* **12**, 6474–6479 (2012).
115. Wu, S., Ge, R., Lu, M., Xu, R. & Zhang, Z. Graphene-based nano-materials for lithium-sulfur battery and sodium-ion battery. *Nano Energy* **15**, 379–405 (2015).
116. Son, Y., Lee, J. S., Son, Y., Jang, J. H. & Cho, J. Recent advances in lithium sulfide cathode materials and their use in lithium sulfur batteries. *Adv. Energy Mater.* **5**, 1–14 (2015).
117. Manthiram, A., Chung, S.-H. & Zu, C. Lithium–sulfur batteries: progress and prospects. *Adv. Mater.* **27**, 1980–2006 (2015).
118. *Safety Data Sheet — Sulfur Nanopowder* (American Elements, 2015).
119. *MSDS Information* (American Polymer Standards Corporation, accessed 22 April 2016); [www.ampolymer.com/15-MSDS.html](http://www.ampolymer.com/15-MSDS.html)
120. *Sicherheitsdatenblatt — Polyaniline* (Globale EHS-Manages, 2012).
121. Nan, C. *et al.* Durable carbon-coated Li<sub>2</sub>(S) core–shell spheres for high performance lithium/sulfur cells. *J. Am. Chem. Soc.* **136**, 4659–4663 (2014).
122. Yang, Y. *et al.* High-capacity micrometer-sized Li<sub>2</sub>S particles as cathode materials for advanced rechargeable lithium-ion batteries. *J. Am. Chem. Soc.* **134**, 15387–15394 (2012).
123. Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegn, H. & Rutz, M. Development of a recycling process for Li-ion batteries. *J. Power Sources* **207**, 173–182 (2012).
124. Reuter, M. A. *et al.* *Metal Recycling: Opportunities, Limits, Infrastructure. A Report of the Working Group on the Global Metal Flows to the International Resource Panel* (UNEP, 2013).
125. Gratz, E., Sa, Q., Apelian, D. & Wang, Y. A closed loop process for recycling spent lithium ion batteries. *J. Power Sources* **262**, 255–262 (2014).
126. Xu, J. *et al.* A review of processes and technologies for the recycling of lithium-ion secondary batteries. *J. Power Sources* **177**, 512–527 (2008).
127. Som, C. *et al.* The importance of life cycle concepts for the development of safe nanoproducts. *Toxicology* **269**, 160–169 (2010).
128. Scofield, M. E., Liu, H. & Wong, S. S. A concise guide to sustainable PEMFCs: recent advances in improving both oxygen reduction catalysts and proton exchange membranes. *Chem. Soc. Rev.* **44**, 5836–5860 (2015).
129. Duan, H. & Xu, C. Nanoporous PtPd alloy electrocatalysts with high activity and stability toward oxygen reduction reaction. *Electrochim. Acta* **152**, 417–424 (2015).
130. Chen, Z., Higgins, D., Yu, A., Zhang, L. & Zhang, J. A review on non-precious metal electrocatalysts for PEM fuel cells. *Energy Environ. Sci.* **4**, 3167–3192 (2011).
131. Shao, M., Chang, Q., Dodelet, J.-P. & Chenitz, R. Recent advances in electrocatalysts for oxygen reduction reaction. *Chem. Rev.* **116**, 3594–3657 (2016).
132. Morozan, A., Josselme, B. & Palacin, S. Low-platinum and platinum-free catalysts for the oxygen reduction reaction at fuel cell cathodes. *Energy Environ. Sci.* **4**, 1238–1254 (2011).
133. Zhang, W. & Pintauro, P. N. High-performance nanofiber fuel cell electrodes. *ChemSusChem* **4**, 1753–1757 (2011).
134. Brodt, M. *et al.* Fabrication, *in-situ* performance, and durability of nanofiber fuel cell electrodes. *J. Electrochem. Soc.* **162**, F84–F91 (2014).
135. Alia, S. M. *et al.* Platinum-coated nickel nanowires as oxygen-reducing electrocatalysts. *ACS Catal.* **4**, 1114–1119 (2014).
136. Wang, C., Markovic, N. M. & Stamenkovic, V. R. Advanced platinum alloy electrocatalysts for the oxygen reduction reaction. *ACS Catal.* **2**, 891–898 (2012).
137. Choi, S.-I. *et al.* Synthesis and characterization of 9 nm Pt–Ni octahedra with a record high activity of 3.3 A/mg(Pt) for the oxygen reduction reaction. *Nano Lett.* **13**, 3420–3425 (2013).
138. Guo, S. *et al.* FePt and CoPt nanowires as efficient catalysts for the oxygen reduction reaction. *Angew. Chem. Int. Ed.* **52**, 3465–3468 (2013).
139. Tseng, C.-J., Lo, S.-T., Lo, S.-C. & Chu, P. P. Characterization of Pt–Cu binary catalysts for oxygen reduction for fuel cell applications. *Mater. Chem. Phys.* **100**, 385–390 (2006).
140. Liu, J. *et al.* Impact of Cu–Pt nanotubes with a high degree of alloying on electro-catalytic activity toward oxygen reduction reaction. *Electrochim. Acta* **152**, 425–432 (2015).
141. Nuss, P. & Eckelman, M. J. Life cycle assessment of metals: a scientific synthesis. *PLOS One* **9**, 1–12 (2014).
142. Proietti, E. *et al.* Iron-based cathode catalyst with enhanced power density in polymer electrolyte membrane fuel cells. *Nat. Commun.* **2**, 416 (2011).
143. Choi, C. H., Chung, M. W., Jun, Y. J. & Woo, S. I. Doping of chalcogens (sulfur and/or selenium) in nitrogen-doped graphene–CNT self-assembly for enhanced oxygen reduction activity in acid media. *RSC Adv.* **3**, 12417–12422 (2013).
144. Wei, Q. *et al.* Nitrogen-doped carbon nanotube and graphene materials for oxygen reduction reactions. *Catalysts* **5**, 1574–1602 (2015).
145. Zhan, Y. *et al.* Iodine/nitrogen co-doped graphene as metal free catalyst for oxygen reduction reaction. *Carbon N. Y.* **95**, 930–939 (2015).
146. Li, H. *et al.* A review of water flooding issues in the proton exchange membrane fuel cell. *J. Power Sources* **178**, 103–117 (2008).
147. Higgins, D. *et al.* Development and simulation of sulfur-doped graphene supported platinum with exemplary stability and activity towards oxygen reduction. *Adv. Funct. Mater.* **24**, 4325–4336 (2014).
148. Shahgaldi, S. & Hamelin, J. Improved carbon nanostructures as a novel catalyst support in the cathode side of PEMFC: a critical review. *Carbon* **94**, 705–728 (2015).
149. Sharma, S. & Pollet, B. G. Support materials for PEMFC and DMFC electrocatalysts — a review. *J. Power Sources* **208**, 96–119 (2012).
150. Higgins, D. C., Meza, D. & Chen, Z. Nitrogen-doped carbon nanotubes as platinum catalyst supports for oxygen reduction reaction in proton exchange membrane fuel cells. *J. Phys. Chem. C* **114**, 21982–21988 (2010).
151. Yee, R. S. L., Rozendal, R. A., Zhang, K. & Ladewig, B. P. Cost effective cation exchange membranes: a review. *Chem. Eng. Res. Des.* **90**, 950–959 (2012).
152. Hongsirikarn, K., Goodwin, J. G., Greenway, S. & Creager, S. Influence of ammonia on the conductivity of Nafion membranes. *J. Power Sources* **195**, 30–38 (2010).
153. Tripathi, B. P. & Shahi, V. K. Organic–inorganic nanocomposite polymer electrolyte membranes for fuel cell applications. *Prog. Polym. Sci.* **36**, 945–979 (2011).
154. Kraysberg, A. & Ein-Eli, Y. Review of advanced materials for proton exchange membrane fuel cells. *Energy Fuels* **28**, 7303–7330 (2014).

155. Ballengee, J. B., Haugen, G. M., Hamrock, S. J. & Pintauro, P. N. Properties and fuel cell performance of a nanofiber composite membrane with 660 equivalent weight perfluorosulfonic acid. *J. Electrochem. Soc.* **160**, F429–F435 (2013).
156. Tanaka, M. Development of ion conductive nanofibers for polymer electrolyte fuel cells. *Polym. J.* **48**, 51–58 (2015).
157. Wycisk, R., Pintauro, P. N. & Park, J. W. New developments in proton conducting membranes for fuel cells. *Curr. Opin. Chem. Eng.* **4**, 71–78 (2014).
158. Ballengee, J. B. & Pintauro, P. N. Composite fuel cell membranes from dual-nanofiber electrospun mats. *Macromolecules* **44**, 7307–7314 (2011).
159. Subianto, S. Recent advances in polybenzimidazole/phosphoric acid membranes for high-temperature fuel cells. *Polym. Int.* **63**, 1134–1144 (2014).
160. *Safety Data Sheet Product — Phosphotungstic Acid* (Ted Pella, 2015).
161. Jun, Y., Zarrin, H., Fowler, M. & Chen, Z. Functionalized titania nanotube composite membranes for high temperature proton exchange membrane fuel cells. *Int. J. Hydrogen Energy* **36**, 6073–6081 (2011).
162. Wang, Y., Jin, J., Yang, S., Li, G. & Qiao, J. Highly active and stable platinum catalyst supported on porous carbon nanofibers for improved performance of PEMFC. *Electrochim. Acta* **177**, 181–189 (2015).
163. Chalkovaa, E. *et al.* Composite proton conductive membranes for elevated temperature and reduced relative humidity PEMFC. *ECS Trans.* **25**, 1141–1150 (2009).
164. Kalappa, P. & Lee, J.-H. Proton conducting membranes based on sulfonated poly(ether ether ketone)/TiO<sub>2</sub> nanocomposites for a direct methanol fuel cell. *Polym. Int.* **56**, 371–375 (2007).
165. Chandan, A. *et al.* High temperature (HT) polymer electrolyte membrane fuel cells (PEMFC) — a review. *J. Power Sources* **231**, 264–278 (2013).
166. Lu, J., Lu, S. & Jiang, S. P. Highly ordered mesoporous Nafion membranes for fuel cells. *Chem. Commun.* **47**, 3216–3218 (2011).
167. Zarrin, H., Higgins, D., Jun, Y., Chen, Z. & Fowler, M. Functionalized graphene oxide nanocomposite membrane for low humidity and high temperature proton exchange membrane fuel cells. *J. Phys. Chem. C* **115**, 20774–20781 (2011).
168. Patel, A. & Dawson, R. Recovery of platinum group metal value via potassium iodide leaching. *Hydrometallurgy* **157**, 219–225 (2015).
169. *Safety Data Sheet — Chlorine 1–6* (Airgas 2015).
170. *Safety Data Sheet — Sodium Cyanide* (Columbus Chemical Industries, 2014).
171. *Safety Data Sheet — Aqua Regia* (Columbus Chemical Industries, 2013).
172. Handley, C., Brandon, N. P. & Van Der Vorst, R. Impact of the European Union vehicle waste directive on end-of-life options for polymer electrolyte fuel cells. *J. Power Sources* **106**, 344–352 (2002).
173. Shiroishi, H. *et al.* Dissolution rate of noble metals for electrochemical recycle in polymer electrolyte fuel cells. *Electrochemistry* **80**, 898–903 (2012).
174. Xu, F., Mu, S. & Pan, M. Recycling of membrane electrode assembly of PEMFC by acid processing. *Int. J. Hydrogen Energy* **35**, 2976–2979 (2010).

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### Additional information

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### Competing financial interests

The authors declare no competing financial interests.

## Corrigendum: Nanotechnology for environmentally sustainable electromobility

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