# Supporting Information

## Summary of scientific papers published over time in this field

For the journal sources, table 1 shows the top 25 productive journals in this field and their growth trends of publications over time are displayed in Figure 1. The amount of articles in the listed 25 journals accounts for about 44% of the total publications in the research field, of which *Journal of Power Sources* is the most, representing 8.6% of total.  As for citations per publication, *Energy and Environmental Science*, *Journal of Materials Chemistry*, *Advanced Energy Materials*, and *Environmental Science and Technology* were cited most per publication, even with less number of publications than top five productive journals. Moreover, amounts of publications with the most rapid growth in the past five years are from *Applied Energy*, *Journal of Electrochemical Society*, *Electrochimica Acta*, and *International Journal of Life Cycle Assessment*.

As for the most cited articles, Table 2 displays the top 25 most cited articles and geographic locations of their authors. *Wang et al., 2010,* published on *Journal of American Chemical Society*, received the most citations in this research field. The majority of the top 25 articles focus on technology development and material innovations of battery, of which only eight papers touch on the environmental and socio-economic aspects. The geographic distribution of most cited articles are of great diversity, including US, Canada, European countries, Australia, China, Korea, Japan, and Singapore, and US is the most cited country among the top 25 articles.

*Table 1. Top 25 productive journals, 1974-2018*

| Rank | Journal | Journal Publication | Ratio of Total Publication (%) | Total Citation | Citation Per Publication |
|---|---|---|---|---|---|
| 1 | *Journal of Power Sources* | 34 | 8.61 | 675 | 19.85 |
| 2 | *Applied Energy* | 15 | 3.80 | 216 | 14.40 |
| 3 | *Journal of Cleaner Production* | 12 | 3.04 | 208 | 17.33 |
| 4 | *Journal of the Electrochemical Society* | 11 | 2.78 | 168 | 15.27 |
| 5 | *Electrochimica Acta* | 9 | 2.28 | 43 | 4.78 |
| 6 | *Journal of Materials Chemistry* | 8 | 2.03 | 751 | 93.88 |
| 7 | *International Journal of Life Cycle Assessment* | 8 | 2.03 | 237 | 29.63 |
| 8 | *Energies* | 8 | 2.03 | 75 | 9.38 |
| 9 | *Environmental Science and Technology* | 7 | 1.77 | 550 | 78.57 |
| 10 | *Resources, Conservation and Recycling* | 7 | 1.77 | 94 | 13.43 |
| 11 | *Renewable and Sustainable Energy Reviews* | 6 | 1.52 | 318 | 53.00 |
| 12 | *RSC Advances* | 5 | 1.27 | 119 | 23.80 |
| 13 | *Energy and Environmental Science* | 4 | 1.01 | 668 | 167.00 |
| 14 | *Advanced Energy Materials* | 4 | 1.01 | 358 | 89.50 |
| 15 | *Science of the Total Environment* | 4 | 1.01 | 110 | 27.50 |
| 16 | *ACS Applied Materials and Interfaces* | 4 | 1.01 | 35 | 8.75 |
| 17 | *Chemistry of Materials* | 4 | 1.01 | 27 | 6.75 |
| 18 | *Applied Thermal Engineering* | 3 | 0.76 | 77 | 25.67 |
| 19 | *Journal of Hazardous Materials* | 3 | 0.76 | 66 | 22.00 |

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|---|---|---|---|---|---|
| 20 | *Energy* | 3 | 0.76 | 59 | 19.67 |
| 21 | *Journal of Industrial Ecology* | 3 | 0.76 | 52 | 17.33 |
| 22 | *Energy Conversion and Management* | 3 | 0.76 | 39 | 13.00 |
| 23 | *Waste Management* | 3 | 0.76 | 21 | 7.00 |
| 24 | *Materials and Design* | 3 | 0.76 | 18 | 6.00 |
| 25 | *Hitachi Review* | 3 | 0.76 | 12 | 4.00 |

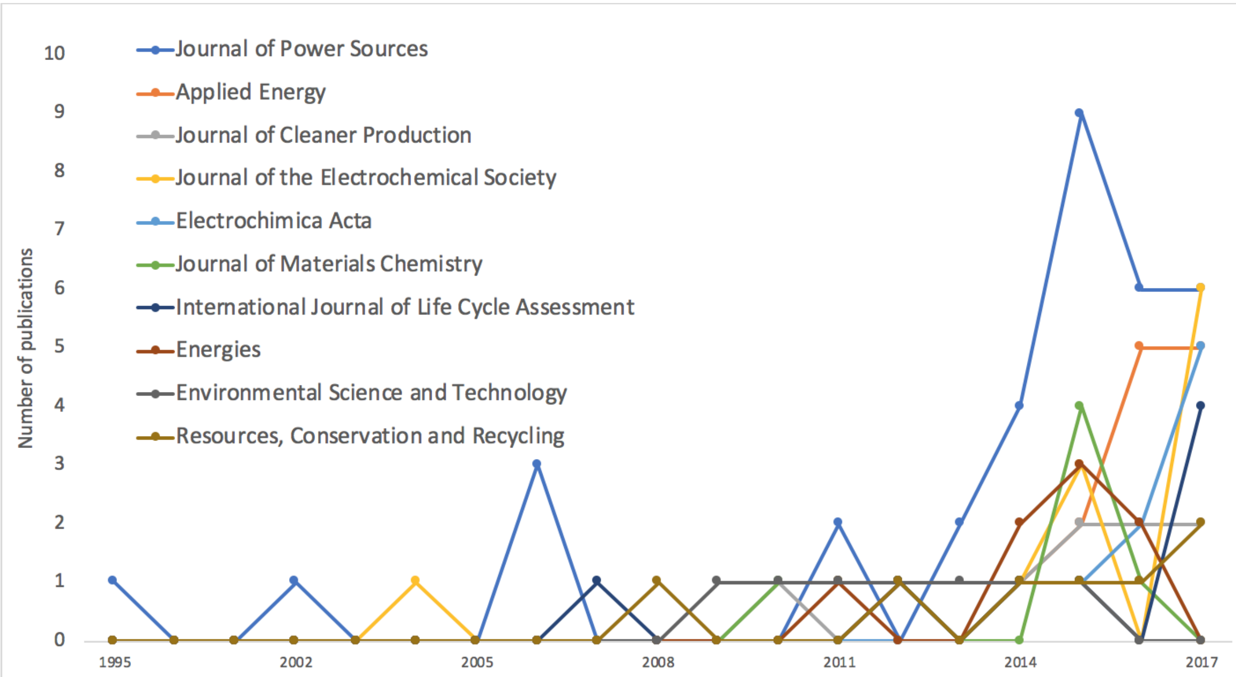


*Figure 1. Timeline of publications in the top 10 productive journals, 1995-2017*

*Table 2. Top 25 most cited articles*

| Rank | Title | Author | Year | Citations | Country |
|---|---|---|---|---|---|
| 1 | *Mn3O4-graphene hybrid as a high-capacity anode material for lithium ion batteries* | Wang et al. | 2010 | 1339 | US |
| 2 | *KOH activation of carbon-based materials for energy storage* | Wang, J., Kaskel, S. | 2012 | 565 | Germany |
| 3 | *Green energy storage materials: Nanostructured TiO2 and Sn-based anodes for lithium-ion batteries* | Deng et al. | 2009 | 562 | Singapore, Korea |
| 4 | *A multifunctional 3.5V iron-based phosphate cathode for rechargeable batteries* | Ellis et al. | 2007 | 535 | Canada |
| 5 | *Nanoscale triboelectric-effect-enabled energy conversion for sustainably powering portable electronics* | Wang et al. | 2012 | 356 | US, China |
| 6 | *Silicon-Based nanomaterials for lithium-ion batteries: A review* | Su et al. | 2014 | 297 | US |
| 7 | *Contribution of Li-ion batteries to the environmental impact of electric vehicles* | Notter et al. | 2010 | 219 | Switzerland |
| 8 | *Nanotechnology for sustainable energy* | Serrano et al. | 2009 | 206 | Spain |
| 9 | *Comparative Environmental Life Cycle Assessment of* | Hawkins et al. | 2013 | 194 | Norway |

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|---|---|---|---|---|---|
| | *Conventional and Electric Vehicles* | | | | |
| 10 | *The lithium/air battery: Still an emerging system or a practical reality?* | Grande et al. | 2015 | 185 | Germany, Italy, Korea |
| 11 | *SUBAT: An assessment of sustainable battery technology* | Van Mierlo et al. | 2006 | 156 | Belgium |
| 12 | *Current research trends and prospects among the various materials and designs used in lithium-based batteries* | Wagner et al. | 2013 | 152 | Germany |
| 13 | *Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles* | Majeau-Bettez et al. | 2011 | 150 | Norway |
| 14 | *Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles-Critical issues* | Zackrisson et al. | 2010 | 147 | Sweden |
| 15 | *Batteries for electric and hybrid-electric vehicles* | Cairns et al. | 2010 | 127 | US |
| 16 | *Opportunities and challenges for first-principles materials design and applications to Li battery materials* | Ceder, G. | 2010 | 117 | US |
| 17 | *Li3V2(PO4)3 cathode materials for lithium-ion batteries: A review* | Rui et al. | 2014 | 111 | Singapore, Australia |
| 18 | *Structure and ionic conductivity in lithium garnets* | Cussen, E.J. | 2010 | 111 | UK |
| 19 | *Batteries for Low Power Electronics* | Powers, R.A. | 1995 | 110 | US |
| 20 | *A fuzzy multi-criteria decision-making model for trigeneration system* | Wang et al. | 2008 | 110 | China |
| 21 | *Environmental impacts of hybrid and electric vehicles-a review* | Hawkins et al. | 2012 | 104 | Norway |
| 22 | *An investigation of self-powered systems for condition monitoring applications* | James et al. | 2004 | 100 | UK |
| 23 | *Review-practical issues and future perspective for Na-ion batteries* | Kubota and Komaba | 2015 | 99 | Japan |
| 24 | *Impact on global metal flows arising from the use of portable rechargeable batteries* | Rydh et al. | 2003 | 91 | Sweden |
| 25 | *Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings* | Dewulf et al. | 2010 | 85 | Belgium |

## Bibliometric Methodology

The bibliometric results are based on the science mapping analysis, which is widely used to detect the hidden key elements (documents, authors, institutions, topics, etc.) and how key elements are related to one another in different research fields (Small 1999). We used a bibliometric approach developed by Cobo *et al* (2011). The approach is based on a co-word analysis and the h-index, to analyze this research field, and detect and visualize its conceptual thematic area and thematic evolution. This established approach consists of four major stages for analyzing a research field in a longitudinal framework:

### *Detection of the research themes*

For each time period under study, co-word analysis (Callon *et al* 1983) is applied to raw data of all publications in this research field to detect the corresponding research themes. Simple centers algorithm (Coulter *et al* 1998) is then applied to cluster keywords belonging to themes by detecting keyword networks that are strongly linked to each other. The developed keyword clusters reflect the centers of research interests or research problems that attract significant interests among researchers. The similarity between keywords is calculated based on the **equivalence index** (Callon *et al* 1991):

$$e_{ij} = \frac{{c_{ij}}^2}{c_i * c_j}$$

where $c_{ij}$ is the number of documents in which two keywords $i$ and $j$ *co*-occur, and $c_i$ and $c_j$ refer to the number of documents in which each one appears.

***Visualization of research themes and thematic network***

The detected research themes are visualized by the strategic diagram (He 1999) that plots the centrality and density of each theme in a two-dimensional diagram. Each theme can be characterized by two measures (Callon et al 1991): centrality and density.

Centrality measures the external strength of the network by measuring degree of a thematic network's interaction with other thematic network. Ranking thematic area for each period of study with respect to their centrality shows the extent to which each area is central within a global network (Bauin et al, 1991). **Centrality** represents the sum of all external link values (Courtial *et al* 1993, Turner *et al* 1988), thus the definition used in this study is based on (Cobo *et al* 2011):

$$c = 10 * \sum e_{kh}$$

where $e_{kh}$ is the external link value, $k$ stands for a keyword belonging to the theme, and $h$ refers to a keyword belonging to other themes.

Density measures the internal strength within the network by measuring the internal links that tie together keywords making up the thematic network. The value of Internal links represents the capacity of a thematic network to maintain itself and to develop over study period of time in the field under consideration (Callon *et al* 1991). The **density** value represents the average value of internal links (Coulter *et al* 1998, Turner *et al* 1988), thus the definition used in this study is based on (Cobo *et al* 2011):

$$d = 100 * \frac{\sum e_{ij}}{w}$$

Where $e_{ij}$ refers to the equivalence index of keywords $i$ and $j$ belonging to the theme, and w refers to the number of keywords in the theme.

***Discovery of thematic areas***

The evolution of the research themes over a series of study periods is explored through the inclusion index (Callon *et al* 1986, Sternitzke *et al* 2009) detecting conceptual nexus between research themes in different periods. Inclusion index is helpful to measure similar sets without being biased by the number of items, therefore identifying the conceptual nexus between two consecutive periods through estimating the elements in common. **Inclusion index** in our approach is based on Cobo *et al* (2011):

$$Inclusion\ Index = \frac{\#(U \cap V)}{\min(\#U, \#V)}$$

Where U representing each detected theme in the period t, V representing each detected theme in the next period t+1, #U and #V refer to the number of keywords in theme U and theme V, respectively. The inclusion index will be equal to 1 if the keywords of the theme V are fully contained in the theme U.

A thematic area is defined as a set of themes that have evolved over a series of time periods (Cobo *et al* 2011). The interconnections between research themes can indicate the similarity and inclusion of one research theme in the period t and another theme in the next period t+1, that implies that one theme could belong to a one or more thematic areas, or could not belong to any.

***Performance analysis***

The performance analysis will be performed as a complement to the science mapping analysis, with the help of bibliometric indicators including number of publications, number of citations, and h-index (Alonso *et al* 2009, Hirsch 2005). **H-index** reflects both the number of publications and the sum of citations, and will be used in this study to represent that a research theme with an index of h has published h papers each of which has been cited in other papers at least h times (Hirsch 2005).

## Periodic Analysis of Research Themes

### *Analysis of First Period (1974-2008)*

Based on the strategic diagram presented in Figure 2, research activities in this research field are concentrated on 8 themes. Our analysis focus on 5 major themes that are categorized as motor or basic themes: *Waste, Environmental Impact, Energy Efficiency, Battery Chemistry, Technology*.

**Environmental Impact** – this theme is the most important and well-developed motor theme of this period, with the largest number of documents, citations, and highest research impact (h-index=15). Studies represented by this theme during this period cover a broad research scope in environmental impact, including environmental pollution caused by industrial development, Li-ion battery/hydrogen fuel cell/nanotechnology as cleaner alternatives to traditional energy sources, comparing environmental impacts across different battery types, mitigation of battery impacts through end-of-life recovery, etc.

**Waste** – this theme is another motor theme showing the highest research density in this period, and it refers to research conducted on wasted electronic products and batteries, industrial wastes, waste management, and issues on the export of e-waste to developing countries. It is the second most important and developed research theme of the studies in the field of 'socio-environmental impacts of lithium extraction and use' during the period of time, even with a few number of publications and citations comparing to other themes. According to the performance measures, other themes of great importance in this period were energy efficiency, battery chemistry, and technology.

**Energy efficiency** – studies related to this theme are centered on the energy density of battery, energy efficiency of battery systems, and energy efficiency improvements on hybrid vehicles and electric powered systems comparing to internal combustion engine powered systems.

**Battery chemistry** – this theme refers to research conducted on the composition of battery chemical systems, comparison of different battery chemistries in terms of costs and performance, battery management strategies for different battery chemistries.

**Technology** -- studies represented by this theme include battery technologies for improving battery performance and its environmental performance, specifically focusing on technologies for energy storage, recycling of materials, extending service lives, and the possibility of producing high quality and clean electricity.

It is worth mentioning that **measurement** theme, which refers to the research conducted on measuring battery resistance to radiation for battery performance purpose, is internally well developed but isolated from the rest of studies in this field, which indicates that a constituted group is actively researched on this topic during this period of time.


*Figure 2. Strategic diagram for the period 1974–2008. (Bubble size represents no. documents with number of citations within parentheses)*

Table 3. Performance Measures for the Themes (1974–2008)

| Theme name | Number of documents | Number of citations | h-index |
|---|---|---|---|
| Waste | 8 | 130 | 3 |
| Environmental Impact | 37 | 1595 | 15 |
| Measurement | 6 | 171 | 4 |
| Energy Efficiency | 13 | 371 | 7 |
| Battery Chemistry | 13 | 742 | 6 |
| Technology | 13 | 584 | 8 |
| Photovoltaic System | 2 | 82 | 2 |
| Lithium Nickel Cobalt Manganese (NMC) Battery | 2 | 50 | 2 |

***Analysis of Second Period (2009-2011)***

Research themes shown in the strategic diagram (Figure 3.) are centered on eight themes with emphasis on five major themes (motor themes and basic themes), including *Electric Vehicle, Material, Greenhouse Gas, Chemical Compound and Energy Consumption*. Motor themes electric vehicle, chemical compound, and material are most influential in constructing and directing the development of this research field over this period, because they are well developed and central to the research network in question. In addition, bibliometric indicators (table 4.) also showed remarkable achievements of motor themes in terms of large number of documents and high research impacts. Basic theme greenhouse gas has the similar number of publications to motor theme material, while achieved much lower research impacts (h-index =7). Another basic theme energy consumption is highlighted by its similar research impacts to theme greenhouse gas with fewer number of publications.

**Electric Vehicle** – this theme is focused on the technology and environmental performance of Hybrid Electric Vehicles and Battery Electric Vehicles, especially compared with conventional vehicles.

**Material** – this theme is related to lightweight materials for battery and vehicle manufacturing, durable anode materials for high energy density, recovery and recycling difficulties of battery materials.

**Chemical compound** -- research represented by this theme are specifically focused on chemical compound materials for battery technology, the composition of organic/inorganic materials, types of compounds for anode material.

**Greenhouse gas** – studies included in this theme are primarily about electric vehicles as a potential alternative for gasoline cars for reduction of greenhouse gas emissions.

**Energy Consumption** – this theme refers to studies about potentials for electric vehicles for reduction of fuel consumption, relationship between vehicle weight and vehicle energy consumption.

In comparison with themes in the first period, several findings are summarized:

- The number of themes is stable, but the number of motor themes is increased.

- The motor theme environmental impact in the first period has been replaced by a new theme of electric vehicle in the second period. The research focus represented by this theme has been specific to electric vehicles, which is considered as a cleaner alternative to traditional vehicles.
- The basic themes focusing on battery technology and chemistry in the first period have gained enough research density to evolve as motor themes in the second period.
- Energy Efficiency as a motor theme in the first period has been weakened as a declining theme.
- Greenhouse gas appears as a new basic and transversal theme, which indicates a shifting of research focus to greenhouse gas emissions during this period of time.
- The appearance of electric vehicle, energy consumption, and greenhouse gas as important new themes can be explained by the new CAFE standard proposed in 2009 and Clean Energy Act in 2009.
- The development and consolidation of themes related to battery technology and electric vehicle technology (i.e., material, chemical compound, electric vehicle), can be supported by the facts that many financial programs and initiatives were active to support innovation on vehicle and battery innovation over this period of time.


*Figure 3. Strategic diagram for the period 2009–2011.*

Table 4. Performance Measures for the Themes (2009–2011)

| Theme name | Number of documents | Number of citations | h-index |
|---|---|---|---|
| Electric Vehicle | 28 | 2983 | 15 |
| Material | 17 | 2852 | 12 |
| Greenhouse Gas | 17 | 680 | 7 |
| Chemical Compound | 14 | 2813 | 12 |

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|---|---|---|---|
| Energy Consumption | 6 | 613 | 6 |
| Design | 8 | 278 | 4 |
| Energy Efficiency | 2 | 0 | 0 |
| Rechargeable Battery | 2 | 236 | 2 |

***Analysis of Third Period (2012-2016)***

According to strategic diagram (Figure 4.), 11 themes are identified to show where the research is focused on over this period, with 6 major research themes: lithium-ion battery, environmental assessment, electrode, vehicle, temperature management, sustainability. It's worth to notice that all the 6 major themes are motor themes, which play a critical role in structuring research in this field. For performance measures, some emerging themes like electronics and capacitor stand out for their prominent research impacts (sum of citations >800, h-index>12).

**Lithium-ion battery** – this theme is the most influential and developed theme in this period, with the largest number of documents, citations, and highest research impact (h-index=34). Lithium-ion battery as the leading theme over this period represents the research conducted on the lithium-ion battery from environment perspective or technological perspective. Environmental assessment refers to assessments of life-cycle environmental impacts, pollutants, hazards, and efficiencies caused by battery systems or systems using batteries.

**Electrode** – studies covered in this theme are primarily focused on electrode material selection and innovation.

**Vehicle** – this theme broadly represents studies on all vehicle types having the potential for utilizing lithium batteries, including bus, railway, motorcycle, and marine vehicles.

**Temperature management** – this theme shows the research specifically centered on the effects of temperature on battery safety, charging efficiency, battery life, and vehicle performance.

**Sustainability** – research represented by this theme is emphasized on sustainable governance of lithium resource, sustainable use of batteries, and sustainable energy storage and transportation.

In comparison with themes in the second period, the following findings should be pointed out:

- In this period, the number of themes and the number of motor themes are both increased.
- The most important motor theme electric vehicle in the second period has been replaced by a new theme lithium-ion battery in this period. The research focus has changed and specified to lithium-ion battery, rather than the vehicle itself.
- Environment-related theme in this period (environmental assessment) has evolved as the second important motor theme which indicates that the research focus has shifted from qualitative analysis to quantitative assessment of environmental impacts. This trend can be explained by the national and state level regulation programs on vehicle emissions (i.e., ZEV program), which may lead to more assessment directed research.
- Themes related to battery materials and technology from the last period (chemical compounds, material), have been developed and divided into new motor themes focusing on more specific topics, such as electrode materials.

- New theme vehicle indicates an increased research scope on the application of lithium-ion batteries, which can be justified by the fact that car manufactures were launching most of new Li-ion battery vehicle models.
- In addition, new themes related to battery performance also appear as a new motor theme (temperature management) and emerging themes (battery life, capacitor).
- New themes partially related to social perspectives appear as one new motor theme (sustainability) and one emerging theme (toxicity). Sustainable governance of lithium resources and human toxicity of battery materials are two major topics been studied in terms of social impacts.

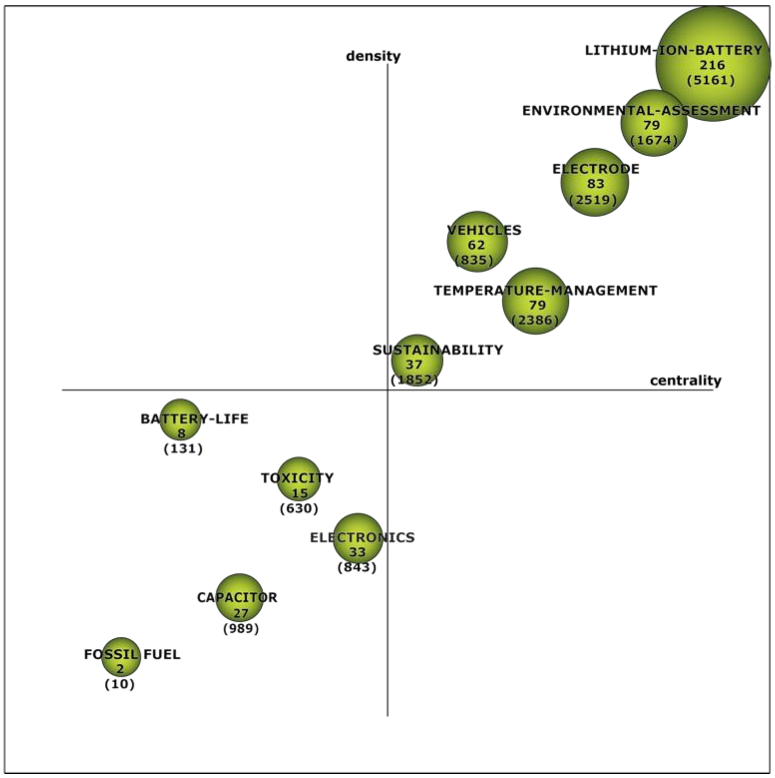


*Figure 4. Strategic diagram for the period 2012–2016.*

Table 5. Performance Measures for the Themes (2012–2016)

| Theme name | Number of documents | Number of citations | h-index |
|---|---|---|---|
| Lithium-ion Battery | 216 | 5161 | 34 |
| Environmental Assessment | 79 | 1674 | 20 |
| Electrode | 83 | 2519 | 22 |
| Vehicles | 62 | 835 | 17 |
| Temperature Management | 79 | 2386 | 23 |
| Sustainability | 37 | 1852 | 14 |
| Electronics | 33 | 843 | 12 |
| Battery Life | 8 | 131 | 6 |
| Toxicity | 15 | 630 | 9 |
| Capacitor | 27 | 989 | 13 |
| Fossil Fuel | 2 | 10 | 2 |

***Analysis of Fourth Period (2017-now)***

The research conducted in this period of time is distributed in 9 themes (Figure 5.), with 5 major research themes (motor themes and basic themes): lithium-ion battery, grid, nanomaterial technology, performance, and analysis. The motor theme lithium-ion battery, grid, nanomaterial technology, and performance are the most influential ones for the structuring of the research field of socio-environmental impacts of lithium extraction and use because they are well developed and central to this research field during this period.

**Lithium-ion battery** – this theme is still the most important theme in this period, and the research represented by the theme lithium-ion battery in this period is the same as in the previous period.

**Grid** – this is a new motor theme which represents the studies on grid-scale renewable energy storage (with Li-ion battery), battery pack reused in 'smart grid', and charging EVs by high carbon intensity power grid.

**Nanomaterial technology** – this  theme refers to the research focus of nanoscale materials as a sustainable anode for Li-ion battery and nanomaterial-specific impact.

**Performance –** the research included in this theme are concentrated on either electrochemical performance regarding endurance and state-of-health, or comprehensive battery performance regarding energy, power, cycle life, cost, safety, and environmental impacts.

**Analysis** – this theme appears as a new basic and transversal theme, which mainly refers to the life cycle assessment research which focuses on the sensitivity analysis for testing the robustness and reliability of their results, or robust comparative analysis of existing LCA studies. With respect to performance measures, it is worth to notice that the emerging theme environmental friendly achieves a more significant number of citations (85 citations) with a fewer number of publications (8 publications), comparing to motor themes like grid and performance.

**Environmental friendly** -- as a new emerging theme, this theme represents studies testing on the claim of "environmental friendly" technology or material and the limitations of this claim.

In comparison with themes in the third period, the following findings are highlighted:

- The most important motor theme lithium-ion battery has not been replaced by any other themes and keeps the highest centrality and density in this research field.
- The new theme grid appears as the second most important theme in this period, which indicates a new important research interest in utilizing Li-ion battery in grid-scale energy storage. The appearance of this research interest can be justified by the facts that many companies (i.e., Tesla, BYD, etc.) started producing large capacity utility storage battery packs since 2016, and the installation of utility storage battery by California Public Utilities Commission in Ontario, CA in 2017.
- Themes related to battery performance in the previous period (temperature management, battery life, etc.) has been replaced by a new motor theme performance in this period, which covers a broader research scope including the comprehensive performance of battery in terms of durance, capacity, cost, safety, and environmental impacts.

- Material related themes in previous periods (material, electrodes, etc.) have been replaced by a new motor theme nanomaterial technology, which potentially directs a new research focus of nanomaterial as a sustainable alternative in this research field.
- The theme fossil fuel has evolved from emerging theme to isolated theme which is well-developed but is still marginal to this research field. The research represented by this theme is centered on vehicle charging by fossil energy dominated electricity mix.


*Figure 5. Strategic diagram for the period 2017–now.*

Table 6. Performance Measures for the Themes (2017–now)

| Theme name | Number of documents | Number of citations | h-index |
|---|---|---|---|
| Lithium-ion Battery | 86 | 199 | 6 |
| Nano-material Technology | 19 | 114 | 4 |
| Grid | 15 | 47 | 4 |
| Fossil Fuel | 25 | 35 | 3 |
| Performance | 35 | 39 | 3 |
| Analysis | 20 | 38 | 4 |
| Battery Model | 13 | 15 | 2 |
| Battery Safety | 15 | 20 | 3 |
| Environmental Friendly | 8 | 85 | 3 |

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