



Study of energy storage systems and environmental challenges of batteries

A.R. Dehghani-Sanij^{a,b,*}, E. Tharumalingam^a, M.B. Dusseault^{a,b}, R. Fraser^{b,c}

^a Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON, Canada

^b Waterloo Institute for Sustainable Energy (WISE), University of Waterloo, Waterloo, ON, Canada

^c Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON, Canada

ARTICLE INFO

Keywords:

Energy storage
Battery
Greenhouse gas emissions
Environmental impacts
Disposal and recycling

ABSTRACT

As more renewable energy is developed, energy storage is increasingly important and attractive, especially grid-scale electrical energy storage; hence, finding and implementing cost-effective and sustainable energy storage and conversion systems is vital. Batteries of various types and sizes are considered one of the most suitable approaches to store energy and extensive research exists for different technologies and applications of batteries; however, environmental impacts of large-scale battery use remain a major challenge that requires further study. In this paper, batteries from various aspects including design features, advantages, disadvantages, and environmental impacts are assessed. This review reaffirms that batteries are efficient, convenient, reliable and easy-to-use energy storage systems (ESSs). It also confirms that battery shelf life and use life are limited; a large amount and wide range of raw materials, including metals and non-metals, are used to produce batteries; and, the battery industry can generate considerable amounts of environmental pollutants (e.g., hazardous waste, greenhouse gas emissions and toxic gases) during different processes such as mining, manufacturing, use, transportation, collection, storage, treatment, disposal and recycling. Battery use at a large scale or grid-scale (> 50 MW), which is widely anticipated, will have significant social and environmental impacts; hence, it must be compared carefully with alternatives in terms of sustainability, while focusing on research to quantify externalities and reduce risk. Alternatives such as pumped hydro and compressed air energy storage must be encouraged because of their low environmental impact compared to different types of batteries.

1. Introduction

Energy underlies the welfare, economics and development state of societies. The dominant primary energy sources are fossil fuels; more specifically, oil, coal and gas, which supply ~85% of mankind's primary energy [1,2]. Population growth, industrial development and economic growth lead to increasing energy demand, particularly in emerging large-population economies [3–8]. Growing demand leads to environmental challenges such as global warming and climate change, air pollution health impacts, and risk of soil and water contamination [7,9–13]. According to Boden and Andres [14] and Heard et al. [15], atmospheric CO₂ concentration increased from ~360 ppm to ~400 ppm between 1995 and 2015, and fossil fuel CO₂ emissions rose from ~6.4

Gt C yr⁻¹ in 1995 to ~9.8 Gt C yr⁻¹ in 2013. To affect these trends, sustainable carbon-free or low-carbon energy sources (wind, solar, tidal, wave, nuclear, etc.) and energy storage must increase quickly. Large-scale energy storage (> 50 MW) is vital to manage daily fluctuating power demands on large grids and to cope with the variable and intermittent nature of renewable sources as they grow to provide large proportions of the energy to grids of all sizes.

Energy storage systems (ESSs) can be classified into five major groups [9,16–18]:

1. Mechanical systems such as pumped hydroelectric storage (PHS), compressed air energy storage (CAES), falling weights, and flywheel energy storage (FES);

Abbreviations: BES, Battery Energy Storage; BEV, Battery Electric Vehicle; BIT, Beijing Institute of Technology; CAES, Compressed Air Energy Storage; CTG, Cradle-To-Gate; DLC, Double Layer Capacitor; DMC, Dimethyl Carbonate; ESSs, Energy Storage Systems; EC, Ethylene Carbonate; FES, Flywheel Energy Storage; GHG, Greenhouse Gas; HEV, Hybrid Electric Vehicle; LCA, Life Cycle Assessment; LFP, Lithium Iron Phosphate; Li-ion, Lithium-ion; Li-S, Lithium-sulphur; LMO, Lithium Manganese Oxide; Na-S, Sodium-sulphur; Ni-Cd, Nickel-cadmium; Ni-MH, Nickel-metal hydride; Ni-Zn, Nickel-zinc; NMC, Lithium Manganese Cobalt Oxide; Pb-A, Lead-acid; PHEV, Plug-in Hybrid Electric Vehicle; PHS, Pumped Hydroelectric Storage; RFB, Redox Flow Battery; SMES, Superconducting Magnetic Energy Storage; SNG, Synthetic Natural Gas; SWOT, Strengths, Weaknesses, Opportunities and Threats; TES, Thermal Energy Storage; VRB, Vanadium Redox Battery; Zn-C, Zinc-carbon

* Corresponding author at: Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON, Canada.

E-mail address: a7dehgha@uwaterloo.ca (A.R. Dehghani-Sanij).

<https://doi.org/10.1016/j.rser.2019.01.023>

Received 7 November 2018; Received in revised form 3 January 2019; Accepted 10 January 2019

Available online 21 January 2019

1364-0321/ © 2019 Elsevier Ltd. All rights reserved.

2. Chemical systems (e.g., hydrogen storage with fuel cell/electrolyser, synthetic natural gas (SNG), and reversible chemical reactions);
3. Electrochemical systems; in particular, different types of batteries;
4. Electrical systems including capacitors, supercapacitors, and superconducting magnetic energy storage (SMES); and,
5. Thermal systems¹ (e.g., sensible heat storage, latent heat storage, as well as thermal absorption and adsorption systems).

ESSs can be used for a wide range of applications for different time and magnitude scales [9]; hence, some systems are appropriate for specific narrow applications (e.g., supercapacitors), whereas others can be chosen for broader applications (e.g., CAES). ESSs must satisfy various criteria such as: capacity reserve, short or long-time storage, quick response time, stationary or portable, energy density rating, conversion rate, storage costs, security, end-use (e.g., grid connected or stand-alone), environmental impacts, and storage time limits [9,19,20]. Some important characteristics such as lifetime, cycling times, cycle efficiency, energy density and power density are compared between different ESSs in Table 1. Table 2 compares various types of ESSs based on costs, such as power capital cost, energy capital cost, as well as operating and maintenance cost. The provided data in Tables 1–2 has been extracted from both academic research and industry application regions [18]. Table 3 is a comparison among several energy storage technologies obtained through SWOT² analysis. Additionally, several comparisons of different types of ESSs using four distinct methods are depicted in Figs. 1–4. Of greatest interest in terms of decarbonization, factoring in more renewables, and reasonable ease of integration with existing infrastructure are grid-scale ESSs, defined roughly as approaches capable of 50 MW scale or more.

ESSs have broad and various specifications, applications, benefits and limitations (Tables 1–3 and Figs. 1–3). For example, FES systems have high efficiency, power density and stability, as well as fast response time [9,21,63,64], but have disadvantages including high self-discharge rates, low overall magnitude, safety and high cost. CAES systems have advantages such as grid-scale potential, flexibility, long life, relatively low operation and maintenance costs, as well as low self-discharge rates [65]; however, the efficiency of these systems is moderate [21] and the geological suitability of the storage site is a key constraint [65]. Batteries are efficient, convenient, reliable, easy to use, and need low maintenance, but environmental concerns, high cost (compared to utility power), need for critical materials (e.g., Li and Co), low energy density, and restricted shelf life are some of batteries' limitations [66].

Provision and consumption of electricity occur simultaneously [9,67], so the quantity generated must meet a varying demand. ESSs help balance supply and demand [68] through short- to long-term storage duration periods, while aiding in frequency and voltage control at local and large grid scales. Electrical energy must be converted into another form to be stored [69], and batteries are an obvious storage option. Batteries will certainly play an important role in integration of intermittent renewable sources (wind, solar), as they smooth output and enhance renewable energy versatility in micro-generation systems, allowing them to supply and distribute steady electrical power [70–72]. Leaving cost and environmental impact aside, BES is perhaps the most efficient method to stabilize power grids that access important quantities of renewable energy (e.g., > 10%) [21]. Among different types with a share of the BES market, Li-ion is the most prominent with a 55% market share (Fig. 5) [72].

BES systems suitable for grid-scale applications are increasingly mentioned because all experts predict a continued strong growth in battery deployment, either as stand-alone arrays or as a distributed system (many plugged-in E-vehicles). This paper examines impacts of

Table 1
Comparison of key factors for a number of ESSs [18,21].

System	Lifetime (years)	Cycling times (cycles)	Cycle efficiency (%)	Energy density (Wh/L)	Power density (W/L)
PHS	40–60 [22], 40 + [23], 30 + [24]	10,000–30,000 [25]	70–85 [22], 70–80 [24], 87 [26], 75–85 [27]	0.5–1.5 [22], 1–2 [28]	0.5–1.5 [22], ~ 1 [28]
Large-scale CAES	20–40 [22], 30 [29], 20 + [23,27]	8000–12,000 [25]	42–54 [22,30], AA-CAES 70 [27,31]	3–6 [22], 2–6 [28]	0.5–2 [22], ~ 1 [28]
Over-ground small CAES	23 + [32]	Test 30,000 stop/starts [32]	-	Higher than large-scale CAES	Higher than large-scale CAES
FES	~ 15 [22], 15 + [23], 20 [33]	20,000 + [22], 21,000 + [23]	~ 90–95 [22], 90 & 95 [29]	20–80 [22,28,34]	1000–2000 [22], ~ 5000 [28]
TES	10–20 [22], 5–15 [22], 30 [27]	-	~ 30–60 [22]	80–120, 120–200, 200–500 [22]	-
SMES	20 + [22], 30 [33]	100,000 + [22], 20,000 + [25]	~ 95–97 [22], 95–98 [35], 95 [29]	0.2–2.5 [22], ~ 6 [28]	1000–4000 [22], ~ 2500 [28]
Capacitor	~ 5 [22], ~ 1–10 [36]	50,000 + [22], 5000 (100% DoD) [37]	~ 60–70 [22], 70 + [37]	2–10 [22], ~ 0.05 [38]	100,000 + [22]
Supercapacitor	10–30 [22], 10–12 [35]	100,000 + [22], 50,000 + [23]	~ 90–97 [22], 84–95 [35]	10–30 [22], ~ 10–30 [34]	100,000 + [22]
Hydrogen fuel cell	5–15 [22], 20 [39], 20 + [35]	1000 + [22], 20,000 + [35]	~ 20–50 [22], 32 [40], 45–66 [41]	500–3000 [22]	500 + [22]
Battery Energy Storage (BES)	5–15 [22,42], 13 [23]	500–1000 [22], 200–1800 [43]	70–80 [22], 63–90 [25], 75–80 [44]	50–80 [22], 50–90 [29]	10–400 [22]
Li-ion	5–15 [22], 14–16 [45]	1000–10,000 [22], up to 20,000 [46]	~ 90–97 [22], 75–90 [47]	200–500 [22], 200–400 [28], 150 [29]	1500–10,000 [28]
Na-S	10–15 [22], 15 [23], 12–20 [48]	2500 [22], 3000 [49], 2500–4500 [25]	~ 75–90 [22], 75 [49], 75–85 [44]	150–250 [22], 150–300 [28]	~ 140–180 [28]
Ni-Cd	10–20 [22], 3–20 [43], 15–20 [42]	2000–2500 [22], 3500 [50]	~ 60–70 [22], 60–83 [25]	60–150 [22], 15–80 [28], 80 [29]	80–600 [28]
Vanadium Redox	5–10 [22], 20 [51]	12,000 + [22], 13,342 [23]	75–85 [22,52], 65–75 [47]	16–33 [22], 25–35 [53]	~ < 2 [28]
Zn-Br	5–10 [22], 10 [23], 8–10 [45]	2000 + [22], 1500 [23]	~ 65–75 [22], 66–80 [25], 66 [33]	30–60 [22], ~ 55–65 [28]	~ < 25 [28]

¹. Thermal energy storage (TES) systems

². SWOT refers to Strengths, Weaknesses, Opportunities and Threats.

Table 2
Comparison of various types of ESSs in terms of costs [18,21].

System	Power capital cost (\$/kW)	Energy capital cost (\$/kWh)	Operating and maintenance cost	
PHS	2500–4300 [47], 2000–4000 [24]	5–10 [22], 10–12 [33]	0.004 \$/kWh [29], ~ 3 \$/kW/year [54]	
Large-scale CAES	400–800 [22], 800–1000 [24]	2–50 [22], 2–120 [55], 2 [29]	0.003 \$/kWh [29], 19–25 \$/kW/year [54]	
Over-ground small CAES	517 [33], 1300–1550 [56]	1MVA from £ 296 k [32], 200–250 [56]	Very low [32]	
FES	250–350 [22]	1000–5000 [22], 1000–14,000 [55]	~ 0.004 \$/kWh [29], ~ 20 \$/kW/year [54]	
TES	200–300 [22], 250 [27], 100–400 [27]	20–50 [22], 30–60 [22], 3–30 [22]	–	
SMES	200–300 [22], 300 [33], 380–489 [56]	1000–10,000 [22], 500–72,000 [33]	0.001 \$/kWh [29], 18.5 \$/kW/year [54]	
Capacitor	200–400 [22]	500–1000 [22]	13 \$/kW/year [54], < 0.05 \$/kWh [37]	
Supercapacitor	100–300 [22], 250–450 [56]	300–2000 [22]	0.005 \$/kWh [29], ~ 6 \$/kW-year [33]	
Hydrogen fuel cell	500 [33], 1500–3000 [57]	15 [33], 2–15 €/kWh [44]	0.0019–0.0153 \$/kWh [57]	
Battery Energy Storage (BES)	Pb-A	300–600 [22], 200–300 [33], 400 [49]	~ 50 \$/kW/year [54]	
	Li-ion	1200–4000 [22], 900–1300 [42], 1590 [47]	–	
	Na-S	1000–3000 [22], 350–3000 [55]	300–500 [22], 350 [49], 450 [58]	~ 80 \$/kW/year [54]
	Ni-Cd	500–1500 [22]	800–1500 [22], 400–2400 [42]	~ 20 \$/kW/year [54]
	Vanadium Redox	600–1500 [22]	150–1000 [22], 600 [58]	~ 70 \$/kW/year [54]
	Zn-Br	700–2500 [22], 400 [59], 200 [33]	150–1000 [22], 500 [60]	–

Table 3
SWOT analysis conducted on several grid-scale ESSs [9,19,61,62].

System	Strengths	Weaknesses	Opportunities	Threats
CAES	High capacity; Low cost per kWh; Minor needs for power electronic converters; Negligible storage losses; Storing energy for more than one year	Need for underground cavities; Need for fuel (e.g., H ₂ and CH ₄) if gas turbines used	Can prospectively be adapted for distributed storage	Popularity related to thermal power plants; Probably, increasing the fuel costs over time
PHS	High capacity; Low cost per kWh; Minor needs for power electronic converters; Long lifetime; Reliable	Centralized storage; Geographical restrictions; High investment cost of installation; Environmental concerns	Can be used for offshore wind parks and with a lower reservoir under sea level	Can become obsolete when distributed storage preferred; Increasing public opposition due to environmental damage
BES	Distributed storage; Good configurability; Fast response time; High energy efficiency and density	High investment costs; Short life span; Temperature issues in cold climates	Emerging technologies, most likely BES will be a distributed system (many cars)	Constant development phase complicates selection; Raw materials' limits; Environmental impacts;
Hydrogen	Distributed storage; Other uses for produced hydrogen; Minor environmental issues	Low efficiency; High investment costs; Need for power electronics and control; Need for stable load	Market penetration; Perspective nanotube storage media; Dedicated converters	Maturing battery technologies; EMI issues related to the use of power electronics converters

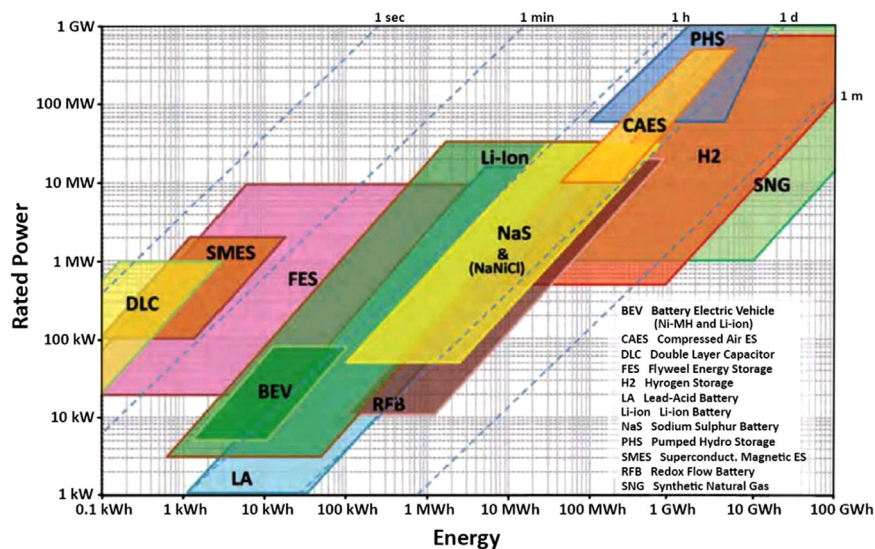


Fig. 1. Comparison of different types of ESSs in terms of rated power, energy, and discharge duration [9].

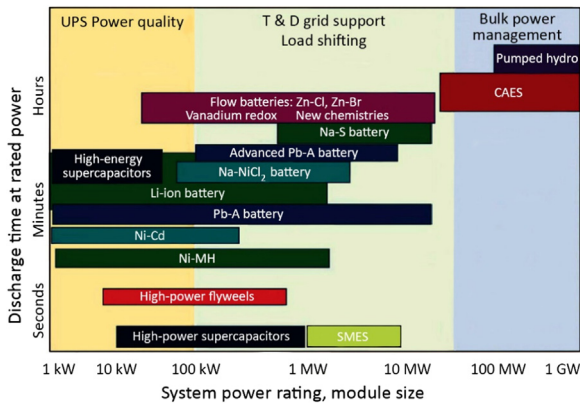


Fig. 2. Comparison of different types of existing ESSs (commercial or near-commercial) in terms of power output, module sizing, and discharge time (adapted from [9,21]).

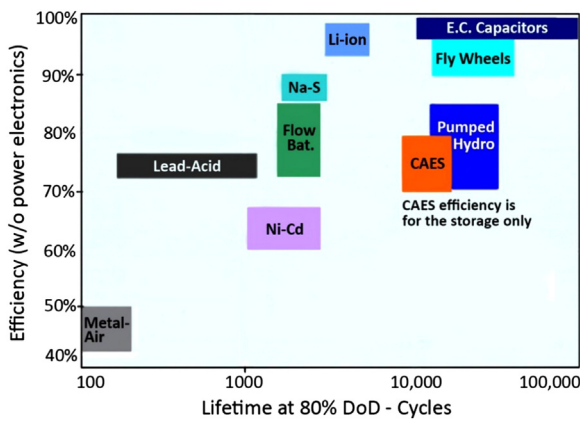


Fig. 3. Comparison of different types of ESSs in terms of cycle life and efficiency [9].

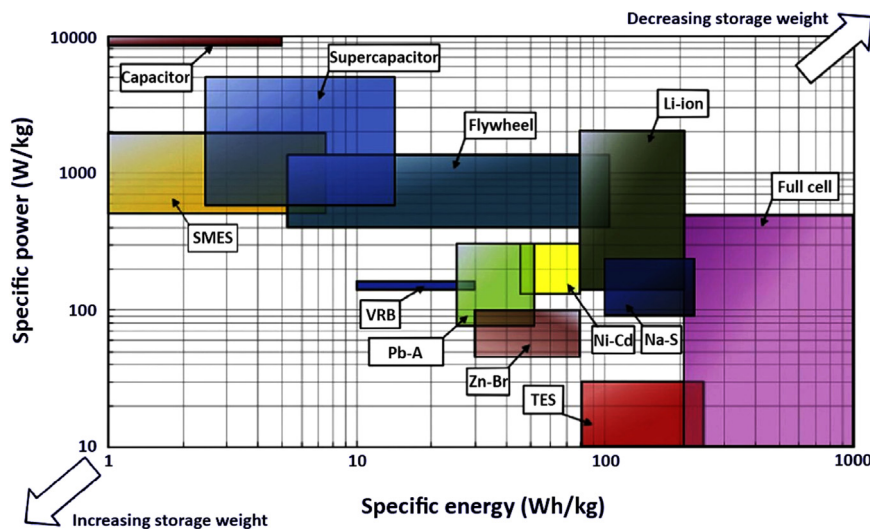


Fig. 4. Comparison of different types of ESSs in terms of specific energy and specific power [18].

different types of batteries on the environment and public health. Design features, advantages and disadvantages of batteries are presented; then, environmental and health impacts are reviewed and discussed from different aspects, including:

- The share of batteries in the use of raw materials and depletion of natural resources;

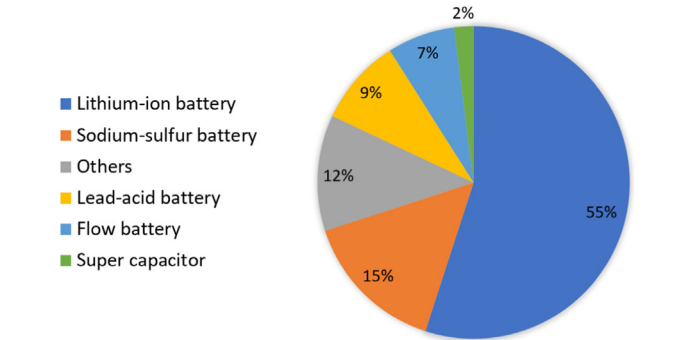


Fig. 5. Worldwide battery energy storage system installed capacity in 2016 [72].

- The role of batteries in environmental pollutants, greenhouse gas (GHG) emissions, and harmful effects on public health during mining, manufacturing, use, collection, transportation and storage; and,
- Hazards and problems caused by disposal and recycling of batteries.

2. Different types of batteries

Batteries are categorized into the following groups [73]: (1) primary batteries, (2) secondary batteries, (3) battery systems for grid-scale energy provision (e.g., flow battery, sodium-sulphur battery), (4) fuel cells, and (5) electrochemical capacitors (supercapacitor).

2.1. Primary batteries

Primary batteries for portable electric devices, typically not recharged after usage and usually not recycled, are convenient, simple, and require little maintenance [73]. Primary batteries are further categorized based on the type of electrolyte they use: aqueous and non-aqueous [21]. These are commercially sold in sizes such as AA, AAA, C,

etc.; the most common being alkaline, zinc-carbon and lithium batteries.

2.1.1. Zinc-carbon (Zn-C) battery

Zinc-carbon batteries accounted for 39% of the European market in 2004 [74], and their use is declining [73]. Also known as Leclanché batteries, they have a low production and watt-hour cost, and come in a

Table 4
Materials used on average in composition of alkaline batteries [78–80].

Material	Percentage of battery weight (%)
Manganese electrolytic	32–38
Graphite	3–5
Zinc	11–16
Steel	19–23
Potassium hydroxide (KOH)	5–9
Barium sulfate (BaSO ₄)	< 5
Water, paper, plastic, other	Balance

large variety of shapes, sizes, voltages, and capacities. Zn-C batteries are reliable and have a moderate shelf life [75]. Zn-C battery disadvantages include low energy density, poor leakage resistance, and voltage drop with discharge [73]. They have a carbon (C) cathode in contact with a paste of MnO₂ with an acid electrolyte, enclosed in a zinc (Zn) case serving as the anode [76]. Large quantities of zinc and manganese are contained in the batteries and they require proper landfill disposal or metals recovery [77].

2.1.2. Alkaline battery

The primary battery market has shifted to the Zn/Alkaline/MnO₂ battery (the ubiquitous “alkaline” cell). They outperform Zn-C batteries by factors of $\times 2$ to $\times 10$ [73], provide good low temperature and high-rate performance, have low cost and a good shelf life [75]. The alkaline cell is similar to the Zn-C cell: it uses zinc and manganese dioxide as an anode and cathode, but with a potassium hydroxide (KOH) electrolyte [78]. Table 4 indicates the materials used and their average percentages in alkaline batteries.

2.1.3. Lithium primary cells

Lithium cells have dominated high-performance primary battery development since 1990 [73]. Lithium cells have high cell voltage, flat discharge, long shelf life, wide operating temperature range, and good power density [81]. Lithium batteries also contain lithium metal and flammable solvents, and flammable hydrogen gas can be generated when the lithium is in contact with water [82]. Another example of lithium primary cells is the lithium-air battery that is under development; it has 5–10 times more energy density compared to standard Li-ion batteries [71].

2.2. Secondary batteries

Secondary batteries are rechargeable cells. They have a wide range of day-to-day applications including car ignition and portable electronic devices (e.g., cell phones, laptop computers), and are being developed as a power source for electric and hybrid vehicles [73]. These batteries have an increasing appeal in residential power storage, as more homes use self-produced electricity [83]. Commercialisation of secondary cells became possible through the development of electrodes that can undergo many deep charge/discharge cycles [81]. Common rechargeable batteries include lead-acid, lithium-ion, nickel-metal hydride, and nickel-cadmium technologies, based on their electrode components [84].

2.2.1. Lead-acid (Pb-A) batteries

Lead-acid batteries have the largest market share for rechargeable batteries both in terms of sales value and MWh of production, mostly in the automotive industry, with a secondary market for industrial use such as standby power to telecommunications and data networks [21]. Pb-A batteries have low production cost, a wide size range, good high-rate performance, good performance in varying temperatures, high voltage, and good charge retention [21,73]. Disadvantages of Pb-A batteries include relatively low cycle life, limited energy density, acid stratification, acid leaks if breached, and difficulty in down-scaling

Table 5
Materials used in composition of a Pb-A battery [87–89].

Material	Percentage of battery weight (%)
Lead	25
Lead oxides	35
Polypropylene	10
Sulfuric acid (H ₂ SO ₄)	10
Water	16
Glass ^a	2
Other (e.g., antimony)	1

^a In new batteries, plastic is used instead of glass or ceramic as separators.

[73]. Lead production and use present well-known environmental concerns, and recycling is required to reduce impacts [85]. The USA Environmental Protection Agency claims that 90% recycling is achieved for automotive Pb-A batteries [86]. Table 5 shows, as an example, the materials used and their percentages in the production of a Pb-A battery.

2.2.2. Lithium-ion (Li-ion) batteries

Lithium batteries can provide a high storage efficiency of 83% [90] and are the power sources of choice for sustainable transport [91]. Li-ion batteries are ideal for small-scale electronics and are extensively applied in renewable energy and micro-grid systems [72]. The advantages of Li-ion batteries include sealed cells that require no maintenance, long cycle life, wide temperature range of operation, rapid charging, high charge/discharge efficiency, high energy density, and ample design flexibility [73]. Flexibility of design involves selection of the salts used as the electrolyte. Conventionally, Li-ion batteries use lithium hexafluorophosphate (LiPF₆) [92]. Batteries that use LiPF₆ are limited by thermal stability, sensitivity to moisture, and they break down into toxic chemicals; alternative salts are being investigated to curtail these drawbacks [93]. Solid-state electrolytes can also be implemented to make Li-ion batteries more effective due to their thermal and chemical stability [94], solid state electrolytes are considered expensive; however, advancements are being made to make them more commercially viable [95]. Disadvantages of Li-ion batteries include a high initial cost, significant charge/discharge randomness, frequent charging needs, and insufficient cycle life [72].

The materials used and their percentages in Li-ion batteries differ according to various factors such as size, application, and the type of cathode consumed [96]. For example, the materials used and their percentage in a typical Li-ion portable battery are lithium cobalt oxide (27.5%), steel (20.2%), graphite (16%), polymer (14%), copper (9%), aluminium (5.5%), nickel (4.3%), and electrolyte (3.5%) [96], which are based on statistics obtained from several battery recycling companies. Table 6 illustrates the materials used and their percentages in manufacturing of Li-ion batteries for a hybrid electric vehicle (HEV), a plug-in hybrid electric vehicle (PHEV), and a battery electric vehicle (BEV).

2.2.3. Lithium-sulphur (Li-S) batteries

Lithium-sulphur batteries are considered promising for their high theoretical capacity and low cost because of the abundance of sulphur [99]. Real implementation of these cells is not as advanced as expected despite a theoretical energy density three to five times higher than that of Li-ion batteries [100]. Major limitations are capacity loss and low coulombic efficiency due to polysulfide shuttling, low volumetric density, high internal resistance, self-discharge, and rapid capacity fading [100,101]. Many of these drawbacks can be curtailed with innovative design of the cells, which is why they are receiving so much attention.

2.2.4. Nickel-metal hydride (Ni-MH) batteries

Nickel-metal hydride batteries are used for power tools and hybrid vehicle applications [87]. Ni-MH batteries were used in electric

Table 6
Materials used in making Li-ion batteries of HEV, PHEV and BEV [97,98].

Component	Percentage of mass (%)		
	HEV	PHEV	BEV
Lithium manganese oxide (LiMn ₂ O ₄)	27	27	33
Graphite/Carbon	12	12	15
Binder	2.1	2.0	2.5
Copper	13	15	11
Wrought aluminium	24	22	19
Lithium pentafluorophosphate (LiPF ₆)	1.5	1.6	1.8
Ethylene carbonate (EC)	4.4	4.7	5.3
Dimethyl carbonate (DMC)	4.4	4.7	5.3
Polypropylene	2.0	2.2	1.7
Polyethylene	0.26	0.40	0.29
Polyethylene terephthalate	2.2	1.6	1.2
Steel	2.8	1.8	1.4
Thermal insulation	0.43	0.33	0.34
Glycol	2.3	1.2	1.0
Electronic parts	1.5	0.9	1.1
Total battery mass (lb)	41	196	463

vehicles, and large vehicle manufacturing companies have also focused on Ni-MH batteries [102]. The battery consists of a nickel hydroxyl oxide cathode, a metal hydride anode, a KOH electrolyte, and a separator [87]. Advantages of Ni-MH batteries are high energy density and specific energy when compared with Pb-A and Ni-Cd, good temperature and rate capability, good charge retention, long cycle life, long shelf life, and rapid charging. Disadvantages of Ni-MH batteries include a higher cost than Pb-A, lower specific energy and specific power, as well as decreased performance at low temperatures [73].

2.2.5. Nickel-cadmium (Ni-Cd) batteries

Nickel-cadmium batteries are used for devices like phones, toys, and hand tools [87]. Ni and Cd are used as electrodes, with the cadmium electrode having a higher capacity [103]. Ni-Cd battery advantages consist of long cycle life, durability, good charge retention, excellent long-term storage, low maintenance, and flat discharge. The major disadvantages are low energy density, high cost relative to Pb-A batteries, and strong memory effects [73]. Cadmium is a highly toxic metal which must be disposed properly, and the Cd levels in municipal solid waste largely come from discarded Ni-Cd batteries [104].

2.2.6. Nickel-zinc (Ni-Zn) batteries

Nickel-zinc batteries are typically used for providing small-scale, portable power at a high rate of discharge. Ni-Zn batteries do so at a low-cost relative to Li-ion batteries, and can replace both Ni-Cd and Ni-MH batteries for most applications [66]. These batteries are considered effective because of their high specific power, high efficiency, low cost and low impact on the environment [105]. However, there are drawbacks to this configuration: disadvantages consist of zinc being a self-corrosive material, Ni-Zn batteries are prone to dry out, and evidence low discharge after a number of cycles [66,105].

2.3. Battery systems for grid-scale energy

Grid-scale storage requires development of specialized battery systems with a number of important characteristics. The grid-scale system must be able to assist in meeting peak power demand, improve grid stability, and provide large amounts of high-quality power quickly and for a sustained period. There are two prominent types of grid-scale battery technologies under development: flow batteries and sodium-sulphur batteries [55]. Advanced Pb-A and Li-ion batteries may also be adapted to grid-scale, but the power provided by these two approaches can only meet energy demand at a lower scale, suitable only for local use or in micro-grids.

2.3.1. Flow batteries

Flow batteries, also known as redox flow batteries (RFBs), induce a chemical reaction in a reaction chamber with electrolytes stored in external tanks [55]. RFB systems in which the electro-active materials are dissolved into a liquid electrolyte [106] produce energy through reduction and oxidation reactions occurring in separate half-cells. Reduction extracts electrons and ions from one electrolyte, oxidation recombines them in the other electrolyte. Both half-cells are connected to an external storage tank [107]. Flow batteries have the ability to separate power and energy; power is controlled by the cell stack, and energy is stored in the separated reactants [53]. Advantages consist of flexible design capability, controllable cell temperature, easy monitoring, straightforward scaling, no self-discharge, quick response time, and good stability after long periods of no discharge [107]. On the negative side, RFBs have low power and energy density and require management of pumps, flow and power. Vanadium is found in most RFBs configurations; it is quite expensive and considered the main cost driver of RFB systems [53].

2.3.2. Sodium-sulphur (Na-S) batteries

Sodium-sulphur batteries are high temperature batteries using liquid sodium and sulphur, potentially useful as ESSs at close to grid-scale [108]. Na-S batteries might have become the energy source of choice for electric vehicle applications except for the need to keep them at their operating temperature of 300 °C [87]. Advantages to Na-S batteries include low cost due to wide availability of materials, high cycle life, high energy density, flexible operation, and insensitivity to ambient conditions [73,109]. Disadvantages revolve around maintaining the high temperature required for operation, including safety issues related to the reactivity of the contents.

2.4. Fuel cells

Fuel cells continuously convert chemical energy of a fuel into electrical energy by external provision of a fuel to a direct oxidation substrate that generates power. Fuel cells are classified as direct systems which directly use fuels such as hydrogen, and indirect systems that use fossil fuels through a series of catalyzed and thermal steps [73]. The most common approach is to generate methanol from methane ($\text{CH}_4 \rightarrow \text{CH}_3\text{OH}$) via the syngas reaction to generate liquid methanol, an easily transported fuel. In the indirect fuel cell, the methanol is passed through a reformer such that $\text{CH}_3\text{OH} \rightarrow \text{CO} + 2\text{H}_2$, and $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$, and the H_2 generates electrical power as it is catalytically oxidized to water. A fuel cell is similar to a battery in that it is composed of an anode, cathode, and electrolyte membrane [9]. Advantages of fuel cells include efficient conversion in the output power cycle, reliability, flexible scaling, and minimal degradation [73,108]. The disadvantages of fuel cells include expensive capital cost, the need for fossil fuels (or other source of methanol), costly conversion reactions to generate methanol, and minimal fuel infrastructure for fuel cell vehicles.

2.5. Electrochemical capacitors

Electrochemical capacitors, also known as supercapacitors, can manage high power output but in very short bursts (low overall energy output) [110]. The device is comprised of two electrodes, a separator and an electrolyte. Electrodes are polarized by an applied voltage, and ions in the electrolyte form double-layers of opposite charge to the electrolyte [111]. Advantages of electrochemical capacitors include low charge time, high efficiency, very high cycle life, and high specific power [110]. Disadvantages are low specific energy, short discharge time, and linear decline of voltage [110,112,113].

3. Environmental and health impacts caused by battery use

Batteries may impact the environment during manufacturing, use, storage, treatment, disposal and recycling. Due to their a vast range of applications, a large number of batteries of different types and sizes are produced globally, leading to different environmental and public health issues. In the following subsections, different adverse influences and hazards created by batteries are discussed.

3.1. Raw materials inputs

Battery manufacture requires large amounts of many different metals and non-metals. The metals used include lead (Pb), lithium (Li), nickel (Ni), cobalt (Co), zinc (Zn), manganese (Mn), magnesium (Mg), mercury (Hg), silver (Ag), cadmium (Cd), vanadium (V), potassium (K), titanium (Ti), chromium (Cr), sodium (Na), tin (Sn), aluminium (Al), iron (Fe), copper (Cu), indium (In), silicon (Si), antimony (Sb), lanthanum (La), and cerium (Ce) [66,114]. The non-metals used include carbon or graphite (C), fluorine (F), chlorine (Cl), bromine (Br), sulphur (S), and germanium (Ge) [66,114]. Increasing battery manufacture affects natural resource access and economics because of the geographical location of metal sources (often in unstable or controlled economies) and the depletion of the easiest sources first. In addition, some of these materials are precious (Ag) and used as currency, and others are expensive (In and Hg) or rare (La and Ce). To provide the increases needed in supplies of metals such as lead, zinc, lithium, aluminium, copper, etc., additional quantities of minerals from existing and new discoveries must be generated [115]. The mining industry itself has environmental and social issues of substantial magnitude, especially in less-developed countries with lax or corrupt regulatory oversight, and these may increase if the demand forces prices upward. In the cost context, examining public commodity indices as of mid-2018, Co had increased in price three-fold in the last two years, Li prices increased four-fold since 2015, and rare earth stock market indices have increased dramatically (China dominated rare earth production at 80% of global total in 2016).

About 85% of worldwide lead consumption is used for the production of Pb-A batteries [21,116,117]. Fig. 6 shows the rate of lead production over time in the world. Sun et al. [118] reported that the total global consumption of lithium (Fig. 7) in making batteries was approximately 35% in 2015, reaching 46% in 2017 [119], driven by battery demand. The worldwide cobalt demand for manufacturing batteries is ~50% of supply [120], as indicated in Fig. 8. According to reports by DS [121], EC [114] and Labie et al. [122], around 10% of global production of graphite in 2010 was for batteries.

Nickel use in batteries accounts for only 3% of its total world production (Fig. 9) [128]. About 5% of global consumption of mercury is for batteries [129], and this is trending downward because of technology changes and toxicity concerns [130]. Batteries account for

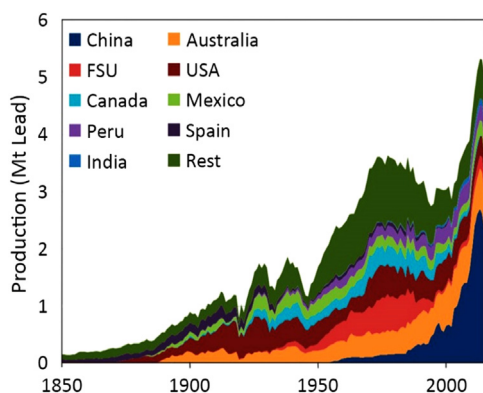


Fig. 6. World production of lead [115,123,124].

~75% of global Cd production [131]. Ni-MH batteries account for ~10% and ~6% of the global consumption of La and Ce, respectively, and ~5% of indium use between 2010 and 2017 was for alkaline batteries [114,121,132]. The worldwide demand of Mn for batteries production has been reported to be ~2% [114]. As illustrated in Fig. 10, the global use of refined tin in Pb-A batteries accounted for ~8% of its total world production in 2016 [133]. According to Chegwidan [134] and Dupont et al. [135], the antimony consumption in Pb-A batteries' production was ~27% in the world in 2010.

Fig. 11 shows the historical lead prices from 1989 to the end of 2018; Pb prices generally increase over time and greater fluctuations in price are evident in recent years. Fig. 12 indicates cobalt prices from 2005 to the end of 2018. Al-Thyabat et al. [137], Ruffino et al. [138], Rydh and Svärd [139] and Song et al. [140] all report that the recent increases in the prices of raw minerals led to greater recycling of used batteries and the recovery of metals (e.g., lead, cobalt, nickel and copper).

3.2. Harmful effects and environmental pollutions caused by using batteries

Some metals and non-metals involved in battery manufacturing can threaten human health via different forms of exposure such as inhalation, skin or eye contact, ingestion and injection. For example, humans generally absorb Pb through ingestion, inhalation and dermal absorption [143–145], Cd by ingestion and inhalation [130,146,147], and Hg through inhalation, ingestion and skin contact [148,149]. Mousavi et al. [150] reported that Pb, Cd, Hg, As, and Cr have noxious effects on human health, and heavy metals in general present risks for public health and the environment [130,151,152].

Metal toxicity is a function of factors including the pathway, period and frequency of exposure, absorbed dose, and chemical species; it also depends on subject age, gender, genetics, and nutritional status [130,147]. In 2016, statistics showed that Pb exposure caused the death of 495,550 people and losses of 9.3 million disability-adjusted life years from long-term influences on health, especially on individuals from low- and middle-income countries [153]. Metals and metal compounds enter soil, groundwater and surface waters through many different pathways during mining and industrial activities. Landfills and tailings ponds affect water, and dust or evaporates (e.g., fumes from burning wastes during recycling) from various stages in transportation, processing and recycling enter the atmosphere. Wastes from battery manufacture and recycling are a crucial and growing challenge for public health owing to their toxicity, abundance and durability in the environment, as well as the huge predicted growth in the manufacture of batteries [154].

In different battery recycling stages, metals, non-metals, electrolytes, hard rubbers (or ebonite) and plastics may form part of solid waste, wastewater, GHG emissions, particulates emissions, and toxic gases [155]. Lead fumes and particles can be released into the air during recycling processes used for Pb-A batteries [155,156]. Li-ion batteries produce around 70 kg CO₂ per kWh [157], so CO₂ emissions along various mining, transportation, manufacturing processes and recycling pathways must be included in any general environmental assessment of batteries. Table 7 shows the effects of different types of batteries on the environment, and risks caused by various kinds of batteries are listed in Table 8.

Pb-A battery use is growing rapidly in China owing to different applications such as electric bicycles, automotive use, and local photovoltaic energy storage industries [161]. For the foreseeable future, China will continue to lead the world's production, refining and use of both lead and Pb-A batteries, and contamination caused by lead and human exposure in China are large challenges for public health, especially for children's health. Millions of Chinese children are exposed to lead poisoning, so that 24% of children under study were lead poisoned with levels of more than 100 µg/L between 2001 and 2007 [161]. Even at levels of 20 µg/L lead has deleterious effects on children's health, and

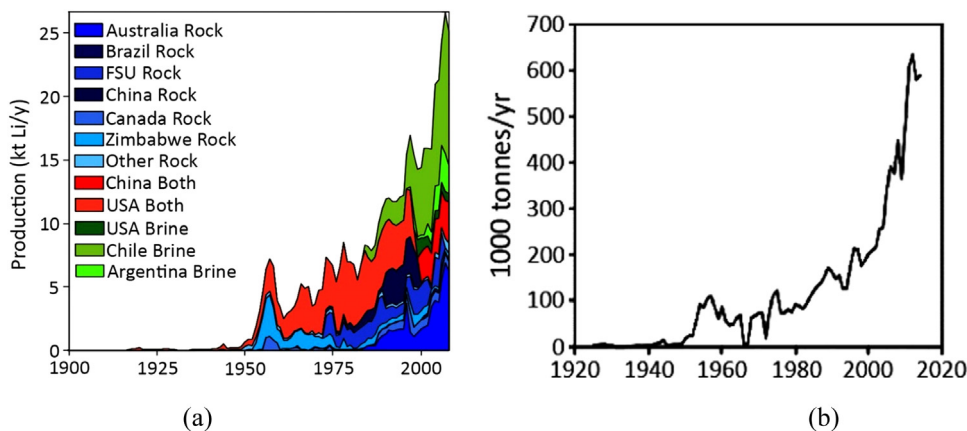


Fig. 7. Global production of lithium (a) by country and mineral type [125,126] and (b) generally around the world [127].

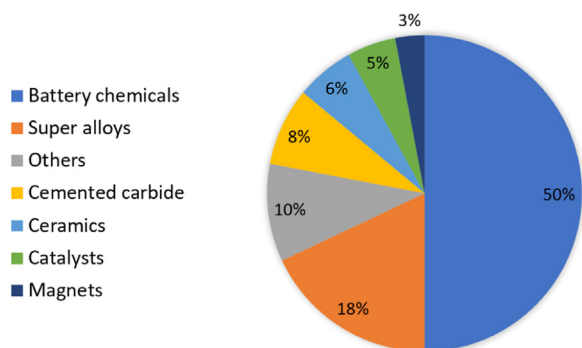


Fig. 8. Global demand for cobalt [120].

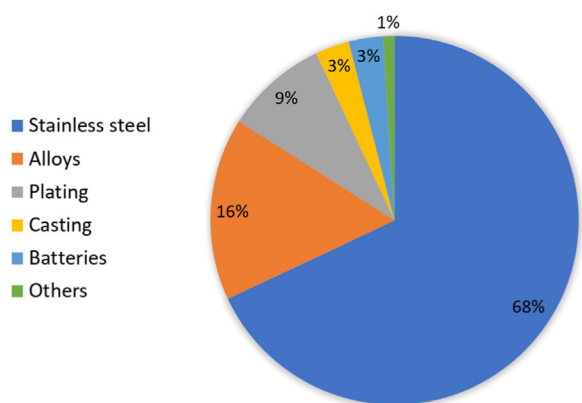


Fig. 9. Different usages of nickel [136].

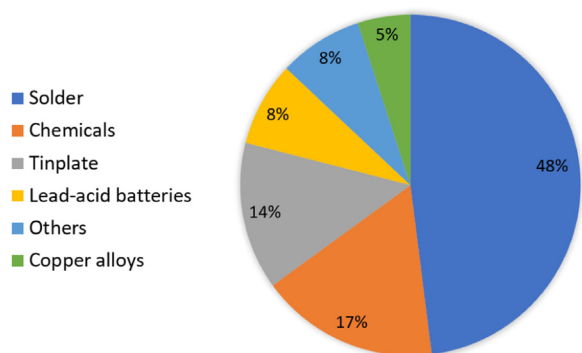


Fig. 10. Worldwide use of tin according to its applications [133].

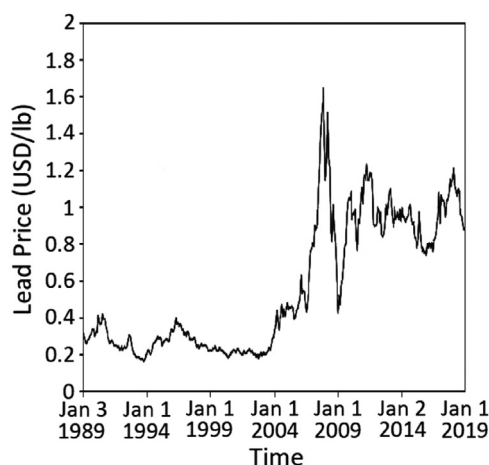


Fig. 11. Lead price changes versus time [141].

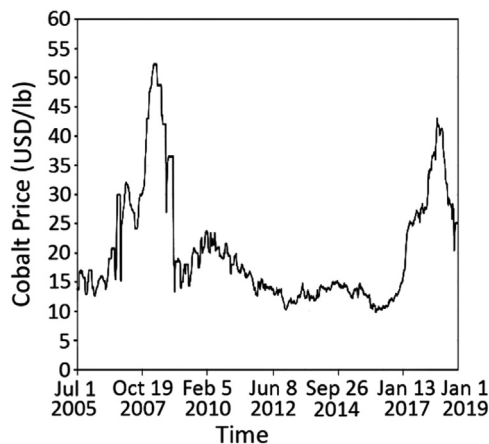


Fig. 12. Cobalt price changes versus time [142].

100 µg/L is considered severe [155].

Sullivan and Gaines [87] published a comprehensive review of cradle-to-gate (GTG) life cycle inventories of different batteries including Pb-A, Ni-Cd, Ni-MH, Na-S and Li-ion. They analyzed emissions created during materials production, battery manufacturing and assembly, as well as associated with recycling of batteries and battery materials. These emissions include CO₂, criteria contaminants (owing to combustion), and process-specific emissions (e.g., heavy metals), both to air and water as well as resident in solid waste. Tables 9 and 10 show the emissions data obtained from various references for different

Table 7
Environmental impacts of different types of batteries [157–159].

Battery type	Environmental impact
Ni–MH (established)	Nickel not green (difficult extraction/unsustainable), toxic. Not rare but limited Recyclable
Pb-A (established)	High-temperature cyclability limited Lead is toxic, but recycling is efficient to 95%
Li-ion (established)	Depletable elements (cobalt) in most applications; replacements manganese and iron are green (abundant and sustainable) Lithium chemistry relatively green (abundant but the chemistry needs to be improved) Recycling feasible but at an extra energy cost
Zn–air (established)	Mostly primary or mechanically rechargeable Zinc smelting not green, especially if primary Easily recyclable
Li–organic (future)	Rechargeable Excellent carbon footprint Renewable electrodes Easy recycling
Li–air (future)	Rechargeability to be proven Excellent carbon footprint Renewable electrodes Easy recycling
Magnesium–sulphur (future)	Magnesium and sulphur are green Recyclable Small carbon footprint
Al–CF _x (future)	Aluminium and fluorine are “green” but their industries are not Recyclable
Proton battery (future)	Green, biodegradable

Table 8
Risks of batteries by type [157,158,160].

Battery	Risk
Alkaline	Benign but corrosive electrolyte
Pb-A	Heavy metals give long-term environmental risk, corrosive electrolyte can be liquid
Ni–Cd	Toxicity
Ni–MH	Mostly harmless, flammable electrodes (self combust when exposed to air) if opened
Li-ion	Internal short circuit, safety issues, medium fire risk
Lithium primary	Safety issues, highest risk of fire if not handled correctly

batteries. Note that the emissions data related to the recycling process was restricted (Table 10).

According to Tables 9 and 10,

- The GHG emissions per kg of battery are generally a bit higher than direct CO₂ emissions, and Pb-A has the lowest quantity of CO₂ emissions (Fig. 13);
- The average emissions for each battery are lower than 30 g/kg of battery for all kinds of emissions, excluding SO_x emissions for Ni-MH and Ni-Cd batteries (Fig. 14). Also, the relative change in the averages among batteries for each emission is approximately the same; and,
- In general, Pb-A batteries have the lowest amount of criteria contaminant emissions among all batteries.

Because the quantity of Li-ion batteries used in light vehicles is growing, interest in energy consumption and GHG emissions from their production is of interest [169–185]. The findings obtained from these studies differ in quality in areas such as transparency, assumptions used, and depth of review, so the reliability of the findings is varied [184]. It is suggested that these issues be resolved as society moves toward larger use of energy storage and rapid growth in battery implementation in E-vehicles and grids. Fig. 15 displays the review findings by Romare and Dahllöf [184] on the GHG emissions caused by Li-

ion batteries production; T-D and B-U refer to top-down and bottom-up approaches for manufacturing, respectively. The data obtained from T-D approaches is likely more complete and accurate since the T-D studies started with production data. They also reported that GHG emissions occur during recycling of Li-ion batteries, although the rate of recycling of Li-ion batteries is currently very low. They conclude that:

- Energy consumption for current battery production is from 350 to 650 MJ/kW h.
- Cell production requires a lot of energy (mainly electricity at this stage), and significant GHG emissions are generated.
- Past studies indicate GHG emissions between 120 and 250 kg CO_{2-eq}/kW h.

Li-ion and Ni-MH batteries are the highest rank CO_{2-eq} emissions producers (Table 11) [70]. It should be noted that lithium batteries are capable of creating a fire if they are exposed to humidity for a duration sufficient to lead to the corrosion of cells [74]. For two main reasons, it is difficult to compare the lithium primary batteries with alkaline batteries in the market [158,186]: this difficulty is associated with (1) very high costs because of production processes, materials consumed in making them, and auxiliary systems needed for their functioning, and (2) the cost of safety issues, although both batteries have similar life spans. Aifantis et al. [186] reported that the production of lithium batteries and cells is a business with particularly advanced technology. For example, assembling these batteries and cells must be carried out in places with a relative humidity (RH) of less than 3% due to safety concerns, although a RH value equal to or lower than 1% has been recommended.

Corrosive battery electrolytes can leak after breaking during storage, use or transportation [187]. Also, the electrolyte contains dissolved metals like lead which can become resident in water or soil in various chemical forms that are mobile. Because of the presence of various metals (especially heavy metals) and electrolytes (e.g., LiPF₆ in Li-ion batteries, sulfuric acid (H₂SO₄) in Pb-A batteries), wastewater generated during different processes (e.g., manufacturing, treatment, recycling) can be dangerous. If wastewater penetrates into the ground and flows into surface waters, it can create many problems for human health, so capture and treatment of contaminated wastewater is very important and vital.

3.3. Disposal and recycling of batteries

Vast quantities of batteries in different forms, sizes and applications are produced; in 2000, worldwide demand for batteries was around \$41 billion, including \$16.2 billion primary and \$24.9 billion secondary [188,189], and this demand reached \$65 billion in 2008 [190], then \$71 billion in 2010 [188,189], with rapid growth envisioned [186,191]. Alkaline and Pb-A batteries accounted for over 50% of the primary and secondary batteries market, respectively, in 2010 [186]. Alkaline batteries in the US account for ~80% of portable batteries produced and the total annual production of these batteries is more than 10 billion units [192]. Worldwide battery sales in 2019 are predicted to reach \$120 billion, increasing at a rate of 7.7% annually [193,194]. Fig. 16 shows the annual sales of plug-in vehicles worldwide from 2011 to 2017. Electric vehicles use different forms and sizes of batteries [195]. As illustrated in this figure, there is a considerable and rapid growth in the sale of plug-in vehicles between 2011 and 2017.

Nearly all batteries pose threats to the environment and public health if not disposed of appropriately and safely; however, some types are more dangerous than others due to metal toxicity. Bernardes et al. [74] stated that there are various options for batteries' end-of-life, including: stabilization, landfill, incineration and recycling. Large amounts of alkaline and Zn-C batteries are landfilled or incinerated, instead of recycled [196,197]; in China most spent batteries (excluding Pb-A batteries) are treated like domestic wastes, disposed of in landfills

Table 9
Air, water and solid wastes for CTG battery manufacture (g/kg of battery, unless differently stated) [87].

	VOC	CO	NO _x	PM	SO _x	CH ₄	N ₂ O	CO ₂ kg/kg	Water (mg/kg)	Air	Reference
Ni-MH	0.11	0.34	1.31	0.79	1.06	1.33	0.04	1.02	60 g Al, Ni, Co, etc., to air/water/solid		[162] ^a
	1.3	4.5	27	2.8	263	22.7	0.19	14.8	18 ^b – heavy metals	100 ^b – heavy metals	[163]
			19		14			15			[164]
	0.7	2.1	8.7	14.0	19.2	11.1	0.11	8.3			[165]
	0.9	3.9	11.4	18.9	20.5	15.3	0.1	10.3			[166] ^c
	1.8	7.5	21.8	36.1	38.9	29.3	0.3	19.5			[166] ^c
Ave.	1.2	4.5	17.6	18.0	71.1	19.6	0.2	13.6			
Pb-A	0.11	0.31	1.13	1.67	2.29	1.64	0.02	1.1	4.8 – Pb	1.2 – Pb	[162] ^a
	2.2	1.3	7.9	0.8	10.3	0.002	0.006	1.1	97 – heavy metals	118 – heavy metals	[167]
			5.8		5.3			5.1			[164]
	0.57	1.65	6.8	11.0	14.9	8.7	0.09	6.4			[165]
	0.2	0.6	1.5	1.3	2.0	3.0	0.02	1.4			[168]
	0.2	0.7	2.1	3.5	3.7	2.9	0.0	1.9			[166] ^c
	0.3	1.2	3.5	5.7	0.6	4.6	0.0	3.1			[166] ^c
Ave.	0.7	1.1	4.6	4.5	7.0	3.8	0.0	3.2			
Ni-Cd									60 – Cd, Co, Ni	40 – Cd, Co, Ni	[162] ^a
	5.9	5.4	40	5.2	265	0.001	0.015	6.2	30 – heavy metals	740 – heavy metals	[167]
	0.6	1.9	8.6	11.3	16.9	9.5	0.1	7.3			[164]
	0.7	2.8	8.1	13.4	14.5	10.9	0.1	7.3			[166] ^c
	0.9	3.8	11.1	18.3	19.8	14.9	0.1	9.9			[166] ^c
	Ave.	2.0	3.5	17.0	12.1	79.0	8.8	0.1	7.7		
Na-S	1.67	5.4	20.5	25.6	38.0	27.3	0.2	18.2			[168]
	1.1	4.4	13.0	21.4	23.4	17.3	0.2	11.6			[166] ^c
	1.2	4.9	14.6	24.2	26.5	19.6	0.2	13.2			[166] ^c
Ave.	1.3	4.9	16.0	23.7	29.3	21.4	0.2	14.3			
Li-ion			22.5		17.5			18.2			[164]
	0.6	1.8	7.6	17.3	16.7	9.7	0.1	7.2			[165]
	1.1	4.3	13.3	21.9	24.9	17.6	0.2	12.1			[166] ^c
	1.7	6.4	20.0	32.9	37.4	26.5	0.2	18.1			[166] ^c
Ave.	0.9	3.0	14.5	19.6	19.7	13.7	0.1	12.5			

^a Does not contain battery production.

^b Solely from Ni production, assumed battery is 25% Ni.

^c Used the average of their total energy amounts.

or incinerators [140]; in the United States, most alkaline batteries are transferred to landfills [192]; in the EU, a vast amount of batteries is disposed of instead of being recycled [70]. Recent rates of used battery recycling in China are lower than 2% as the collection system for batteries is weak [198].

As mentioned previously, batteries are produced from various materials such as metals, non-metals, plastics, paper (or paperboard), and electrolytes [69,199,200] (see Tables 4–6), and how to collect, treat, recycle and bury them is environmentally important. Used battery disposal is of general concern because of the hazardous nature of the metallic waste [201], which is costly to dispose safely. According to the US Environmental Protection Act in 1995 (40 CFR 273), batteries were categorized as universal and hazardous waste so that storage, recycling, treatment and disposal of them were regulated [202]. Various jurisdictions have developed regulations and product stewardship programs to control and minimize the environmental influences of batteries [193].

To meet more stringent environmental regulations, better recycling procedures and technologies have been established [203], and most battery materials can be recycled, albeit not cheaply, using chemical and mechanical techniques [204] for re-use in continued battery production and other purposes. Recycling of used batteries reduces

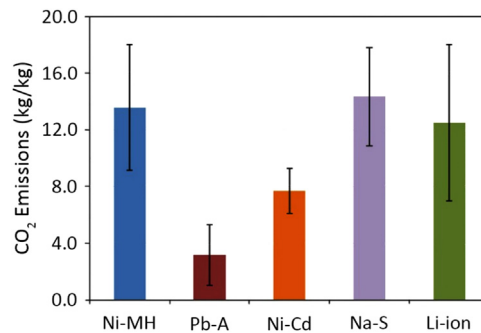


Fig. 13. Mean CTG CO₂ emissions with ± one standard deviation to produce a kg of different battery [87].

production costs and raw materials consumption, mitigating environmental impacts [74,78,197,203,205], although the costs for the complex recycling remains high. Fig. 17 shows, as an example, Zn and Mn recycling from alkaline and Zn-C batteries.

The major challenge for recycling is collection, which depends on the contribution and support of the public, government, business and other social organizations [206]. For batteries using cadmium (e.g., Ni-

Table 10
Emissions to air, water and solids caused by battery recycling (g/kg of battery, unless differently stated) [87].

	VOC	CO	NO _x	PM	SO _x	CH ₄	N ₂ O	CO ₂ (kg/kg)	Water (mg/kg)	Air	Reference
Ni-MH	0.107	0.386	1.390	2.047	2.786	1.619	0.016	1.234	0.24 kg slag and 30 g toxics – solid		[162]
Pb-A	0.425	1.762	1.966	0.520	0.522	0.768	0.025	0.604	< 0.1 Sb, Hg, Ni, Pb, etc.	5.0 – Pb, Cd, Cu, Zn, As	[162]
Ni-Cd	0.111	0.429	3.1	0.386	2.71	0.492	0.014	0.378	< 0.1 – Cd, Ni	1.0 – Cd, Ni	[162]

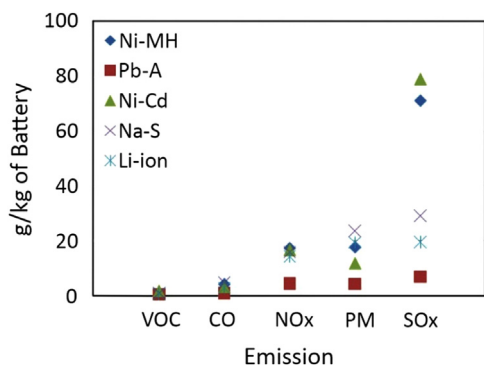


Fig. 14. Mean criteria contaminant emissions (g) per kg of battery for different batteries [87].

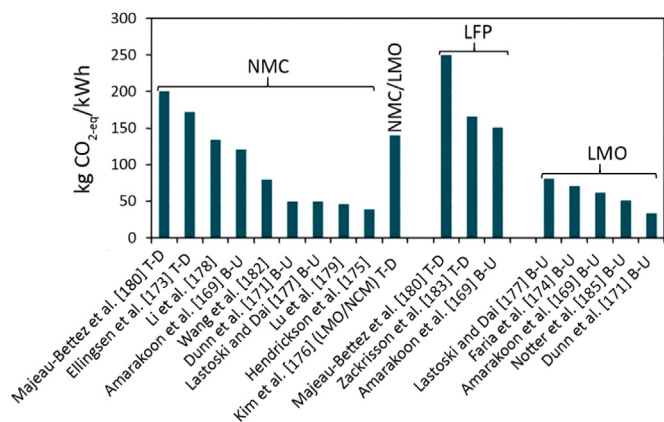


Fig. 15. Computed GHG emissions for various life cycle assessment (LCA) of Li-ion batteries for the chemistries NMC, NMC/LMO, LFP and LMO. In this figure, NMC refers to lithium manganese cobalt oxide, LFP refers to lithium iron phosphate, and LMO refers to lithium manganese oxide [184].

Table 11
Specific effect per kg of battery production [70].

	Climate impact (kg CO ₂ -eq)
Pb-A	0.9
Li-ion (NMP solvent)	12.5
Li-ion (water solvent)	4.4
Ni-Cd	2.1
Ni-MH	5.3
Na-S	1.2

Cd batteries), collecting and recycling is deemed vital because Cd can be highly toxic [131]. To diminish exposure and environmental risk, recycling must be carried out at appropriate facilities that are adequately equipped and regulated, and recycling in crowded urban regions is to be discouraged [207]. Trained staff, necessary engineering controls, preparation and use of protective equipment, and environmental and occupational monitoring are vital for recycling plants because of the health risks and broader pollution potential [155,208].

Lead (Pb) forms approximately 65% of the mass of lead-based batteries and the great majority is recycled [21,160], accounting for ~60% of total global lead production. Around 99% of lead-based batteries in the EU and the US are recycled, and 95–99% overall in the OEDC. Nevertheless, in countries with less advanced technologies and lax regulatory enforcement, lead recycling is a significant source of environmental pollution leading to human exposure [87,155,161,209,210] since recycling is typically performed without the essential procedures and technologies to control emissions. Furthermore, the level of regulatory enforcement and available industry

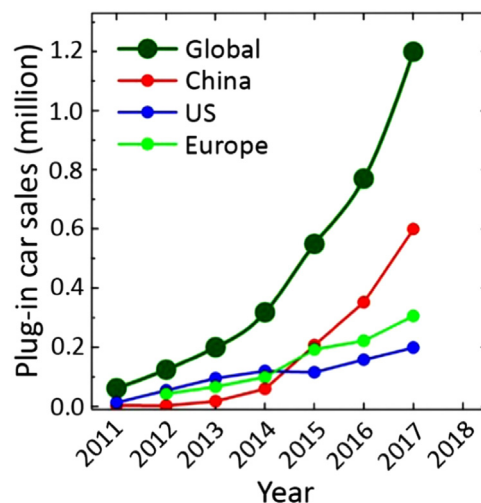


Fig. 16. Annual sales of plug-in vehicles around the world as well as in China, the US and Europe [195].

infrastructure to recycle lead in developing countries remains weak, and in the absence of enforced standards and employee protection (Fig. 18), even industrial-scale recycling can lead to substantial environmental pollutant and human exposure [208].

The recycling of Pb-A batteries is performed in several stages [155,211]: (a) collection and transportation of the batteries, (b) separation of their component parts through breaking them, (c) smelting and refining of the lead components, (d) washing and shredding or melting of the plastic components, (e) purification and treatment of the H₂SO₄ electrolyte, and (f) treatment and disposal of the remaining waste. Many researchers have reported the details of recycling and disposal of Pb-A batteries [21,87,155,211–217], and Fig. 19 shows the general recycling process. According to May et al. [21], around 650 kg of Pb will be recovered from every tonne of Pb-A scrap batteries. In addition, different metals such as antimony, arsenic, tin, copper, silver, barium and cadmium can be recovered from the recycling process [21,87,155].

At present, the recycling of Li-ion batteries is limited [96,184,218] (lower than 3% [219,220]), but with increasing demand for electric vehicles and restricted virgin materials access [218,219,221], recycling of these types of batteries has become a vital issue for the near future. Gaines [222] stated that no regulations currently exist to guide the recycling of Li-ion batteries at a large scale. Several researchers have described various processes for recycling different types of Li-ion batteries [21,96,97,219,221–225].

Three general methods exist to recycle Li-ion batteries [96,97]: mechanical, pyrometallurgical and hydrometallurgical processes. These methods are mostly intended to recover different materials (lithium, copper, cobalt, nickel, iron, aluminium and manganese). Some processes are currently under development to better recycle these types of batteries [97,223], such as the Beijing Institute of Technology (BIT) recycling process (Fig. 20) [226]. The level of toxicity of substances used in Li-ion batteries is less than other types of batteries [227], so in some countries, they are disposed in landfills [96].

4. Summary and conclusion

Battery energy storage is reviewed from a variety of aspects such as specifications, advantages, limitations, and environmental concerns; however, the principal focus of this review is the environmental impacts of batteries on people and the planet. Batteries are the most common and efficient storage method for all small-scale power needs, and vast numbers of batteries of different types and sizes are manufactured annually; this will grow as population and demand for portable

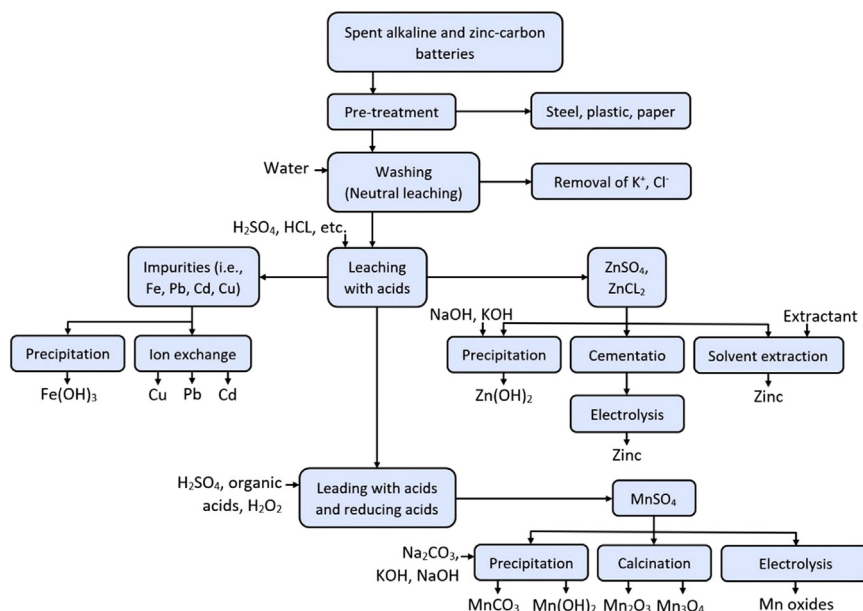


Fig. 17. Recycling of Zn and Mn from used alkaline and Zn-C batteries [201].

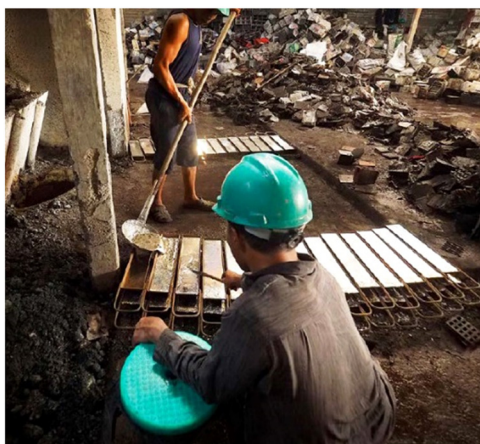


Fig. 18. Non-regulated recycling process for spent Pb-A batteries [155].

electronic devices increase (e.g., laptops and cellphones), as the vehicle fleet becomes electrified, and as other uses such as remote sensor arrays and grid-scale energy storage are envisioned and implemented. Concern for environmental impacts and personal (and population) health is increasing worldwide, and more attention and risk quantification are needed, especially on health impacts and the cost of externalities (e.g., the impact of secondary pollution associated with recycling or landfill placement).

A wide variety of raw materials, including metals and non-metals, is needed for the large numbers of batteries manufactured: global consumption for making batteries accounts for large fractions of produced lead (85%), cadmium (75%), cobalt (50%), lithium (46%), antimony (27%), lanthanum (10%), and graphite (10%). With sharply increasing battery production for E-vehicles, microgrid energy storage, and larger-scale grid applications, resource depletion pressures and price rises seem certain, particularly for those metals that are precious (Ag), expensive (In), and rare (e.g., La and Ce).

Batteries generate environmental pollutants, including hazardous waste, GHG emissions, and toxic fumes, in different ways during manufacturing, use, transportation, collection, storage, treatment, disposal and recycling. The share of batteries' manufacturing processes in causing environmental contaminants (especially CO₂ emissions) is

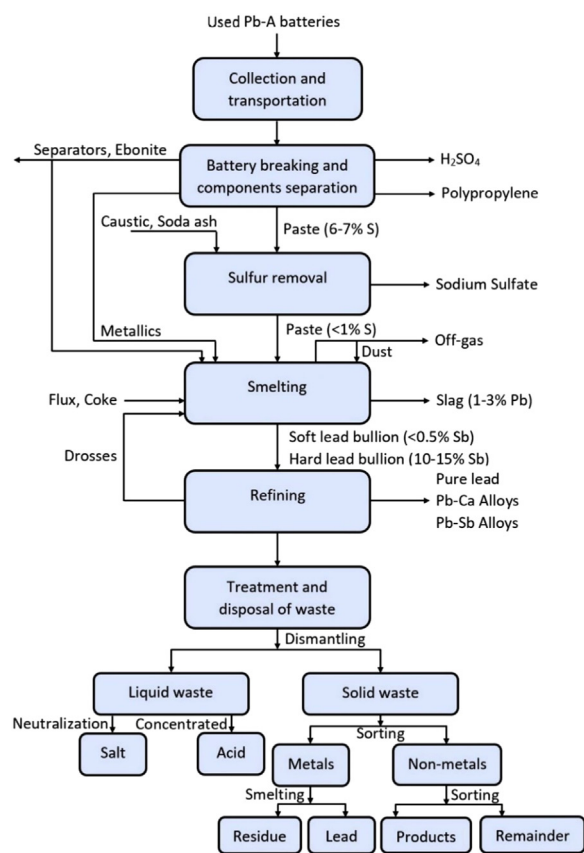


Fig. 19. Schematic diagram of the general recycling process of used Pb-A batteries (adapted from [212,213]).

significant because of the high energy consumption, compared to other energy storage processes. The heavy metals used in making batteries (e.g., Pb, Cd, Hg, As, Cr) are harmful to human health if exposure exceeds certain limits, and exposure affects developing children more than adults.

Collection, recycling and disposal of small batteries is a challenge: most batteries are currently sent to landfills at the end of useful life

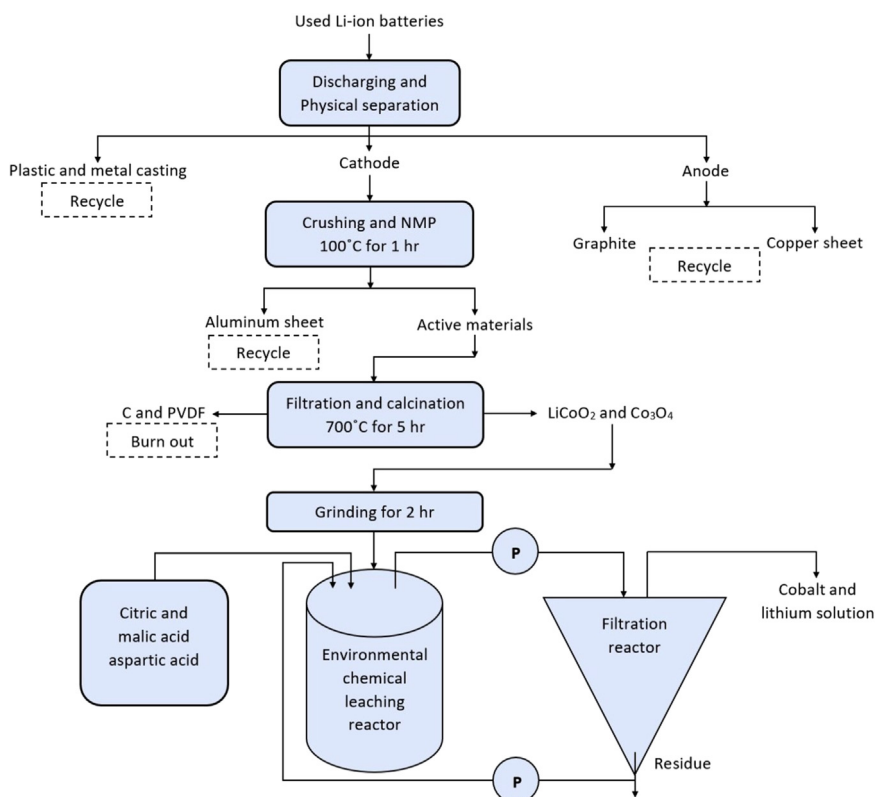


Fig. 20. Schematic diagram of BIT recycling process [97,227].

instead of collection and recycling. Recycling waste batteries and recovery of metals is costly, but will be increasingly necessary as use rises. Lead-acid vehicle batteries are almost entirely recycled in developed countries, but lax controls and enforcement and inadequate facilities in many places cause major environmental and health problems. Solutions to these problems are obvious, but difficult to implement and costly in less developed economies.

It is reasonable to suppose that large battery use will increase rapidly in the next generation, and grid-scale battery energy storage (> 50 MW) is being considered, using purpose-built and distributed sources (plugged-in vehicles). It is strongly recommend that energy storage systems be far more rigorously analyzed in terms of their full life-cycle impact. For example, the health and environmental impacts of compressed air and pumped hydro energy storage at the grid-scale are almost trivial compared to batteries, thus these solutions are to be encouraged whenever appropriate. A combination of different types of ESSs will be the most effective and appropriate approach to increase efficiency and sustainability while decreasing energy losses, costs, environmental impacts and health concerns.

Acknowledgements

The authors gratefully acknowledge permission to include the following copyright materials, for the use of some tables and figures, from: “Hydrometallurgy” journal (Elsevier), “Applied Energy” journal (Elsevier), “Nature” journal (Springer Nature), and “Renewable and Sustainable Energy Reviews” journal (Elsevier).

References

- [1] Dehghani-Sanij AR, Dehghani SR, Naterer GF, Muzychka YS. Marine icing phenomena on vessels and offshore structures: prediction and analysis. *Ocean Eng* 2017;143:1–23.
- [2] Dehghani-Sanij AR, Soltani M, Raahemifar K. A new design of wind tower for passive ventilation in buildings to reduce energy consumption in windy regions. *Renew Sustain Energy Rev* 2015;42:182–95.
- [3] Dudley B, Dale S. *BP energy outlook - 2018 edition*. 2018. p. 124.
- [4] Bahadori MN, Dehghani-Sanij AR. Wind towers: architecture, climate and sustainability. In: Sayigh A. editor. Springer International Publishing; 2014.
- [5] Soltani M, Dehghani-Sanij AR, Sayadnia A, Kashkooli FM, Gharali K, Mahbaz SB, Dusseault MB. Investigation of airflow patterns in a new design of wind tower with a wetted surface. *Energies* 2018;11(5):1–23.
- [6] Girouard N, Konialis E, Tam C, Taylor P. *OECD Green Growth Studies: Energy. Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA) publications.* <<https://www.oecd.org/greengrowth/greening-energy/49157219.pdf>>. [accessed 1 January 2019]; 2011.
- [7] Mardiana A, Riffat SB. Building energy consumption and carbon dioxide emissions: threat to climate change. *J Earth Sci Clim Change* 2015;S3:001.
- [8] Mohamed MR, Leung PK, Sulaiman MH. Performance characterization of a vanadium redox flow battery at different operating parameters under a standardized test-bed system. *Appl Energy* 2015;137:402–12.
- [9] Guney MS, Tepe Y. Classification and assessment of energy storage systems. *Renew Sustain Energy Rev* 2017;75:1187–97.
- [10] Htut AY, Shrestha S, Nitivattananon V, Kawasaki A. Forecasting climate change scenarios in the Bago River Basin, Myanmar. *J Earth Sci Clim Change* 2014;5(9):228. <https://doi.org/10.4172/2157-7617.1000228>.
- [11] Khajuria A, Ravindranath NH. Climate change vulnerability assessment: approaches DPSIR framework and vulnerability index. *J Earth Sci Clim Change* 2012;3(1):109. <https://doi.org/10.4172/2157-7617.1000109>.
- [12] Pérez-Lombard L, Ortiz J, Pout ChA. review on buildings energy consumption information. *Energy Build* 2008;40:394–8.
- [13] Sepehri A, Sarrafzadeh MH. Effect of nitrifiers community on fouling mitigation and nitrification efficiency in a membrane bioreactor. *Chem Eng Process-Process Intensif* 2018;128:10–8.
- [14] Boden T, Andres B. Global CO₂ emissions from fossil-fuel burning, cement manufacture, and gas flaring: 1751–2013 Oak Ridge. Tennessee Carbon Dioxide Information Analysis Centre. Oak Ridge, TN: Oak Ridge National Laboratory; 2016.
- [15] Heard BP, Brook BW, Wigley TML, Bradshaw CJA. Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems. *Renew Sustain Energy Rev* 2017;76:1122–33.
- [16] Dehghani-Sanij AR. *Cisterns: sustainable development, architecture and energy.* In: Sayigh A. editor. River Publishers, Denmark; 2016.
- [17] Dincer I, Rosen MA. *Thermal energy storage: Systems and applications*. 2nd ed. UK: John Wiley & Sons Ltd; 2011.
- [18] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl Energy* 2015;137:511–36.
- [19] Andrijanovits A, Hoimoja H, Vinnikov D. Comparative review of long-term energy storage technologies for renewable energy systems. *Electron Electr Eng*

- 2012;2(118):21–6.
- [20] Bhatnagar D, Loose V. Evaluating utility procured electric energy storage resources: a perspective for state electric utility regulators. A study for the DOE energy storage systems program. New Mexico, CA, USA: Sandia National Laboratories, SAND2012-9422; 2012.
- [21] May GJ, Davidson A, Monahov B. Lead batteries for utility energy storage: a review. *J Energy Storage* 2018;15:145–57.
- [22] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: a critical review. *Prog Nat Sci* 2009;19:291–312.
- [23] Kondoh J, Ishii I, Yamaguchi H, Murata A, Otani K, Sakuta K, et al. Electrical energy storage systems for energy networks. *Energy Convers Manag* 2000;41:1863–74.
- [24] International Renewable Energy Agency (IRENA). Electricity storage: technology brief. IEA-ETSAP and IRENA© Technology Policy Brief E18; 2012. <<http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E18%20Electricity-Storage.pdf>>. [accessed 1 January 2019].
- [25] Beaudin M, Zareipour H, Schellenberglobe A, Rosehart W. Energy storage for mitigating the variability of renewable electricity sources: an updated review. *Energy Syst Dev* 2010;14:302–14.
- [26] Hawaiian Electric Company (HEC). Clean energy – issues and challenges – energy storage. 2019 <<http://www.heco.com/heco/Clean-Energy/Issues-and-Challenges/Energy-Storage>>. [accessed 1 January 2019].
- [27] Andrepont SJ. Energy storage – thermal energy storage coupled with turbine inlet cooling. In: 14th annual electric power conf. & exhibition; 2012. <http://www.turbineinletcooling.org/resources/papers/Andrepont_2012EP.pdf>. [accessed 1 January 2019].
- [28] International Electrotechnical Commission (IEC). Electrical energy storage: White paper. Electrical energy storage project team; 2011. (Technical report).
- [29] Farret FA, Simões MG. Integration of alternative sources of energy. 1st ed. John Wiley & Sons Inc; 2006.
- [30] Finkenrath M, Pazzi S, D'Ercole M. Status and technical challenges of advanced compressed Air Energy Storage (CAES) technology. Munich, Germany: International Workshop on Environment and Alternative Energy; 2009.
- [31] RWE Power. ADELE – Adiabatic compressed-air energy storage (CAES) for electricity supply. 2019 <<http://www.rwe.com/web/cms/mediablob/en/391748/data/235554/1/rwe-power-ag/press/company/Brochure-ADELE.pdf>>. [accessed 1 January 2019].
- [32] Flowgroup. Compressed air batteries. 2019 <<http://www.flowbattery.co.uk>>. [accessed 1 January 2019].
- [33] Shoenung SM. Characteristics and technologies for long- vs. short-term energy storage: a study by the DOE energy storage systems program. USA: Sandia National Laboratories, United States Department of Energy; 2001. [Technical report, SAND2001-0765].
- [34] Electricity Storage Association (ESA). Electricity storage technology comparison. 2013 <http://www.electricity.storage.org/technology/storage_technologies/technology_comparison>. [accessed 22 November 2013].
- [35] Smith W. The role of fuel cells in energy storage. *J Power Sources* 2000;86:74–83.
- [36] Emerson Network Power (ENP). Capacitors age and capacitors have an end of life. A white paper from the experts in business-critical continuity. 2019 <<http://www.emersonnetworkpower.com/documentation/en-us/brands/liebert/documents/white%20papers/sl-24630.pdf>>. [accessed 1 January 2019].
- [37] Miller RJ. Capacitors for power grid storage - multi-hour bulk energy storage using capacitors. JME, Inc. and Case Western Reserve University, In: Trans-Atlantic Workshop on Storage Technologies for Power Grids, Washington, DC; 2010.
- [38] Winter M, Brodd RJ. What are batteries, fuel cells, and supercapacitors? *Chem Rev* 2004;104:4245–70.
- [39] Baxter R. Energy storage: a nontechnical guide. 1st ed Pennwell; 2006.
- [40] Barton JP, Infield DG. Energy storage and its use with intermittent renewable energy. *IEEE Trans Energy Convers* 2004;19:441–8.
- [41] Schaber C, Mazza P, Hammerschlag R. Utility-scale storage of renewable energy. *Electr J* 2004;17:21–9.
- [42] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. *Renew Sust Energy Rev* 2009;13:1513–22.
- [43] Díaz-González F, Sumper A, Gomis-Bellmunt O, Villafafila-Robles R. A review of energy storage technologies for wind power applications. *Renew Sust Energy Rev* 2012;16:2154–71.
- [44] Kaldellis JK, Zafirakis D. Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency. *Energy* 2007;32:2295–305.
- [45] Rydh CJ, Sanden BA. Energy analysis of batteries in photovoltaic systems — part I: performance and energy requirements. *Energy Convers Manag* 2005;46:1957–79.
- [46] Department of Trade and Industry (DTI). Review of electrical energy storage technologies and systems and of their potential for the UK. UK Department of Trade and Industry; 2004. [DTI Report, DG/DTI/00055/00/00].
- [47] Rastler D. Electricity energy storage technology options: a white paper primer on applications, costs, and options. Electric Power Research Institute (EPRI) Inc; 2010. [Technical report, 1020676].
- [48] Moghaddam MP, Haghifam MR, Yousefi GR. Electric energy storage systems in a market-based economy: comparison of emerging and traditional technologies. *Renew Energy* 2009;34:2630–9.
- [49] Schoenung S. Energy storage systems cost update: a study for the DOE energy storage systems program. Sandia National Laboratories; 2011. [Technical report].
- [50] McDowell J. Integrating energy storage with wind power in weak electricity grids. *J Power Sources* 2006;162:59–64.
- [51] Ponce de León C, Frías-Ferrer A, González-García J, Szánto DA, Walsh FC. Redox flow cells for energy conversion. *J Power Sources* 2006;160:716–32.
- [52] Amodeo SJ, Chiacchiarini HG, Solsóna JA, Busada CA. High-performance sensorless nonlinear power control of a flywheel energy storage system. *Energy Convers Manag* 2009;50:1722–9.
- [53] Weber AZ, Mench MM, Meyers JP, Ross PN, Gostick JT, Liu Q. Redox flow batteries: a review. *J Appl Electrochem* 2011;41(10):1137–64.
- [54] Paul B. The future of electrical energy storage: the economics and potential of new technologies. Report, Business Insights (Energy). Table of Contents and brochure; 2009.
- [55] Taylor P, Bolton R, Stone D, Zhang X-P, Martin C, Upham P. Pathways for energy storage in the UK. The Centre for Low Carbon Futures; 2012. p. 56.
- [56] Dan R. Overview of energy storage options for the electric enterprise. Electric Power Research Institute (EPRI); 2019.
- [57] Mekhilef S, Saidur R, Safari A. Comparative study of different fuel cell technologies. *Renew Sust Energy Rev* 2012;16:981–9.
- [58] Barin A, NevesCanha L, Magnago K, da Rosa Abaide A. Fuzzy multi-sets and multirules: analysis of hybrid systems concerning renewable sources with conventional and flow batteries. In: 2009 15th Int. Conf. Intell. Syst. Appl. to Power Syst., IEEE, 2009, p. 1–6.
- [59] Divya KC, Østergaard J. Battery energy storage technology for power systems—an overview. *Electr Power Syst Res* 2009;79:511–20.
- [60] Baker J. New technology and possible advances in energy storage. *Energy Policy* 2008;36:4368–73.
- [61] Cole S, Hertem DV, Dirk Van Hertem, Meeus L, Belmans R. SWOT analysis of utility-side energy storage technologies. Proc. of the 5th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines, Tenerife, Spain, December 2005 16-18; 2005; p. 446–451.
- [62] European Commission (EC). D4.1 SWOT Analysis. Executive Agency for Competitiveness and Innovation (EACI), EIE/07/159/SI2. <https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/stories_swot_analysis.pdf>. [accessed 1 January 2019]; 2010.
- [63] Hehner R, Beno J, Walls A. Flywheel batteries come around again. *IEEE Spectr* 2002;39(4):46–51.
- [64] Liu Ch-Ch, McArthur S, Lee S-J, editors. Smart Grid Handbook, 1. John Wiley & Sons; 2016.
- [65] Sabihuddin S, Kiprakis AE, Mueller M. A Numerical and graphical review of energy storage technologies. *Energies* 2015;8:172–216.
- [66] Reddy TB. Linden's handbook of batteries. 4th ed USA: McGraw Hill Professional; 2010.
- [67] Ela E, Wang C, Moorty S, Ragsdale K, O'Sullivan J, Rothleder M, Hobbs B. Electricity markets and renewables: a survey of potential design changes and their consequences. *IEEE Power Energy Mag* 2017;15(6):70–82.
- [68] Amiryar ME, Pullen KR. A review of flywheel energy storage system technologies and their applications. *Appl Sci* 2017;7(286):1–21.
- [69] Kiehne HA, editor. Battery Technology Handbook. 2nd ed CRC Press; 2003.
- [70] McManus MC. Environmental consequences of the use of batteries in low carbon systems: the impact of battery production. *Appl Energy* 2012;93:288–95.
- [71] Rahman MdA, Wang X, Wen C. High energy density metal-air batteries: a review. *J Electro- Chem Soc* 2013;160(10):A1759–71.
- [72] Zhang Ch, Wei Y-L, Cao P-F, Lin M-Ch. Energy storage system: current studies on batteries and power condition system. *Renew Sustain Energy Rev* 2018;82:3091–106.
- [73] Linden D, Reddy TB. Handbook of batteries. 3rd ed. New York: McGraw-Hill; 2002.
- [74] Bernardes AM, Espinosa DCR, Tenorio JAS. Recycling of batteries: a review of current processes and technologies. *J Power Sources* 2004;130:291–8.
- [75] Abdul-Zehra H. Zinc carbon batteries. University of Babylon; 1999 [Lecture No.17] <http://www.uobabylon.edu.iq/eprints/paper_4_22941_736.pdf>. [accessed 1 January 2019].
- [76] Avraamides J, Senanayake G, Clegg R. Sulfur dioxide leaching of spent zinc-carbon-battery scrap. *J Power Sources* 2006;159(2):1488–93.
- [77] Panero S, Romoli C, Achilli M, Cardarelli E, Scrosati B. Impact of household batteries in landfills. *J Power Sources* 1995;57(1–2):9–12.
- [78] De Souza CCBM, De Oliveira C, Tenorio JAS. Characterisation of used alkaline batteries powder and analysis of zinc recovery by acid leaching. *J Power Sources* 2001;103:120–6.
- [79] Masanet E, Horvath A. Single-use alkaline battery case study, the potential impacts of extended producer responsibility (EPR) in California on Global Greenhouse Gas (GHG) emissions. Berkeley, CA, USA: California Department of Resources Recycling and Recovery, University of California; 2012. [CalRecycle report].
- [80] Vindt T, Takáčová F, Kukurugya F, Havlik T. Recycling of used portable Zn batteries optimization of mechanical pretreatment of Zn-C and alkaline batteries and characterization of obtained active mass. *Metall* 2015;69(4):127–33.
- [81] Vincent CA. Lithium batteries: a 50-year perspective, 1959–2009. *Solid State Ion* 2000;134(1–2):159–67.
- [82] Lisbona D, Snee T. A review of hazards associated with primary lithium and lithium-ion batteries. *Process Saf Environ Prot* 2011;89(6):434–42.
- [83] Hoppmann J, Volland J, Schmidt TS, Hoffmann VH. The economic viability of battery storage for residential solar photovoltaic systems - A review and a simulation model. *Renew Sustain Energy Rev* 2014;39:1101–18.
- [84] Liu C, Li F, Ma L-P, Cheng H-M. Advanced materials for energy storage. *Adv Mater* 2010;22(8):E28–62.
- [85] Davidson AJ, Binks SP, Gediga J. Lead industry life cycle studies: environmental impact and life cycle assessment of lead battery and architectural sheet production. *Int J Life Cycle Assess* 2016;21(11):1624–36.
- [86] <<https://www.epa.gov>>. [accessed 1 January 2019].

- [87] Sullivan JL, Gaines LL. A review of battery life cycle analysis: state of knowledge and critical needs. Oak Ridge, TN, USA: U.S. Department of Energy; 2010. [Argonne National Laboratory, ANL/ESD/10-7, ANL/ESD/10-7].
- [88] Jülich V, Telsnig T, Schulz M, Hartmann N, Thomsen J, Eltrop L, Schlegel T. A holistic comparative analysis of different storage systems using leveled cost of storage and life cycle indicators. *Energy Proc* 2015;73:18–28.
- [89] Unterreiner L, Jülich V, Reith S. Recycling of battery technologies – ecological impact analysis using life cycle assessment (LCA). *Energy Proc* 2016;99:229–34.
- [90] Manuel WG. *Turlock Irrigation District: Energy Storage Study 2014*. Commission Report, Turlock, CA, USA; 2014.
- [91] Scrosati B, Garche J. Lithium batteries: status, prospects and future. *J Power Sources* 2010;195(9):2419–30.
- [92] Goodenough JB, Kim Y. Challenges for rechargeable Li batteries. *Chem Mater* 2010;22(3):587–603.
- [93] Mauger A, Julien CM, Paoletta A, Armand M, Zaghbi K. A comprehensive review of lithium salts and beyond for rechargeable batteries: progress and perspectives. *Mater Sci Eng R* 2018;134:1–21.
- [94] Commarieu B, Paoletta A, Daigle JC, Zaghbi K. Toward high lithium conduction in solid polymer and polymer–ceramic batteries. *Curr Opin Electrochem* 2018;9:56–63.
- [95] Gao Z, Sun H, Fu L, Ye F, Zhang Y, Luo W, Huang Y. Promises, challenges, and recent progress of inorganic solid-state electrolytes for all-solid-state lithium batteries. *Adv Mater* 2018;30(17):1–27.
- [96] Boyden A, Soo VK, Doolan M. The environmental impacts of recycling portable lithium-ion batteries. *Proc CIRP* 2016;48:188–93.
- [97] Gaines LL, Jennifer Dunn JB. Lithium-Ion battery environmental impacts. In: Pistoia G, editor. *Lithium-ion batteries: advances and applications*. 1st ed. Elsevier; 2014. p. 483–508.
- [98] Dunn JB, Gaines LL, Barnes M, Sullivan JL, Wang M. Material and energy flows in the materials production, assembly, and end-of-life stages of the automotive lithium-ion battery life cycle. Argonne, IL, USA: Argonne National Lab. (ANL); 2014. [Technical report, ANL/ESD/12-3 Rev.109509].
- [99] Seh ZW, Sun Y, Zhang Q, Cui Y. Designing high-energy lithium-sulfur batteries. *Chem Soc Rev* 2016;45:5605–34.
- [100] Ji X, Lee KT, Nazar LF. A highly ordered nanostructured carbon-sulphur cathode for lithium-sulphur batteries. *Nat Mater* 2009;8:500–6.
- [101] Fang R, Zhao S, Sun Z, Wang D-W, Cheng H-M, Li F. More reliable lithium-sulfur batteries: status, solutions and prospects. *Adv Mater* 2017;29(48):1–25.
- [102] Dhar SK, Ovshinsky SR, Gifford PR, Corrigan DA, Fetcenko MA, Venkatesan S. Nickel/metal hydride technology for consumer and electric vehicle batteries- a review and up-date. *J Power Sources* 1997;65(1–2):1–7.
- [103] Sakai T, Yuasa A, Ishikawa H, Miyamura H, Kuriyama N. Nickel-metal hydride battery using microencapsulated alloys. *J Less-Common Met* 1991;172–174:1194–204.
- [104] Hazotte C, Leclerc N, Meux E, Lapique F. Direct recovery of cadmium and nickel from Ni-Cd spent batteries by electroassisted leaching and electrodeposition in a single-cell process. *Hydrometallurgy* 2016;162:94–103.
- [105] Liu Y, Yang Z, Yan J. Zinc Hydroxystannate as High Cycle Performance Negative Electrode Material for Zn/Ni Secondary Battery 2016;163(14):3146–3151.
- [106] Nguyen T, Savinell RF. Flow batteries. *Electrochem Soc Interface* 2010;19(3):54–6.
- [107] Alotto P, Guarnieri M, Moro F. Redox flow batteries for the storage of renewable energy: a review. *Renew Sustain Energy Rev* 2014;29:325–35.
- [108] Wen Z, Cao J, Gu Z, Xu X, Zhang F, Lin Z. Research on sodium sulfur battery for energy storage. *Solid State Ion* 2008;179(27–32):1697–701.
- [109] Kumar D, Rajouria SK, Kuhar SB, Kanchan DK. Progress and prospects of sodium-sulfur batteries: a review. *Solid State Ion* 2017;312:8–16.
- [110] González A, Goikolea E, Barrera JA, Mysyk R. Review on supercapacitors: technologies and materials. *Renew Sustain Energy Rev* 2016;58:1189–206.
- [111] Conway BE, Birss V, Wojtowicz J. The role and utilization of pseudocapacitance for energy storage by supercapacitors. *J Power Sources* 1997;66(1–2):1–14.
- [112] Conway BE. Transition from “Supercapacitor” to “Battery” behavior in electrochemical energy storage. *J Electrochem Soc* 1991;138(6):1539–48.
- [113] Chen S-M, Ramachandran R, Mani V, Saraswathi R. Recent advancements in electrode materials for the high-performance electrochemical supercapacitors: a review. *Int J Electrochem Sci* 2014;9:4072–85.
- [114] European Commission (EC). Report on raw materials for battery applications. 2018. [Commission Staff Working Document, SWD (2018) 245 final, Brussels, Belgium].
- [115] Mohr S, Giurco D, Retamal M, Mason L, Mudd G. Global projection of lead-zinc supply from known resources. *Resources* 2018;7(1):17.
- [116] International Lead Association (ILA). *Lead use-statistics*; 2019. <<http://www.ila-lead.org/lead-facts/lead-uses-statistics>>. [accessed 1 January 2019].
- [117] United States Geological Survey (USGS). *Minerals yearbook*. USA: Reston, VA; 2014.
- [118] Sun X, Hao H, Zhao F, Liu Z. Tracing global lithium flow: a trade-linked material flow analysis. *Resour Conserv Recycl* 2017;124:50–61.
- [119] United States Geological Survey (USGS). *Mineral commodity summaries 2018*. USA: Reston, VA; 2018.
- [120] DBS Group Research. *China Basic Material Sector: Industry Focus*. China; 2018.
- [121] Deloitte Sustainability (DS). Study on data for a raw material system analysis: roadmap and test of the fully operational MSA for raw materials. European Commission, DG GROW; 2015.
- [122] Labie R, Willems G, Nelen D, Acker KV. Recuperation of critical metals in Flanders: scan of possible short term opportunities to increase recycling. Leuven, Belgium: Policy Research Centre Sustainable Materials Management; 2015. [Research paper 15].
- [123] British Geological Survey (BGS). *World Mineral Production*, Minerals UK. Nottingham, UK; 2000–2017.
- [124] Mudd G, Jowitt SM, Werner TT. The world’s lead-zinc mineral resources: scarcity, data, issues and opportunities. *Ore Geol Rev* 2017;80:1160–90.
- [125] Garrett DE. *Handbook of lithium and natural calcium chloride: their deposits, processing, uses and properties*. 1st ed Amsterdam, The Netherlands: Elsevier; 2004.
- [126] Mohr S, Mudd G, Giurco D. Lithium resources and production: critical assessment and global projections. *Minerals* 2012;2:65–84.
- [127] *Lithium World Production*. <https://en.wikipedia.org/wiki/Lithium_as_an_investment#/media/File:Lithium_world_production.svg>. [accessed 12 December 2018]; 2018.
- [128] Metal Bulletin Research (MBR). *Battery metals: nickel use in batteries*. 2012. p. 71–4.
- [129] UN Environment. *Global mercury: supply, trade and demand*. Geneva, Switzerland: United Nations Environment Programme, Chemicals and Health Branch; 2017.
- [130] Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Beeregowda KN. Toxicity, mechanism and health effects of some heavy metals. *Interdiscip Toxicol* 2014;7(2):60–72.
- [131] Swedish Environmental Protection Agency (SEPA). *Cadmium in power tool batteries, The possibility and consequences of a ban*. Sweden: CM Gruppen AB; 2009. [Report 5901].
- [132] Indium Corporation (IC). *The Indium Market, 2017 CRM assessment*; 2017.
- [133] MetalMiner. Tin prospects looking positive, sourcing & trading intelligence for global metals markets. 2019 <<https://agmetminer.com/2018/03/20/tin-prospects-looking-positive>>. [accessed 1 January 2019].
- [134] Chegwidan J. Study of the antimony market. London, UK: Roskill Consulting Group Ltd.; 2011.
- [135] Dupont D, Arnout S, Jones PT, Binnemans K. Antimony recovery from end-of-life products and industrial process residues: a critical review. *J Sustain Metall* 2016;2:79–103.
- [136] International Nickel Study Group (INSG). *World Nickel Statistics: Production, Usage and Prices, Monthly Bulletin*; 2018. <<http://www.insg.org/prodnickel.aspx>>. [accessed 12 December 2018].
- [137] Al-Thyabat S, Nakamura T, Shibata E, Iizuka A. Adaptation of minerals processing operations for lithium-ion (LiBs) and nickel metal hydride (NiMH) batteries recycling: critical review. *Miner Eng* 2013;45:4–17.
- [138] Ruffino B, Zanetti M, Marini P. A mechanical pretreatment process for the valorization of useful fractions from spent batteries. *Resour Conserv Recycl* 2011;55(3):309–15.
- [139] Rydh CJ, Svård B. Impact on global metal flows arising from the use of portable rechargeable batteries. *Sci Total Environ* 2003;302(1–3):167–84.
- [140] Song X, Hu Sh, Chen D, Zhu B. Estimation of waste battery generation and analysis of the waste battery recycling system in China. *J Ind Ecol* 2016;21(1):57–67.
- [141] InfoMine Inc.. Historical lead prices and price chart. 2019 <<http://www.infomine.com/investment/metal-prices/lead/all>>. [accessed 1 January 2019].
- [142] InfoMine Inc.. Historical cobalt prices and price chart. 2019 <<http://www.infomine.com/investment/metal-prices/cobalt/all>>. [accessed 1 January 2019].
- [143] Agency for Toxic Substances and Disease Registry (ATSDR). *Case studies in environmental medicine—lead toxicity*. Atlanta, GA, USA: U.S. Department of Health and Human Services, Public Health Service; 1992.
- [144] Cherrie JW, Semple S, Christopher Y, Saleem A, Hughson GW, Philips A. How important is inadvertent ingestion of hazardous substances at work? *Ann Occup Hyg* 2006;50(7):693–704.
- [145] Wani AL, Ara A, Usmani JA. Lead toxicity: a review. *Interdiscip Toxicol* 2015;8(2):55–64.
- [146] Bernard A. Cadmium & its adverse effects on human health. *Indian J Med Res* 2008;128:557–64.
- [147] Tchounwou PB, Yedjou CG, Patolla AK, Sutton DJ. Heavy metals toxicity and the environment. *EXS* 2012;101:133–64.
- [148] Bernhoft RA. Mercury toxicity and treatment: a review of the literature. *J Environ Public Health* 2012. [Article ID 460508].
- [149] Berlin M, Zalups RK, Fowler BA. Mercury, in *Handbook on the Toxicology of Metals*. Nordberg GF, Fowler BA, Nordberg M, Friberg LT. Eds. Chapter 33, Elsevier, New York, NY, USA, 3rd ed.; 2007.
- [150] Mousavi SR, Balali-Mood M, Riahi-Zanjani B, Yousefzadeh H, Sadeghi M. Concentrations of mercury, lead, chromium, cadmium, arsenic and aluminum in irrigation water wells and wastewaters used for agriculture in Mashhad, Northeastern Iran. *Int J Occup Environ Med* 2013;4(2):80–6.
- [151] Gallegos MV, Falco LR, Peluso MA, Sambeth JE, Thomas HJ. Recovery of manganese oxides from spent alkaline and zinc-carbon batteries—An application as catalysts for VOCs elimination. *Waste Manag* 2013;33(6):1483–90.
- [152] Guevara-García JA, Montiel-Corona V. Used battery collection in central Mexico: metal content, legislative management situation and statistical analysis. *J Environ Manag* 2012;95(Supplement):S154–7.
- [153] Institute for Health Metrics and Evaluation (IHME). *Global lead exposure*. Seattle, WA, USA: University of Washington; 2016. [GBD Compare [website]].
- [154] Li Y, Xi G. The dissolution mechanism of cathodic active materials of spent Zn–Mn batteries in HCl. *J Hazard Mater* 2005;B127:244–8.
- [155] Schaddelee-Scholten B, Tempowski J. Recycling used lead-acid batteries: health considerations. Geneva, Switzerland: Department of Public Health, Environmental and Social Determinants of Health at the World Health Organization (WHO); 2017.
- [156] United Nations Environment Programme (UNEP). *Guidelines for environmentally*

- sound management of used lead batteries in the Mediterranean. Athens, Greece: The Strategic Partnership for the Mediterranean Sea Large Marine Ecosystem (MedPartnership); 2015.
- [157] Armand M, Tarascon JM. Building better batteries. *Nature* 2008;451(7):652–7.
- [158] Posada J, Rennie A, Villar S, Martins V, Marinaccio J, Barnes A, Glover C, Worsley D, Hall P. Aqueous batteries as grid scale energy storage solutions. *Renew Sustain Energy Rev* 2017;68:1174–82.
- [159] Poullikkas A. A comparative overview of large-scale battery systems for electricity storage. *Renew Sustain Energy Rev* 2013;27:778–88.
- [160] Valpak Consulting (VC). Battery Recycling Market Research Study. In response to RENEW's tender invitation dated 04 March 2009, UK; 2010.
- [161] van der Kuip TJ, Huang L, Cherry CR. Health hazards of China's lead-acid battery industry: a review of its market drivers, production processes, and health impacts. *Environ Health* 2013;12(61):1–10.
- [162] Rantik M. Life cycle assessment of five batteries for electric vehicles under different charging regimes. Goteborg, Sweden: Chalmers University of Technology; 1999. [KFB-Meddelande 1999:28].
- [163] Gaines LL, Elcock D, Singh M Nickel-Metal Hydride Batteries: Energy Use and Emissions from Production and Recycling. SAE 2002; Paper 02FCC-49.
- [164] Ishihara K, Nishimura K, Uchiyama Y. Life Cycle Analysis of Electric Vehicles with Advanced Battery in Japan. Proceedings of the Electric Vehicle Symposium, 16, 1999, pp. 7–10, Beijing, China.
- [165] GREET 2.7. Argonne National Laboratory. 2007. <http://www.transportation.anl.gov/modeling_simulation/GREET/index.htm>. [accessed 1 January 2019].
- [166] Rydh CJ, Sanden BA. energy analysis of batteries in photovoltaic systems – part II: energy return factors and overall battery efficiencies. *Energy, Convers Manag* 2005;46:1980–2000.
- [167] Kertes A. Life cycle assessment of three available battery technologies for electric vehicles in a swedish perspective [M.S. thesis]. Stockholm, Sweden: Royal Institute of Technology; 1996.
- [168] Sullivan D, Morse T, Patel P, Patel S, Bondar J, Taylor L. Life cycle energy analysis of electric vehicle storage batteries. Columbia, Maryland, USA: Hitman Associates Inc.; 1980. [H-1008/001-80-964, U.S. Department of Energy, Contract No. AC02-79ET25420].
- [169] Amarakoon S, Smith J, Segal B. Application of life-cycle assessment to nanoscale technology: lithium-ion batteries for electric vehicles. USA: U.S. Environmental Protection Agency; 2013. [EPA 744-R-12-001].
- [170] Ambrose H, Kendall A. Effects of battery chemistry and performance on the life cycle. *Transp Res Part D: Transp Environ* 2016;47:182–94.
- [171] Dunn JB, Gaines LL, Sullivan JL, Wang MQ. Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries. *Environ Sci Technol* 2012;46(22):12704–10.
- [172] Ellingsen LA-W, Hung CR, Strömman AH. Lifecycle impacts of lithium-ion batteries: a review. Quebec, Canada; 2016.
- [173] Ellingsen LA-W, Majeau-Bettez G, Singh B, Srivastava AK, Valøen LO, Strömman AH. Life cycle assessment of a lithium-ion battery vehicle pack. *J Ind Ecol* 2013;18(1):113–24.
- [174] Faria R, Marques P, Garcia R, Moura P, Freire F, Delgado J, de Almeida AT. Primary and secondary use of electric mobility batteries from a life cycle perspective. *J Power Sources* 2014;262:169–77.
- [175] Hendrickson TP, Kavvada O, Shah N, Sathre R, Scown CD. Life-cycle implications and supply chain logistics of electric vehicle battery recycling in California. *Environ Res Lett* 2015;10(1):014011.
- [176] Kim HC, Wallington TJ, Arsenault R, Bae Ch, Ahn S, Lee J. Cradle-to-gate emissions from a commercial electric vehicle Li-ion battery: a comparative analysis. *Environ Sci Technol* 2016;50(14):7715–22.
- [177] Lastoskie CM, Dai Q. Comparative life cycle assessment of laminated and vacuum vapor-deposited thin film solid-state batteries. *J Clean Prod* 2015;91:158–69.
- [178] Li B, Gao X, Li J, Yuan C. Life cycle environmental impact of high-capacity lithium-ion battery with silicon nanowires anode for electric vehicles. *Environ Sci Technol* 2014;48(5):3047–55.
- [179] Lu Q, Wu PF, Shen WX, Wang XC, Zhang B, Wang C. Life cycle assessment of electric vehicle power battery. *Mater Sci Forum* 2016;847:403–10.
- [180] Majeau-Bettez G, Hawkins TR, Strömman AH. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environ Sci Technol* 2011;45(10):4548–54.
- [181] Peters JF, Baumann M, Zimmermann B, Braun J, Weil M. The environmental impact of Li-ion batteries and the role of key parameters: a review. *Renew Sustain Energy Rev* 2017;67(C):491–506.
- [182] Wang Y, Yu Y, Huang K, Chen B, Deng W, Yao Y. Quantifying the environmental impact of a Li-rich high-capacity cathode material in electric vehicles via life cycle assessment. *Environ Sci Pollut Res* 2017;24:1251–1260.
- [183] Zackrisson M, Avellán L, Orlenius J. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles—Critical issues. *J Clean Prod* 2010;18:1519–29.
- [184] Romare M, Dahllöf L. The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries. A study with focus on current technology and batteries for light-duty vehicles. Stockholm, Sweden: Swedish Energy Agency, Swedish Transport Administration; 2017. [No. C 243].
- [185] Notter DA, Gauch M, Widmer R, Wäger P, Stamp A, Zah R, Althaus H-J. Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environ Sci Technol* 2010;44(17):6550–6.
- [186] Aifantis KE, Hackney SA, Kumar RV, editors. High Energy Density Lithium Batteries: Materials, Engineering, Applications. 1st edWeinheim, Germany: Wiley-VCH; 2010.
- [187] United Nations Environment Programme (UNEP). Technical guidelines for the environmentally sound management of waste lead-acid batteries. Secretariat of the Basel Convention, Basel Convention series/SBC No. 2003/9, Geneva, Switzerland; 2003.
- [188] Brodd RJ. Batteries for sustainability: selected entries from the encyclopedia of sustainability science and technology. New York, USA: Springer; 2012.
- [189] Yuan X, Liu H, Zhang J. Lithium-ion batteries: advanced materials and technologies. green chemistry and chemical engineering. CRC Press; 2011.
- [190] GreenIT. Batteries for IT systems: environmental issues, sustainable information technology. 2005 <<https://www.greenit.net/downloads/GreenIT-Envissues-Batteries.pdf>>. [accessed 1 January 2019].
- [191] Soltani M, Kashkooli FM, Dehghani-Sani AR, Kazemi AR, Bordbar N, Farshchi MJ, Elmi M, Gharali K, Dusseault MB. A comprehensive study of geothermal heating and cooling systems. *Sustain Cities Soc* 2019;44:793–818.
- [192] Olivetti E, Gregory J, Kirchain R. Life cycle impacts of alkaline batteries with a focus on end-of-life, A study conducted for the national electrical manufacturers association. USA: Materials Systems Lab, Massachusetts Institute of Technology; 2011.
- [193] Adebambo O, Owen R. Universal waste management, battery recycling programs in Nova Scotia. Halifax NS, Canada: Dalhousie University; 2017.
- [194] Battery University. BU-103: global battery markets. 2017 <http://www.batteryuniversity.com/learn/article/global_battery_markets>. [accessed 1 January 2019].
- [195] Pelegov DV, Pontes J. Main drivers of battery industry changes: electric vehicles—a market overview. *Batteries* 2018;4:65. <https://doi.org/10.3390/batteries4040065>.
- [196] Ferella F, De Michelis I, Veglio F. Process for the recycling of alkaline and zinc-carbon spent batteries. *J Power Sources* 2008;183:805–11.
- [197] De Michelis I, Ferella F, Karakaya E, Beolchini F, Veglio F. Recovery of zinc and manganese from alkaline and zinc-carbon spent batteries. *J Power Sources* 2007;172:975–83.
- [198] Sheng L. Analysis of problems and countermeasures about recycling used batteries. *J Green Sci Technol* 2012;104:216–7. [in Chinese].
- [199] Pistoia G, Wiaux J-P, Wolsky SP. Used battery collection and recycling 10. Elsevier Science; 2001.
- [200] Wilson B. Recycling Used Lead Acid Batteries – A Model Life Cycle Approach. 13th Asian Battery Conference International Proceedings of the Secondary Lead Conference, De Macau, China.
- [201] Sayilgan E, Kukrer T, Givlekoglu G, Ferella F, Akcil A, Veglio F, Kitis M. A review of technologies for the recovery of metals from spent alkaline and zinc-carbon batteries. *Hydrometallurgy* 2009;97:158–66.
- [202] U.S. Environmental Protection Act (U.S. EPA). Introduction to United States Environmental Protection Agency Hazardous Waste Identification (40 CFR Parts 261). Solid Waste and Emergency Response (5305W), EPA530-K-05-012, USA; 2005.
- [203] Veloso LRS, Rodrigues LEOC, Ferreira DA, Magalhaes FS, Mansur MB. Development of a hydrometallurgical route for the recovery of zinc and manganese from spent alkaline batteries. *J Power Sources* 2005;152:295–302.
- [204] De Souza CCBM, Tenorio JAS. Simultaneous recovery of zinc and manganese dioxide from household alkaline batteries through hydrometallurgical processing. *J Power Sources* 2004;136:191–6.
- [205] Salgado AL, Veloso AMO, Pereira DD, Gontijo GS, Salum A, Mansur MB. Recovery of zinc and manganese from spent alkaline batteries by liquid-liquid extraction with Cyanex 272. *J Power Sources* 2003;115:367–73.
- [206] Espinosa DCR, Bernardes AM, Tenório JAS. Brazilian policy on battery disposal and its practical effects on battery recycling: short communication. *J Power Sources* 2004;137:134–9.
- [207] Haefliger P, Mathieu-Nolf M, Locicero S, Ndiaye C, Coly M, Diouf A, Faye AL, Sow A, Tempowski J, Pronczuk J, Filipe Junior AP, Bertolini R, Neira M. Mass lead intoxication from informal used lead-acid battery recycling in Dakar, Senegal. *Environ Health Perspect* 2009;117(10):1535–40.
- [208] California Environmental Protection Agency (CEPA). DTSC announces order to close Exide facility and steps to protect community with enhanced cleanup. USA: Department of Toxic Substances Control News Release; 2015.
- [209] Manhart A, Smera T, Kuepouo G, Mathai D, Mng'anya S, Schleicher T. The deadly business: Findings from the lead recycling Africa project. Freiburg: Oeko-Institut e.V; 2016 <<https://www.oeko.de/oekodoc/2549/2016-076-de.pdf>>. [accessed 1 January 2019].
- [210] United Nations Environment Programme (UNEP). Final review of scientific information on lead. Nairobi: United Nations Environment Programme, Chemicals Branch, DTIE; 2010.
- [211] Jolly R, Rhin C. The recycling of lead-acid batteries: production of lead and polypropylene. *Resour, Conserv Recycl* 1994;10(1–2):137–43.
- [212] Xiaojuan D, Jinxing D, Xue W. Preparation of polypyrrole nanocomposites for supercapacitor using spent battery powder as raw materials. *Electrochim Acta* 2016;210:646–54.
- [213] Li M, Liu J, Han W. Recycling and management of waste lead-acid batteries: a mini-review. *Waste Manag Res* 2016;34(4):298–306.
- [214] Genaidy AM, Sequeira R, Tolaymat T, Kohler J, Rinder M. An exploratory study of lead recovery in lead-acid battery lifecycle in US market: an evidence-based approach. *Sci Total Environ* 2008;407:7–22.
- [215] Ellis TW, Mirza AH. The refining of secondary lead for use in advanced lead-acid batteries. *J Power Sources* 2010;195:4525–9.
- [216] Zhang W, Yang J, Wu X, Hu Y, Yu W, Wang J, Dong J, Li M, Liang Sh, Hu J, Kumar RV. A critical review on secondary lead recycling technology and its prospect. *Renew Sustain Energy Rev* 2016;61:108–22.
- [217] Ballantyne AD, Hallett JP, Riley JD, Shah N, Payne DJ. Lead acid battery recycling for the twenty-first century. *R Soc Open Sci* 2018;5(5):1–12.

- [218] Sonoc A, Jeswiet J, Soo VK. Opportunities to improve recycling of automotive lithium-ion batteries. *Proc CIRP* 2015;29:752–7.
- [219] Vikström H, Davidsson S, Höök M. Lithium availability and future production outlooks. *Appl Energy* 2013;110:252–66.
- [220] Georgi-Maschler T, Friedrich B, Weyhe R, Heegn H, Rutz M. Development of a recycling process for Li-ion batteries. *J Power Sources* 2012;207(3):173–82.
- [221] Sonoc A, Jeswiet J. Review of lithium supply and demand and a preliminary investigation of a room temperature method to recycle lithium ion batteries to recover lithium and other materials. *Proc CIRP* 2014;15:289–93.
- [222] Gaines LL. The future of automotive lithium-ion battery recycling: charting a sustainable course. *Sustain Mater Technol* 2014;1–2:2–7.
- [223] Zeng X, Li J, Singh N. Recycling of spent lithium-ion battery: a critical review. *Crit Rev Environ Sci Technol* 2014;44(10):1129–65.
- [224] Nitta N, Wu F, Lee JT, Yushin G. Li-ion battery materials: present and future. *Mater Today* 2015;18(5):252–64.
- [225] Li L, Zhang X, Li M, Chen R, Wu F, Amine Kh, Lu J. The recycling of spent lithium-ion batteries: a review of current processes and technologies. *Electrochem Energy Rev* 2018;1:461–82.
- [226] Li L, Ge J, Wu F, Chen R, Chen S, Wu B. Recovery of cobalt and lithium from spent lithium ion batteries using organic citric acid as leachant. *J Hazard Mater* 2010;176(1–3):288–93.
- [227] Gold Peak Industries, Ltd. *Li-ion Technical handbook*. Vol.1, GPPA1THL-A, Taiwan; 2007. <http://gpbattery.co.kr/pdf/Li-ion_handbook.pdf>. [accessed 1 January 2019].