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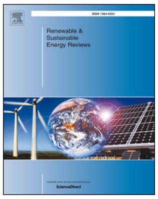

Study of energy storage systems and environmental challenges of batteries

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

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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 CO_2 concentration increased from ~360 ppm to ~400 ppm between 1995 and 2015, and fossil fuel CO_2 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).

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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 systems[1] (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 SWOT[2] 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 (W h/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)	Pb-A	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]

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[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 ($/kW)	Energy capital cost ($/kW h)	Operating and maintenance cost
PHS		2500–4300 [47], 2000–4000 [24]	5–100 [22], 10–12 [33]	0.004 $/kW h [29], ~ 3 $/kW/year [54]
Large–scale CAES		400–800 [22], 800–1000 [24]	2–50 [22], 2–120 [55], 2 [29]	0.003 $/kW h [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 $/kW h [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 $/kW h [29], 18.5 $/kW/year [54]
Capacitor		200–400 [22]	500–1000 [22]	13 $/kW/year [54], < 0.05 $/kW h [37]
Supercapacitor		100–300 [22], 250–450 [56]	300–2000 [22]	0.005 $/kW h [29], ~ 6 $/kW-year [33]
Hydrogen fuel cell		500 [33], 1500–3000 [57]	15 [33], 2–15 €/kW h [44]	0.0019–0.0153 $/kW [57]
Battery Energy Storage (BES)	Pb-A	300–600 [22], 200–300 [33], 400 [49]	200–400 [22], 50–100 [42], 330 [49]	~ 50 $/kW/year [54]
	Li-ion	1200–4000 [22], 900–1300 [42], 1590 [47]	600–2500 [22], 2770–3800 [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

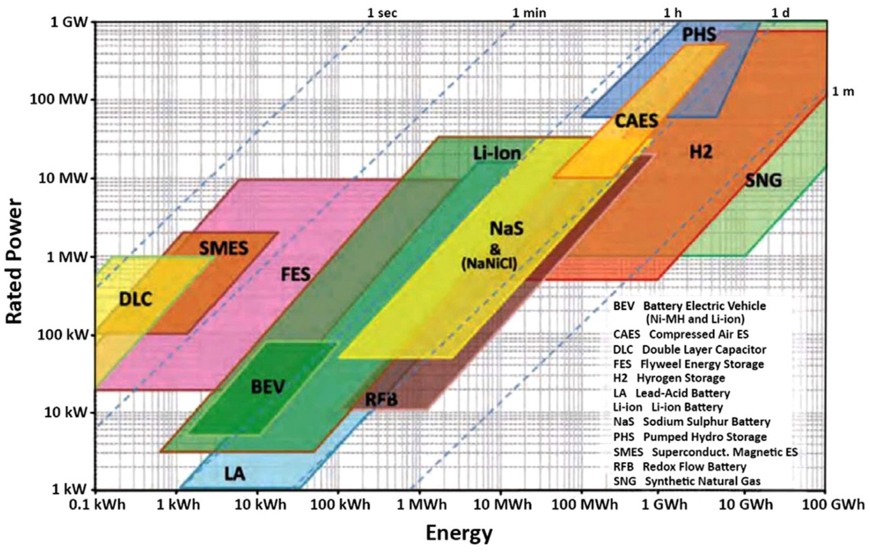


Fig. 1. Comparison of different types of ESSs in terms of rated power, energy, and discharge duration [9].

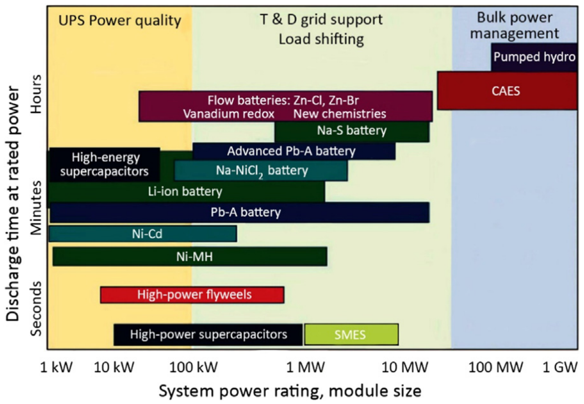


Fig. 2. Comparison of different types of existing ESSs (commercial or near-commercial) in terms of power output, module sizing, and discharge time (adapted from [9,21]).

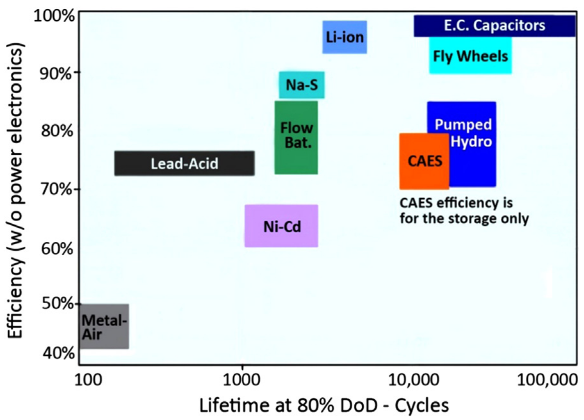


Fig. 3. Comparison of different types of ESSs in terms of cycle life and efficiency [9].

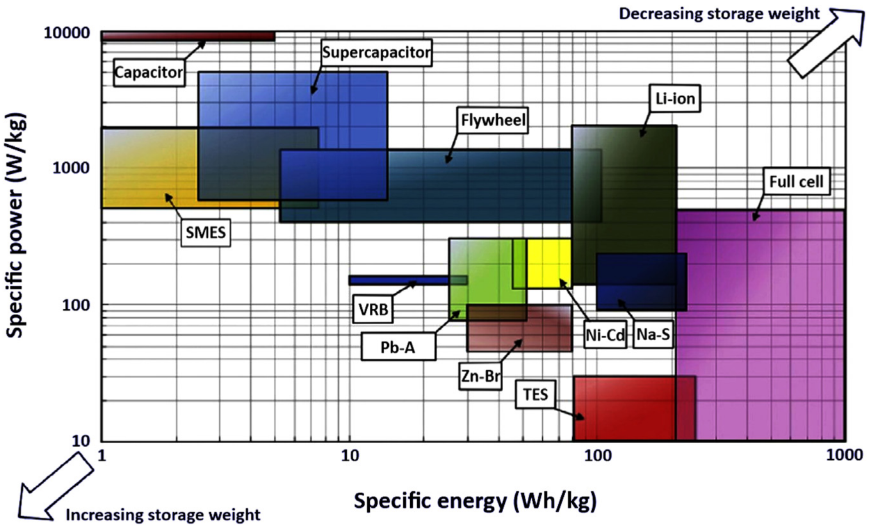


Fig. 4. Comparison of different types of ESSs in terms of specific energy and specific power [18].

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;

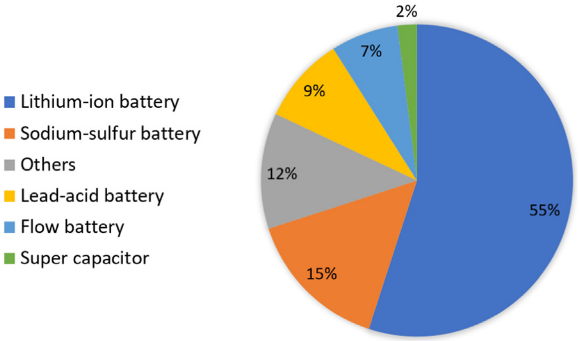


Fig. 5. Worldwide battery energy storage system installed capacity in 2016 [72].

- 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 MnO_2 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/MnO_2 battery (the ubiquitous “alkaline” cell). They outperform Zn-C batteries by factors of × 2 to × 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 MW h 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 [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.

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_2SO_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.

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 ($LiPF_6$) [92]. Batteries that use $LiPF_6$ 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 ($LiMn_2O_4$)	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 ($CH_4 \rightarrow CH_3OH$) 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 $CH_3OH \rightarrow CO + 2H_2$, and $CO + H_2O \rightarrow CO_2 + H_2$, 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 ~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 Chegwidden [134] and Dupont et al. [135], the antimony consumption in Pb-A batteries' production was ~27% in the world in 2010.

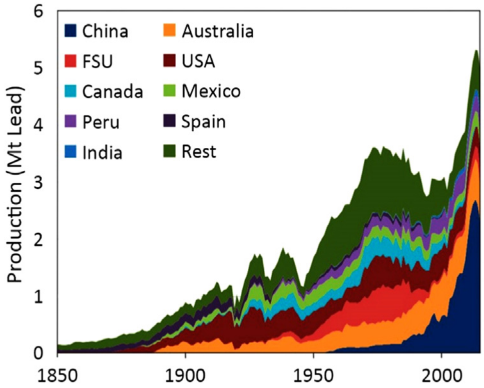


Fig. 6. World production of lead [115,123,124].

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).

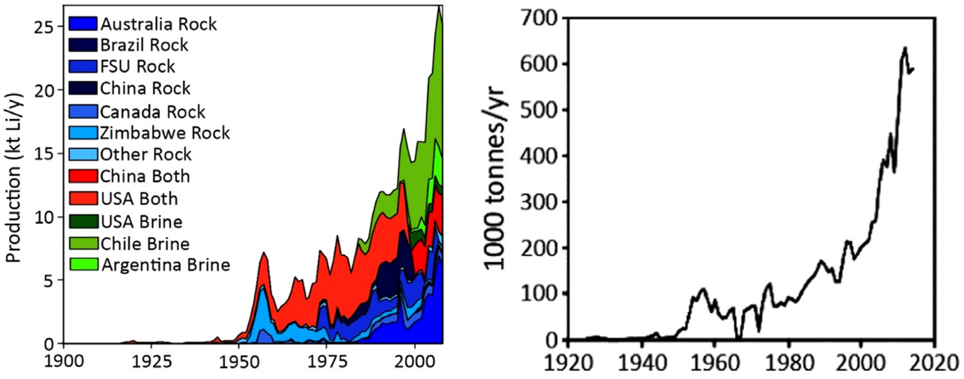
3.2. Harmful effects and environmental pollutions caused by using batteries

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 CO_2 per kW h [157], so CO_2 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



(a) (b)

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

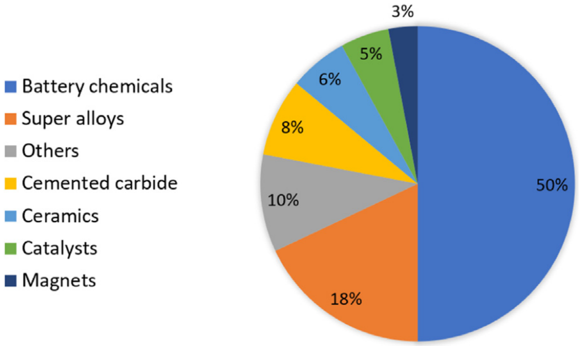


Fig. 8. Global demand for cobalt [120].

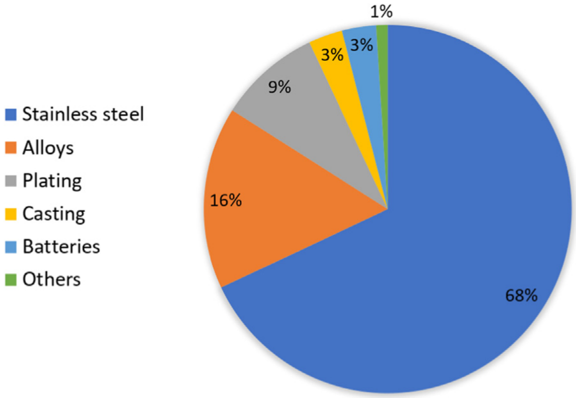


Fig. 9. Different usages of nickel [136].

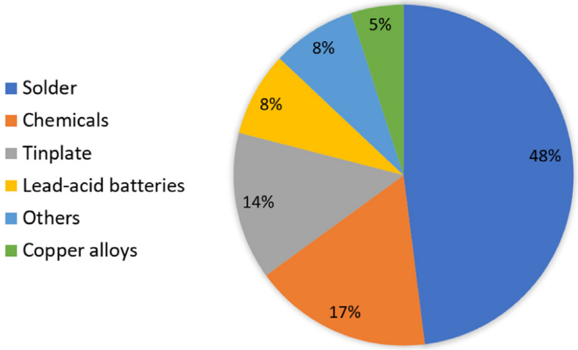


Fig. 10. Worldwide use of tin according to its applications [133].

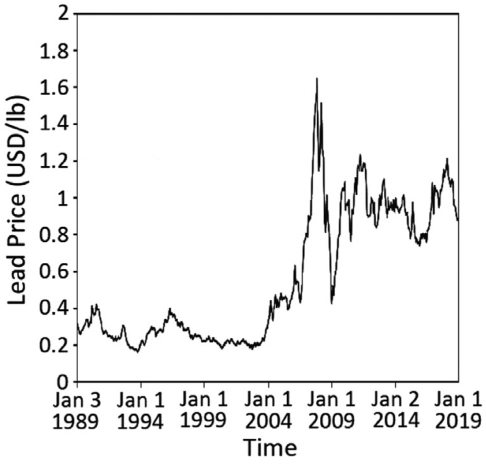


Fig. 11. Lead price changes versus time [141].

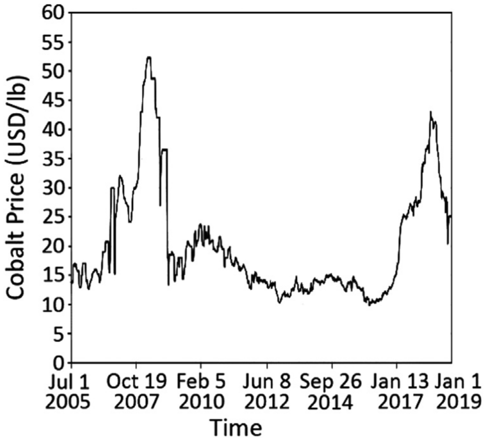


Fig. 12. Cobalt price changes versus time [142].

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 CO_2, 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 CO_2 emissions, and Pb-A has the lowest quantity of CO_2 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 $CO_{2\text{-eq}}$/kW h.

Li-ion and Ni-MH batteries are the highest rank $CO_{2\text{-eq}}$ 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., $LiPF_6$ in Li-ion batteries, sulfuric acid (H_2SO_4) 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_2O	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 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.

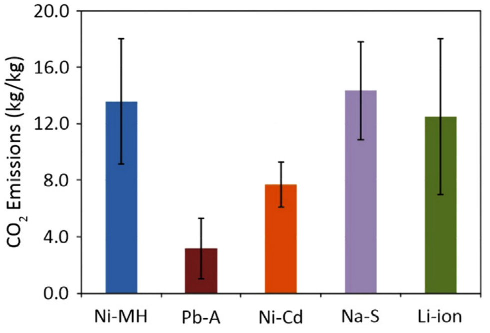


Fig. 13. Mean CTG CO_2 emissions with ± one standard deviation to produce a kg of different battery [87].

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_2O	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]

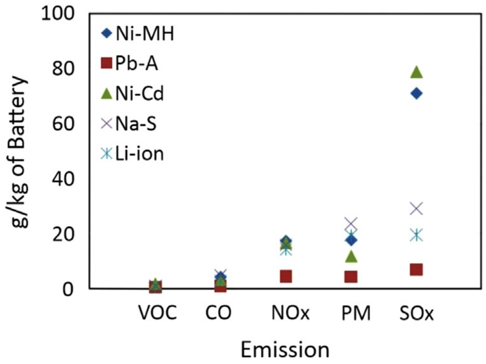


Fig. 14. Mean criteria contaminant emissions (g) per kg of battery for different batteries [87].

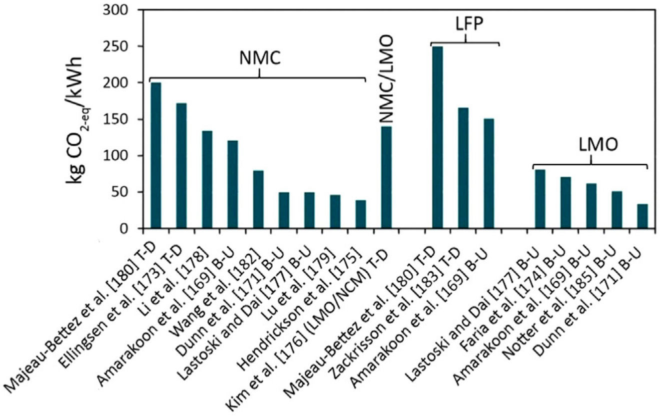


Fig. 15. Computed GHG emissions for various life cycle assessment (LCA) of Li-ion batteries for the chemistries NMC, NMC/LMO, LFP and LMO. In this figure, NMC refers to lithium manganese cobalt oxide, LFP refers to lithium iron phosphate, and LMO refers to lithium manganese oxide [184].

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

	Climate impact (kg CO$_{2\text{-eq}}$)
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 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].

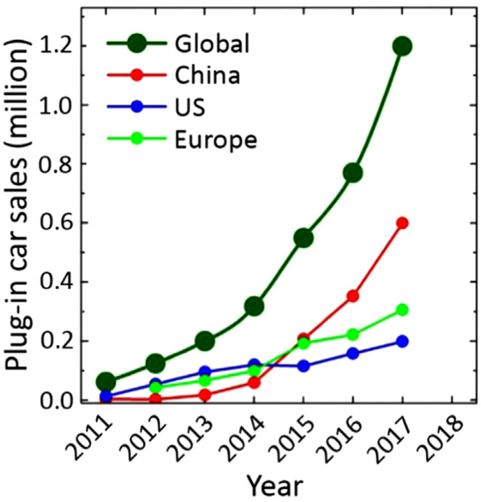


Fig. 16. Annual sales of plug-in vehicles around the world as well as in China, the US and Europe [195].

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 H_2SO_4 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

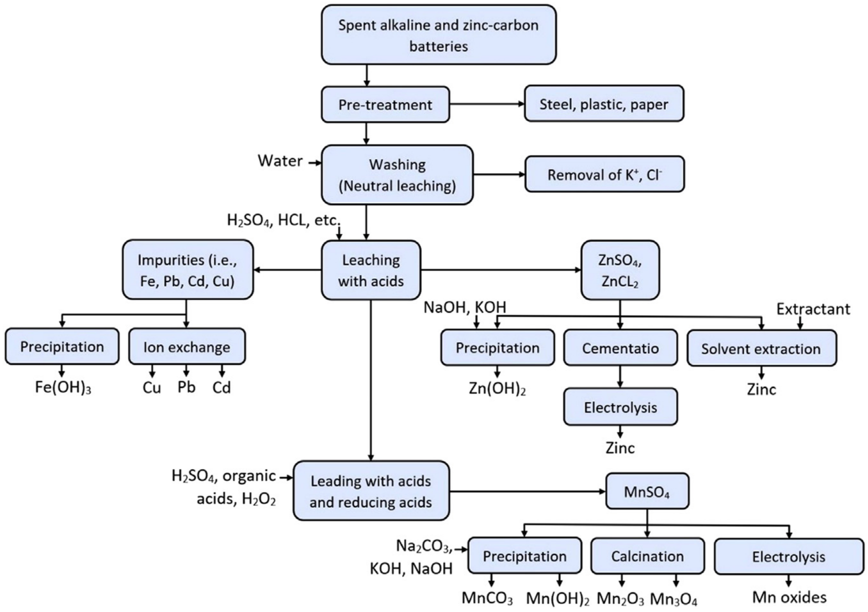


Fig. 17. Recycling of Zn and Mn from used alkaline and Zn-C batteries [201].

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 CO_2 emissions) is 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.

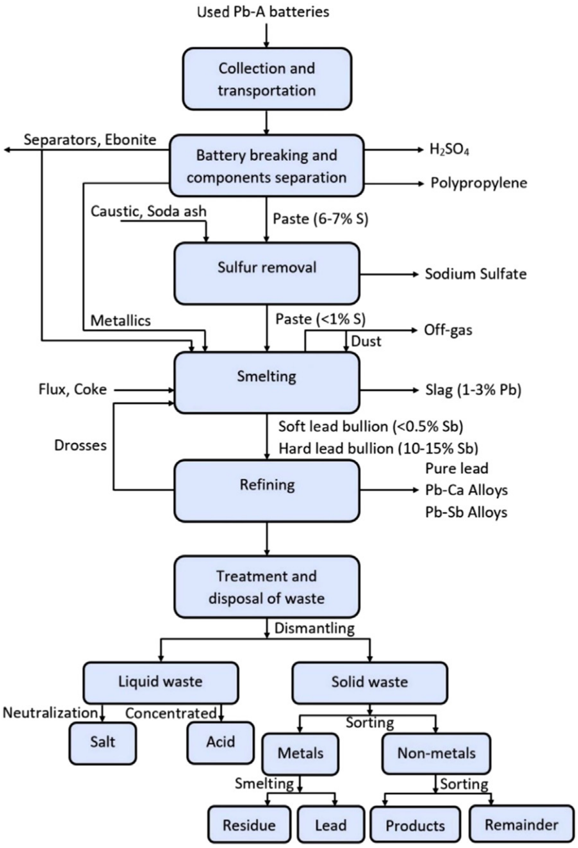


Fig. 19. Schematic diagram of the general recycling process of used Pb-A batteries (adapted from [212,213]).

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

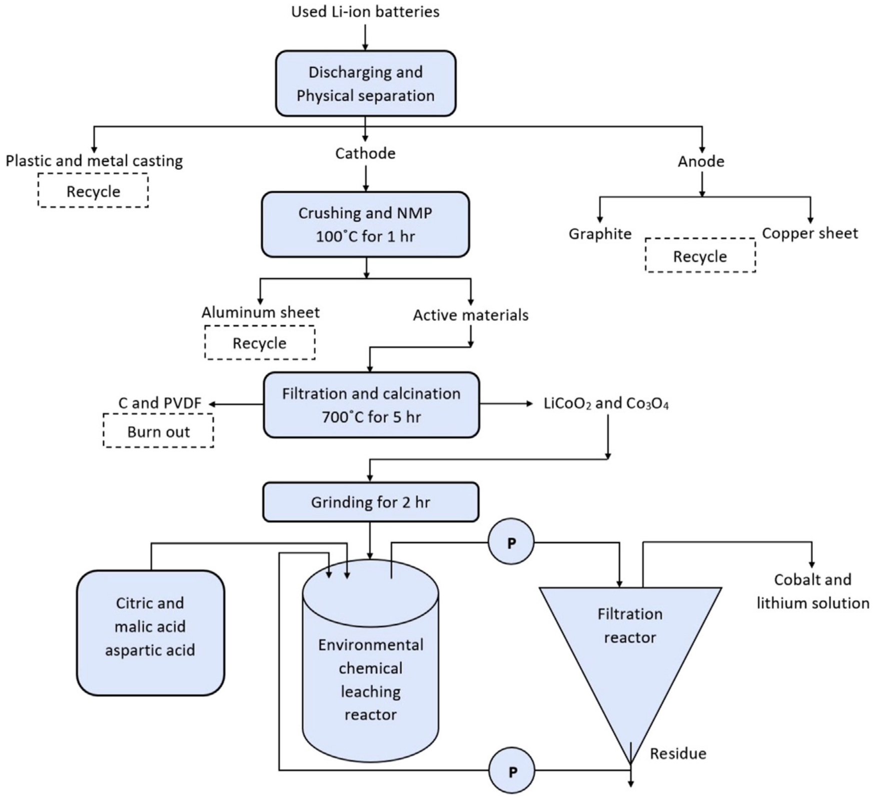


Fig. 20. Schematic diagram of BIT recycling process [97,227].

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.

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