Lithium-ion batteries and the transition to electric vehicles: environmental challenges and opportunities from a life cycle perspective

Xu, C.

References

1 Pörtner, H. O. et al. Climate change 2022: impacts, adaptation and vulnerability. (2022).

2 Michalek Jeremy, J. et al. Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits. *Proceedings of the National Academy of Sciences* **108**, 16554-16558 (2011).

3 Richter, A., Löwner, M.-O., Ebendt, R. & Scholz, M. Towards an integrated urban development considering novel intelligent transportation systems: Urban Development Considering Novel Transport. *Technological Forecasting and Social Change* **155**, 119970 (2020).

4 Coppola, P. & Silvestri, F. in *Autonomous Vehicles and Future Mobility* (eds. Coppola, P. & Esztergár-Kiss, D.) 1-15 (Elsevier, 2019).

5 Mounce, R. & Nelson, J. D. On the potential for one-way electric vehicle car-sharing in future mobility systems. *Transportation Research Part A: Policy and Practice* **120**, 17-30 (2019).

6 *Global EV Outlook 2022* (International Energy Agency Paris, France, 2022). https://www.iea.org/reports/global-ev-outlook-2022

7 Xu, C. et al. Future material demand for automotive lithium-based batteries. *Commun. Mater.* **1**, 99 (2020).

8 Berkeley, N., Bailey, D., Jones, A. & Jarvis, D. Assessing the transition towards Battery Electric Vehicles: A Multi-Level Perspective on drivers of, and barriers to, take up. *Transportation Research Part A: Policy and Practice* **106**, 320-332 (2017).

9 Skeete, J.-P., Wells, P., Dong, X., Heidrich, O. & Harper, G. Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition. *Energy Research & Social Science* **69**, 101581 (2020).

10 Turcheniuk, K., Bondarev, D., Amatucci, G. G. & Yushin, G. Battery materials for low-cost electric transportation. *Materials Today* **42**, 57-72 (2021).

11 Schade, W., Haug, I. & Berthold, D. The future of the automotive sector. (2022).

12 Mancini, L. & Nuss, P. Responsible Materials Management for a Resource-Efficient and Low-Carbon Society. *Resources* **9** (2020).

13 Lèbre, É. et al. The social and environmental complexities of extracting energy transition metals. *Nat. Commun.* **11**, 4823 (2020).

14 Guille, C. & Gross, G. A conceptual framework for the vehicle-to-grid (V2G) implementation. *Energy Policy* **37**, 4379-4390 (2009).

15 *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries*

(National Renewable Energy Lab, 2015). https://www.osti.gov/biblio/1171780

16 Haram, M. H. S. M. et al. Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges. *Alexandria Engineering Journal* **60**, 4517-4536 (2021).

17 Harper, G. et al. Recycling lithium-ion batteries from electric vehicles. *Nature* **575**, 75-86 (2019).

18 Müller, E., Hilty, L. M., Widmer, R., Schluep, M. & Faulstich, M. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environmental Science & Technology* **48**, 2102-2113 (2014).

19 Brunner, P. H. & Rechberger, H. *Handbook of material flow analysis: For environmental, resource, and waste engineers*. (CRC press, 2016).

20 Kawecki, D., Scheeder, P. R. & Nowack, B. Probabilistic material flow analysis of seven commodity plastics in Europe. *Environmental science & technology* **52**, 9874-9888 (2018).

21 Du, X. & Graedel, T. E. Global in-use stocks of the rare earth elements: a first estimate. *Environmental science & technology* **45**, 4096-4101 (2011).

22 Song, J. et al. Material flow analysis on critical raw materials of lithium-ion batteries in China. *Journal of Cleaner Production* **215**, 570-581 (2019).

23 Finnveden, G. et al. Recent developments in Life Cycle Assessment. *Journal of Environmental Management* **91**, 1-21 (2009).

24 Thonemann, N., Schulte, A. & Maga, D. How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance. *Sustainability* **12** (2020).

25 Tsoy, N., Steubing, B., van der Giesen, C. & Guinée, J. Upscaling methods used in ex ante life cycle assessment of emerging technologies: a review. *The International Journal of Life Cycle Assessment* **25**, 1680-1692 (2020).

26 Mendoza Beltran, A. et al. When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *Journal of Industrial Ecology* **24**, 64-79 (2020).

27 van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J. & Tukker, A. A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production* **259**, 120904 (2020).

28 Sacchi, R. et al. PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable and Sustainable Energy Reviews* **160**, 112311 (2022).

29 Ryu, H.-H., Sun, H. H., Myung, S.-T., Yoon, C. S. & Sun, Y.-K. Reducing cobalt from lithium-ion batteries for the electric vehicle era. *Energy & Environmental Science* **14**, 844-852 (2021).

30 Simon, B., Ziemann, S. & Weil, M. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: Focus on Europe. *Resour. Conserv. Recycl.* **104**, 300-310 (2015).

31 Richa, K., Babbitt, C. W., Gaustad, G. & Wang, X. A future perspective on lithium-ion battery waste flows from electric vehicles. *Resour. Conserv. Recycl.* **83**, 63-76 (2014).

32 Gaines, L. & Nelson, P. Lithium-ion batteries: possible materials issues. in *13th international battery materials recycling seminar and exhibit, Broward County Convention Center, Fort Lauderdale, Florida* (2009).

33 Ziemann, S., Müller, D. B., Schebek, L. & Weil, M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. *Resour. Conserv. Recycl.* **133**, 76-85 (2018).

34 Hao, H. et al. Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment. *Nat. Commun.* **10**, 5398 (2019).

35 Deetman, S., Pauliuk, S., van Vuuren, D. P., van der Voet, E. & Tukker, A. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. *Environ. Sci. Technol.* **52**, 4950-4959 (2018).

36 Weil, M., Ziemann, S. & Peters, J. in *Behaviour of Lithium-Ion Batteries in Electric Vehicles: Battery Health, Performance, Safety, and Cost* (eds. Pistoia, G. & Liaw, B.) 59-74 (Springer International Publishing, 2018).

37 Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M. & Van Mierlo, J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment* **19**, 1866-1890 (2014).

38 Tagliaferri, C. et al. Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chemical Engineering Research and Design* **112**, 298-309 (2016).

39 Hawkins, T. R., Singh, B., Majeau-Bettez, G. & Strømman, A. H. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology* **17**, 53-64 (2013).

40 Ellingsen, L. A.-W. et al. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *Journal of Industrial Ecology* **18**, 113-124 (2014).

41 Hiremath, M., Derendorf, K. & Vogt, T. Comparative Life Cycle Assessment of Battery Storage

Systems for Stationary Applications. *Environmental Science & Technology* **49**, 4825-4833 (2015).

42 Zackrisson, M., Avellán, L. & Orlenius, J. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues. *Journal of Cleaner Production* **18**, 1519-1529 (2010).

43 Ellingsen, L. A.-W., Hung, C. R. & Strømman, A. H. Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. *Transportation Research Part D: Transport and Environment* **55**, 82-90 (2017).

44 Peters, J. F., Baumann, M., Zimmermann, B., Braun, J. & Weil, M. The environmental impact of Li-Ion batteries and the role of key parameters – A review. *Renewable and Sustainable Energy Reviews* **67**, 491-506 (2017).

45 Peters, J. F. & Weil, M. Providing a common base for life cycle assessments of Li-Ion batteries. *Journal of Cleaner Production* **171**, 704-713 (2018).

46 Mohr, M., Peters, J. F., Baumann, M. & Weil, M. Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes. *Journal of Industrial Ecology* **24**, 1310-1322 (2020).

47 Kelly, J. C., Dai, Q. & Wang, M. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. *Mitigation and Adaptation Strategies for Global Change* **25**, 371-396 (2020).

48 Spangenberger, J., Gaines, L. & Dai, Q. Recell; A Closed-Loop Battery Recycling Model. *ECS Meeting Abstracts* **MA2018-01**, 616-616 (2018).

49 Ciez, R. E. & Whitacre, J. F. Examining different recycling processes for lithium-ion batteries. *Nature Sustainability* **2**, 148-156 (2019).

50 Schulz-Mönninghoff, M., Bey, N., Nørregaard, P. U. & Niero, M. Integration of energy flow modelling in life cycle assessment of electric vehicle battery repurposing: Evaluation of multi-use cases and comparison of circular business models. *Resources, Conservation and Recycling* **174**, 105773 (2021).

51 Hawkins, T. R., Gausen, O. M. & Strømman, A. H. Environmental impacts of hybrid and electric vehicles—a review. *The International Journal of Life Cycle Assessment* **17**, 997-1014 (2012).

52 Knobloch, F. et al. Net emission reductions from electric cars and heat pumps in 59 world regions over time. *Nature Sustainability* **3**, 437-447 (2020).

53 Sovacool, B. K., Axsen, J. & Kempton, W. The Future Promise of Vehicle-to-Grid (V2G) Integration: A Sociotechnical Review and Research Agenda. *Annual Review of Environment and Resources* **42**, 377-406 (2017).

54 Sovacool, B. K., Noel, L., Axsen, J. & Kempton, W. The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review. *Environmental Research Letters* **13**, 013001 (2018).

55 Ralon, P., Taylor, M., Ilas, A., Diaz-Bone, H. & Kairies, K. Electricity storage and renewables: Costs and markets to 2030. *International Renewable Energy Agency: Abu Dhabi, UAE* (2017).

56 *Global Renewables Outlook: Energy transformation 2050* (International Renewable Energy Agency, 2020). https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

57 *Global EV Outlook 2020* (IEA, 2020). https://www.iea.org/reports/global-ev-outlook-2020

58 *Second-life EV batteries: The newest value pool in energy storage* (McKinsey & Company, 2019). https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

59 Baghdadi, I., Briat, O., Delétage, J.-Y., Gyan, P. & Vinassa, J.-M. Lithium battery aging model based on Dakin's degradation approach. *Journal of Power Sources* **325**, 273-285 (2016).

60 Naumann, M., Spingler, F. B. & Jossen, A. Analysis and modeling of cycle aging of a commercial LiFePO4/graphite cell. *Journal of Power Sources* **451**, 227666 (2020).

61 Smith, K. et al. Life prediction model for grid-connected Li-ion battery energy storage system. in *2017 American Control Conference (ACC)* 4062-4068.

62 Deng, J., Bae, C., Denlinger, A. & Miller, T. Electric Vehicles Batteries: Requirements and Challenges. *Joule* **4**, 511-515 (2020).

63 *Global EV Outlook 2020: Entering the decade of electric drive?* (International Energy Agency, 2020). https://www.iea.org/reports/global-ev-outlook-2020

64 Ponrouch, A. & Rosa Palacín, M. Post-Li batteries: Promises and challenges. *Philos. Trans. R. Soc. A-Math. Phys. Eng. Sci.* **377** (2019).

65 Olivetti, E. A., Ceder, G., Gaustad, G. G. & Fu, X. Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. *Joule* **1**, 229-243 (2017).

66 Van den Brink, S., Kleijn, R., Sprecher, B. & Tukker, A. Identifying supply risks by mapping the cobalt supply chain. *Resour. Conserv. Recycl.* **156** (2020).

67 Banza Lubaba Nkulu, C. et al. Sustainability of artisanal mining of cobalt in DR Congo. *Nat. Sustain.* **1**, 495-504 (2018).

68 Thies, C., Kieckhäfer, K., Spengler, T. S. & Sodhi, M. S. Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries. in *Procedia CIRP* 292-297.

69 Müller, D. B. Stock dynamics for forecasting material flows—Case study for housing in The

Netherlands. *Ecol. Econ.* **59**, 142-156 (2006).

70 *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Third Edition* (Argonne National Lab, 2019). https://www.osti.gov/servlets/purl/1503280

71 *Global EV Outlook 2019: Scaling-up the transition to electric mobility* (International Energy Agency, 2019). https://www.iea.org/reports/global-ev-outlook-2019

72 Sitty, G. & Taft, N. What Will the Global Light-Duty Vehicle Fleet Look like through 2050? (2016).

73 *World Energy Outlook 2020* (IEA, 2020). https://www.iea.org/reports/world-energy-outlook-2020

74 *Vehicle Size Classes Used in the Fuel Economy Guide* (EPA, 2019).

75 Severson, K. A. et al. Data-driven prediction of battery cycle life before capacity degradation. *Nature Energy* **4**, 383-391 (2019).

76 *Find Electric Vehicle Models* (US Department of Energy, 2019).

77 Ai, N., Zheng, J. & Chen, W.-Q. US end-of-life electric vehicle batteries: Dynamic inventory modeling and spatial analysis for regional solutions. *Resour. Conserv. Recycl.* **145**, 208-219 (2019).

78 Oguchi, M. & Fuse, M. Regional and longitudinal estimation of product lifespan distribution: a case study for automobiles and a simplified estimation method. *Environ. Sci. Technol.* **49**, 1738-1743 (2015).

79 Zhang, L., Yuan, Z. & Bi, J. Predicting future quantities of obsolete household appliances in Nanjing by a stock-based model. *Resour. Conserv. Recycl.* **55**, 1087-1094 (2011).

80 *Electrochemical energy storage technical team roadmap* (USDRIVE, 2017). https://www.energy.gov/sites/prod/files/2017/11/f39/EESTT%20roadmap%202017-10-16%20Final.pdf

81 *Inventing the sustainable batteries of the future* (BATTERY 2030+, 2020). https://battery2030.eu/digitalAssets/816/c_816048-l_1-k_roadmap-27-march.pdf

82 *Roadmap for an integrated cell and battery production in Germany* (The Federal Government's Joint Office for Electric Mobility, 2016). http://nationale-plattform-elektromobilitaet.de/fileadmin/user_upload/Redaktion/Publikationen/AG2_Roadmap_Zellfertigung_eng_bf.pdf

83 Chen, K., Zhao, F., Hao, H. & Liu, Z. Selection of lithium-ion battery technologies for electric vehicles under China's new energy vehicle credit regulation. *Energy Procedia* **158**, 3038-3044 (2019).

84 *NCM 811: The future of electric car batteries?* (INSIDEEVs, 2018).

85 *The Rechargeable Battery Market and Main Trends 2018-2030* (Avicenne Energy, 2019).

86 Faguy, P. The Low Co, Co-free Initiative for Next Generation Li-ion Cathode Materials. in *U.S. Department of Energy Vehicle Technologies Office 2019 Annual Merit Review* (2019).

87 *Tesla wins China approval to build Model 3 vehicles with LFP batteries: ministry - Reuters* (Reuters, 2020).

88 *LFP chemistry is emerging as the future of batteries* (Clean Future, 2020).

89 Cano, Z. P. et al. Batteries and fuel cells for emerging electric vehicle markets. *Nat. Energy* **3**, 279-289 (2018).

90 *It's safer with OXIS lithium sulfur rechargeable batteries* (OXIS Energy, 2016). http://oxisenergy.com/wp-content/uploads/2016/05/oxis-brochure.pdf

91 *Samsung's lithium-air battery could help double EV range* (World industrial reporter, 2017). https://worldindustrialreporter.com/samsungs-lithium-air-battery-could-help-double-ev-range/amp/?from=singlemessage&isappinstalled=0

92 *Comparison of plug-in hybrid electric vehicle battery life across geographies and drive-cycles* (National Renewable Energy Lab, 2012). https://www.nrel.gov/docs/fy12osti/53817.pdf

93 *Mineral Commodity Summaries 2020* (USGS, 2020). https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

94 *EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model* (Argonne National Lab, 2019). https://publications.anl.gov/anlpubs/2019/07/153050.pdf

95 Chen, M. et al. Recycling end-of-life electric vehicle lithium-ion batteries. *Joule* **3**, 2622-2646 (2019).

96 Reck, B. K. & Graedel, T. E. Challenges in metal recycling. *Science* **337**, 690-695 (2012).

97 Richa, K., Babbitt, C. W., Nenadic, N. G. & Gaustad, G. Environmental trade-offs across cascading lithium-ion battery life cycles. *Int. J. Life Cycle Assess.* **22**, 66-81 (2017).

98 *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries* (National Renewable Energy Lab, 2015). https://www.osti.gov/servlets/purl/1171780

99 Ahmadi, L., Young, S. B., Fowler, M., Fraser, R. A. & Achachlouei, M. A. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. *Int. J. Life Cycle Assess.* **22**, 111-124 (2017).

100 Kamath, D., Arsenault, R., Kim, H. C. & Anctil, A. Economic and Environmental Feasibility of Second-Life Lithium-Ion Batteries as Fast-Charging Energy Storage. *Environ. Sci. Technol.* **54**, 6878-6887 (2020).

101 Nitta, N., Wu, F., Lee, J. T. & Yushin, G. Li-ion battery materials: present and future. *Materials Today* **18**, 252-264 (2015).

102 Said, A. O., Lee, C. & Stoliarov, S. I. Experimental investigation of cascading failure in 18650 lithium ion cell arrays: Impact of cathode chemistry. *J. Power Sources* **446**, 227347 (2020).

103 Casals, L. C., García, B. A. & Canal, C. Second life batteries lifespan: Rest of useful life and environmental analysis. *J. Environ. Manag.* **232**, 354-363 (2019).

104 *Tesla is working on new ~110 kWh battery pack for more than 400 miles of range* (Electrek, 2020).

105 *SET-Plan ACTION n°7-Declaration of Intent "Become competitive in the global battery sector to drive e-mobility forward"* (European Commission, 2016).

106 *CATL batteries energise Powin's new 'long duration, long life' Li-Ion systems* (Energy Storage News, 2020).

107 Benveniste, G., Rallo, H., Casals, L. C., Merino, A. & Amante, B. Comparison of the state of Lithium-Sulphur and lithium-ion batteries applied to electromobility. *J. Environ. Manag.* **226**, 1-12 (2018).

108 *LEAF WARRANTY INFORMATION BOOKLET* (NISSAN, 2020). https://www.nissanusa.com/content/dam/Nissan/us/manuals-and-guides/leaf/2020/2020-nissan-leaf-warranty-booklet.pdf

109 Mayyas, A., Steward, D. & Mann, M. The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. *Sustain. Mater. Technol.* **19**, e00087 (2019).

110 Gaines, L. Lithium-ion battery recycling processes: Research towards a sustainable course. *Sustain. Mater. Technol.* **17**, e00068 (2018).

111 Richa, K., Babbitt, C. W., Nenadic, N. G. & Gaustad, G. Environmental trade-offs across cascading lithium-ion battery life cycles. *Int. J. Life Cycle Assess.* **22**, 66-81 (2015).

112 Lang, J. et al. High-purity electrolytic lithium obtained from low-purity sources using solid electrolyte. *Nat. Sustain.* **3**, 386-390 (2020).

113 *Study on Critical Raw Materials at EU Level* (Oakdene Hollins and Fraunhofer ISI, 2013). http://ec.europa.eu/DocsRoom/documents/5605/attachments/1/translations/en/renditions/native

114 Helbig, C., Bradshaw, A. M., Wietschel, L., Thorenz, A. & Tuma, A. Supply risks associated with lithium-ion battery materials. *J. Clean Prod.* **172**, 274-286 (2018).

115 Alves Dias, P., Blagoeva, D., Pavel, C. & Arvanitidis, N. Cobalt: demand-supply balances in the

transition to electric mobility. *European Commission, Joint Research Centre, EUR-Scientific and Technical Research Reports Publications Office of the European Union DOI* **10**, 97710 (2018).

116 Prior, T., Giurco, D., Mudd, G., Mason, L. & Behrisch, J. Resource depletion, peak minerals and the implications for sustainable resource management. *Glob. Environ. Change* **22**, 577-587 (2012).

117 Delogu, M., Zanchi, L., Dattilo, C. A. & Pierini, M. Innovative composites and hybrid materials for electric vehicles lightweight design in a sustainability perspective. *Mater. Today Commun.* **13**, 192-209 (2017).

118 Eberle, U. & Von Helmolt, R. Sustainable transportation based on electric vehicle concepts: a brief overview. *Energy Environ. Sci.* **3**, 689-699 (2010).

119 Saxena, S., Le Floch, C., MacDonald, J. & Moura, S. Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models. *Journal of Power Sources* **282**, 265-276 (2015).

120 Neubauer, J. & Wood, E. The impact of range anxiety and home, workplace, and public charging infrastructure on simulated battery electric vehicle lifetime utility. *J. Power Sources* **257**, 12-20 (2014).

121 Brown, S., Pyke, D. & Steenhof, P. Electric vehicles: The role and importance of standards in an emerging market. *Energy Policy* **38**, 3797-3806 (2010).

122 Prior, T., Wäger, P. A., Stamp, A., Widmer, R. & Giurco, D. Sustainable governance of scarce metals: The case of lithium. *Sci. Total Environ.* **461-462**, 785-791 (2013).

123 Zwolinski, P. & Tichkiewitch, S. An agile model for the eco-design of electric vehicle Li-ion batteries. *CIRP Annals* **68**, 161-164 (2019).

124 Meng, F., McNeice, J., Zadeh, S. S. & Ghahreman, A. Review of Lithium Production and Recovery from Minerals, Brines, and Lithium-Ion Batteries. *Miner. Process Extr. Metall. Rev.* (2019).

125 *Find Electric Vehicle Models* (US Department of Energy, 2019). https://www.energy.gov/eere/electricvehicles/find-electric-vehicle-models

126 *Electric Vehicle Outlook 2020* (Bloomberg NEF, 2020). https://bnef.turtl.co/story/evo-2020/?teaser=yes

127 *BP Energy Outlook 2019 edition* (BP, 2019). https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf

128 *World Oil Outlook 2040* (OPEC, 2018). https://elperiodicodelaenergia.com/wp-content/uploads/2018/09/WOO_2018.pdf

129 *Charging upwards: BHP recharges its electric vehicle take-up forecasts* (BHP, 2019). https://www.smh.com.au/business/companies/bhp-recharges-its-electric-vehicle-take-up-forecasts-20190521-p51pix.html

130 *MOVIN'ON: TOTAL'S TAKE ON MOBILITY OF THE FUTURE* (TOTAL, 2018). https://www.total.com/en/news/movinon-totals-take-mobility-future?folder=9487

131 *Up to 50% of the global car fleet could be electric in 2050* (Enerdata, 2018). https://www.enerdata.net/publications/executive-briefing/half-car-fleet-electric-2050.html

132 *Global EV Outlook 2019* (IEA, 2019). https://www.iea.org/reports/global-ev-outlook-2019

133 Al-Alawi, B. M. & Bradley, T. H. Review of hybrid, plug-in hybrid, and electric vehicle market modeling studies. *Renew. Sust. Energ. Rev.* **21**, 190-203 (2013).

134 *Annual energy outlook 2020 with projections to 2050: light-duty vehicle sales by technology type* (U.S. Energy Information Administration, 2020). https://www.eia.gov/outlooks/aeo/data/browser/#/?id=48-AEO2020&sourcekey=0

135 Ko, M. et al. Scalable synthesis of silicon-nanolayer-embedded graphite for high-energy lithium-ion batteries. *Nat. Energy* **1**, 1-8 (2016).

136 *New lithium-air battery could drive huge performance gains* (ExtremeTech, 2015). https://www.extremetech.com/mobile/217191-new-lithium-air-battery-could-drive-huge-performance-gains?from=singlemessage&isappinstalled=0

137 Tsach, S., Tatievsky, A. & London, L. Future Commercial Aviation Trends. in *Israel Annual Conference on Aerospace Sciences* (2012).

138 *Why the future of batteries is lithium and why their impact will be bigger than you think* (Energy Post, 2017). https://energypost.eu/future-batteries-lithium-impact-will-bigger-think/?from=singlemessage&isappinstalled=0

139 Aurbach, D., McCloskey, B. D., Nazar, L. F. & Bruce, P. G. Advances in understanding mechanisms underpinning lithium–air batteries. *Nat. Energy* **1**, 1-11 (2016).

140 *Lithium-sulfur batteries: from materials understanding to device integration* (Yi Cui, 2017). https://www.energy.gov/sites/prod/files/2018/06/f52/bat361_cui_2018_o.pdf

141 Zhang, J.-G., Wang, D., Xu, W., Xiao, J. & Williford, R. E. Ambient operation of Li/Air batteries. *J. Power Sources* **195**, 4332-4337 (2010).

142 Park, J. O. et al. A 1000 Wh kg− 1 Li–Air battery: Cell design and performance. *J. Power Sources* **419**, 112-118 (2019).

143 Lee, H. C. et al. High-energy-density Li-O2 battery at cell scale with folded cell structure. *Joule* **3**, 542-556 (2019).

144 *Mineral Commodity Summaries 2020* (USGS, 2020). https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

145 *What do we know about next-generation NMC 811 cathode?* (Research Interfaces, 2018). https://researchinterfaces.com/know-next-generation-nmc-811-cathode/

146 *Advanced battery materials for xEV and high-performance consumer products* (BASF, 2014).

147 Ryu, H.-H., Park, K.-J., Yoon, C. S. & Sun, Y.-K. Capacity Fading of Ni-Rich Li [Ni x Co y Mn1–x–y] O2 (0.6≤ x≤ 0.95) Cathodes for High-Energy-Density Lithium-Ion Batteries: Bulk or Surface Degradation? *Chem. Mater.* **30**, 1155-1163 (2018).

148 *Process development and manufacturing R&D at the national laboratories* (Argonne National Laboratory, 2016). https://www.energy.gov/sites/prod/files/2018/03/f49/FY2016_APR_Advanced_Batteries_R%26D_Part-3of5-opt.pdf

149 *Supplementary materials for cobalt in lithium-ion batteries* (Science, 2020).

150 Chae, S., Ko, M., Kim, K., Ahn, K. & Cho, J. Confronting issues of the practical implementation of Si anode in high-energy lithium-ion batteries. *Joule* **1**, 47-60 (2017).

151 Kumar, R. R. & Alok, K. Adoption of electric vehicle: A literature review and prospects for sustainability. *Journal of Cleaner Production* **253**, 119911 (2020).

152 Wells, P. & Nieuwenhuis, P. Transition failure: Understanding continuity in the automotive industry. *Technological Forecasting and Social Change* **79**, 1681-1692 (2012).

153 Baumstark, L. et al. REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geosci. Model Dev.* **14**, 6571-6603 (2021).

154 *PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective Life Cycle Assessment using Integrated Assessment Models* (2021). https://github.com/romainsacchi/premise

155 Chengjian, X. et al. Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030. *Submitted to Nature Communications* (2022).

156 Change, I. C. (Cambridge Univ. Press, 2013).

157 Steubing, B., de Koning, D., Haas, A. & Mutel, C. L. The Activity Browser — An open source LCA software building on top of the brightway framework. *Software Impacts* **3**, 100012 (2020).

158 Wernet, G. et al. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment* **21**, 1218-1230 (2016).

159 O'Neill, B. C. et al. A new scenario framework for climate change research: the concept of

shared socioeconomic pathways. *Climatic Change* **122**, 387-400 (2014).

160 Harpprecht, C., van Oers, L., Northey, S. A., Yang, Y. & Steubing, B. Environmental impacts of key metals' supply and low-carbon technologies are likely to decrease in the future. *Journal of Industrial Ecology* **25**, 1543-1559 (2021).

161 van der Meide, M., Harpprecht, C., Northey, S., Yang, Y. & Steubing, B. Effects of the energy transition on environmental impacts of cobalt supply: A prospective life cycle assessment study on future supply of cobalt. *Journal of Industrial Ecology* **n/a** (2022).

162 *GLOBAL ALUMINIUM CYCLE 2019* (International Aluminium Institute, 2019). https://alucycle.world-aluminium.org/public-access/

163 Ambrose, H. & Kendall, A. Understanding the future of lithium: Part 1, resource model. *Journal of Industrial Ecology* **24**, 80-89 (2020).

164 Ambrose, H. & Kendall, A. Understanding the future of lithium: Part 2, temporally and spatially resolved life-cycle assessment modeling. *Journal of Industrial Ecology* **24**, 90-100 (2020).

165 *Environmental impact assessment report in China* (Eiafans, 2022). http://www.eiafans.com/forum.php

166 Erakca, M. et al. Energy flow analysis of laboratory scale lithium-ion battery cell production. *iScience* **24**, 102437 (2021).

167 Bouter, A. & Guichet, X. The greenhouse gas emissions of automotive lithium-ion batteries: A statistical review of life cycle assessment studies. *Journal of Cleaner Production*, 130994 (2022).

168 Bieker, G. A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars. *communications* **49**, 847129-847102 (2021).

169 Yang, X.-G., Liu, T. & Wang, C.-Y. Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles. *Nature Energy* **6**, 176-185 (2021).

170 *Tesla Gigafactory* (Tesla, 2022). https://www.tesla.com/gigafactory

171 Kelly, J. C., Wang, M., Dai, Q. & Winjobi, O. Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. *Resources, Conservation and Recycling* **174**, 105762 (2021).

172 Ratvik, A. P., Mollaabbasi, R. & Alamdari, H. Aluminium production process: from Hall–Héroult to modern smelters. *ChemTexts* **8**, 10 (2022).

173 Tilley, J. Automation, robotics, and the factory of the future. *McKinsey. https://www. mckinsey.*

com/business-functions/operations/our-insights/automation-robotics-and-the-factory-of-the-future (2017).

174 Manthiram, A., Yu, X. & Wang, S. Lithium battery chemistries enabled by solid-state electrolytes. *Nature Reviews Materials* **2**, 16103 (2017).

175 European, C. et al. *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA : final report*. (Publications Office, 2020).

176 Albatayneh, A., Assaf, M. N., Alterman, D. & Jaradat, M. Comparison of the overall energy efficiency for internal combustion engine vehicles and electric vehicles. *Rigas Tehniskas Universitates Zinatniskie Raksti* **24**, 669-680 (2020).

177 Richardson, D. B. Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews* **19**, 247-254 (2013).

178 Xu, C. et al. Future greenhouse gas emissions of automotive lithium-ion battery cell production. *submitted to Resources, Conservation & Recycling* (2022).

179 *Greenhouse Gas Emissions from a Typical Passenger Vehicle* (United States Environmental Protection Agency, 2022). https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

180 Luderer, G. et al. Description of the REMIND model (Version 1.6). (2015).

181 *The road ahead for e-mobility* (McKinsey, 2020). https://www.mckinsey.com/~/media/mckinsey/industries/automotive%20and%20assembly/our%20insights/the%20road%20ahead%20for%20e%20mobility/the-road-ahead-for-e-mobility-vf.pdf

182 *THE GLOBAL BATTERY ARMS RACE: LITHIUM-ION BATTERY GIGAFACTORIES AND THEIR SUPPLY CHAIN* (The Oxford Institute for Energy Studies, 2021). https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/02/THE-GLOBAL-BATTERY-ARMS-RACE-LITHIUM-ION-BATTERY-GIGAFACTORIES-AND-THEIR-SUPPLY-CHAIN.pdf

183 *Lithium-ion battery supply chain technology development and investment opportunities* (Benchmark Mineral Intelligence, 2020). https://www.benchmarkminerals.com/wp-content/uploads/20200608-Vivas-Kumar-Carnegie-Mellon-Battery-Seminar-V1.pdf

184 Luksch, U., Steinbach, N. & Markosova, K. (2006).

185 Dunn, J. B., Gaines, L., Sullivan, J. & Wang, M. Q. Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries. *Environmental science & technology* **46**, 12704-12710 (2012).

186 Larouche, F. et al. Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond. *Materials* **13** (2020).

187 Greenblatt, J. B. & Saxena, S. Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. *Nature Climate Change* **5**, 860-863 (2015).

188 Lund, P. D., Lindgren, J., Mikkola, J. & Salpakari, J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews* **45**, 785-807 (2015).

189 Palensky, P. & Dietrich, D. Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. *IEEE Transactions on Industrial Informatics* **7**, 381-388 (2011).

190 Brown, T., Schlachtberger, D., Kies, A., Schramm, S. & Greiner, M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy* **160**, 720-739 (2018).

191 Naumann, M., Schimpe, M., Keil, P., Hesse, H. C. & Jossen, A. Analysis and modeling of calendar aging of a commercial LiFePO4/graphite cell. *Journal of Energy Storage* **17**, 153-169 (2018).

192 Guerra, O. J. Beyond short-duration energy storage. *Nature Energy* **6**, 460-461 (2021).

193 *Energy Storage Grand Challenge: Energy Storage Market Report* (U.S. Department of Energy, 2020). https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Market%20Report%202020_0.pdf

194 *Electric Insights Quarterly* (Drax, 2019). https://www.drax.com/wp-content/uploads/2019/12/191202_Drax_Q3_Report.pdf

195 *Global EV Data Explorer* (IEA, 2021). https://www.iea.org/articles/global-ev-data-explorer

196 *Electric vehicle capitals: Cities aim for all-electric mobility* (The International Council on Clean Transportation, 2020). https://theicct.org/publications/electric-vehicle-capitals-update-sept2020

197 *Electric Vehicle Industry in India: Why Foreign Investors Should Pay Attention* (India Briefing, 2021). https://www.india-briefing.com/news/electric-vehicle-industry-in-india-why-foreign-investors-should-pay-attention-21872.html/

198 *The Rechargeable Battery Market and Main Trends 2018-2030* (Avicenne Energy, 2019). https://www.bpifrance.fr/content/download/76854/831358/file/02%20-%20Presentation%20Avicenne%20-%20Christophe%20Pillot%20-%2028%20Mai%202019.pdf

199 *MPG and Cost Calculator and Tracker* (Spritmonitor, 2020). https://www.spritmonitor.de/en/

200 Plötz, P., Funke, S. A., Jochem, P. & Wietschel, M. CO2 Mitigation Potential of Plug-in Hybrid Electric Vehicles larger than expected. *Scientific Reports* **7**, 16493 (2017).

201 Hoekstra, A. The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions. *Joule* **3**, 1412-1414 (2019).

202 Brooker, A. et al. (SAE International, 2015).

203 *Mitsubishi i-Miev charging cost and time calculator* (EVcompare.io, 2009). https://evcompare.io/cars/mitsubishi/mitsubishi_i-miev/charging/

204 *What does Elevated Self-discharge Do?* (Battery University, 2011). https://batteryuniversity.com/learn/article/elevating_self_discharge

205 *BatPaC: Battery Manufacturing Cost Estimation* (Argonne National Laboratory, 2021). https://www.anl.gov/partnerships/batpac-battery-manufacturing-cost-estimation

206 *Climate Data Online: Dataset Discovery* (National Oceanic and Atmospheric Administration, 2021). https://www.ncdc.noaa.gov/cdo-web/datasets

207 *CLIMATE DATA FOR CITIES WORLDWIDE* (CLIMATE-DATA.ORG, 2021). https://en.climate-data.org/

208 *Climates for travelers. Information on the climates in the world to plan a trip* (Climates to travel, 2021). https://www.climatestotravel.com/

209 *Climate Zone Finder* (Weather and Climate, 2021). https://tcktcktck.org/

210 Uddin, K., Dubarry, M. & Glick, M. B. The viability of vehicle-to-grid operations from a battery technology and policy perspective. *Energy Policy* **113**, 342-347 (2018).

211 Safari, M., Morcrette, M., Teyssot, A. & Delacourt, C. Multimodal Physics-Based Aging Model for Life Prediction of Li-Ion Batteries. *Journal of The Electrochemical Society* **156**, A145 (2009).

212 Zhang, Y. et al. Identifying degradation patterns of lithium ion batteries from impedance spectroscopy using machine learning. *Nat. Commun.* **11**, 1706 (2020).

213 Edge, J. S. et al. Lithium ion battery degradation: what you need to know. *Physical Chemistry Chemical Physics* **23**, 8200-8221 (2021).

214 Safari, M. & Delacourt, C. Modeling of a Commercial Graphite/LiFePO4 Cell. *Journal of The Electrochemical Society* **158**, A562 (2011).

215 Schimpe, M. et al. Comprehensive Modeling of Temperature-Dependent Degradation Mechanisms in Lithium Iron Phosphate Batteries. *Journal of The Electrochemical Society* **165**, A181-A193 (2018).

216 Peterson, S. B., Apt, J. & Whitacre, J. F. Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization. *Journal of Power Sources* **195**, 2385-2392

(2010).

217 Martinez-Laserna, E. et al. Technical Viability of Battery Second Life: A Study From the Ageing Perspective. *IEEE Transactions on Industry Applications* **54**, 2703-2713 (2018).

218 Neubauer, J., Pesaran, A., Williams, B., Ferry, M. & Eyer, J. Techno-Economic Analysis of PEV Battery Second Use: Repurposed-Battery Selling Price and Commercial and Industrial End-User Value. (Sponsor Org.: USDOE Office of Energy Efficiency and Renewable Energy (EERE), Vehicle Technologies Office (EE-3V)).

219 Thompson, A. W. Economic implications of lithium ion battery degradation for Vehicle-to-Grid (V2X) services. *Journal of Power Sources* **396**, 691-709 (2018).

220 DeRousseau, M., Gully, B., Taylor, C., Apelian, D. & Wang, Y. Repurposing Used Electric Car Batteries: A Review of Options. *JOM* **69**, 1575-1582 (2017).

221 Reinhardt, R., Christodoulou, I., Gassó-Domingo, S. & Amante García, B. Towards sustainable business models for electric vehicle battery second use: A critical review. *Journal of Environmental Management* **245**, 432-446 (2019).

222 Casals, L. C., Amante García, B. & Canal, C. Second life batteries lifespan: Rest of useful life and environmental analysis. *Journal of Environmental Management* **232**, 354-363 (2019).

223 Podias, A. et al. Sustainability Assessment of Second Use Applications of Automotive Batteries: Ageing of Li-Ion Battery Cells in Automotive and Grid-Scale Applications. *World Electric Vehicle Journal* **9** (2018).

224 *The Present & Future Of Vehicle-To-Grid Technology* (CleanTechnica, 2020). https://cleantechnica.com/2020/09/05/the-present-future-of-vehicle-to-grid-technology/

225 Zonneveld, J. A. Increasing participation in V2G through contract elements: Examining the preferences of Dutch EV users regarding V2G contracts using a stated choice experiment.

226 Anwar, M. B. et al. Assessing the value of electric vehicle managed charging: a review of methodologies and results. *Energy & Environmental Science* (2022).

227 *A Vision for a Sustainable Battery Value Chain in 2030* (2019). https://www.globalbattery.org/media/publications/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf

228 Sapunkov, O., Pande, V., Khetan, A., Choomwattana, C. & Viswanathan, V. Quantifying the promise of 'beyond' Li–ion batteries. *Translational Materials Research* **2**, 045002 (2015).

229 Srdic, S. & Lukic, S. Toward Extreme Fast Charging: Challenges and Opportunities in Directly Connecting to Medium-Voltage Line. *IEEE Electrification Magazine* **7**, 22-31 (2019).

230 *What can 6,000 electric vehicles tell us about EV battery health?* (GEOTAB, 2020).

https://www.geotab.com/blog/ev-battery-health/

231 Park, Y.-U. et al. A New High-Energy Cathode for a Na-Ion Battery with Ultrahigh Stability. *Journal of the American Chemical Society* **135**, 13870-13878 (2013).

232 Alam, M. et al. Real-Time Smart Parking Systems Integration in Distributed ITS for Smart Cities. *Journal of Advanced Transportation* **2018**, 1485652 (2018).

233 Giordano, V. & Fulli, G. A business case for Smart Grid technologies: A systemic perspective. *Energy Policy* **40**, 252-259 (2012).

234 Zheng, Y. et al. Electric Vehicle Battery Charging/Swap Stations in Distribution Systems: Comparison Study and Optimal Planning. *IEEE Transactions on Power Systems* **29**, 221-229 (2014).

235 *Innovation in Batteries and Electricity Storage* (IEA, 2020). https://www.iea.org/reports/innovation-in-batteries-and-electricity-storage

236 *Global energy transformation: A roadmap to 2050 (2019 edition)* (IRENA, 2019). https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition

237 *Electricity storage and renewables: Costs and markets to 2030* (IRENA, 2017). https://www.irena.org/publications/2017/oct/electricity-storage-and-renewables-costs-and-markets

238 *Energy Storage Investments Boom As Battery Costs Halve in the Next Decade* (BloombergNEF, 2019). https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/

239 *Global EV Outlook 2021* (IEA, 2021). https://www.iea.org/reports/global-ev-outlook-2021

240 Elwert, T., Hua, Q. S. & Schneider, K. Recycling of lithium iron phosphate batteries: future prospects and research needs. in *Materials Science Forum* 49-68(Trans Tech Publ).

241 Soundharrajan, V. et al. The advent of manganese-substituted sodium vanadium phosphate-based cathodes for sodium-ion batteries and their current progress: a focused review. *Journal of Materials Chemistry A* **10**, 1022-1046 (2022).

242 Zeng, X. et al. Commercialization of Lithium Battery Technologies for Electric Vehicles. *Advanced Energy Materials* **9**, 1900161 (2019).

243 Allwood, J. M., Ashby, M. F., Gutowski, T. G. & Worrell, E. Material efficiency: A white paper. *Resources, Conservation and Recycling* **55**, 362-381 (2011).

244 McManus, M. C. Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Applied Energy* **93**, 288-295 (2012).

245 Child, M., Breyer, C., Bogdanov, D. & Fell, H.-J. The role of storage technologies for the transition to a 100% renewable energy system in Ukraine. *Energy Procedia* **135**, 410-423 (2017).

246 Lipu, M. S. H. et al. A review of state of health and remaining useful life estimation methods for lithium-ion battery in electric vehicles: Challenges and recommendations. *Journal of Cleaner Production* **205**, 115-133 (2018).

247 *Lithium Prices Surge on Increased Battery Demands* (Foley & Lardner LLP, 2022). https://www.foley.com/en/insights/publications/2022/04/lithium-prices-surge-on-increased-battery-demands

248 *Why lithium stocks are falling despite surging demand for EVs* (Money magazine, 2022). https://www.moneymag.com.au/why-lithium-stocks-are-falling-despite-surging-demand-for-evs

249 Eddy, J. et al. Metal mining constraints on the electric mobility horizon. (2018).

250 *The supply of critical raw materials endangered by Russia's war on Ukraine* (OECD, 2022). https://www.oecd.org/ukraine-hub/policy-responses/the-supply-of-critical-raw-materials-endangered-by-russia-s-war-on-ukraine-e01ac7be/

251 Sen, P. K. Metals and materials from deep sea nodules: an outlook for the future. *International Materials Reviews* **55**, 364-391 (2010).

252 *Billionaire group invests into mining project in Greenland for e-transportation* (POLAR JOURNAL, 2022). https://polarjournal.ch/en/2022/08/11/billionaire-group-invests-into-mining-project-in-greenland-for-e-transportation/

253 Curry, C. Lithium-ion battery costs and market. *Bloomberg New Energy Finance* **5**, 4-6 (2017).