Driving the sustainable transition: battery material dynamics and emission assessments of EU electric mobility

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References

References

Abdelbaky, M., Peeters, J.R., Dewulf, W., 2021. On the influence of second use, future battery technologies, and battery lifetime on the maximum recycled content of future electric vehicle batteries in Europe. Waste Management 125, 1 – 9.

ACEA, 2020. Making The Transition to Zero-Emission Mobility.

Albertsen, L., Richter, J.L., Peck, P., Dalhammar, C., Plepys, A., 2021. Circular business models for electric vehicle lithium-ion batteries: An analysis of current practices of vehicle manufacturers and policies in the EU. Resour Conserv Recycl 172, 105658.

Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A., Meinert, L.D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., Yakovleva, N., 2017. Mineral supply for sustainable development requires resource governance. Nature 543, 367 – 372.

Amatuni, L., Ottelin, J., Steubing, B., Mogollón, J.M., 2020. Does car sharing reduce greenhouse gasemissions? Assessing the modal shift and lifetime shift rebound effects from a life cycle perspective. J Clean Prod 266, 121869.

Amatuni, L., Yamamoto, T., Baldé, C.P., Clemm, C., Mogollón, J.M., 2023. Quantifying total lifetimes of consumer products: Stochastic modelling accounting for second-hand use and establishing an open-collaborative database. Resour Conserv Recycl 197, 107103.

Arvidsson, R., Tillman, A.-M., Sandén, B.A., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2017. Environmental Assessment of Emerging Technologies Recommendations for Prospective LCA. J Ind Ecol 22, 6.

AR5 Climate Change 2013: The Physical Science Basis — IPCC, 2022
URL https://www.ipcc.ch/report/ar5/wg1/ (accessed 10.25.2022).

Arshad, F., Lin, J., Manurkar, N., Fan, E., Ahmad, A., Tariq, M.-N., Wu, F., Chen, R., Li, L., 2022. Life Cycle Assessment of Lithium-ion Batteries: A Critical Review. Resour Conserv Recycl 180, 106164.

Asian Batteries Power Global EV Fleet. Asian Batteries Power Global EV Fleet.
URL https://www.statista.com/chart/26584/worldwide-market-share-of-the-biggest-electric-vehicle-battery-makers/ (accessed 03.31.2022).

Ausfuhrkontrolle, B. für W. und, 2020. Integrated National Energy and Climate Plan for Germany.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E., Heidrich, O., 2021. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat Sustain 4, 71–79.

Bicer, Y., Dincer, I., 2018. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. Resour Conserv Recycl 132, 141 – 157.

Bobba, S., Mathieux, F., Blengini, G.A., 2019. How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. Resour. Conserv. Recycl. 145, 279 – 291.

Berger, K., Schöggl, J.P., Baumgartner, R.J., 2022. Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. J Clean Prod 353, 131492.

Burchart-Korol, D., Jursova, S., Folęga, P., Pustejovska, P., 2020. Life cycle impact assessment of electric vehicle battery charging in European Union countries. J Clean Prod 257, 120476.

Bradley, J.E., Auping, J.E., Kleijn, W.L., Kwakkel, R.H., Sprecher, J.H., 2024. Reassessing tin circularity and criticality. J Ind Ecol 28, 232 – 246.

Bridge, G., Faigen, E., 2022. Towards the lithium-ion battery production network: Thinking beyond mineral supply chains. Energy Res Soc Sci 89, 1 – 19.

British Geological Survey, 2021. Global material flows of lithium for the lithium-ion and lithium iron phosphate battery markets.

Canals Casals, L., Barbero, M., Corchero, C., 2019. Reused second life batteries for aggregated demand response services. J Clean Prod 212, 99 – 108.

Catton, J.W.A., Walker, S.B., McInnis, P., Fowler, M., Fraser, R.A., Young, S.B., Gaffney, B., 2019. Design and analysis of the use of re-purposed electric vehicle batteries for stationary energy storage in canada. Batteries 5, 14.

Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M., Chen, Z., Zachary P. Cano, 2018. Batteries and fuel cells for emerging electric vehicle markets. Nat. Energy 3, 279 – 289.

Campestrini, M., Mock, P., 2021. European vehicle market statistics. International Council on Clean Transportation. 1 -50.

CBS Open Data Source.
URL https://www.cbs.nl/nl-nl/onze-diensten/open-data (accessed 11.16.2019).

Chen, W., Sun, X., Liu, L., Liu, X., Zhang, R., Zhang, S., Xue, J., Sun, Q., Wang, M., Li, X., Yang, J., Hertwich, E., Ge, Q., Liu, G., 2022. Carbon neutrality of China's passenger car sector requires coordinated short-term behavioral changes and long-term technological solutions. One Earth 5, 875 – 891.

Chen, M., Ma, X., Chen, B., Arsenault, R., Karlson, P., Simon, N., Wang, Y., 2019. Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries. Joule 3, 2622–2646.

Chen, W.Q., Graedel, T.E., 2012. Anthropogenic Cycles of the Elements: A Critical Review. Environ Sci Technol 46, 8574 – 8586.

Chirumalla, K., Kulkov, I., Vu, F., Rahic, M., 2023. Second life use of Li-ion batteries in the heavy-duty vehicle industry: Feasibilities of remanufacturing, repurposing, and reusing approaches. Sustain Prod Consum 42, 351 – 366.

CO_2 emission performance standards for cars and vans.
URL https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en (accessed 12.20.2020).

Cox, B., Bauer, C., Mendoza Beltran, A., van Vuuren, D.P., Mutel, C.L., 2020. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Appl Energy 269, 115021.

Cox, B., Mutel, C.L., Bauer, C., Mendoza Beltran, A., Van Vuuren, D.P., 2018. Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles. Environ Sci Technol 52, 4989 – 4995.

Cozzi, L., Gould, T., Bouckart, S., Crow, D., Kim, T. Y., McGlade, C., Olejarnik, P., Wanner, B., Wetzel, D., 2020. World Energy Outlook 2020.

Crabtree, G., 2019. The coming electric vehicle transformation: A future electric transportation market will depend on battery innovation. Science 366, 422 – 424.

da Silva Lima, L., Cocquyt, L., Mancini, L., Cadena, E., Dewulf, J., 2022. The role of raw materials to achieve the Sustainable Development Goals: Tracing the risks and positive contributions of cobalt along the lithium-ion battery supply chain. J Ind Ecol. 27, 777 – 794.

Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019a. Life cycle analysis of lithium-ion batteries for automotive applications. Batteries 5, 48.

Data and maps — European Environment Agency, IEA.
URL https://www.eea.europa.eu/data-and-maps (accessed 02.24.2021).

Davis, K., Demopoulos, G.P., 2023. Hydrometallurgical recycling technologies for NMC Li-ion battery cathodes: current industrial practice and new R&D trends. RSC Sustainability 1, 1932–1951.

Deetman, S., Pauliuk, S., Van Vuuren, D.P., Van Der Voet, E., Tukker, A., 2018. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. Environ. Sci. Technol 52, 4950 – 4959.

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

Degen, F., Winter, M., Bendig, D., Tübke, & J., 2023. Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells. Nat Energy 8, 1284 – 1295.

de Souza, L.L.P., Lora, E.E.S., Palacio, J.C.E., Rocha, M.H., Renó, M.L.G., Venturini, O.J., 2018. Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil. J Clean Prod 203, 444 – 468.

Deprez, A., Leadley, P., Dooley, K., Williamson, P., Cramer, W., Gattuso, J.P., Rankovic, A., Carlson, E.L., Creutzig, F., 2024. Sustainability limits needed for CO_2 removal. Science 383, 484–486.

Dewulf, J., Van der Vorst, G., Denturck, K., Van Langenhove, H., Ghyoot, W., Tytgat, J., Vandeputte, K., 2010. Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings. Resour Conserv Recycl 54, 229–234.

Dunn, J., James, C., Gaines, L., Gallagher, K., Dai, Q., Kelly, J., 2015. Material and energy flows in the production of cathode and anode materials for lithium ion batteries. J Chem Inf Model 53, 1689 – 1699.

Dunn, J.B., Gaines, L., Kelly, J.C., James, C., Gallagher, K.G., 2015. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy Environ Sci 8, 158 – 168.

Dunn, J., Slattery, M., Kendall, A., Ambrose, H., Shen, S., 2021. Circularity of Lithium-Ion Battery Materials in Electric Vehicles. Environ Sci Technol 55, 5189–5198.

Dominish, E., Florin, N., Wakefield-Rann, R., 2021. Reducing new mining for electric vehicle battery metals: responsible sourcing through demand reduction strategies and recycling.

Dong, D., Tukker, A., der Voet, E., 2019. Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. J. Ind. Ecol. 23, 1363 – 1380.

Dutch Ministry of Economic Affairs and Climate, 2019. National Climate Agreement-The Netherlands 1 – 247.

Ellingsen, L.A.W., Majeau-Bettez, G., Singh, B., Srivastava, A.K., Valøen, L.O., Strømman, A.H., 2014. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. J Ind Ecol 18, 113–124.

Ellingsen, L.A.-W., Singh, B., Strømman, A.H., 2016. The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environmental Research Letters 11, 054010.

Energy Storage News, 2020. CATL batteries energise Powin's new 'long duration, long life' Li-Ion systems. (accessed 01.18.2021)

Energy News, 2024. Stellantis and Orano cancel their battery recycling project. URL https://energynews.pro/en/stellantis-and-orano-cancel-their-battery-recycling-project (accessed 12.14.2024).

European Automobile Manufacturers' Association, 2023. Statistic-ACEA. URL https://www.acea.auto (accessed 12.24.2023).

European Commission, 2023. Database - Eurostat. URL https://ec.europa.eu/eurostat/data/database (accessed 12.16.2023).

European Commission, 2024. Database - Eurostat. URL https://ec.europa.eu/eurostat/data/database (accessed 03.24.2024).

European Commission, 2019a. The European Green Deal.

European Commission, 2019b. Setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011. Official Journal of the European Union 62, 13 – 53.

European Commission, 2019c. Transport in the European Union - Current Trends and Issues.

European Commission, 2022a. "Fit for 55" legislation.

European Commission, 2022b. Proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006 / 66 / EC and amending Regulation (EU) No 2019 / 1020.

Fishman, T., Myers, R.J., Rios, O., Graedel, T.E., 2018. Implications of emerging vehicle technologies on rare earth supply and demand in the United States. Resources 7, 9.

Fu, X., Beatty, D.N., Gaustad, G.G., Ceder, G., Roth, R., Kirchain, R.E., Bustamante, M., Babbitt, C., Olivetti, E.A., 2020. Perspectives on Cobalt Supply through 2030 in the Face of Changing Demand. Environ Sci Technol 54, 2985 – 2993.

Geels, F.W., Kern, F., Clark, W.C., 2023. Sustainability transitions in consumption-production systems. Proc Natl Acad Sci 120, e2310070120.

Ginster, R., Blömeke, S., Popien, J. L., Scheller, C., Cerdas, F., Herrmann, C., Spengler, T. S., Pauliuk, S., 2024. Circular battery production in the EU: Insights from integrating life cycle assessment into system dynamics modeling on recycled content and environmental impacts. J Ind Ecol 28, 1165 – 1338.

Gourcerol, B., Gloaguen, E., Melleton, J., Tuduri, J., Galiegue, X., 2019. Re-assessing the European lithium resource potential – A review of hard-rock resources and metallogeny. Ore Geol Rev 109, 494 – 519.

Godoy León, M.F., Blengini, G.A., Dewulf, J., 2020. Cobalt in end-of-life products in the EU, where does it end up? - The MaTrace approach. Resour. Conserv. Recycl. 158, 104842.

Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What do we know about metal recycling rates? J. Ind. Ecol. 15, 355 – 366.

Gracia, M., Paz, M.J., Rísquez, M., 2024. Analysis of the transition to electric vehicles in Europe from a core-periphery approach. Structural Change and Economic Dynamics 69, 652 – 663.

Green Car Congress, 2024. Eramet suspends ReLieVe battery recycling project in Europe. URL https://www.greencarcongress.com/2024/10/20241029-eramet.html (accessed 12.14.2024).

Greenwood, M., Wentker, M., Leker, J., 2021. A region-specific raw material and lithium-ion battery criticality methodology with an assessment of NMC cathode technology. Appl Energy 302, 117512.

Greim, P., Solomon, A.A., Breyer, C., 2020. Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation. Nat Commun 11, 1 – 11.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How Circular is the Global Economy? An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. J Ind Ecol 19, 765 – 777.

Haidar, B., Aguilar Rojas, M.T., 2022. The relationship between public charging infrastructure deployment and other socio-economic factors and electric vehicle adoption in France. Research in Transportation Economics 95, 101208.

Hache, E., Seck, G.S., Simoen, M., Bonnet, C., Carcanague, S., 2019. Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport. Appl. Energy 240, 6 – 25.

Hao, H., Mu, Z., Jiang, S., Liu, Z., Zhao, F., 2017. GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China. Sustainability 9, 504.

Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2013a. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J Ind Ecol 17, 53 – 64.

Helander, H., Ljunggren, M., 2023. Battery as a service: Analysing multiple reuse and recycling loops. Resour Conserv Recycl 197, 107191.

Held, M., Rosat, N., Georges, G., Pengg, H., Boulouchos, K., 2021. Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. European Transport Research Review 13, 1–13.

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

Hellenic Republic - Ministry of the Environment and Energy, 2020. National Energy and Climate Plan for Hungry.

Horn, S., Gunn, A.G., Petavratzi, E., Shaw, R.A., Eilu, P., Törmänen, T., Bjerkgård, T., Sandstad, J.S., Jonsson, E., Kountourelis, S., Wall, F., 2021. Cobalt resources in Europe and the potential for new discoveries. Ore Geol Rev 130, 103915.

Huang, S., Hodge, B.M.S., Taheripour, F., Pekny, J.F., Reklaitis, G. V., Tyner, W.E., 2011. The effects of electricity pricing on PHEV competitiveness. Energy Policy 39, 1552 – 1561.

Huisman, J., Habib, H., Brechu, M.G., Downes, S., Herreras, L., Lovik, A.N., Wager, P., Cassard, D., Tertre, F., Mahlitz, P., Rotter, S., Chancerel, P., Soderman, M.L., 2017. ProSUM: Prospecting secondary Raw Materials in the Urban Mine and Mining Wastes.

Hund, K., Porta, D. La, Fabregas, T.P., Laing, T., Drexhage, J., 2020. Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.

Hung, C.R., Kishimoto, P., Krey, V., Strømman, A.H., Majeau-Bettez, G., 2022. ECOPT2: An adaptable life cycle assessment model for the environmentally constrained optimization of prospective technology transitions. J Ind Ecol 26, 1616–1630.

Hung, C.R., Völler, S., Agez, M., Majeau-Bettez, G., Strømman, A.H., 2021. Regionalized climate footprints of battery electric vehicles in Europe. J Clean Prod 322, 129052.

International Energy Agency, 2019. Data & Statistics – IEA. Electricity Information. URL https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy supply&indicar or=TPESbySource (accessed 02.24.2021).

International Energy Agency, 2018. Global EV Outlook 2018 - Towards cross-modal electrification.

International Energy Agency, 2020. Global EV Outlook 2020 - Entering the decade of electric drive?

International Energy Agency 2021. Global EV Outlook 2021 - Accelerating ambitions despite the pandemic.

International Energy Agency, 2023. Global EV Outlook 2023 - Catching up with climate ambitions.

International Energy Agency, 2024. Global EV Outlook 2024 - Moving towards increased affordability.

International Council on Clean Transportation. 2021. Beyond road vehicles: Survey of zero-emission technology options across the transport sector.

Iqbal, H., Sarwar, S., Kirli, D., Shek, J.K.H., Kiprakis, A.E., 2023. A survey of second-life batteries based on techno-economic perspective and applications-based analysis. Carbon Neutrality 2–8.

Istrate, R., Mas-Fons, A., Beylot, A., Northey, S., Vaidya, K., Sonnemann, G., Kleijn, R., Steubing, B., 2024. Decarbonizing lithium-ion battery primary raw materials supply chain. Joule. 8, 2992–3016.

Janek, J., Zeier, W.G., 2016. A solid future for battery development. Nat Energy 1,16141.

Jones, B., Elliott, R.J.R., Nguyen-Tien, V., 2020. The EV revolution: The road ahead for critical raw materials demand. Appl Energy 280, 115072.

Jos. G. J. Olivier, J.A.H.W.P., 2019. Trends in Global CO_2 and Total Greenhouse Gas Emissions. PBL Netherlands Environmental Assessment Agency

Jin, S., Mu, D., Lu, Z., Li, R., Liu, Z., Wang, Y., Tian, S., Dai, C., 2022. A comprehensive review on the recycling of spent lithium-ion batteries: Urgent status and technology advances. J Clean Prod 340, 130535.

Kallitsis, E., Lindsay, J.J., Chordia, M., Wu, B., Offer, G.J., Edge, J.S., 2024. Think global act local: The dependency of global lithium-ion battery emissions on production location and material sources. J Clean Prod 449, 141725.

Kastanaki, E., Giannis, A., 2023. Dynamic estimation of end-of-life electric vehicle batteries in the EU-27 considering reuse, remanufacturing and recycling options. J Clean Prod 393, 136349.

Kelly, J.C., Dai, Q., Wang, M., 2020. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. Mitig Adapt Strateg Glob Chang. 25, 371–396.

Kim, H.C., Wallington, T.J., Arsenault, R., Bae, C., Ahn, S., Lee, J., 2016. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis. Environ. Sci. Technol. 50, 7715 – 7722.

Koide, R., Yamamoto, H., Nansai, K., Murakami, S., 2023. Agent-based model for assessment of multiple circular economy strategies: Quantifying product-service diffusion, circularity, and sustainability. Resour Conserv Recycl 199, 107216.

Küfeoğlu, S., Khah Kok Hong, D., 2020. Emissions performance of electric vehicles: A case study from the United Kingdom. Appl Energy 260, 114241.

Kraytsberg, A., Ein-Eli, Y., Kraytsberg, A., Ein-Eli, Y., 2012. Higher, stronger, better ... A review of 5 volt cathode materials for advanced lithium-ion batteries. Adv Energy Mater 2, 922 – 939.

Kumar Nayak, P., Yang, L., Brehm, W., Adelhelm, P., 2017. From Lithium-Ion to Sodium-Ion Batteries:Advantages, Challenges, and Surprises. Angewandte Chemie 57, 102–120.

Kucharavy, D., De Guio, R., 2011. Logistic substitution model and technological forecasting. Procedia Eng. 9, 402 – 416.

Kwade, A., Haselrieder, W., Leithoff, R., Modlinger, A., Dietrich, F., Droeder, K., 2018. Current status and challenges for automotive battery production technologies. Nat. Energy 3, 290 – 300.

Langkau, S., Steubing, B., Mutel, C., Ajie, M.P., Erdmann, L., Voglhuber-Slavinsky, A., Janssen, M., 2023. A stepwise approach for Scenario-based Inventory Modelling for Prospective LCA (SIMPL). International Journal of Life Cycle Assessment 28, 1169 – 1193.

Latini, D., Vaccari, M., Lagnoni, M., Orefice, M., Mathieux, F., Huisman, J., Tognotti, L., Bertei, A., 2022. A comprehensive review and classification of unit operations with assessment of outputs quality in lithium-ion battery recycling. J Power Sources 546, 231979.

Li, J., Yang, B., 2020. Analysis of greenhouse gas emissions from electric vehicle considering electric energy structure, climate and power economy of ev: A China case. Atmos Pollut Res 11, 1–11.

Li, W., Erickson, E.M., Manthiram, A., 2020. High-nickel layered oxide cathodes for lithium-based automotive batteries. Nat Energy 5, 26 – 34.

Lu, J., Fowler, M., Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. Nat Energy 3, 279 – 289.

Makuza, B., Tian, Q., Guo, X., Chattopadhyay, K., Yu, D., 2021. Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review. J Power Sources 491, 229622.

Mahmoudzadeh Andwari, A., Pesiridis, A., Rajoo, S., Martinez-Botas, R., Esfahanian, V., 2017. A review of Battery Electric Vehicle technology and readiness levels. Renewable and Sustainable Energy Reviews 78, 414–430.

Ma, X., Meng, Z., Bellonia, M.V., Spangenberger, J., Harper, G., Gratz, E., Olivetti, E., Arsenault, R., Wang, Y., 2025. The evolution of lithium-ion battery recycling. Nature Reviews Clean Technology 1, 75 – 94.

Mason, A.R., Bide, T., Wang, J., Morley, J., Arora, M., Yayla, A., Stegemann, J.A., Myers, R.J., 2025. Bayesian material flow analysis of the construction aggregate cycle in England. Resour Conserv Recycl 215, 108135.

Mathieu, L., 2020. Mission (almost) accomplished.

Mayyas, A., Steward, D., Mann, M., 2019. The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. Sustainable Materials and Technologies 19, e00087.

Melin, H.E., Rajaeifar, M.A., Ku, A.Y., Kendall, A., Harper, G., Heidrich, O., 2021. Global implications of the EU battery regulation. Science 373, 384 – 387.

Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D.P., Font Vivanco, D., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A., 2020. When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. J Ind Ecol 24, 64 – 79.

Mendoza Beltran, A., Prado, V., Font Vivanco, D., Henriksson, P.J.G., Guinée, J.B., Heijungs, R., 2018. Quantified Uncertainties in Comparative Life Cycle Assessment: What Can Be Concluded? Environ Sci Technol 52, 2152 – 2161.

Messagie, M., 2017. Life Cycle Analysis of the Climate Impact of Electric Vehicles. Transport and Environment, 1 – 14.

Milovanoff, A., Kim, H.C., De Kleine, R., Wallington, T.J., Posen, I.D., MacLean, H.L., 2019. A Dynamic Fleet Model of U.S Light-Duty Vehicle Lightweighting and Associated Greenhouse Gas Emissions from 2016 to 2050. Environ Sci Technol 53, 2199 – 2208.

Milovanoff, A., Posen, I.D., MacLean, H.L., 2020. Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nat Clim Chang 10, 1102 – 1107.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis.

Ministère de la Transition écologique, 2020. Integrated National Energy and Climate plan for France.

Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling metal stocks and flows: A review of dynamic material flow analysis methods. Environ Sci Technol 48, 2102 – 2113.

Murdock, Beth E, Toghill, Kathryn E, Tapia-Ruiz, Nuria, Murdock, B E, Toghill, K E, Tapia-Ruiz, N, 2021. A Perspective on the Sustainability of Cathode Materials used in Lithium-Ion Batteries. Adv Energy Mater 11, 2102028.

Navinkumar, T.M., Bharatiraja, C., 2025. Sustainable hydrogen energy fuel cell electric vehicles: A critical review of system components and innovative development recommendations. Renewable and Sustainable Energy Reviews. 215, 115601.

Nealer, R., Hendrickson, T.P., 2015. Review of Recent Lifecycle Assessments of Energy and Greenhouse Gas Emissions for Electric Vehicles. Current Sustainable/Renewable Energy Reports 2, 66–73.

Nong, D., Schandl, H., Lu, Y., Verikios, G., 2023. Resource efficiency and climate change policies to support West Asia’s move towards sustainability: A computable general equilibrium analysis of material flows. J Clean Prod 421, 139458.

Notter, D.A., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., Althaus, H. J., 2010. Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles. Environ. Sci. Technol. 44, 6550 – 6556.

Nurdiawati, A., Kumar Agrawal, T., 2022. Creating a circular EV battery value chain: End-of-life strategies and future perspective. Resour Conserv Recycl 185. 106484

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

Olsson, L., Fallahi, S., Schnurr, M., Diener, D., van Loon, P., 2018. Circular Business Models for Extended EV Battery Life. Batteries 4, 1 – 15.

Park, S., Taguchi, H., Kan, J., Han, S.H., Dunwoodie, M., Kim, C., Ha, V., 2016. EV battery makers.

Pauliuk, S., Müller, D.B., 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. Glob. Environ. Chang. 24, 132 – 142.

Pauliuk, S., Heeren, N., 2020. ODYM—An open software framework for studying dynamic material systems: Principles, implementation, and data structures. J Ind Ecol 24, 446 – 458.

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

Petrauskienė, K., Skvarnavičiūtė, M., Dvarionienė, J., 2020. Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. J Clean Prod 246, 119042.

Pelegov, D., Pontes, J., 2018. Main Drivers of Battery Industry Changes: Electric Vehicles - A Market Overview. Batteries 4, 65.

Peng, R., Tang, J.H.C.G., Yang, X., Meng, M., Zhang, J., Zhuge, C., 2024. Investigating the factors influencing the electric vehicle market share: A comparative study of the European Union and United States. Appl Energy 355, 122327.

Puig-Samper Naranjo, G., Bolonio, D., Ortega, M.F., García-Martínez, M.J., 2021. Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain. J Clean Prod 291, 125883.

Rajaeifar, M.A., Raugei, M., Steubing, B., Hartwell, A., Anderson, P.A., Heidrich, O., 2021. Life cycle assessment of lithium-ion battery recycling using pyrometallurgical technologies. J Ind Ecol 25, 1560 – 1571.

Rahimpour Golroudbary, S., Farfan, J., Lohrmann, A., Kraslawski, A., 2022. Environmental benefits of circular economy approach to use of cobalt. Global Environmental Change 76, 102568.

Rallo, H., Canals Casals, L., De La Torre, D., Reinhardt, R., Marchante, C., Amante, B., 2020. Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases. J Clean Prod 272, 122584.

RDW Open Data Source 2020. URL https://opendata.rdw.nl/en/brouse (accessed 01.14.2020).

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change 42, 153 – 168.

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

Richter, J.L., 2022. A circular economy approach is needed for electric vehicles. Nat Electron 5, 5 – 7.

Rizos, V., Urban, P., 2024. Barriers and policy challenges in developing circularity approaches in the EU battery sector: An assessment. Resour Conserv Recycl 209, 107800.

Ribeiro da Silva, E., Lohmer, J., Rohla, M., Angelis, J., 2023. Unleashing the circular economy in the electric vehicle battery supply chain: A case study on data sharing and blockchain potential. Resour Conserv Recycl 193, 106969.

Rogge, K.S., Goedeking, N., 2024. Challenges in accelerating net-zero transitions: insights from transport electrification in Germany and California. Environmental Research Letters 19, 044007.

Rosenberg, S., Kurz, L., Huster, S., Wehrstein, S., Kiemel, S., Schultmann, F., Reichert, F., Wörner, R., Glöser-Chahoud, S., 2023. Combining dynamic material flow analysis and life cycle assessment to evaluate environmental benefits of recycling – A case study for direct and hydrometallurgical closed-loop recycling of electric vehicle battery systems. Resour Conserv Recycl 198, 107145.

Rudola, A., Sayers, R., Wright, C.J., Barker, J., 2023. Opportunities for moderate-range electric vehicles using sustainable sodium-ion batteries. Nat Energy 8, 215 – 218.

Rufino Júnior, C.A., Riva Sanseverino, E., Gallo, P., Koch, D., Kotak, Y., Schweiger, H.G., Zanin, H., 2023. Towards a business model for second-life batteries – barriers, opportunities, uncertainties, and technologies. Journal of Energy Chemistry. 78, 507 – 525.

Santos da Silva, S.R., Hejazi, M.I., Iyer, G., Wild, T.B., Binsted, M., Miralles-Wilhelm, F., Patel, P., Snyder, A.C., Vernon, C.R., 2021. Power sector investment implications of climate impacts on renewable resources in Latin America and the Caribbean. Nat Commun 12, 1276.

Sanjuan, B., Gourcerol, B., Millot, R., Rettenmaier, D., Jeandel, E., Rombaut, A., 2022. Lithium-rich geothermal brines in Europe: An up-date about geochemical characteristics and implications for potential Li resources. Geothermics 101, 102385.

Santillán-Saldivar, J., Cimprich, A., Shaikh, N., Laratte, B., Young, S.B., Sonnemann, G., 2021. How recycling mitigates supply risks of critical raw materials: Extension of the geopolitical supply risk methodology applied to information and communication technologies in the European Union. Resour Conserv Recycl 164, 105108.

Sato, F.E.K., Nakata, T., 2020. Recoverability analysis of critical materials from electric vehicle lithium-ion batteries through a dynamic fleet-based approach for Japan. Sustain. 12, 147.

Schmuch, R., Wagner, R., Hörpel, G., Placke, T., Winter, M., 2018. Performance and cost of materials for lithium-based rechargeable automotive batteries. Nat. Energy 3, 267-278.

Schulz-Mönninghoff, M., Neidhardt, M., Niero, M., 2023. What is the contribution of different business processes to material circularity at company-level? A case study for electric vehicle batteries. J Clean Prod 382, 135232.

Schneider, E.L., Kindlein, W., Souza, S., Malfatti, C.F., 2009. Assessment and reuse of secondary batteries cells. J. Power Sources 189, 1264 – 1269.

Seck, G.S., Hache, E., Barnet, C., 2022. Potential bottleneck in the energy transition: The case of cobalt in an accelerating electro-mobility world. Resources Policy 75, 102516.

Seebauer, S., 2018. The psychology of rebound effects: Explaining energy efficiency rebound behaviours with electric vehicles and building insulation in Austria. Energy Res Soc Sci 46, 311–320.

Simas, M.S., Bly, K., Arega, M.A., Aponte, F.R., Silva, T.L., Wiebe, K.S., 2025. Sustainability effects of material demand by next-generation lithium-ion battery technologies: A global value chain perspective. Resour Conserv Recycl 219, 108294.

Singh, V., Singh, T., Higueras-Castillo, E., Liebana-Cabanillas, F.J., 2023. Sustainable road transportation adoption research: A meta and weight analysis, and moderation analysis. J Clean Prod 392, 136276.

Sihvonen, J., 2018. CNG and LNG for vehicles and ships--the facts.

Sommerville, R., Zhu, P., Rajaeifar, M.A., Heidrich, O., Goodship, V., Kendrick, E., 2021. A qualitative assessment of lithium ion battery recycling processes. Resour Conserv Recycl 165, 105219.

Song, J., Yan, W., Cao, H., Song, Q., Ding, H., Lv, Z., Zhang, Y., Sun, Z., 2019. Material flow analysis on critical raw materials of lithium-ion batteries in China. J. Clean. Prod 215, 570 – 581.

Sovacool, B.K., Ali, S.H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., Mulvaney, D., 2020. Sustainable minerals and metals for a low-carbon future. Science 367, 30 – 33.

Sovacool, B.K., Geels, F.W., Andersen, A.D., Grubb, M., Jordan, A.J., Kern, F., Kivimaa, P., Lockwood, M., Markard, J., Meadowcroft, J., Meckling, J., Moore, B., Raven, R., Rogge, K.S., Rosenbloom, D., Schmidt, T.S., Schot, J., Sharp, D., Stephenson, J., Vormedal, I., Yang, K., 2025. The acceleration of low-carbon transitions: Insights, concepts, challenges, and new directions for research. Energy Res Soc Sci 121, 103948.

Speirs, J., Contestabile, M., 2014. The Future of Lithium Availability for Electric Vehicle Batteries. Renew. Sustainable Energy Rev. 35, 183 – 193.

Sun, X., Hao, H., Zhao, F., Liu, Z., 2018. Global Lithium Flow 1994-2015: Implications for Improving Resource Efficiency and Security. Environ Sci Technol 52, 2827 – 2834.

Sun, X., Hao, H., Hartmann, P., Liu, Z., Zhao, F., 2019. Supply risks of lithium-ion battery materials: An entire supply chain estimation. Mater Today Energy 14, 100347.

Sun, X., Hao, H., Zhao, F., Liu, Z., 2019. The Dynamic Equilibrium Mechanism of Regional Lithium Flow for Transportation Electrification. Environ Sci Technol 53, 743 – 751.

Sun, X., Luo, X., Zhang, Z., Meng, F., Yang, J., 2020. Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. J Clean Prod 273, 123006

Sun, X., Liu, Z., Zhao, F., Hao, H., 2021. Global Competition in the Lithium-Ion Battery Supply Chain: A Novel Perspective for Criticality Analysis. Environ Sci Technol 55, 12180 – 12190.

Talens Peiró, L., Villalba Méndez, G., Ayres, R.U., 2013. Lithium: Sources, production, uses, and recovery outlook. JOM 65, 986 – 996.

Tanç, B., Arat, H.T., Baltacıoğlu, E., Aydın, K., 2019. Overview of the next quarter century vision of hydrogen fuel cell electric vehicles. Int J Hydrogen Energy 44, 10120 – 10128.

Tang, C., Sprecher, B., Tukker, A., Mogollón, J.M., 2021. The impact of climate policy implementation on lithium, cobalt and nickel demand: The case of the Dutch automotive sector up to 2040. Resources Policy 74, 102351.

Tang, C., Tukker, A., Sprecher, B., Mogollón, J.M., 2023. Assessing the European Electric-Mobility Transition: Emissions from Electric Vehicle Manufacturing and Use in Relation to the EU Greenhouse Gas Emission Targets. Environ Sci Technol 57, 44 – 52.

Tang, C., Tukker, A., Mogollón, J.M., 2025. The demand and recycling potential for lithium, cobalt, and nickel in the European electric-mobility transition. Environ Res Commun 7, 061007.

Tao, R., Xing, P., Li, H., Sun, Z., Wu, Y., 2022. Recovery of spent $LiCoO_2$ lithium-ion battery via environmentally friendly pyrolysis and hydrometallurgical leaching. Resour Conserv Recycl 176, 105921.

Ternel, C., Bouter, A., Melgar, J., 2021. Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: Comparison with greenhouse gas emissions of electric vehicles and forecast to 2030. Transp Res D Transp Environ 97, 102897.

Tian, G., Yuan, G., Aleksandrov, A., Zhang, T., Li, Z., Fathollahi-Fard, A.M., Ivanov, M., 2022. Recycling of spent Lithium-ion Batteries: A comprehensive review for identification of main challenges and future research trends. Sustainable Energy Technologies and Assessments 53, 102447.

Tisserant, A., Pauliuk, S., 2016. Matching global cobalt demand under different scenarios for co-production and mining attractiveness. J Econ Struct 5, 4.

Thompson, D.L., Hartley, J.M., Lambert, S.M., Shiref, M., Harper, G.D.J., Kendrick, E., Anderson, P., Ryder, K.S., Gaines, L., Abbott, A.P., 2020. The importance of design in lithium ion battery recycling-a critical review. Green Chemistry 22, 7585.

Tran, M.K., Rodrigues, M.-T.F., Kato, K., Babu, G., Ajayan, P.M., 2019. Deep eutectic solvents for cathode recycling of Li-ion batteries. Nat Energy 4, 339 – 345.

Tisserant, A., Pauliuk, S., 2016. Matching global cobalt demand under different scenarios for co-production and mining attractiveness. J. Econ. Struct. 5, 4.

Tsui, T., Venverloo, T., Benson, T., Duarte, F., 2024. Spatial optimization of circular timber hubs. npj Urban Sustainability 4, 13.

U.S. Geological Survey, 2023a. Cobalt Statistics and Information.

U.S. Geological Survey, 2023b. Lithium Statistics and Information.

U.S. Geological Survey, 2023c. Nickel Statistics and Information.

Usiskin, R., Lu, Y., Popovic, J., Law, M., Balaya, P., Hu, Y.S., Maier, J., 2021. Fundamentals, status and promise of sodium-based batteries. Nat Rev Mater. 6,1020 – 1035.

Usón, A.A., Capilla, A.V., Bribián, I.Z., Scarpellini, S., Sastresa, E.L., 2011. Energy efficiency in transport and mobility from an eco-efficiency viewpoint. Energy 36, 1916 – 1923.

Vaalma, C., Buchholz, D., Weil, M., Passerini, S., 2018. A cost and resource analysis of sodium-ion batteries. Nature 3, 18013.

Valero, Alicia, Valero, Antonio, Calvo, G., Ortego, A., 2018. Material bottlenecks in the future development of green technologies. Renewable and Sustainable Energy Reviews. 93, 178 – 200.

van den Brink, S., Kleijn, R., Sprecher, B., Tukker, A., 2020. Identifying supply risks by mapping the cobalt supply chain. Resour. Conserv. Recycl. 156, 104743.

van Oorschot, J., Sprecher, B., Roelofs, B., van der Horst, J., van der Voet, E., 2022. Towards a low-carbon and circular economy: Scenarios for metal stocks and flows in the Dutch electricity system. Resour Conserv Recycl 178, 106105.

Van Neuss, L., 2019. The driver of structural change. J Econ Surv 33, 309 – 349.

Vermeersch, E., D'angelo, E., Bliklen, R., Frick, F., Caldarelli, P., Stringa, F., Leroy, P., 2024. Challenges and Best Practices in the Collection of Small WEEE and Waste Portable Batteries in Europe. Electronic Goes Green Conference (2024).

Wagner, M.A., Habib, H., Herreras, L., van der Voet, E., 2023. Unlocking the potential of e-waste: A material quantification analysis of Cu, Cr, In, Mg, Nb, and Nd in the EU. Resour Conserv Recycl 199, 107243.

Watari, T., McLellan, B.C., Giurco, D., Dominish, E., Yamasue, E., Nansai, K., 2019. Total material requirement for the global energy transition to 2050: A focus on transport and electricity. Resour Conserv Recycl 148, 91 – 103.

Wesselkämper, J., von Delft, S., 2024. Current status and future research on circular business models for electric vehicle battery recycling. Resour Conserv Recycl. 206, 107596.

Wesselkämper, J., Hendrickson P., Simon Lux. S., von Delft, S., 2025. Recycling or Second Use? Supply Potentials and Climate Effects of End-of-Life Electric Vehicle Batteries Environ Sci Technol 59, 15751 – 15765.

Windisch-Kern, S., Gerold, E., Nigl, T., Jandric, A., Altendorfer, M., Rutrecht, B., Scherhaufer, S., Raupenstrauch, H., Pomberger, R., Antrekowitsch, H., Part, F., 2022. Recycling chains for lithium-ion batteries: A critical examination of current challenges, opportunities and process dependencies. Waste Management 138, 125 – 139.

Wu, Z., Wang, C., Wolfram, P., Zhang, Y., Sun, X., Hertwich, E., 2019. Assessing electric vehicle policy with region-specific carbon footprints. Appl Energy 256, 113923.

World Economic Forum, 2019. A Vision for a Sustainable Battery Value Chain in 2030: Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation.

Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., Steubing, B., 2020. Future material demand for automotive lithium-based batteries. Commun. Mater. 1, 99.

Xu, C., Steubing, B., Hu, M., Harpprecht, C., van der Meide, M., Tukker, A., 2022. Future greenhouse gas emissions of automotive lithium-ion battery cell production. Resour Conserv Recycl 187, 106606.

Yao, A., Benson, S.M., Chueh, W.C., 2025. Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries. Nat Energy 10, 404 – 416.

Yao, Y., Zhu, M., Zhao, Z., Tong, B., Fan, Y., Hua, Z., 2018. Hydrometallurgical Processes for Recycling Spent Lithium-Ion Batteries: A Critical Review. ACS Sustain Chem Eng 6, 13611 – 13627.

Ziemann, S., Weil, M., Schebek, L., 2012. Tracing the fate of lithium - The development of a material flow model. Resour Conserv Recycl 63, 26 – 34.

Zhang, C., Zhao, X., Sacchi, R., You, F., 2023. Trade-off between critical metal requirement and transportation decarbonization in automotive electrification. Nature Communications 14, 1 – 16.

Zhang, R., Zhang, J., Long, Y., Wu, W., Liu, J., Jiang, Y., 2021. Long-term implications of electric vehicle penetration in urban decarbonization scenarios: An integrated land use–transport–energy model. Sustain Cities Soc 68, 102800.

Zhou, H., Yang, Y., Li, W., McKechnie, J., Thiede, S., Wang, P., 2024. EU's recycled content targets of lithium-ion batteries are likely to compromise critical metal circularity. One Earth 7, 1288 – 1300.

Zhu, A., Bian, X., Han, W., Cao, D., Wen, Y., Zhu, K., Wang, S., 2022. The application of deep eutectic solvents in lithium-ion battery recycling: A comprehensive review. Resour Conserv Recycl 188, 106690.

Zhu, J., Mathews, I., Ren, D., Li, W., Cogswell, D., Xing, B., Sedlatschek, T., Nithin, S., Kantareddy, R., Yi, M., Gao, T., Xia, Y., Zhou, Q., Wierzbicki, T., Bazant, M.Z., 2021. End-of-life or second-life options for retired electric vehicle batteries. Cell Rep Phys Sci 2, 100537.

Zubi, G., Dufo-López, R., Carvalho, M., Pasaoglu, G., 2018. The lithium-ion battery: State of the art and future perspectives. Renewable and Sustainable Energy Reviews 89, 292 – 308.

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List of Publications

Tang, C., Sprecher, B., Tukker, A., Mogollón, J.M., 2021. The impact of climate policy implementation on lithium, cobalt and nickel demand: The case of the Dutch automotive sector up to 2040. Resources Policy 74, 102351.

Tang, C., Tukker, A., Sprecher, B., Mogollón, J.M., 2023. Assessing the European Electric-Mobility Transition: Emissions from Electric Vehicle Manufacturing and Use in Relation to the EU Greenhouse Gas Emission Targets. Environ. Sci. Technol. 57, 44 – 52.

Tang, C., Tukker, A., Mogollón, J.M., 2025. The demand and recycling potential for lithium, cobalt, and nickel in the European electric-mobility transition. Environ. Res. Commun. 7, 061007.

Belyaeva, L., **Tang, C.,** Juurlink, L., Schneider, G., 2021. Macroscopic and Microscopic Wettability of Graphene. Langmuir 37, 14, 4049 – 4055.

Curriculum Vitae

Chen was born on the 26th of March 1992 in Dalian, China. After completing high school in 2010, she began her undergraduate studies in environmental science at Liaoning University, where her research work on the photo-catalytic degradation of wastewater pollutants sparked an interest in developing effective catalysts for industrial waste. She went on to pursue a master's degree in 2014 at the Dalian University of Technology. Joining the air pollution control group in the School of Environmental Science and Technology, her research focused on designing carbon-based catalysts and understanding reaction mechanisms for the selective catalytic reduction of nitrogen oxides to mitigate emissions from power plants. She finished her master study in June 2017. In September 2017, she joined the catalysis and surface chemistry group at Leiden University to explore the wetting properties of graphene surfaces, aiming to facilitate new applications of graphene-based materials. Motivated to prevent rather than merely mitigate air pollution, she later pivoted to the emerging low-carbon technologies. At the Institute of Environmental Sciences (CML), her research has focused on understanding the material and emission impacts of the transition towards an electrified transport system in the EU countries.

Appendix

Appx A1. Lifespan scenarios

To calculate the lifetime of the vehicles and describe survival possibility, we applied Weibull cumulative distribution function $f(T, \tau, k, \lambda)$:

$$f(T, \tau, k, \lambda) = 1 - e^{-\left(\frac{T-\tau}{\lambda}\right)^{k}}$$

in which, k is a shape parameter and λ is a scale parameter.

As shown in Table A1 and Figure A1, the parameters $k = 4.03$ and $\lambda = 13.43$ for the long lifespan scenario were fitted from the outage data published by CBS ("CBS Open Data Source", 2019), which provided a survsival curve of about 75% after 11 years and less than 10% after 16.4 years. The parameters $k = 1.89$ and $\lambda = 10.3$ for the short lifespan scenario were based on the previous study (Deetman et al., 2018), which provided a survival curve of about 80% after 5 years, 50% after 8.5 years.

Table A1. Lifespan parameters for different scenarios

Scenario	EVs	EV battery
Short lifespan scenario	$k = 1.89$ $\lambda = 10.3$	$k = 1.89$ $\lambda = 10.3$
Long lifespan scenario	$k = 4.03$ $\lambda = 13.43$	$k = 4.03$ $\lambda = 13.43$
Extended EV use scenario	$k = 4.03$ $\lambda = 13.43$	8 years

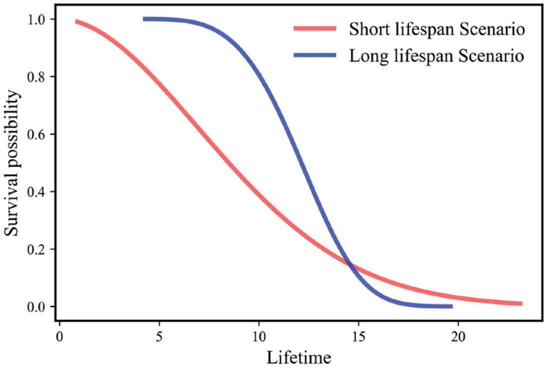

Figure A1. Survival possibility distribution for different scenarios.

Appx A2. Dutch government goals for promoting electric vehicle sales

The Climate Agreement stipulates a target of 30% GHG emissions reduction from the passenger transport sector by 2030, compared to 1990 level (Dutch Ministry of Economic Affairs and Climate, 2019). To meet the goal, one of the key actions is to phase out passenger cars with internal combustion engines by promoting the adoption of electric vehicles. The government has presented a detailed plan to virtually ban the sales of petrol- and diesel-powered cars in favor of battery-powered vehicles:

- by 2020, 10% of new passenger cars sold will have an electric powertrain and a plug.
- by 2025, 50% of new cars sold will be equipped with an electric powertrain and a plug, and at least 15% of these vehicles will be fully electric-powered.
- by 2030, 100% of new cars sold will be emissions-free.

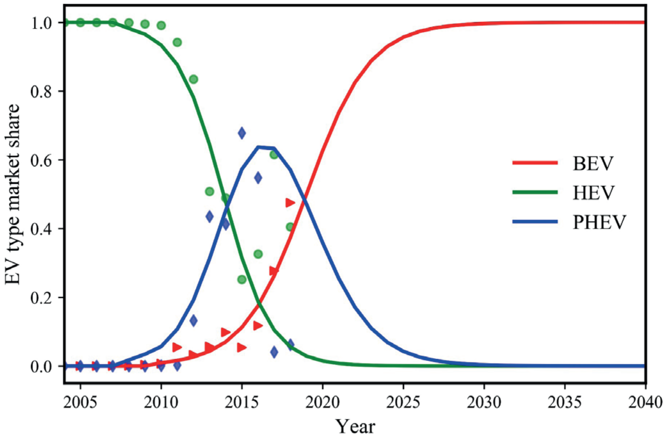

Figure A2. Market share of HEVs, PHEVs and BEVs in the Netherlands through 2040. Scatters represent historical data before 2019.

Table A2. Top sales BEV and PHEV models in the Netherlands by 2019

Vehicle type	EV model	Lauched time	Total sales	Battery cathode chemistry	Battery capacity (kWh)	Stated driving range (km)
BEV	Nissan LEAF	2011	2312	LMO-poly	24/30	125
	Renault Zoe (2012)	2012	1797	LMO-poly	26	140
	FIAT 500E	2012	789	LMO-poly	24	145
	BMW i3 (2013)	2013	1031	LMO-poly	22	130
	Tesla Model S	2013	13922	NCA	75 - 100	330 - 490
	SMART - For Two	2013	630	NMC-111	17	101
	SMART - For Four	2013	416	NMC-111	17.6	101
	Mercedes-Benz B250E	2015	370	NCA	28	150
	Volkswagen Golf	2015	263	NMC-111	24	130
	Volkswagen Golf (after 2016)	2016	5326	LMO-poly	35.8	300
	Tesla Model X	2016	4632	NCA	75 - 100	330 - 490
	Hyundai ioniq	2016	2646	NMC-622	28	190
	Opel Ampera	2016	1246	NMC-622	60	380
	BMW i3 (2017)	2017	2240	LMO-poly	33	183
	Tesla Model 3	2017	7463	NCA	85 - 100	350 - 500
	Jaguar I-pace	2017	3514	NMC-622	90	415
	Renault Zoe (2017)	2017	2944	NMC-622	41	255
	BMW i3 (2018)	2018	1681	LMO-poly	42.2	220
	BMW i3s	2018	1005	LMO-poly	42.2	220
	Nissan LEAF (2018)	2018	5258	NMC-523	40	245
	Hyundai Kona	2018	3598	NMC-622	39.2	246
	KIA Niro	2018	2241	NMC-622	39.2	246
	AUDI e-tron	2018	720	NMC-622	71.2	260
PHEV	Mitsubishi Outlander	2013	23943	LMO/NMC	12	--
	Vovol V60 Plug-in	2013	13847	NMC-111	10.4	--
	Volkswagen Golf	2014	10915	NMC-111	8.8	--
	Volkswagen Passat	2014	8065	NMC-111	10	--

Data source: RDW, CBS, EV Database

Battery capacity and Metal intensity

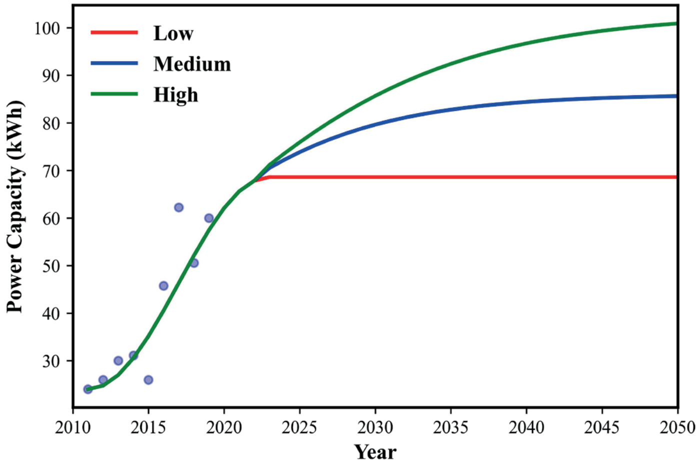

Figure A3. Estimated power capacity of EV battery used in BEVs based on the driving range assumptions for 350 km, 450 km and 550 km (Low/ Medium/ High). Scatters represent average battery power capacity of the lunched BEV models by 2019.

Table A3. Metal intensities in different type of lithium batteries

Battery chemistry	Li (kg / kWh)	Co (kg / kWh)	Ni (kg / kWh)
LMO-poly	0.113	0	0
NCA	0.115	0.141	0.749
NMC-111	0.170	0.445	0.443
NMC-622	0.145	0.211	0.675
NMC-811	0.115	0.094	0.749

Appx A3. Sensitivity analysis

We also tested the uncertainty ranges for the metal intensity in battery packs under the consideration of potential enhancement of lithium-ion battery performance, which is mainly governed by the energy density of LIBs (Cano et al., 2018; Schmuch et al., 2018). The calculation was based on medium power capacity assumption for different lifespan scenarios. As shown in Figure A4, the yearly range of Li, Co and Ni was about 7% to 8%.

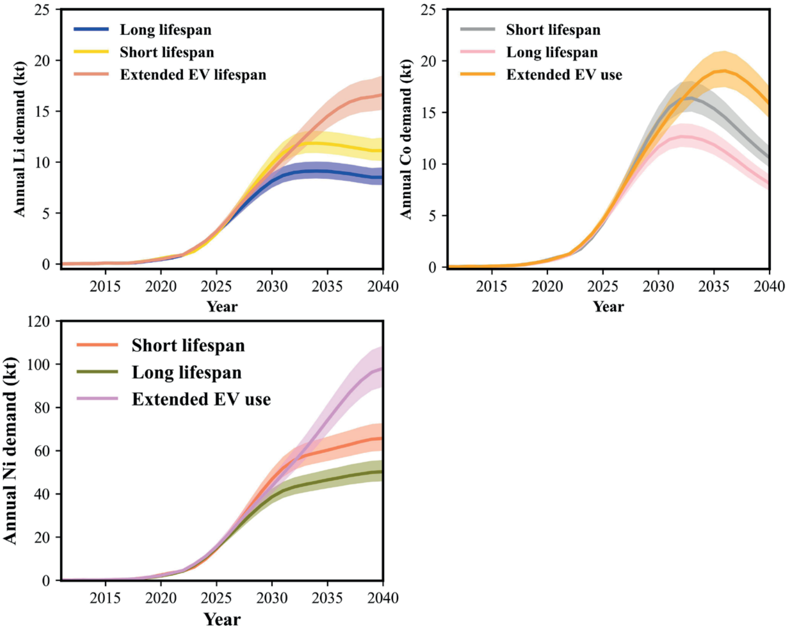

Figure A4. Variation of annual Li, Co and Ni demand caused by the uncertainty of metal intensity. Solid lines represent the results under the assumption of battery capacity for the medium driving range.

Appx A4. Estimation on potential secondary Li, Co and Ni

In order to test whether the recovered metals can meet the dutch primary demand for Li, Ni, and Co in the coming future, we estimated the amount of metals potentially recovered through the recycling processes. The collection rates of discarded EV batteries was assumed to be 100%.

In open loop recycling, the recycled metals may subsequently be used in any industrial sectors (e.g., recycled Co and Ni applied in the production of catalysts, superalloy and hard metals; recycled Li applied in cement production (Godoy León et al., 2020; Kayo et al., 2019; Song et al., 2019). The open-loop recycling rates of Li, Co and Ni based on the previous studies were listed in Table A4, and they were assumed to keep increasing in the future due to the development of recycling technology (Godoy León et al., 2020; Graedel et al., 2011; Harper et al., 2019; Hund et al., 2020; Song et al., 2019). The amount of recovered metals was calculated by multiplying the outflow from the end-of-life EV batteries for each lifespan scenarios to their recycling rates, shown in Figure A5. To assess whether the potential secondary metals to meet demands for the Dutch industry in the future, the imported record of primary Li, Co, and Ni in the Netherlands in 2019 was collected from the database of UN comtrade (HS code of commodities contained each metals were listed in Table A5). The metal content the commodities was determined with reference to ore grades, composition formulae of compounds and content ratios specified by industrial standards.

In closed loop recycling, the recycled metals may be returned to the manufacturing processes within the same sector minus minimum losses in refining, which means that recycled Li, Co and Ni would be required to meet battery-grade quality and be shipped to the original country of battery production. To date, the closed-loop recycling rates for Li, Co and Ni within the battery sector is still less than 5%, and no major improvement is expected in the coming decade (Harper et al., 2019; Hund et al., 2020; Xu et al., 2020).Although the closed-loop recycling rate is expected to grow in the late 2020s, the expected amount of the recycled metals in the Netherlands for new battery production would only account for 10% of its total annual demand in 2040.

Table A4. Average open-loop recycling rate of metals

Year	Li	Co	Ni
2010-2020	1%	55%	45%
2020-2030	15%	70%	60%
2030-2040	60%	85%	85%

Table A5. Imported commodities containing primary Li, Co and Ni in 2019 in the Netherlands

HS code	Commodity name	HS code	Commodity name
260400	Nickel ores and concentrates	282520	Lithium oxide and hydroxide
260500	Cobalt ores and concentrates	283691	Carbonates; lithium carbonate
282200	Cobalt oxides and hydroxides; commercial cobalt oxides	283324	Sulphates; of nickel
282734	Cobalt chloride	282735	Chlorides; of nickel
810510	Cobalt, unwrought, matte & other intermediate products,waste,scrap	750100	Nickel mattes; nickel oxide sinters and other intermediate products of nickel metallurgy
282540	Nickel oxide and hydroxide	750210	Nickel; unwrought

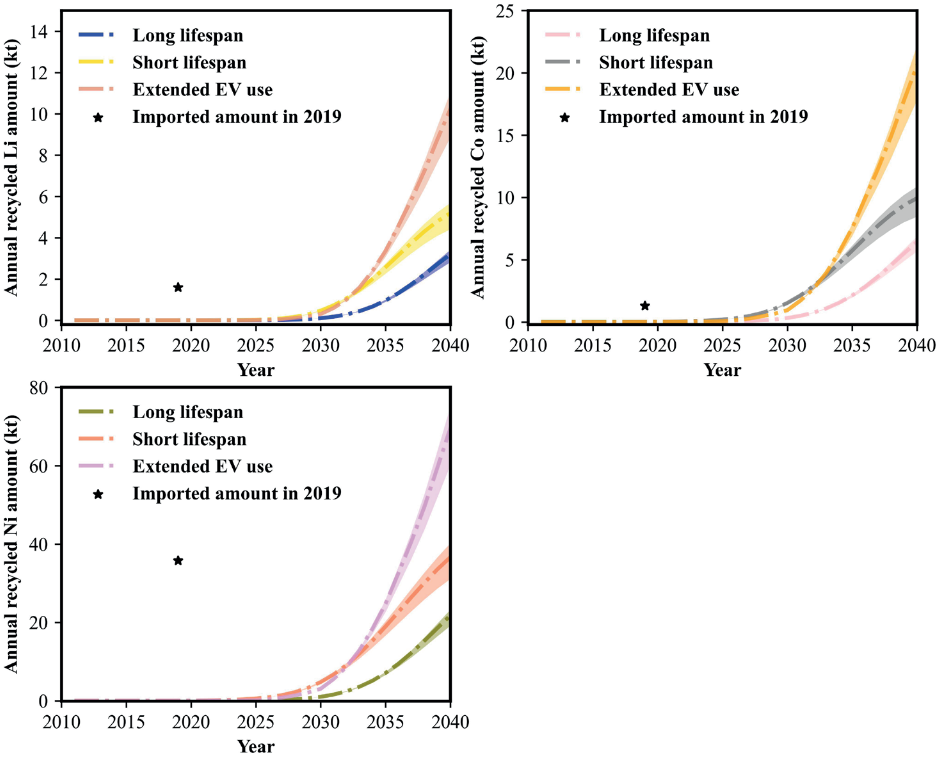

Figure A5. Estimated amount of potential secondary Li, Co and Ni in the Netherlands through 2040. Solid-dashed lines represen t the results under the assumption for medium battery capacitys. Scatters represent the imported record of primary metals in 2019 in the Netherlands based on the data collected from the UN Comtrade database (https://comtrade.un.org/data).

References

Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M., Chen, Z., Zachary P. Cano, 2018. Batteries and fuel cells for emerging electric vehicle markets. Nat. Energy 3, 279 – 289.

CBS Open Data Source. URL https://www.cbs.nl/nl-nl/onze-diensten/open-data (accessed 11.16.2019)

Deetman, S., Pauliuk, S., Van Vuuren, D.P., Van Der Voet, E., Tukker, A., 2018. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. Environ. Sci. Technol. 52, 4950–4959.

Dutch Ministry of Economic Affairs and Climate, 2019. National Climate Agreement - The Netherlands, 1 – 247.

EV Database, 2019. EV Database: een overzicht van alle elektrische auto's. https://ev-database.nl (accessed 04.21.2020)

Godoy León, M.F., Blengini, G.A., Dewulf, J., 2020. Cobalt in end-of-life products in the EU, where does it end up? - The MaTrace approach. Resour. Conserv. Recycl. 158, 104842.

Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What do we know about metal recycling rates? J. Ind. Ecol. 15, 355–366.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., Anderson, P., 2019. Recycling lithium-ion batteries from electric vehicles. Nature. 575, 75-86.

Hund, K., Porta, D. La, Fabregas, T.P., Laing, T., Drexhage, J., 2020. Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.

Kayo, C., Dente, S.M.R., Aoki-Suzuki, C., Tanaka, D., Murakami, S., Hashimoto, S., 2019. Environmental Impact Assessment of Wood Use in Japan through 2050 Using Material Flow Analysis and Life Cycle Assessment. J. Ind. Ecol. 23, 635–648.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Chang. 42, 153–168.

Schmuch, R., Wagner, R., Hörpel, G., Placke, T., Winter, M., 2018. Performance and cost of materials for lithium-based rechargeable automotive batteries. Nat. Energy. 3, 267–278.

Song, J., Yan, W., Cao, H., Song, Q., Ding, H., Lv, Z., Zhang, Y., Sun, Z., 2019. Material flow analysis on critical raw materials of lithium-ion batteries in China. J. Clean. Prod. 215, 570–581.

Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., Steubing, B., 2020. Future material demand for automotive lithium-based batteries. Commun. Mater. 1, 99.

Appx B1. Dynamic MFA model

Four types of passenger vehicles were included in this study: Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Hybrid Electric Vehicles (HEVs), Internal Combustion Engine Vehicles powered by gasoline (ICEV-G) or diesel (ICEV-D). The future stock of passenger vehicles for each country was estimated from historical registration data collected from the Eurostat (European Commission, 2023) and the European Automobile Manufacturers Association (ACEA) (European Automobile Manufacturers' Association, 2021) by assuming a vehicle-to-population ratio and future population growth from the Shared Socio-economic Pathway, SSP2 (Riahi et al., 2017) (Figure B1). The SSP2 scenario outlines a middle-of-the-road scenario in terms of socioeconomic developments. It represents moderate population growth and a path in which "social, economic, and technological trends do not shift markedly from historical patterns" (Riahi et al., 2017). The projected population data was collected from the SSP database (SSP Database, 2020).

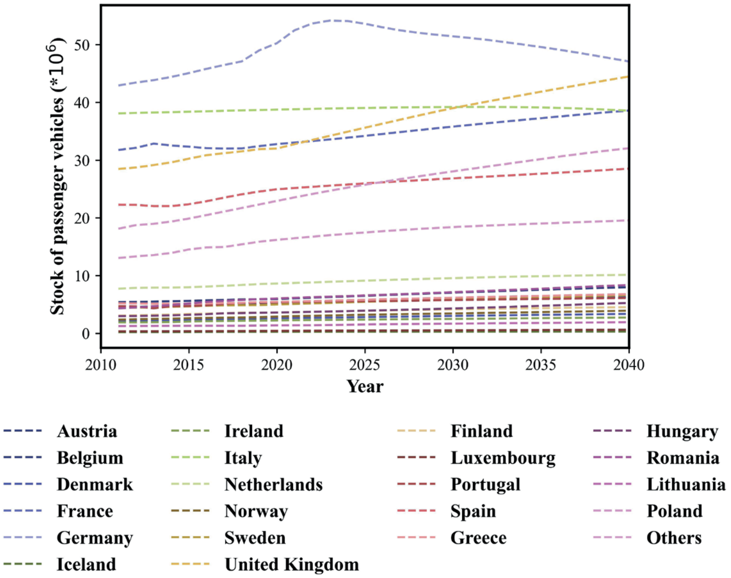

Figure B1. The estimated total stock of passenger vehicles for the 27 EU + 3 countries through 2040. ("Others" represents the countries the low ambition group with lowest goals in market share of EVs.)

The market share of various passenger vehicle types was calculated based on the annual numbers of registered passenger vehicles for recent years (2011 – 2020) collected from the ACEA (European Automobile Manufacturers' Association, 2023). The assumptions from 2021 for each country fitted by the individual future policy targets of EVs (BEVs and PHEVs) and the same historical sales trend of HEVs and ICEVs, as shown in Figure B2. The market share of ICEV-G was assumed to be double than ICEV-D following the historical sales statistics (European Automobile Manufacturers' Association, 2021). For the scenario with more ambitious e-mobility transition, BEVs would fully dominate the market of passenger vehicles by 2030 within all the 27 EU +3 countries. Best-selling EV models within the 27 EU + 3 countries by 2020 were listed in Table B1.

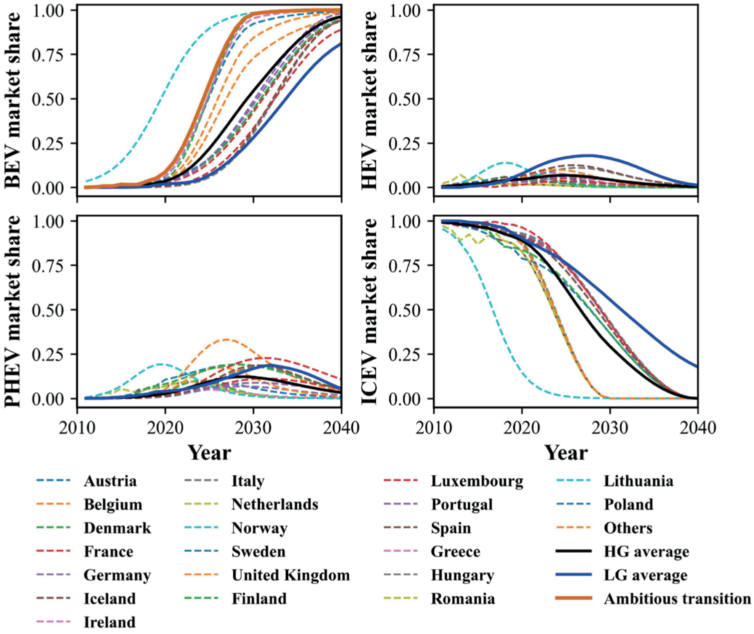

Figure B2. Market share for BEVs, HEVs, PHEVs, and ICEVs of the 27 EU + 3 countries through 2040 following the individual stated e-mobility plans (dashed lines). Solid lines in black and blue represent the average level of the countries with high ambition group (HG) and low ambition group (LG) following the stated e-mobility transition. The solid line in brown represents the market share of BEVs for the 27 EU + 3 countries in the ambitious transition scenario. ("Others" represents the countries the low ambition group with lowest goals in market share of EVs.).

Table B1. Top sales EV models in the European countries by 2020

Vehicle type	EV model	Lauched time	Total sales	Battery cathode chemistry	Battery capacity (kWh)	Stated driving range (km)
BEV	Mitsubishi i-MiEV	2010	8119	LMO-poly	16	85
	Peugeot I-On	2010	13823	LMO-poly	14.5	85
	Citroën C-Zero	2010	14314	LMO-poly	14.5	85
	Nissan LEAF (2011)	2011	81811	LMO-poly	24 / 30	125
	Renault Zoe (2012)	2013	89389	LMO-poly	26	140
	BMW i3 (2013)	2013	95548	LMO-poly	22	130
	Tesla Model S	2013	78541	NCA	75 - 100	330 - 490
	SMART - for Two / Four	2013	54022	NMC-111	17.6	101
	KIA Soul	2014	30887	LMO-poly	32	170
	Volkswagen e - Golf	2015	117475	NMC-111	24	130
	Tesla Model X	2016	39978	NCA	60 - 100	330 - 490
	Hyundai Ioniq	2016	36237	NMC-622	28	190
	Tesla Model 3	2017	181147	NCA	85 - 100	350 - 500
	Jaguar I-pace	2017	31970	NMC-622	90	415
	Renault Zoe (2017)	2017	212657	NMC-622	41	255
	Nissan Leaf (2018)	2018	101709	NMC-523	40	245
	Hyundai Kona	2018	73904	NMC-622	39.2	246
	AUDI e-tron	2018	54022	NMC-622	71.2	330
	Volkswagen ID.3	2020	54495	NMC-622	45	275
	Peugeot e-208	2020	31287	NMC-622	45	275
PHEV	Mitsubishi Outlander	2013	185458	LMO/NMC	12	--
	Vovol V60 Plug-in	2013	41693	NMC-111	10.4	--
	Volkswagen Golf	2014	58271	NMC-111	8.8	--
	Volkswagen Passat	2014	69189	NMC-111	10	--
	AUDI Q5	2019	21099	NMC-622	14.1	--
	Ford Kuga	2020	22628	NMC-622	14.4	--

References: Hawkins et al. (Hawkins et al., 2013); Kim et al. (Kim et al., 2016); Küfeoğlu and Khah Kok Hong (Küfeoğlu and Khah Kok Hong., 2010).

The lifespan of passenger vehicles determines their survival time in the dynamic MFA model. The lifespan was assumed to follow a Weibull distribution function with scale and shape parameters (λ and k), as shown below:

$$f(T, t, k, \lambda) = 1 - e^{\left(-\frac{T-t}{\lambda}\right)^{k}}$$

The average lifespan of the passenger vehicles for each country was based on a previous study (Held et al., 2021), representing the historical turnover frequency of passenger vehicles. Overall, the average lifespan of the counties in the high ambition group was about 18.4 years, whereas for countries in the low ambition group it was about 24.8 years. The scale and shape parameters (λ and k) are listed in Table B2.

Table B2. Historical average lifespan of passenger vehicles for each country

Country	Lifespan (λ, k)	Country	Lifespan (λ, k)	Country	Lifespan (λ, k)
Austria	15.9, 3.4	Sweden	19.4, 4.9	Greece	33.9, 4.2
Belgium	11.7, 2.0	United Kingdom	14.2, 4.0	Czech	15.4, 3.6
Danmark	16.9, 3.4	Finland	24.9, 3.2	Slovakia	24.8, 4.03
France	15.2, 6.0	Luxembourg	8.0, 2.0	Croatia	30.9, 6.0
Germany	14.8, 2.4	Portugal	23.1, 6.0	Cyprus	24.8, 4.03
Iceland	19.7, 4.3	Spain	19.4, 3.2	Malta	24.8, 4.03
Ireland	15.0, 4.3	Hungary	23.1, 6.0	Bulgaria	24.8, 4.03
Italy	19.6, 2.7	Romania	24.8, 4.03	Estonia	24.8, 4.03
Norway	19.8, 6.0	Lithuania	24.8, 4.03	Latvia	24.8, 4.03
Netherlands	17.2, 4.4	Poland	24.8, 4.03	Slovenia	20.0, 6.0

Reference: Held et al., 2021

However, the average lifespan of EVs is about 12 years as suggested by many EV automakers (Harper et al., 2019), representing a survival probability about 50% after 10.2 years (Figure B3). Considering the mismatch of lifespans between the conventional ICEVs and the EVs, and we made different assumptions on the lifespans in different scenarios for the assessment in the scenario years (from 2021 onwards). In the no e-mobility scenario and stated transition scenario, the average lifespan of ICEVs in each country was assumed to follow the historical values, and the average lifespan of EVs was assumed to be 12 years. In the more ambitious, however, with EVs rapidly dominating the sales market, the average lifespan was assumed to be 12 years for all vehicle types, which accounts for an accelerated phase-out of ICEVs to a lower lifespan of 12 years. However, for the specific case of Luxembourg the average lifespan for all passenger vehicles in all scenarios was assumed to follow their historical turnover frequency as 8 years.

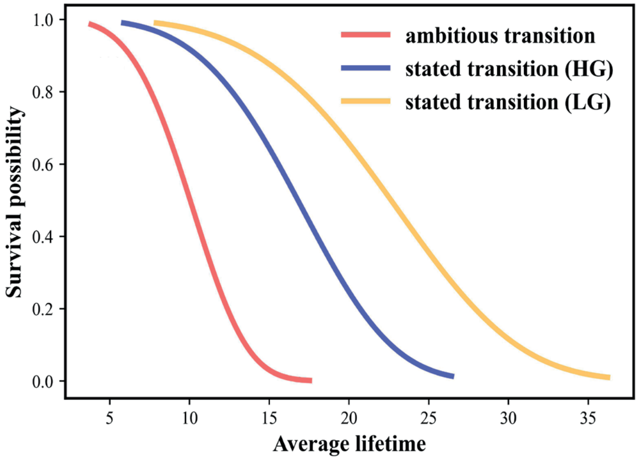

Figure B3. Survival possibility distribution for average lifespan of passenger vehicles in the stated transition scenario and in the ambitious transition scenario.

Appx B2. Assessment of GHG emissions

Appx B2.1 Assessment of GHG emissions from passenger vehicle manufacturing

The GHG emissions from the production of passenger vehicles were calculated by multiplying the total annual demand of various passenger vehicles with their GHG emission factors per unit. We chose the lower-medium size as the average model of the passenger cars, as they have been among the most commonly sold in the European countries in the recent years (Campestrini and Mock, 2021). The description of the passenger vehicles powered by different fuel type was listed in Table B3. The production GHG emission factors per manufactured unit for the assessment in the historical years (from 2011 to 2020) were based on previous studies (Hawkins et al., 2013; Kim et al., 2016; Küfeoğlu and Khah Kok Hong, 2020; Milovanoff et al., 2019; Moreno et al., 2021; Nealer and Hendrickson, 2015; Notter et al., 2010). They were adjusted to correspond to the reference models of the passenger vehicles involved in our study, as listed in Table B3.

For the assessment in the scenario years, the use of historical GHG intensity data as aforementioned would create a bias since the EV manufacturing has been dominated by the countries outside the EU (e.g., China, Japan, Korea and the US) (S&P Global Market Intelligence, 2021). It is however likely that in future EV production in the EU will catch up. Moreover, the GHG emissions factor of BEVs were also determined by the EV battery capacity (Dai et al., 2019; Delogu et al., 2017; Ellingsen et al., 2016; Hawkins et al., 2013; Kim et al., 2016; Küfeoğlu and Khah Kok Hong, 2020; Li and Yang, 2020; Milovanoff et al., 2019; Nealer and Hendrickson, 2015; Notter et al., 2010, 2010; Peters et al., 2017; Sun et al., 2020). Therefore, we assumed dynamic manufacturing GHG emission factors for the scenario years related to the change of electricity consumption (from 2021 to 2040), determined by the allocation of passenger vehicle manufacturing countries, related reduction of GHG emissions from the electricity generation in those countries, and the dynamic change of average EV battery capacity for EVs. The average electricity consumption for various types of passenger vehicles and EV battery manufacturing is listed in Table B4. The GHG emissions related to other forms of energy consumption were assumed to remain constant in time for all passenger vehicles and the EV battery pack (listed in Table B4) (Dai et al., 2019; Ellingsen et al., 2017, 2016; Hawkins et al., 2013; Majeau-Bettez et al., 2011; Milovanoff et al., 2020; Notter et al., 2010; Onat et al., 2019; Sun et al., 2020).

Table B3. Passenger vehicle description and historical GHG emission factors for manufacturing process

Passenger vehicle type	Description	Main components of the passenger vehicles	GHG emission factors in 2011
ICEV-G	ICEV-G refers to the current most common vehicle technology that burns gasoline to power an engine, with an average weight of 1280 kg per unit.	general glider, powertrain, wheels, transmission, others (e.g., PbA batteries, fluids)	7948 kg / unit
ICEV-D	ICEV-D refers to a vehicle that burns diesel to power an engine, with an average weight of 1280 kg per unit	general glider, powertrain, wheels, transmission, others (e.g., PbA batteries, fluids)	7948 kg / unit
HEV	HEV draws propulsion energy from both an internal combustion engine or heat engine using consumable fuel, and a piece of rechargeable battery pack getting energy solely from sources onboard the vehicle, with an average weight of 1340 kg per unit.	general glider, powertrain, electric motor and controller, transmission, wheels, EV battery, others (e.g., PbA batteries, fluids)	9447 kg / unit
PHEV	PHEV is a hybrid electric vehicle that has the capability to charge the battery from an off-vehicle electric source, with an average weight of 1400 kg per unit. The probability of user operating PHEV in electric mode is set as 0.5.	general glider, powertrain, electric motor and controller, transmission, wheels, EV battery, others (e.g., PbA batteries, fluids)	10324 kg /unit
BEV	BEV is powered solely by an electric motor drawing by currently rechargeable EV battery pack, with an average weight of 1320 kg per unit (including 22 kWh EV battery pack).	general glider, electric motor and controller, wheels, EV battery pack, others (e.g., fluids)	10617 kg / unit

Reference: Hawkins et al., 2013; Kim et al., 2016; Küfeoğlu and Khah Kok Hong, 2020; Milovanoff et al., 2019; Moreno et al., 2021; Nealer and Hendrickson, 2015; Notter et al., 2010

Table B4. Average electricity consumption for passenger vehicle manufacturing

Vehicle type and EV battery	Electricity consumption from manufacturing process	GHG emission factor from other forms of energy consumption	References
ICEV-G	7257 kWh / unit	4882 kg / unit	Moreno et al. (Moreno et al., 2021); Hawkins et al. (Hawkins et al., 2013)
ICEV-D	7257 kWh / unit	4882 kg / unit	Moreno et al. (Moreno et al., 2021); Hawkins et al. (Hawkins et al., 2013)
HEV (without EV battery)	8239 kWh / unit	5277 kg / unit	Moreno et al. (Moreno et al., 2021); Milovanoff et al. (Milovanoff et al., 2020)
PHEV (without EV battery)	8424 kWh / unit	5353 kg / unit	Moreno et al. (Moreno et al., 2021); Milovanoff et al. (Milovanoff et al., 2020); Majeau-Bettez et al. (Majeau-Bettez et al., 2011); Onat et al. (Onat et al., 2019)
BEV (without EV battery)	6580 kWh / unit	4562 kg / unit	Moreno et al. (Moreno Ruiz E., 2021); Milovanoff et al. (Milovanoff et al., 2020); Moreno et al. (Moreno et al., 2021); Hawkins et al. (Hawkins et al., 2013)
EV battery pack	120 kWh / kWh battery capacity	47.2 kg / kWh battery capacity	Moreno et al. (Moreno et al., 2021); Sun et al. (Sun et al., 2020); Dai et al. (Dai et al., 2019), Ellingsen et al. (Ellingsen et al., 2016, 2017)

The distribution of manufacturing countries for different scenarios was assumed based on the EU historical import statistics of various passenger vehicles in the 2010s collected from ACEA (European Automobile Manufacturers' Association, 2021). For the no e-mobility scenario, the prospective allocation of manufacturing countries was assumed to remain constant until 2040. For the scenarios in which EVs promotion would take place (stated transition scenario and ambitious transition scenario), we assumed an annual increase of 1% in EV production within the EU, while the remaining demand for EVs were assumed to be supplied by non-EU countries according to their historical manufacture market shares ("Asian Batteries Power Global EV Fleet.", 2021), as listed in Table B5. The manufacturing allocation of ICEVs and HEVs in these two scenarios was assumed to keep the same trend as in the historical years.

The choice of electricity sources (electricity mixes) has a significant impact on the GHG emissions from the electricity generation. In this study, we therefore took the historical data (the year 2011 - 2019) of electricity mixes of manufacturing countries from the statistics data offered by IEA (International Energy Agency, 2019) and the estimated energy mixes (from the year 2020 onwards) based on the "stated policies scenario" and "sustainable development scenario" from IEA Energy Outlook 2020 (Cozzi et al., 2020). The IEA scenarios included the forecast for share and compound average annual growth rate (CAAGR) of each resource until 2040. The electricity mixes for the scenarios were assigned based on the contribution share to the future goal of total electricity production volume from each country (Figure B4). Eight major resources for electricity generation and the carbon equivalent emission factors for each source were taken from the previous study (Schlömer et al., 2014) and listed in Table B6.

The average battery capacity of BEVs from 2011 to 2020 were calculated based on the manufacturing reports of the most popular BEV models sold in EU countries (Table B2). Future battery capacity of BEVs (from 2021 to 2040) was estimated around 80 kWh by assuming an extended driving range to 550 km (Notter et al., 2010), as shown in Figure B5. For PHEVs, their average battery capacity was assumed as 12 kWh (Tang et al., 2021), remaining constant through 2040.

Table B5. Allocation of the manufacturing countries for various pasenger vehicles in different scenarios

Vehicle type	Historical allocation of the manufacturing countries (from 2011 to 2020)	Assumptions about prospective allocation of the manufacturing countries (from 2021 to 2040)	References
ICEVs and HEVs	27 EU + 3 countries (65%), Japan (10%), Turkey (8%),Korea (6%), The U.S. (6%), Others (5%)	No e-mobility scenario: same as in historical years. Scenarios with EV promotion: same trend as in historical years.	"Asian Batteries Power Global EV Fleet.", 2022; European Automobile Manufacturers' Association, 2021
PHEVs and BEVs	China (39.5%), Korea (32%), Japan (15%), The U.S. (13.5%)	No e-mobility scenario: same as in historical years. Scenarios with EV promotion: An annual increase of 1% in manufacturing share within the EU, with non-EU manufacturing keeping the historical market share of exports to EU.	

Table B6. GHG emission factors of different types of fuel in electricity generation

Fule type	GHG emission factors (g CO_2-eq / kWh)	Fule type	GHG emission factors (g CO_2-eq / kWh)	Fule type	GHG emission factors (g CO_2-eq / kWh)
biomass	230	natural gas	490	solar	44
coal	820	solid waste	52	nuclear	12
oil	730	wind	11	hydro power	24

Reference: Schlömer S et al. (Schlömer S. et al., 2014)

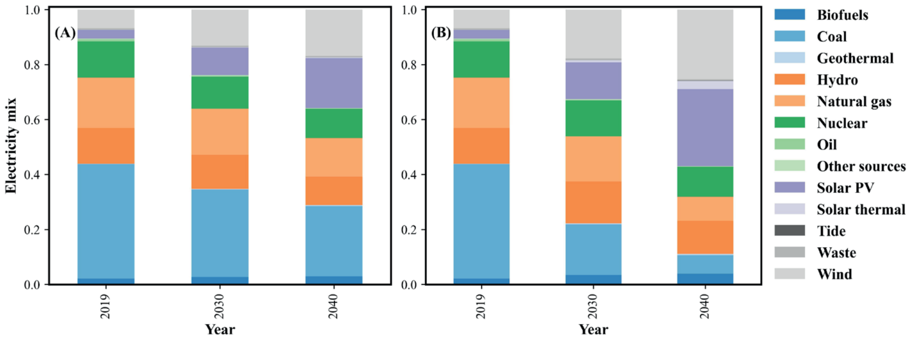

Figure B4. Integrated electricity mix of all passenger vehicle manufacturing countries in 2019, 2030 and 2040, for (A) the stated transition scenario, and (B) the ambitious transition scenario. The allocation of the manufacturing countries was described in Table B5 and the electricity mix in 2030 and 2040 followed the prediction by the "stated policy scenario" and "sustainable development scenario" in the report from IEA (Cozzi et al., 2020).

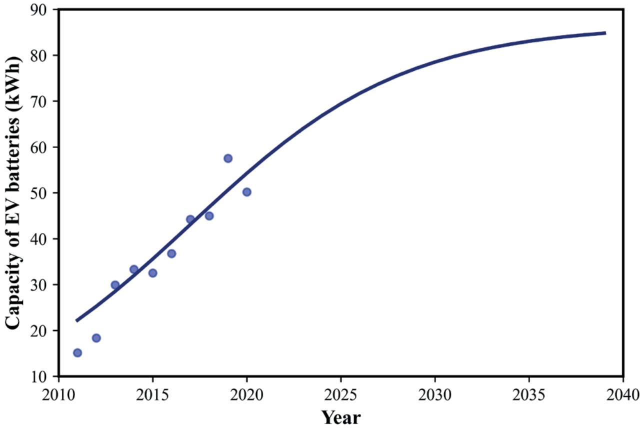

Figure B5. Estimated power capacity of EV battery used in BEVs based on the driving range assumptions for 550 km. Scatters represent average battery power capacity of the lunched BEV models by 2020 as listed in Table B1.

Appx B2.2 Assessment of GHG emissions from in-use vehicles

The annual emissions from the in-use passenger vehicles were assessed by multiplying the total annual traveled distance (Vehicle Kilometer Travel, VKT, listed in Table B7) with the energy consumption of different types of passenger vehicles and with the respective emission factors of related to fuel type or electricity use.

Table B7. Annual distance travelled (VKT) by the passenger vehicle for each country

Country	VKT (km)	Country	VKT (km)	Country	VKT (km)
Austria	14100	Sweden	12000	Greece	11500
Belgium	14770	United Kingdom	12000	Czech	8000
Danmark	16000	Finland	15000	Slovakia	8000
France	12000	Luxembourg	14000	Croatia	16000
Germany	14700	Portugal	13060	Cyprus	11000
Iceland	10500	Spain	12500	Malta	8000
Ireland	17000	Hungary	13000	Bulgaria	7000
Italy	10500	Romania	10000	Estonia	14000
Norway	15000	Lithuania	12000	Latvia	11000
Netherlands	13200	Poland	8000	Slovenia	8000

The assumptions on their average in-use energy consumption from 2010 to 2040 were listed in Table B8. In our model, we incorporated a decrease in fuel consumption of new ICEVs due to the improved technologies toward 2040. Using the historical fuel consumption values in 2000 as the initial values (7.6 L /100 km for petrol and 6.2 L /100 km for diesel), the fuel consumption remained annually decreased at the rate of 1.14% and 1.34% for petrol and diesel (Usón et al., 2011). Emission factors of the passenger vehicles with fuel consumption (ICEVs, HEVs and PHEVs) were 2.31 kg CO_2-eq / L and 2.69 kg CO_2-eq / L for petrol and diesel, taken from a previous study (Küfeoğlu and Khah Kok Hong, 2020).

The fuel consumption of HEVs is 30% – 50% less than that of a comparable ICEVs and was also assumed to remain constant until 2040, as hybrid systems have been taken as a bridge to meeting tougher tailpipe-emissions requirements and the automakers are focusing more on the zero-emission passenger vehicles (e.g., BEVs) (Lucien and Julia, 2020).

The total energy consumption of PHEV depends strongly on the driving and charging patterns of vehicle users to choose the driving mode, and it is hard to precisely estimate. Therefore, we set the parameter of this probability as 0.5, which means that half of the total energy consumption per traveled distance contributes from the electricity and the other half contributes from fuel (only gasoline-electricity PHEVs were considered in this study). The energy consumption of PHEVs was taken from previous study and assumed to be constant until 2040 (Milovanoff et al., 2019).

For the BEVs, the average electric energy consumption from basic driving and charging loss (Küfeoğlu and Khah Kok Hong, 2020), was assumed to be dynamic following the changes in the EV battery capacity as shown in Figure B5. The energy consumption for BEVs was calculated based on an average of 5.4 Wh per additional 100 kilogram in vehicle weight, as demonstrated by a previous study (Ellingsen et al., 2016). The weight changes in glider size were negligible compared to the changes in EV battery weight and thus were neglected in this study. Other factors such as motor efficiency, cargo load and driving behavior were not included. The electricity mixes of each EU country in the scenario years were assumed to follow the IEA scenarios (Cozzi et al., 2020), as shown in Figure B6.

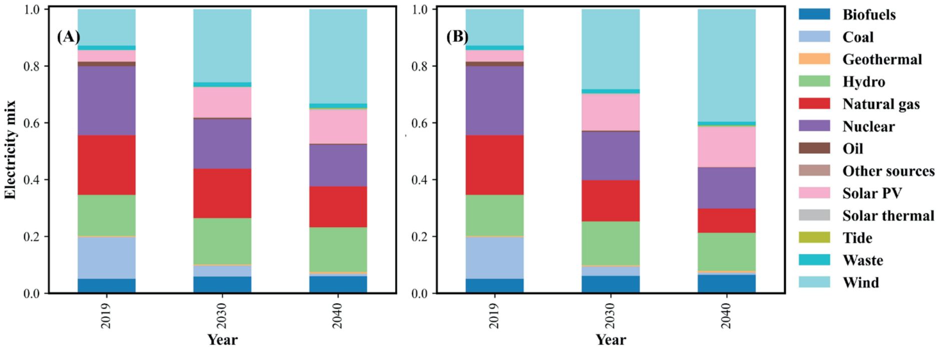

Figure B6. Electricity mix of the 27 EU + 3 countries in 2019, 2030 and 2040. The electricity mix in 2030 and 2040 followed the prediction by the (A) "stated policy scenario" and (B) "sustainable development scenario" in the report from IEA (Cozzi et al., 2020).

Table B8. Passenger vehicle type description and average energy consumption of in-use phase

Vehicle type and EV battery	Fuel type	Average driving energy consumption	References
ICEV-G	unleaded petrol E5 (L)	6.8 L / 100 km in 2011 6.1 L / 100 km in 2020 5.5 L / 100 km in 2030 4.9 L / 100 km in 2040	Molovanoff et al. (Milovanoff et al., 2019); Küfeoğlu et al. (Küfeoğlu and Khah Kok Hong, 2020); Uson et al. (Usón et al., 2011) ; Lucien et al. (Lucien and Julia, 2020)
ICEV-D	diesel fuel B7 (L)	5.4 L / 100 km in 2011 4.7 L / 100 km in 2020 4.2 L / 100 km in 2030 3.7 L / 100 km in 2040	Molovanoff et al. (Milovanoff et al., 2019) ; Uson et al. (Usón et al., 2011) ; Lucien et al. (Lucien and Julia, 2020)
HEV	unleaded petrol E5 (L)	4.8 L / 100 km	Molovanoff et al. (Milovanoff et al., 2019)
PHEV	only unleaded petrol E5 (L) + only electricity (kWh)	6.7 L /100 km + 21.7 kWh /100 km	Küfeoğlu et al. (Küfeoğlu and Khah Kok Hong, 2020); Zhang et al. (Zhang et al., 2019)
BEV	electricity (kWh)	15.6 kWh / 100 km in 2011 16.8 kWh / 100 km in 2020 17.6 kWh / 100 km in 2030 17.9 kWh / 100 km in 2040	Ellingsen et al. (Ellingsen et al., 2016); Zhang et al. (Zhang et al., 2019); Cox et al. (Cox et al., 2020)

Appx B3. Uncertainty analysis

A Monte Carlo analysis was used to estimate the uncertainty in future GHG emissions of the in-use passenger vehicles from the input parameters in our model. Table B9 lists specific distributions of the related input parameters to model the GHG emissions.

Table B9. Input parameters description of the uncertainty analysis

Input parameter	Unit	Distribution	Base value	Value range (lower, upper)	References
Annual distance travelled	km	normal	listed in Table B8	±10% of the base value	ACEA (European Automobile Manufacturers' Association, 2021)
Fuel consumption of ICEVs	L / 100 km	triangular	dynamic, listed in Table B8	85% to 118% of the base value	Hawkins et al. (Hawkins et al., 2013))
Fuel consumption of HEVs	L / 100 km	triangular	4.8	4.08 – 5.9	Milovanoff et al. (Milovanoff et al., 2020)
Energy consumption of BEVs	kWh / 100 km	triangular	dynamic, listed in Table B8	96% to 106% of the base value	Zhang et al. (Zhang et al., 2019); Ellingsen et al. (Ellingsen et al., 2016)
Energy consumption of PHEVs	L / 100 km + kWh / 100 km	triangular	6.7 + 0.217	5.8 – 7.2 + 0.2 – 0.223	Küfeoğlu et al. (Küfeoğlu and Khah Kok Hong, 2020)
Driving model probability of PHEVs	none	triangular	0.5	0 – 1	Zhang et al. (Zhang et al., 2019)

Appx B4. Additional results

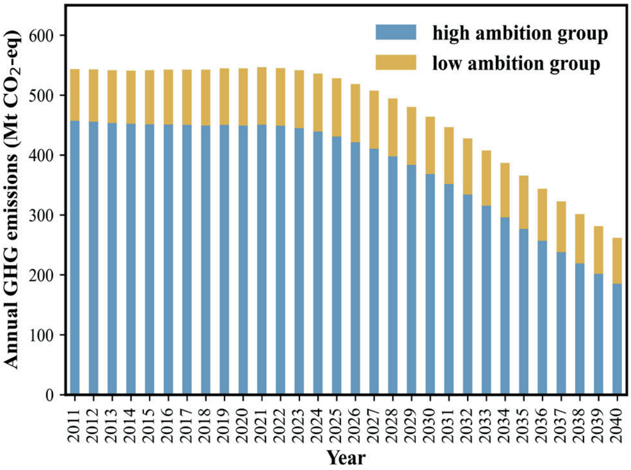

Figure B7. Annual GHG emission (Mt CO₂-eq) from driving passenger vehicles within the 27 EU + 3 countries until 2040 during the e-mobility transition under the stated policies.

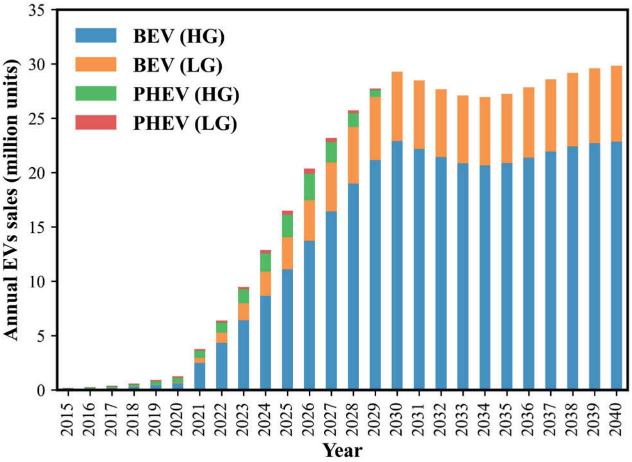

Figure B8. Annual BEVs and PHEVs demand (million units) under the promotion of a more ambitious e-mobility transition pace and an accelerated phase-out of ICEVs for countries in the high ambition group (HG) and the low ambition group (LG).

Appx B5. Lifespan extension

A sensitivity analysis was performed for the ambitious transition scenario to assess how the extension of EV lifetime will influence GHG emissions. We explored two options for extending the lifespan of BEV, including:

An **extended BEV use** from 12 years to 24 years, assuming that the replacement of EV battery would happen when the first EV battery reaches its end of life and the replaced EV battery has a lifespan of 12 years;

An **extended BEV lifespan** from 12 years to 18.4 years, representing an optimistic assumption that future EV battery technology would improve to the point of enabling BEVs to meet the historical average lifespan of the ICEVs in the high ambition group.

As shown in Figure B9, there are no major differences in GHG emissions from the manufacturing process at the early stage of the e-mobility transition (in the 2020s). Cumulative EV demand in the 2030s can decrease by 34% by expanding EV lifetimes from 12 to 24 years. This demand decrease would lead to 615 million tons drop in manufacturing GHG emissions. An extension of lifespan for both EV batteries and BEV from 12 years to 18.4 years would lead to a 27% decrease in cumulative EV demand and 930 million ton of GHG reductions from the manufacturing process, as it reduces the production of energy-intensive EV batteries. Longer EV battery lifespans will allow for longer EV service time and fewer EV battery replacements, contributing to greater improvement in the environmental benefits of BEV adoption.

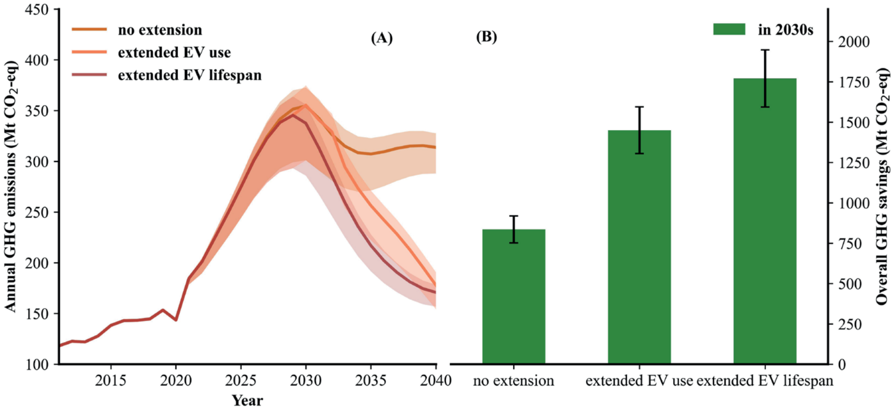

Figure B9. (A) Annual GHG emissions from the production of demanded passenger vehicles following different lifespan extension options under the ambitious trnasition scenario. (B) Overall GHG savings (difference between driving GHG emission reductions and manufacturing GHG emissions) in the 2030s following different lifespan extension options under the ambitious trnasition scenario.

References

Asian Batteries Power Global EV Fleet. https://www.statista.com/chart/26584/worldwide-market-share-of-the-biggest-electric-vehicle-battery-makers/ (accessed 03.31.2022).

Campestrini, M., Mock, P., 2021. European vehicle market statistics. International Council on Clean Transportation, 1 – 50.

Cox, B., Bauer, C., Mendoza Beltran, A., van Vuuren, D.P., Mutel, C.L., 2020. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Appl. Energy. 269, 115021.

Cozzi, L., Gould, T., Bouckart, S., Crow, D., Kim, T.-Y., McGlade, C., Olejarnik, P., Wanner, B., Wetzel, D., 2020. World Energy Outlook 2020. 1 – 461.

Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019. Life cycle analysis of lithium-ion batteries for automotive applications. Batteries. 5, 48.

Data and maps — European Environment Agency. https://www.eea.europa.eu/data-and-maps (accessed 02.24.2021).

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

Ellingsen, L.A.W., Hung, C.R., Strømman, A.H., 2017. Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. Transport. Res. D Transport. Environ. 55, 82 – 90.

Ellingsen, L.A.-W., Singh, B., Strømman, A.H., 2016. The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environ. Res. Lett. 11, 054010.

European Automobile Manufacturers' Association, 2021, Statistic-ACEA. https://www.acea.auto/reliable-data-statistics (accessed 12.24.2021).

European Commission, 2021. Database - Eurostat. https://ec.europa.eu/eurostat/data/database (accessed 06.27.2021).

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., Anderson, P., 2019. Recycling lithium-ion batteries from electric vehicles. Nature. 575, 75 – 86.

Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2013a. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J. Ind. Ecol. 17, 53 – 64.

Held, M., Rosat, N., Georges, G., Pengg, H., Boulouchos, K., 2021. Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. Eur. Transp. Res. Rev. 13, 1–13.

International Energy Agency, 2019. Data & Statistics - IEA Electricity Information. https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy supply&indicator=TPESbySource (accessed 02.24.21).

Kim, H.C., Wallington, T.J., Arsenault, R., Bae, C., Ahn, S., Lee, J., 2016. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis. Environ. Sci. Technol. 50, 7715–7722.

Küfeoğlu, S., Khah Kok Hong, D., 2020. Emissions performance of electric vehicles: A case study from the United Kingdom. Appl. Energy. 260, 114241.

Li, J., Yang, B., 2020. Analysis of greenhouse gas emissions from electric vehicle considering electric energy structure, climate and power economy of ev: A China case. Atmos.Pollut. Res. 11, 1 – 11.

Lucien, M., Julia P., 2020. Mission (almost) accomplished

Majeau-Bettez, G., Hawkins, T.R., Strømman, A.H., 2011. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environ. Sci. Technol. 45, 4548 – 4554.

Milovanoff, A., Kim, H.C., De Kleine, R., Wallington, T.J., Posen, I.D., MacLean, H.L., 2019. A Dynamic Fleet Model of U.S Light-Duty Vehicle Lightweighting and Associated Greenhouse Gas Emissions from 2016 to 2050. Environ. Sci. Technol. 53, 2199 – 2208.

Milovanoff, A., Posen, I.D., MacLean, H.L., 2020. Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nat. Clim. Chang. 10, 1102–1107.

Moreno R.E., FitzGerald, D., Symeonidis, A., Ioannidou, D. ,Müller, J., Valsasina, L., Vadenbo, C., Minas, N., Sonderegger, T., Dellenbach, D., 2021. Documentation of changes implemented in the ecoinvent database v3.8

Nealer, R., Hendrickson, T.P., 2015. Review of Recent Lifecycle Assessments of Energy and Greenhouse Gas Emissions for Electric Vehicles. Curr. Sustain./Renew. Energy Rep. 2, 66 – 73.

Notter, D.A., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., Althaus, H.-J., 2010. Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles. Environ. Sci. Technol. 44, 6550 – 6556.

Onat, N.C., Kucukvar, M., Aboushaqrah, N.N.M., Jabbar, R., 2019. How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar. Appl. Energy. 250, 461 – 477.

Peters, J.F., Baumann, M., Zimmermann, B., Braun, J., Weil, M., 2017. The environmental impact of Li-Ion batteries and the role of key parameters – A review, Renew.Sustain. Energy Rev. 67, 491 – 506.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Chang. 42, 153 – 168.

Schlömer S., T. Bruckner, L., Fulton A. McKinnon D. Perczyk J. Roy R. Schaeffer R. Sims P. Smith and R. Wiser, E.H., 2014. Annex III: Technology-specific cost and performance parameters in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

SSP Database. https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10 (accessed 11.01.2020).

Sun, X., Luo, X., Zhang, Z., Meng, F., Yang, J., 2020. Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. J. Clean. Prod. 273, 123006.

Tang, C., Sprecher, B., Tukker, A., Mogollón, J.M., 2021. The impact of climate policy implementation on lithium, cobalt and nickel demand: The case of the Dutch automotive sector up to 2040. Resour. Policy. 74, 102351.

Top electric vehicle markets dominate lithium-ion battery capacity growth, S&P Global Market Intelligence. 2021. https://www.spglobal.com/marketintelligence/en/news-insights/blog/top-electric-vehicle-markets-dominate-lithium-ion-battery-capacity-growth (accessed 04.01.2021).

Usón, A.A., Capilla, A.V., Bribián, I.Z., Scarpellini, S., Sastresa, E.L., 2011. Energy efficiency in transport and mobility from an eco-efficiency viewpoint. Energy. 36, 1916 – 1923.

Zhang, C., Yang, F., Ke, X., Liu, Z., Yuan, C., 2019. Predictive modeling of energy consumption and greenhouse gas emissions from autonomous electric vehicle operations. Appl. Energy. 254, 113597.

Appx C1. Modelling EV demands

The future total passenger cars for each country was estimated based on historical stock data collected from the Eurostat (European Commission, 2023) and European Automobile Manufacturers Association (ACEA) (European Automobile Manufacturers' Association, 2023) by assuming a vehicle-to-population ratio and future population growth from the Shared Socio-economic Pathway, SSP2 (Riahi et al., 2017), shown in Figure C1 (A). The SSP2 scenario outlines a middle-of-the-road scenario in terms of socioeconomic development. It represents moderate population growth and a path in which trends do not remain roughly aligned with historical patterns (Riahi et al., 2017). The projected population data was collected from the SSP database (SSP Database, 2021).The market share of BEVs was calculated based on the annual numbers of registered passenger vehicles for recent years (2011 – 2021) collected from the ACEA (European Automobile Manufacturers' Association, 2023). The scenario years (from 2022 onwards) were developed under two scenarios. The "strengthened transition" was assumed according to the updated EU climate plans for promoting zero-emission vehicles (in our case BEVs). The "ambitious transition" scenario was assumed a more accelerated transition that all the 27 EU + 3 countries would promote a more ambitious EV adoption, with ICEV sales phased-out by 2030. More details on the promotion targets were described in Table C1, shown in Figure C1 (B)). Changes in vehicle-to-population ratio were considered in a sensitivity analysis.An annual growth rate of ±7.5% of the base value was assumed, based on the average variation rate of vehicle ownership in the EU countries from 2017 to 2021 (European Automobile Manufacturers' Association, 2023)

Table C1. Policy plans on the promotion of EVs sales

Scenarios	Countries	Policy plans on promoting EVs sales (from 2022 onwards)
Strengthened transition	Norway, Austria, Ireland, Iceland, the Netherlands	BEVs sales share follows their announced promotion targets (Figure C1 (B)). Overall, these countries plan to have a full BEV sales market by the end of 2030.
	Other countries included in this study	BEVs sales share 100% of the market by the end of 2035, following the updated EU climate policies.
Ambitious transition	All 27 EU + 3 countries	BEV sales will account for 100% of the sales market in all 27 EU + 3 countries by the end of 2030. Noted that Norway and Iceland will follow their own announced plans for the rollout of EVs, as aforementioned.

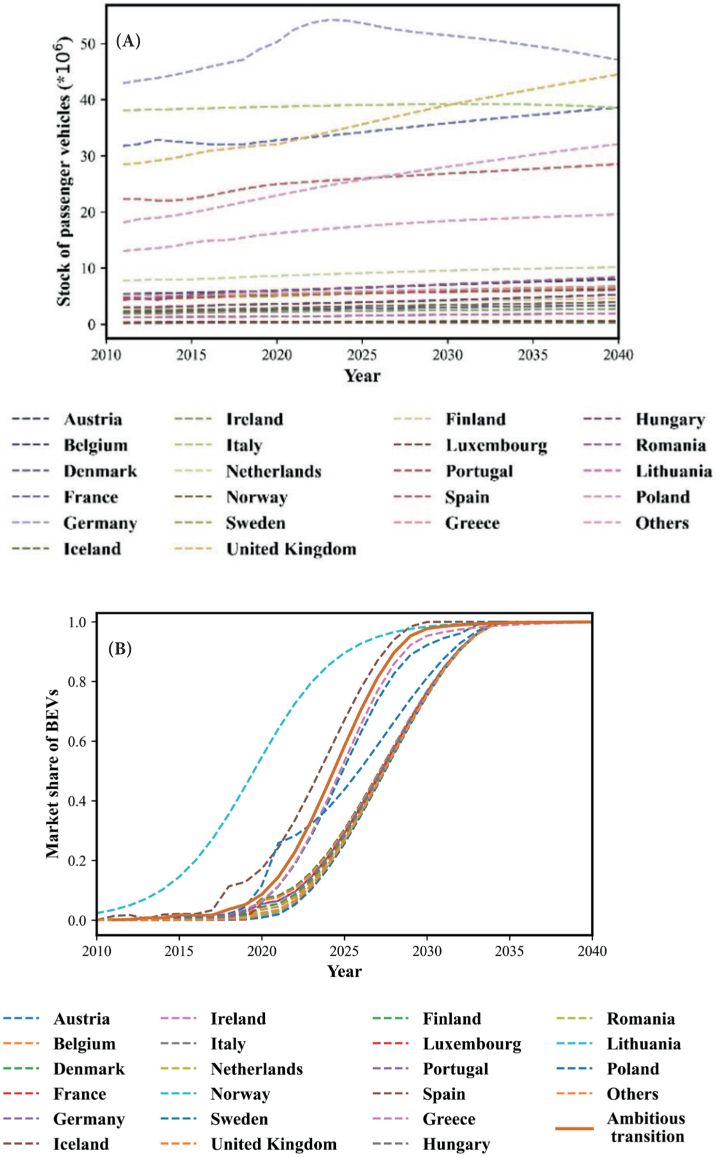

Figure C1. (A) The estimated total stock of passenger vehicles for the 27 EU + 3 countries through 2040. (B) Market share for BEVs in the 27 EU + 3 countries through 2040 for two scenarios. The dashed lines represent the results fitted for each country in the strengthened transition, and the solid line represents aggregated results in the ambitious transition except Norway and Iceland, as they will follow their own announced plans for the rollout of EVs. ("Others" represents the aggregated results of other EU countries that are not shown separately.)

The average lifespan of the passenger vehicles was assumed to follow a Weibull distribution function with scale and shape parameters (λ and k), as shown below:

$$f(T, t, k, \lambda) = 1 - e^{\left(-\frac{T-t}{\lambda}\right)^{k}}$$

The historical lifespan of passenger vehicles for the 27 EU + 3 countries was based on a previous study (Held et al., 2021), listed in Table C2. For scenario years, the average lifespan of ICEVs, PHEVs, and HEVs was assumed to follow historical trajectories across countries. The average lifespan of BEVs was assumed to be equal to the EV battery (12 years), as suggested by many EV automakers (Dominish et al., 2021).

In addition, a sensitivity analysis was performed to assess how the extension of EV battery lifespans and cahnges in shape parameters will influence future metal demand. We assumed an extended BEV lifespan from 12 years to 18.1 years and the changes of shape parameter following hisrotical trends of each country, representing an optimistic assumption that future EV battery technology would improve to the point of enabling

Table C2. Historical average lifespan of passenger vehicles for each country

Country	Lifespan (λ, k)	Country	Lifespan (λ, k)	Country	Lifespan (λ, k)
Austria	15.9, 3.4	Sweden	19.4, 4.9	Greece	33.9, 4.2
Belgium	11.7, 2.0	United Kingdom	14.2, 4.0	Czech	15.4, 3.6
Danmark	16.9, 3.4	Finland	24.9, 3.2	Slovakia	24.8, 4.03
France	15.2, 6.0	Luxembourg	8.0, 2.0	Croatia	30.9, 6.0
Germany	14.8, 2.4	Portugal	23.1, 6.0	Cyprus	24.8, 4.03
Iceland	19.7, 4.3	Spain	19.4, 3.2	Malta	24.8, 4.03
Ireland	15.0, 4.3	Hungary	23.1, 6.0	Bulgaria	24.8, 4.03
Italy	19.6, 2.7	Romania	24.8, 4.03	Estonia	24.8, 4.03
Norway	19.8, 6.0	Lithuania	24.8, 4.03	Latvia	24.8, 4.03
Netherlands	17.2, 4.4	Poland	24.8, 4.03	Slovenia	20.0, 6.0

Reference: Held et al., 2021

BEVs to meet the historical average lifespan of the ICEVs in the west European countries (Held et al., 2021).

Appx C2. Materials demands and recycling potential

Appx C2.1 Material demands

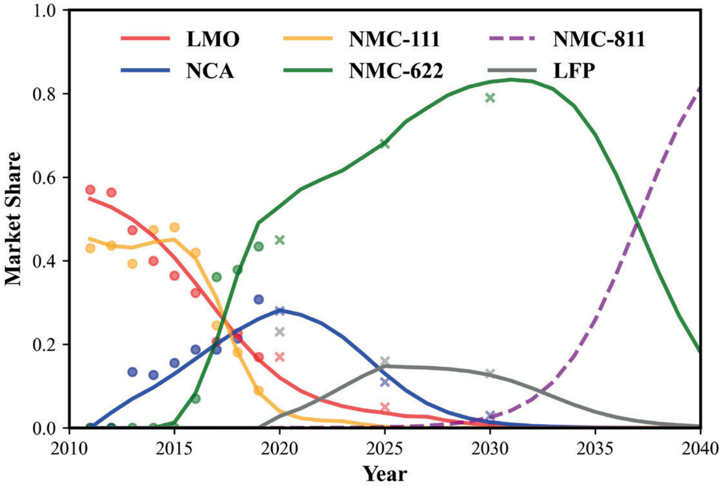

Figure C2. Market share for different types of EV battery cathode technology applied on BEVs through 2040. The scatters before 2020 represent historical data within our study scope (Tang et al., 2023). Scatters between 2020 – 2030 represent the aggregated projections by the report from the World Bank Group (Hund et al., 2020).

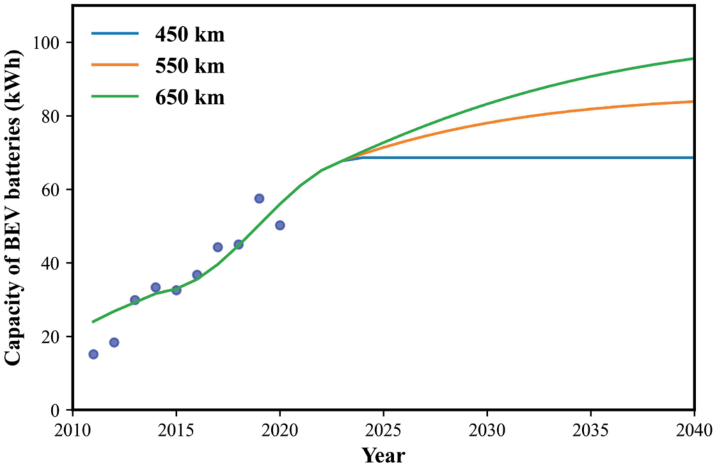

Figure C3. Estimated power capacity of EV battery used in BEVs based on a driving range assumptions of 450 km, 550 km and 650 km. The scatters represent average battery power capacity of the lunched BEV models by 2021 based on previous study (Tang et al., 2023).

Table C3. Metal intensities in different types of lithium batteries at cell level (kg / kW)

Battery Cathode	Li	Co	Ni
LMO	0.113	0	0
NCA	0.115	0.141	0.749
LFP	0.116	0	0
NMC-111	0.170	0.445	0.443
NMC-622	0.145	0.211	0.675
NMc-811	0.115	0.094	0.749

Appx C2.2 Recycling facility and recycling rates

As of 2021, the commercial recycling facilities in the EU countries reach a capacity of 40 kilotons battery packs per year, with the pyrometallurgical process dominating the recycling technology. To address the anticipated increase of EOL EV batteries and improve material circularity, the EU has promoted extended producer responsibility, urging automakers to strengthen the collection of spent EV batteries. Recyclers are in the process of scaling up the EU recycling facilities. Hydrometallurgical processes are increasingly being prioritized due to their technological feasibility in efficiently recovering a wide range of battery components with minimal material loss, high selectivity, and high efficiency. The high-purity materials recovered through hydrometallurgy can be directly used in the production of new batteries, offering a promising pathway to secure material availability and support the EU's goal of localizing EV manufacturing closer to the market (Zhou et al., 2024).

Due to the economic benefits, Co and Ni are given the priority in the hydrometallurgical recycling process, with general recovery rates over 95%. Contamination and mass loss happen after multiple leaching and separation processes, leading to the recovery rate of Li ranging from 60% to 90%. The recovery rate of Li has been reported to improve with the application of innovative leaching solvents. Bioleaching, which utilizes microorganisms, has demonstrated Li recovery rates exceeding 90%, while deep eutectic solvents (DESs) have achieved rates surpassing 70%. These advancements are attributed to the reduction of losses caused by multiple refining processes (Tran et al., 2019, Zhu et al., 2022, Wang et al., 2019). Other innovative recycling technology, such as electrochemical leaching (Adhikari et al., 2023, Diaz et al., 2020), carbothermic reduction process (Yu et al., 2023), and direct regeneration of cathode (Jing et al., 2020, Ciez and Whitacre 2019) have demonstrated recycling efficiencies of Li, Co and Ni above 95%. Although these technologies are still at the laboratory scale, they show optimistic opportunities for enhancing recovery efficiencies of end-of-life batteries in the coming future. Based on these developments, we assumed an improvement of the recycling efficiencies of Li, Co and Ni until 2040 to evaluate the recycling potential in the EU countries (Figure C4). We assumed an ambiguous improvement in the recycling process, with 95% recycling rates available for all metals. The collection rate of EOL EV batteries was assumed to be 100%, along with the strong promotions of high collection rates to ensure proper end-of-life treatment to reduce environmental burden and preserve the value of materials required in the updated EU Battery Directive (European Commission 2022). The collection rate of spent EV batteries was evaluated with alternatives at 50% and 75%.

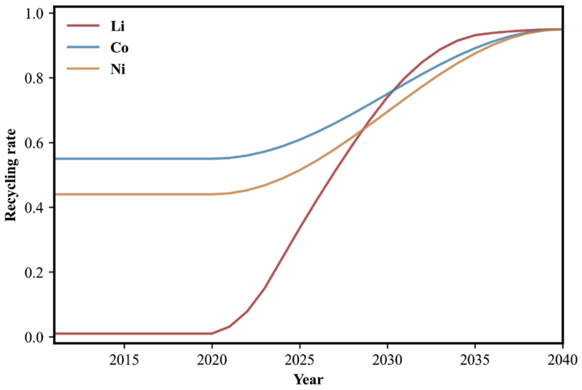

Figure C4. Recycling rates of Li, Co, and Ni until 2040, based on the updated EU Battery Directive that requires promotion of recycling rates (Zhu et al. 2022, Tran et al. 2019, Yu et al. 2023, European Commission 2022).

Appx C3. Sensitivity analysis

A sensitivity analysis was performed for the "strengthened transition" scenario to evaluate the sensitivity of material demands and availability of secondary materials to the variation of input parameters in our model, as listed in Table C4.

Table C4. Input parameters description of the sensitivity analysis

Input parameter	Unit	Base value	Assumptions of change in base value	References
Vehicle ownership	units / 1000 pop	A constant vehicle-to-population ratio for each country, following their historical trends.	An annual growth rate of ±7.5% of the base value, based on the average variation rate of vehicle ownership in the EU countries from 2017 to 2021.	ACEA(European Automobile Manufacturers' Association, 2023)
Lifetime distribution of BEVs	Scale parameter (λ): years	12	18.1 (explained in Appx C1)	Held et al., 2021; Tang et al., 2023
	Shape parameter (k): none	4.03	It was assumed to follow the empirical data of each country, as listed in Table C2.	Held et al., 2021; Tang et al., 2023
EV battery capacity	kWh	Dynamic, based on assumption of a 550 km driving range (shown in Figure C4).	Lower value: based on assumption of a 650 km driving range (Figure C3). Upper value: based on assumption of a 450 km driving range (Figure C3).	Tang et al., 2023
Collection rate of the spent EV battery	none	100%	Reduced collection rates: 50% and 75%.	European Commission 2022
Recycling rates	none	Assumptions based on the updated EU Battery Directive (Figure C4).	A more optimistic improvement in the recycling rates, as elaborated in Appx C2.2.	Zhu et al., 2022, Tran et al., 2019, Yu et al., 2023, European Commission 2022

Appx C4. Additional results

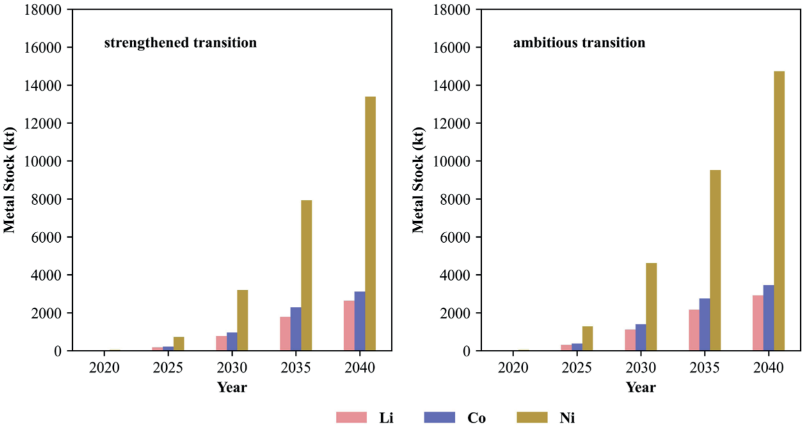

Figure C5. Stock for Li, Co and Ni for the 27 EU + 3 countries under the EV promotion following the strengthened policies and the assumption on an ambitious transition through 2040.

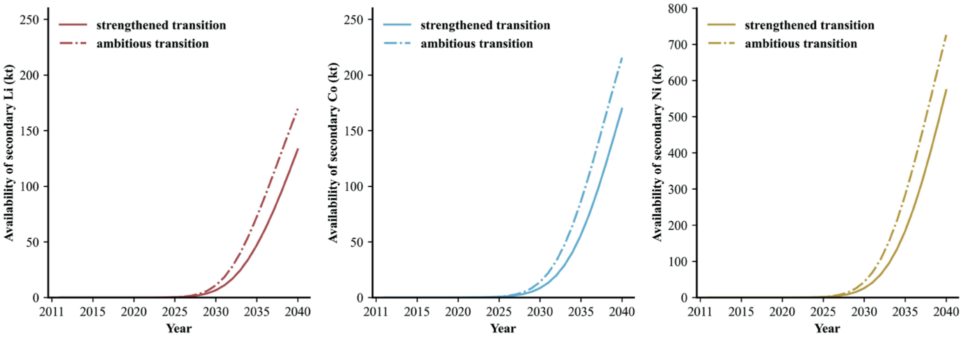

Figure C6. Availability of secondary Li, Co and Ni for the 27 EU + 3 countries with the implementation of EU recycling directives under the EV promotion following the strengthened policies and the assumption on an ambitious transition through 2040.

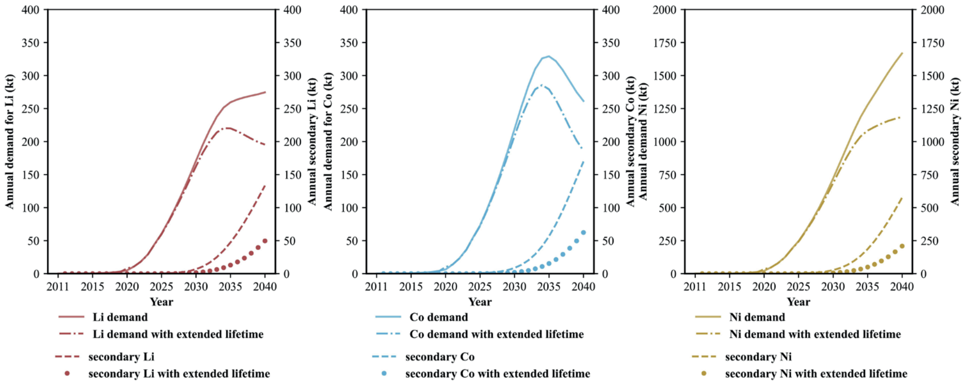

Figure C7. Annual demand and secondary availability of Li, Co, and Ni for the 27 EU + 3 countries under EV promotion following the strengthened policies. The dot-dashed lines and dots represent the annual demand and availability for each metal assuming the lifespan of EV batteries is extended to 18.1 years. Note that these results are based on the assumption of medium battery capacity.

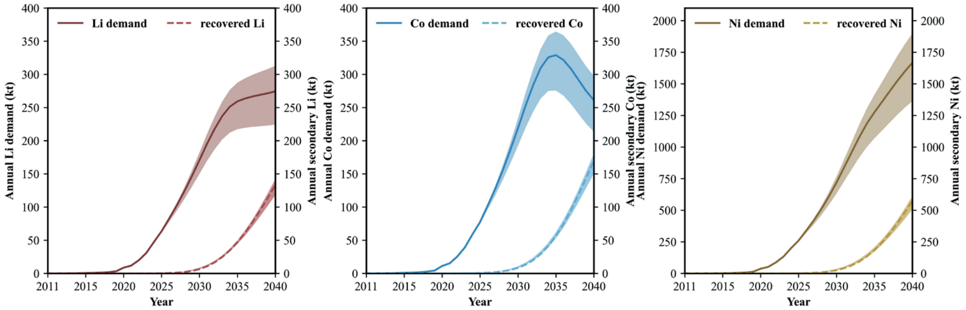

Figure C8. Annual demand and secondary availability of Li, Co and Ni for the 27 EU + 3 countries under the EV promotion following the strengthened policies. The result bands represent the range of the results under the assumptions (high, medium and low) on EV battery capacity.

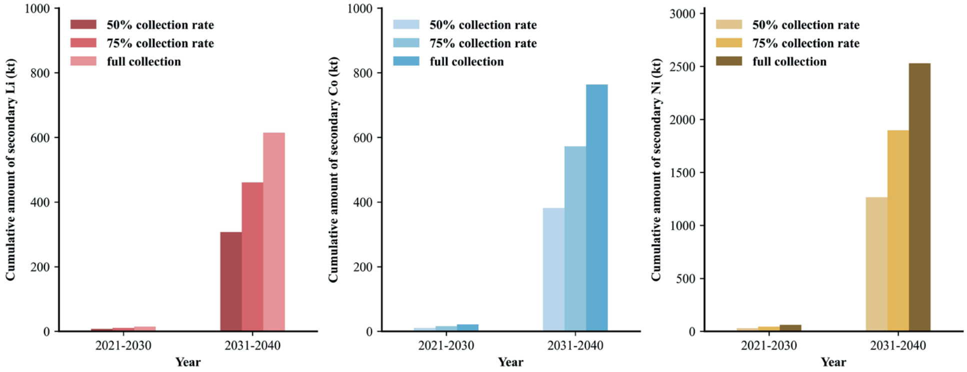

Figure C9. Cumulative availability of secondary Li, Co and Ni for the 27 EU + 3 countries under the assumption of a reduction in the collection rate of spent EV batteries in the strengthened transition scenario.

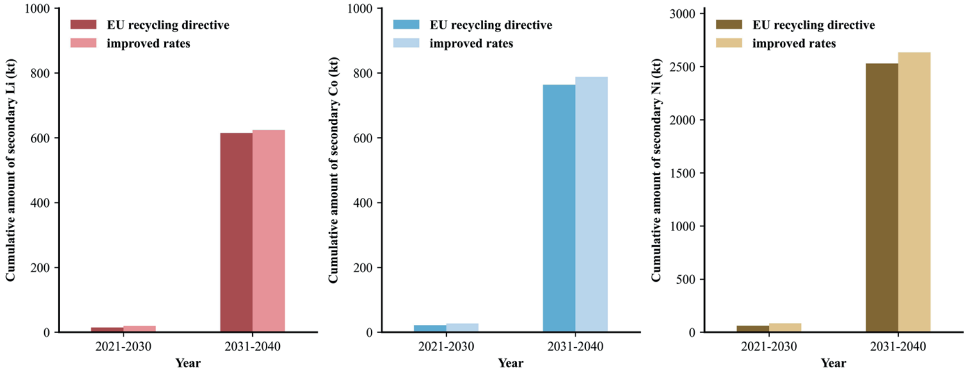

Figure C10. Cumulative availability of secondary Li, Co and Ni for the 27 EU + 3 countries under the assumption of an imporovement of the recycling rate of spent EV batteries in the strengthened transition scenario.

References

Adhikari B, Chowdhury N A, Diaz L A, Jin H, Saha A K, Shi M, Klaehn J R and Lister T E 2023 Electrochemical leaching of critical materials from lithium-ion batteries: A comparative life cycle assessment Resour. Conserv. Recycl. 193, 106973.

Chen M, Ma X, Chen B, Arsenault R, Karlson P, Simon N and Wang Y 2019 Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries Joule 3, 2622 – 2646.

Ciez R E and Whitacre J F 2019 Examining different recycling processes for lithium-ion batteries Nat. Sustain. 2, 148 – 156.

Diaz L A, Strauss M L, Adhikari B, Klaehn J R, McNally J S and Lister T E 2020 Electrochemical-assisted leaching of active materials from lithium ion batteries Resour. Conserv. Recycl. 161, 104900.

Dominish E, Florin N and Wakefield-Rann R 2021 Reducing new mining for electric vehicle battery metals: responsible sourcing through demand reduction strategies and recycling.

European Automobile Manufacturers' Association 2023 Statistic-ACEA.

European Commission 2021 Database - Eurostat. https://ec.europa.eu/eurostat/data/database (accessed 06.27.2021)

European Commission 2022 Proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/ 66 / EC and amending Regulation (EU) No 2019/1020.

Held M, Rosat N, Georges G, Pengg H and Boulouchos K 2021 Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics European Trans. Research. Review. 13, 1 – 13.

Hund K, Porta D La, Fabregas T P, Laing T and Drexhage J 2020 Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.

Jing Q, Zhang J, Liu Y, Zhang W, Chen Y and Wang C 2020 Direct Regeneration of Spent LiFePO4Cathode Material by a Green and Efficient One-Step Hydrothermal Method ACS Sustain. Chem. Eng. 8, 17622 – 17628.

Melin H E, Rajaeifar M A, Ku A Y, Kendall A, Harper G and Heidrich O 2021 Global implications of the EU battery regulation Science 373, 384 – 397.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Chang. 42, 153–168.

Tang C, Tukker A, Sprecher B and Mogollón J M 2023 Assessing the European Electric-Mobility Transition: Emissions from Electric Vehicle Manufacturing and Use in Relation to the EU Greenhouse Gas Emission Targets Environ. Sci. Technol. 57, 44 – 52.

Tran M K, Rodrigues M-T F, Kato K, Babu G and Ajayan P M 2019 Deep eutectic solvents for cathode recycling of Li-ion batteries Nat. Energy. 4, 339 – 345.

Wang M, Tan Q, Liu L and Li J 2019 A low-toxicity and high-efficiency deep eutectic solvent for the separation of aluminum foil and cathode materials from spent lithium-ion batteries J. Hazard. Mater. 380, 120846.

Yu W, Zhang Y, Hu J, Zhou J, Shang Z, Zhou X and Xu S 2023 Controlled carbothermic reduction for enhanced recovery of metals from spent lithium-ion batteries Resour. Conserv. Recycl. 194, 107005.

Zhou H, Yang Y, Li W, McKechnie J, Thiede S and Wang P 2024 EU's recycled content targets of lithium-ion batteries are likely to compromise critical metal circularity One Earth 7, 1288 – 1300.

Zhu A, Bian X, Han W, Cao D, Wen Y, Zhu K and Wang S 2022 The application of deep eutectic solvents in lithium-ion battery recycling: A comprehensive review Resour. Conserv. Recycl. 188, 106690.

Appx D1. Demand and availability of secondary materials for BEV battery production

In this study, we applied a dynamic material flow analysis (MFA) to estimate the demand and discards for the BEVs from 2021 to 2036, based on the changes in fleet stock and lifetime distribution of vehicles in each country. Historical data of total passenger vehicle stock for each country until 2021 was collected from the Eurostat database (European Commission, 2023). Prospective stock of total passenger vehicles from 2022 onwards was estimated using a constant vehicle-to-population ratio with the future population growth obtained from the Shared Socio-economic Pathways, SSP2, as shown in Figure D1.

The average lifetime of passenger vehicles either fully or partially equipped with internal combustion engines was assumed to correspond with the historical trends observed across nations detailed in Table C2 in Appx C (Held et al., 2021). For BEVs, we assumed them to be equipped with one new EV battery pack for their entire lifetime. Their lifetime was assumed to be 12 years ($\lambda = 12$, $k = 4.03$) for all countries. For the sensitivity analysis, the lifetime was assumed to extent to 18.1 years ($\lambda = 18.1$, $k = 4.03$), following the historical average lifetime of vehicles in the EU countries, listed in Table C2 in Appx C.

The demand for BEVs was determined by the policies on promoting the roll-out of low-carbon emission vehicles in the EU transport sector, as listed in Table D1.

Table D1. Policy plans on the promotion of EV sales

E-mobility transition	Countries	Policy plans on promoting EV sales (from 2022 onwards)
Strengthened transition	Austria, Ireland, and the Netherlands	Share of BEV sales will follow their announced promotion targets (Figure D1 (A)). Overall, these countries plan to have a full BEV sales market by the end of 2030.
	Other EU countries	Sales of BEVs will share 100% of the market by the end of 2035, following the updated EU climate policies.

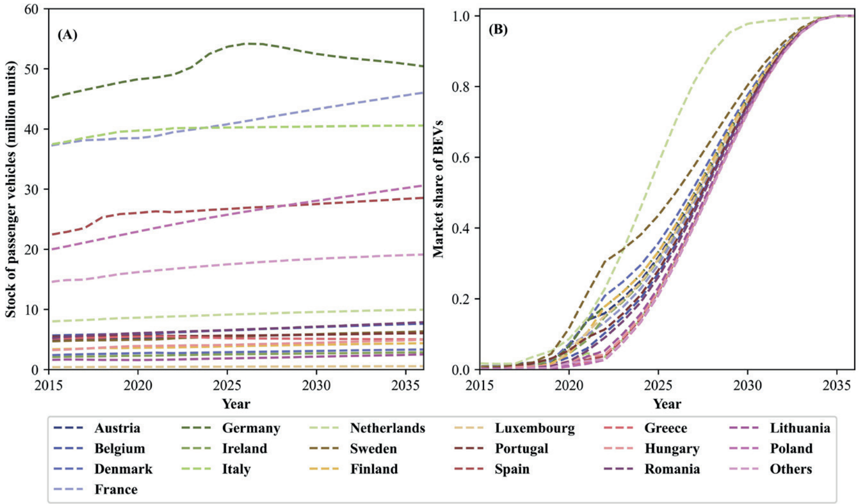

Figure D1. (A) The estimated total stock of passenger vehicles for the 27 EU countries through 2036. (B) Market share for BEVs in the 27 EU countries through 2036 following the pace of EU e-mobility transition as listed in Table D1. ("Others" represents the aggregated results of other EU countries that are not shown separately.)

Historical record of annual registrations of BEVs was derived from the database of the European Automobile Manufacturers Association (ACEA) (European Automobile Manufacturers' Association, 2023). The historical volume of BEVs placed on the market (POM) was determined by the historical records of exports, imports, and BEV manufacturing volume derived from the PRODCOM database (Eurostat, 2024). As shown in Figure D2, we noticed a deviation between the POM and annual registration of BEVs, which may be caused by different data sources. Therefore, we calculated the ratio (*R0*) between BEV registration and the POM volume. We took the average number (*R0* = 1.14) to estimate prospective POM of BEVs from 2023 onwards.

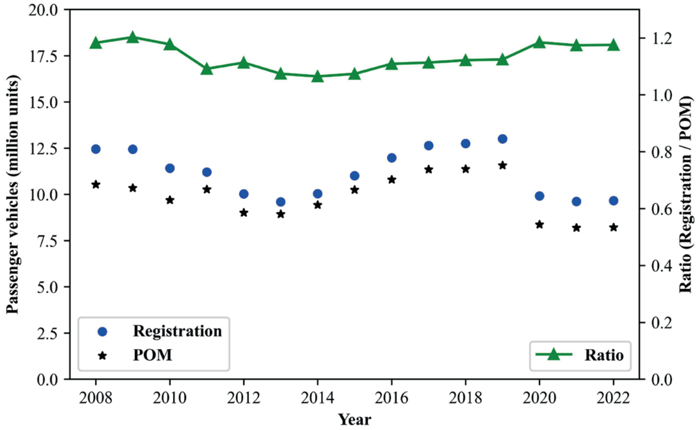

Figure D2. Historical record of annual registrations and volumes of passenger vehicles placed on the market (POM) in EU countries from 2008 to 2022. The ratio of annual registration to POM is shown on the right axis.

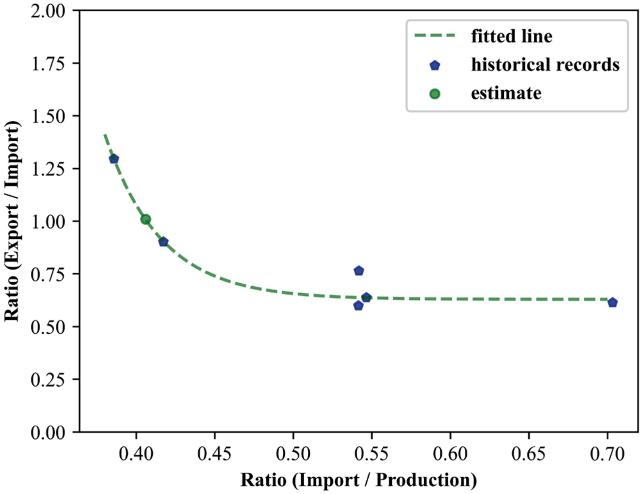

Figure D3. Ratio of imports to exports (*R1*) and imports to production (R2) for BEVs. Blue dots show historical data from 2016 to 2022 sourced from the PRODCOM database. The dashed line indicates the fitted relationship between R1 and R2. The green dot marks the estimated value of R2 under a balanced trade scenario (imports equal exports).

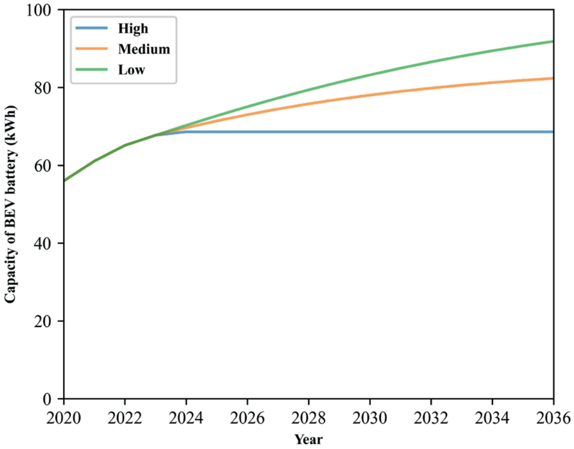

Figure D4. Estimated capacity of EV battery used in BEVs in the EU countries based on previous study (Tang et al., 2023).

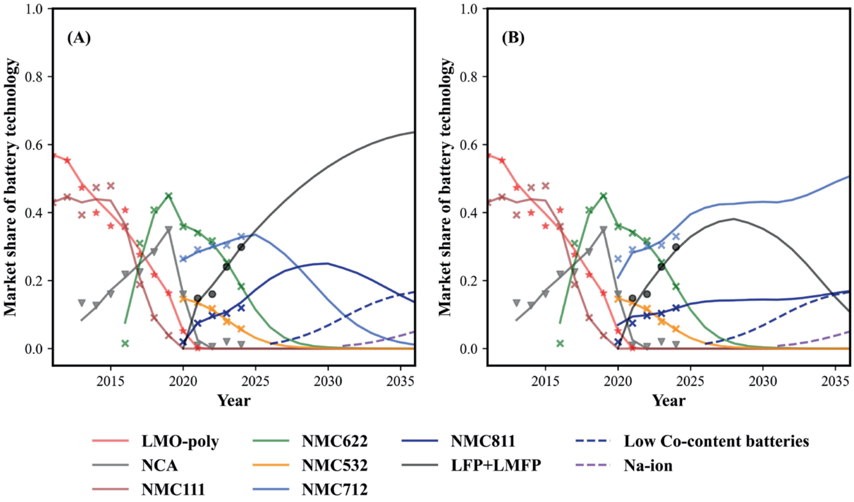

Figure D5. Projected market share for various battery cathode technologies in BEVs through 2036 under (A) a low-Co battery-dominated scenario and, (B) a high-Co battery-dominated scenario. The scatters before 2024 represent historical data based on the most popular BEV models sold in the European countries. The assumption of the projected market share of various battery types from 2024 onwards was based on the information from the report (International Renewable Energy Agency (IRENA), 2024).

Table D2. Metal intensities in different type of lithium batteries

Battery chemistry	Li (kg / kWh)	Co (kg / kWh)	Ni (kg / kWh)
LMO-poly	0.113	0	0
NCA	0.115	0.141	0.749
LFP and LFMP	0.116	0	0
NMC-111	0.170	0.445	0.443
NMC-622	0.145	0.211	0.675
NMC-811	0.115	0.094	0.749
Low-Co batteries*	0.23	0.03	1.1
Sodium-ion batteries	0	0	0.26

*Note: "Low-Co batteries" represents the battery chemistry with low cobalt content, such as Li-Mg-rich NMC batteries (LMR-NMC), Ni-rich lithium oxide battery (e-LNO). The metal intensity represents the estimated average level based on reports and studies (Abdelbaky et al., 2021; International Energy Agency, 2018; International Renewable Energy Agency (IRENA), 2024).

Table D3. Summary of expected development of the EU recycling system

Year		By 2021	By 2026	By 2031	By 2036
Spoke level (kt battery / year)		17	95.6	177.6	292.6
Hub level (kt battery / year)		21	65.2	193.2	343.4
Total recycling capacity (kt battery / year)		38	160.8	370.8	636.0
Overall recycling process efficiency	Li	45.5%	75.8%	85.4%	87.5%
	Co	86.1%	88.0%	88.6%	88.7%
	Ni	87.7%	88.5%	88.8%	88.8%

Appx D2. Additional results

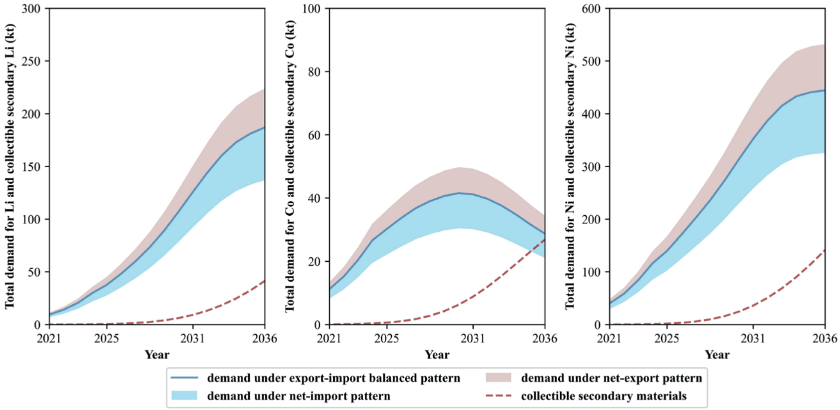

Figure D6. Total demand for Li, Co and Ni required by growth in manufacturing capacity of BEV batteries under different trade patterns and collectible secondary Li, Co and Ni from end-of-life EV batteries.

Table D4. Summary of availability of secondary materials processed at different end-of-life processing stages

Material recoverability (kt / year)		By 2021	By 2026	By 2031	By 2036
Total available amount of secondary materials expected from spent EV batteries	Li	0.01	0.4	5.8	31.5
	Co	0.03	0.5	6.2	22.8
	Ni	0.05	1.6	24	112.8
Collectible amount of secondary materials from spent EV batteries (90%)	Li	0.01	0.4	5.2	28.3
	Co	0.03	0.5	5.5	20.5
	Ni	0.05	1.5	21.6	101.6
Total recoverable materials from developed recycling system	Li	0.5	4.4	6.1	17.0
	Co	1.2	6.0	6.2	12.1
	Ni	4.4	20.7	24.4	60.2
Total recovered materials at the hub level	Li	0.2	2.7	6.1	9.2
	Co	0.8	3.8	6.2	6.6
	Ni	3.0	13.1	24.4	32.5

References

Abdelbaky, M., Peeters, J.R., Dewulf, W., 2021. On the influence of second use, future battery technologies, and battery lifetime on the maximum recycled content of future electric vehicle batteries in Europe. Waste Management 125, 1 – 9. .

European Automobile Manufacturers' Association, 2023. Statistic-ACEA. URL https://www.acea.auto (accessed 12.24.2023).

European Commission, 2023. Database - Eurostat. URL https://ec.europa.eu/eurostat/data/database (accessed 12.16.2023).

Eurostat, 2024. Database - ProdCom - statistics by product. URL https://ec.europa.eu/eurostat/web/prodcom/database (accessed 04.22.2024).

Held, M., Rosat, N., Georges, G., Pengg, H., Boulouchos, K., 2021. Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. European Transport Research Review 13, 1 – 13.

International Energy Agency, 2018. Global EV Outlook 2018:Towards cross-modal electrification.

International Renewable Energy Agency (IRENA), 2024. Critical materials: Batteries for electric vehicles.

Tang, C., Tukker, A., Sprecher, B., Mogollón, J.M., 2023. Assessing the European Electric-Mobility Transition: Emissions from Electric Vehicle Manufacturing and Use in Relation to the EU Greenhouse Gas Emission Targets. Environ. Sci. Technol. 57, 44 – 52