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A perspective on carbon footprint of decentralized manufacturing of lithium-ion cells industrialization

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Lithium-ion cells are in high demand worldwide due to the rise in EVs, green energy storage, and consumer electronic devices. Establishing a decentralized manufacturing ecosystem for LIB cells is essential as local public and private firms strive to become major participants in this sector. This research article focuses on the carbon footprint of producing current lithium-ion batteries (LIBs; LFP ~152 kgCO$_2$eq/kWh, NMC811~ 205 kgCO$_2$eq/kWh and NMC622~202 kgCO$_2$eq/kWh, respectively), discusses on different stage of sustainable manufacturing ecosystem, and investigates the carbon footprint dependency on decentralized manufacturing in any geographic area. As a result of this the overall emissions generated across all production steps of lithium-ion cells may be expected to reduce about 6%–7% by 2030.

KEYWORDS

carbon footprint, decentralization, gigafactories, lithium-ion cells, transportation sector

1 Introduction

Global warming, fuelled by the accumulation of greenhouse gases (GHGs) in the atmosphere, poses one of the most critical challenges of the 21st century (Masson-Delmotte et al., 2020). The rapid increase in carbon dioxide (CO$_2$) and other GHG emissions from human activities is fuelling a rise in global temperatures, resulting in significant alterations to weather patterns, rising sea levels, and widespread ecological disruption (O'Neill, 2020). Some of the major sectors contributing to this phenomenon include industry, power generation and transportation, which were mainly focused on this article. (Bruhwiler et al., 2021; Faze and l, 2024).

In particular, 1) some of the industrial sectors such as cement production, chemical processing, and metal refining, etc., emits substantial amounts of carbon through various stages of material processing. 2) Power generation is also considered as one of the major contributors which is a cornerstone of global electricity supply, has traditionally depended on coal, oil, and natural gas, further intensifying the climate crisis. Similarly, the transportation sector, encompassing road, air, rail, and maritime travel, remains a major emitter due to its heavy dependence on non-renewable energy source like gasoline and diesel (Puttanapong and Bowonthumrongchai, 2025; Hoicka et al., 2021). As a result, the global carbon footprint (CF) is largely the result of the cumulative impact of these energy-intensive sectors, which continue to expand alongside increasing demands for

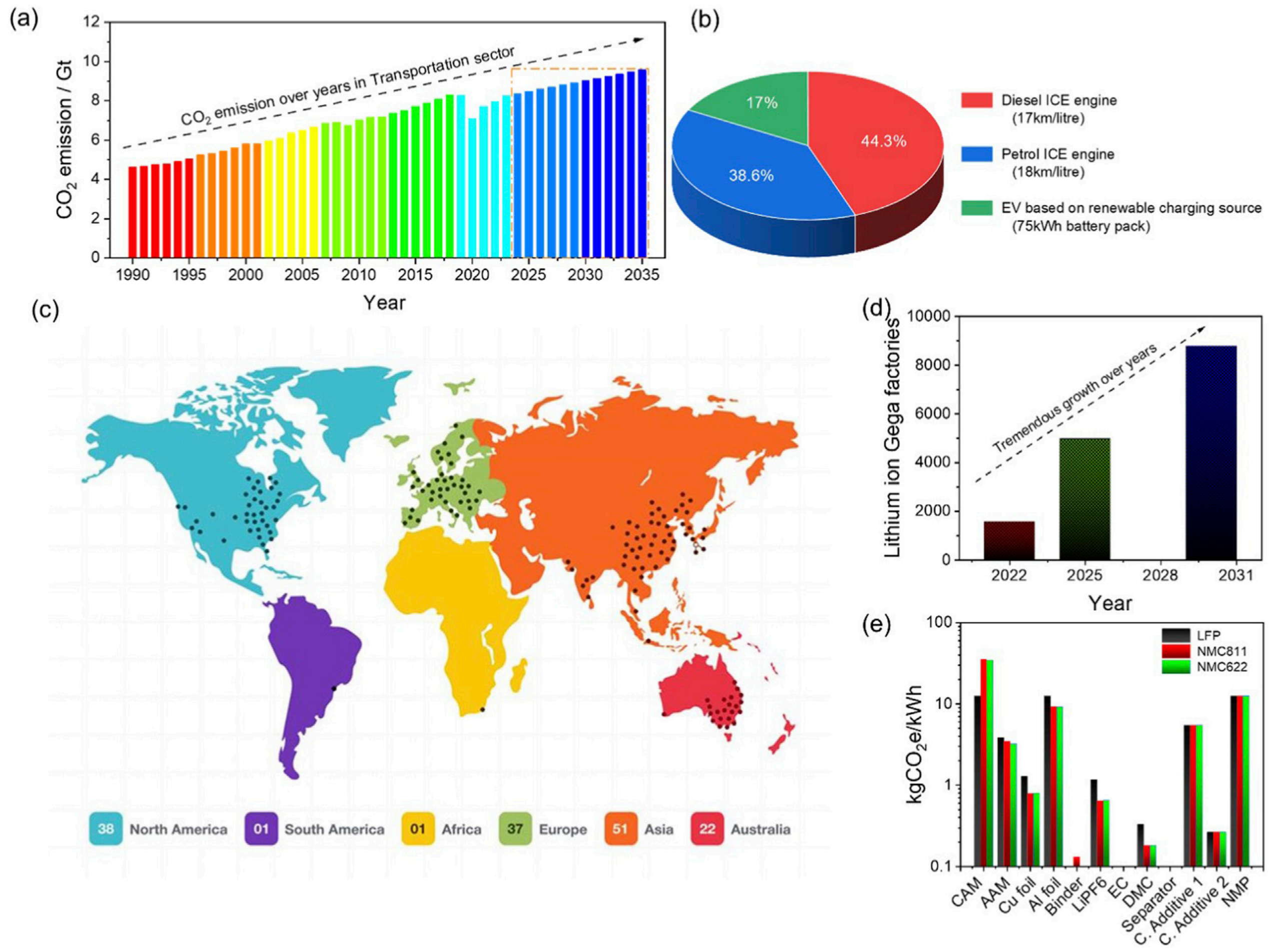

FIGURE 1
(a) Represents global CO2 emissions in the transportation sector over the year (in gigatonnes) from (1990–2023) (Taylor et al., 2024) and their projections over 2035; **(b)** Comparative study of EV v/s ICE (Gas, 2021). **(c)** Represents the global gigafactories which is well established globally (Panchal et al., 2025); **(d)** The remarkable expansion of giga factories from 2022 to 2031 (Sarvestani et al., 2025), **(e)** Carbon emission of the total battery materials such as Cathode active material, Negative active material, Collector foils, binder (PVDF), electrolytes and their solvents (LiPF6, EC, DMC), Carbon Additives (C65, KS6L). of 100Ah LFP, 5Ah NMC811, and 4.5Ah NMC622 cells (Chen et al., 2025; International Energy Agency, 2023; Brodnicke et al., 2023; Llamas-Orozco et al., 2023; Garcia-Herrero et al., 2016; Kallitsis et al., 2024; Peiseler et al., 2023; The Wall Street Journal, 2025).

goods, services, and mobility (Gür, 2022; Koytsoumpa et al., 2018). Various strategies were planned in each sector to reduce CF and one among them is in the transportation. Figure 1a illustrates the global CO_2 emissions from the transportation sector over the years 1990–2035 (in gigatonnes) (Taylor et al., 2024). From 1990 to 2020, there is a noticeable upward trend, reflecting the continuous growth in transportation activities. A slight decline in emissions is observed around 2020, primarily due to the global pandemic. However, emissions begin to rise again post-2020, albeit at a slower rate. The dashed box (2025–2035) highlights a critical period, projecting future emission trends and emphasizing the importance of sustainable interventions in this sector (Taylor et al., 2024).

However, the escalating climate crisis has catalysed a profound transformation in global energy systems, with a heightened focus on sustainable practices and low-carbon energy sources. This energy transition spans several critical sectors—industrial operations, power generation and transportation—each playing a significant role in reduction of carbon emissions and promoting long-term environmental sustainability (Kabeyi and Olanrewaju, 2022; Alreshidi et al., 2025; Heffron et al., 2020). At present, industries are increasingly adopting advanced technologies and optimizing manufacturing processes to enhance energy efficiency and cut emissions, though challenges remain in energy-intensive sectors where emissions are more difficult to mitigate (Jaiswal et al., 2022; Maradin, 2021). Similarly in the power sector, green energy sources such as solar, wind, and hydropower are progressively replacing fossil fuels, offering cleaner, more resilient alternatives for electricity production, and directly contributing to a reduced CF (Farghali et al., 2023). Collectively, these changes are crucial to lessening the overall global CF, aligning with the growing need to combat climate change (Lee et al., 2024; Cao, 2019).

Recently, the “transportation sector” is undergoing a transformative shift with the transition from fossil-fuel based to electric vehicles (EVs), which is a pivotal development in global decarbonization efforts (Lee et al., 2024; Cao, 2019; Ferrer and Thome, 2023). In contrast to traditional internal combustion (IC) engine, EVs vehicles offer zero tailpipe emissions and significantly lower lifecycle emissions, notably when powered by a cleaner electricity mix (such as solar, wind, hydropower, etc.) (Linder, 2023). This transition is being driven by rapid advancements in lithium-ion battery (LIB) technology, improved integration of renewable energy into the grid, and supportive policy frameworks that encourage the adoption of cleaner mobility solutions which helps in reducing carbon emission (Gas, 2021; Singer et al., 2023; Kumar et al., 2025; Wu et al., 2018). Figure 1b illustrates the comparative CO_2 equivalents (CO_2e) produced by the complete production to the end of cycle life of vehicle (150,000 km). Wherein, the CO_2e represents the conversion of various GHG emissions (based on the global warming potential) to equivalent amount of CO_2. The number of kilometres delivered by diesel ICE vehicle is about 17 km/L and for petrol is 18 km/L and these values were considered in the present study (Gas, 2021; Peshin et al., 2022). This life cycle emissions analysis highlights the environmental benefits of EVs which are closely tied to the utilization of clean energy sources for charging and implementing sustainable practices in battery production (Amjad et al., 2010; Bork et al., 2015; Patil et al., 2024; Ling et al., 2024).

It is estimated that the production of one large battery pack (75 kW h battery pack emits >7 tons of CO_2e) for EV is account to be about 40%–60% of the total emissions produced for the manufacturing of one complete EV (Linder, 2023). The main reason for this emission is the raw materials used in manufacturing of batteries such as Mn, Ni, Co., Li, graphite, etc., should be processed via mining, refining, making active and inactive battery components and final cell assembly (Gutsch and Leker, 2024; Peiseler et al., 2024). Additionally, transportation of these processed chemical/materials from one location site to the other locations after each processing steps will top-up the emission intensities. However, there is a considerable scope in steep reduction of this carbon emission by developing sustainable ecosystem by using renewable energy sources for electricity generation (Šima et al., 2025). It is also reported in the literature that the implementation of recent advancements in hybrid battery thermal management (nano-PCM, copper foam, optimized mini channels), multi-physics real-time monitoring, and AI-based SOH estimation in battery pack can collectively expected to improve the battery efficiency, lifetime, and safety (Hmidi et al., 2026; Madani et al., 2025; Xie et al., 2025; Sarvestani et al., 2025). These technologies can help in reducing the overall carbon footprint by enabling longer-lasting batteries, lower cooling energy demand, safer fast charging, and fewer battery replacements which can support more to sustainable EV and ESS (Energy storage systems) development (Mohapatra et al., 2025; Fan et al., 2025; Panchal et al., 2025; Chen et al., 2025).

The present study is to explore strategies to enhance the environmental performance of LIBs, focusing on how sensitive their environmental impact (CF) on overall battery supply chain. It begins with the present evaluation of CF associated with LIB production, considering the environmental effects at every stage, starting from mining to cell production and their targeted application. A central recommendation is proposed by identifying key areas for improvement is to decentralize the LIB manufacturing ecosystem, wherein India is taken as an example model, which may help foster sustainability by reducing reliance on large-scale centralized manufacturing ecosystem.

2 Sustainable LIB production for EVs and their CF traceability

The LIB is about to hit a historically unprecedented growth spurt which is central to the transition towards clean energy and electrification. However, the current manufacturing processes are often centralized, leading to inefficiencies and high carbon emissions which are the key factors for life cycle assessment (LCA) and product life cycle management (PLM) (International Energy Agency, 2023). According to estimates, the whole battery supply chain contributes between 1.3 and 1.5 gigatons of CO_2 yearly, making the manufacturing process of LIB a considerable contributor to global CO_2 emissions (Taylor et al., 2024; Patil et al., 2024). More precisely, a sizable amount of batteries' CF comes from upfront resource extraction from mining and utilization activities in refining raw materials due to their high material input requirements followed by transportation of these intermediate chemicals to the production facility (for example, cathode or anode or electrolyte, etc.) (Brodnicke et al., 2023). Llamas et al., has reported a detailed statistic of the major precursors, which are the main contributors to the CO_2 emissions in the leading cathodes of the LIB cell (Llamas-Orozco et al., 2023). Furthermore, the energy contributions from the synthesis/preparation of active and inactive components and the final cell assembly will also contribute to additional carbon emissions, exacerbating the environmental impact of the industry (Brodnicke et al., 2023; Garcia-Herrero et al., 2016). Moreover, the location of production also plays a crucial role in the overall GHG emission of a LIB, as the carbon intensity of the power supply can vary significantly. For instance, CO_2 emissions from products made in China have a carbon footprint 26%–140% higher than those manufactured in Europe or countries with cleaner energy sources (Kallitsis et al., 2024). This discrepancy has played a big role in stimulating some regions to develop their battery supply chains (Garcia-Herrero et al., 2016; Peiseler et al., 2023).

Another important dimension of reducing CF is by integration of advanced technologies such as modelling, digital twins, and predictive analytics across the battery pack manufacturing process (Hmidi et al., 2026; Madani et al., 2025; Fan et al., 2025). For instance, Xie et al. (2025) has developed a thermal model which can provide detailed information related to heat generation and transfer throughout the battery pack and they claimed that the real time reconstruction with this model shows high accuracy with reliable results under different controlled experimental conditions. The combination of these high-fidelity multi-physics models with real-time data acquisition can enable the manufacturers to optimize cell formation protocols, thermal profiles, and production line energy consumption. As a result, these advancements in the downstream process can contribute to a more circular and decarbonized battery supply chain by improving manufacturing sustainability, operational efficiency, and long-term resource utilization particularly for EV and ESS applications.

3 Gigafactories: driving innovations in battery manufacturing

The accelerating demand for electric vehicles and renewable energy storage has spotlighted gigafactories which are pivotal drivers for large-scale battery production. These large-scale facilities are essential in scaling up battery manufacturing, reducing costs, and promoting sustainable practices within the industry (The Wall Street Journal, 2025). However, some of the key challenges in building of gigafactories such as 1) high initial investments for plant construction, manufacturing equipment's and infrastructure (Frith et al., 2023). Moreover, the lead time for establishing of these factories is about 3–5 years which may create financial risks before initiation of cell production. 2) securing raw materials supply chain and inbound/outbound logistics (Olivetti et al., 2017; Habib et al., 2016), 3) shortage of high skilled labours specialized in cell manufacturing and quality control processes (Pardi, 2023). 4) complexity at every stage of cell manufacturing processes and their scale up without high defect rate are highly challenging (Kwade et al., 2018). 5) lot of environmental and regulatory issues due to high consumption of water, electricity, impact natural habitation, air pollution and health and safety regulations of workers (Chordia et al., 2021).

At present, Asian countries such as China, Japan and South Korea are dominant in battery as well as equipment manufacturing. Some of the major players in the automotive and energy sectors, such as Tesla, Panasonic, and CATL, CALB, BYD, LG, Samsung, SK Innovation, Gotion High-tech etc., have established massive production facilities across various regions (Bridge and Faigen, 2022). These factories not only enhance production capacities but also propel innovation in battery tech, resulting in higher energy density, faster charging, and improved efficiency. Furthermore, the establishment of these gigafactories has significant implications for local economies. They create thousands of jobs, stimulate local supply chains, and foster technological advancements. For instance, the Tesla Gigafactory in Nevada has transformed the region into a hub for battery manufacturing, attracting various suppliers and service providers (Llamas-Orozco et al., 2023). A tremendous growth of giga factories has been forecasted from 2022 to 2031 which is driven by several key factors, including the increasing demand for electric vehicles (EVs) and the advancements in battery technologies (Figures 1c,d) (Xu et al., 2022). As governments in many countries implement stricter environmental regulations and offer incentives for EV adoption, automakers have committed to transitioning to electric fleets, creating a strong need for large-scale production facilities. This shift has been further supported by technological advancements in automation and battery production, making it more cost-effective to scale operations. Additionally, "governments worldwide are investing in green energy infrastructure, offering funding and tax incentives for the construction of giga factories focused on EVs, batteries, and renewable energy solutions" (Xu et al., 2022; Shaikh and Ben, 2023; Khaleel et al., 2024). For example, countries like Europe, India, and the United States are investing heavily in domestic battery manufacturing facilities to reduce dependence on Asian markets and strengthen their own energy security (International Energy Agency, 2024).

3.1 Carbon footprint of LFP, NMC811 and NMC622 chemistries

A lifecycle assessment of LIBs indicates that the production of a typical EV battery (approx. 30 kWh) emits around 150–200 kg of CO_2 equivalent (Verma et al., 2025). Moreover, the carbon emission of LIBs not only varied with material sources and manufacturing locations but also with the battery chemistry, as the energy densities and the type of materials used may influence the Li-ion cell production. For example, Kelly et al. (2020) and Winjobi et al. (2022) highlights the regional CF differences linked to dominant supply chains (Garcia-Herrero et al., 2016). They claimed that difference in lithium source extracted from Australia and Chile have a significant variation in carbon emission (20% for NMC811 and upto 45% for NMC622 cathodes). However, both studies primarily used a single source—the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model—for their analysis (Kelly et al., 2020). In addition to the material sourcing and production location, different type of model such as Ecoinvent v3.9, EPA (2013), Greet-2015, EverBatt models, etc (Xu et al., 2022; Romare and Dahllöf, 2017; Manjong et al., 2024), were used to calculate the emission generated from above-mentioned chemistries and the values may differ by several hundred manifolds in terms of CF (Shaikh and Ben, 2023).

Here in the present study, three different chemistries were selected such as LFP, NMC811 and NMC622 based on their demand and a growing portion of LIB in EV market. Therefore, most widely used cell formats were selected to analyse the carbon emissions such as 100 Ah LFP prismatic, 5 Ah NMC811, and 4.5 Ah NMC622 cylindrical (Figure 1e) and the corresponding calculated numerical data for all these chemistries were given in Supplementary Table 3 of supporting information (Šima et al., 2025; International Energy Agency, 2023; Brodnicke et al., 2023; Llamas-Orozco et al., 2023; Garcia-Herrero et al., 2016; Kallitsis et al., 2024; Peiseler et al., 2023). It is clearly observed from the data that the cathode active material (CAM), positive foil, and electrolyte are the key contributors to the carbon emissions. Among CAMs, NMC811 and NMC622 variants showed higher emission, and their corresponding cell production also shows higher CF (67 and 66 $kgCO_2eq/kWh$; Supplementary Table 3) (Bridge and Faigen, 2022; Vig et al., 2022). While LFP cells generally have a different emissions profile, therefore the analysis shows that the material quantities involved in each cell's production play a crucial role in determining total emissions (50 $kgCO_2eq/kWh$; Supplementary Table 3). A notable advantage of LFP cells is that they do not require nickel, cobalt, and manganese—elements which are associated with higher pollution- and environmental degradation (NMC cell production) (Fredershausen et al., 2021). This emphasizes the importance of assessing the types of materials used and their respective quantities when evaluating the environmental impacts of battery technologies (Notter et al., 2010; Botejara Antúnez et al., 2024). To reduce the CF, many countries like the U.S., Germany, and South Korea, etc., were planning to expand their local manufacturing of battery active and inactive components to reduce reliance on international supply chains (World Resources Institute, 2024).

4 Results and discussion

4.1 1Decentralization of LIB manufacturing ecosystem

It is reported that until 2,031, there is a continuous expansion of giga factories in different countries throughout the world, which will

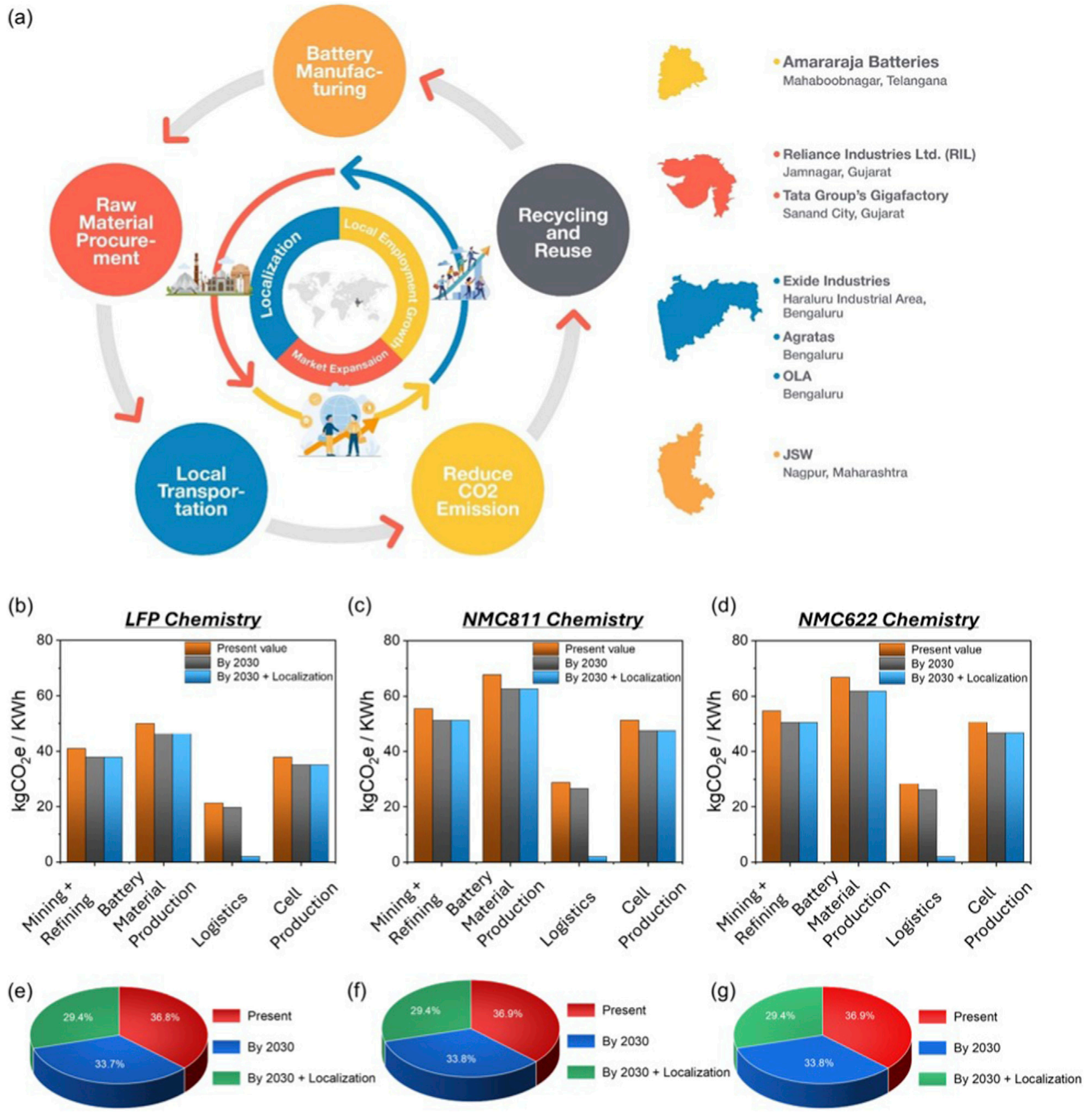

FIGURE 2
(a) Localization of Li-ion battery giga factories (e.g., India is taken as an example model), 2b to 2 g) shows the comparison of 3 cell chemistries, **(b,e)** LFP (100 Ah), **(c,f)** NMC811 (5 Ah), and **(d,g)** NMC622 (4.5 Ah) and their corresponding emissions under three scenarios: present value, projections for 2030 (Ferrer and Thome, 2023), and projections for 2030 with localization strategies.

significantly contribute to the global transition toward clean energy, reduce carbon emissions, and create millions of jobs in the green technology sector (Figures 1d, 2a) (International Energy Agency, 2024). In addition to the present global players, the rise of localized gigafactories is reshaping the landscape of battery production. These facilities focus on serving regional markets and adapting to local needs, which can reduce transportation costs and minimize CF. Moreover, localized gigafactories are essential for enhancing energy security and promoting sustainable practices tailored to specific regions (World Resources Institute, 2024; Kelly et al., 2021). Therefore, in the present study we consider India as an example model for estimating the CF of LIBs via localization because it is the fourth-largest market for passenger cars and one of the biggest markets for two- and three-wheeled vehicles worldwide (Emilsson and Dahllöf, 2019). More than 37 million automobiles and more than 75 million two- and three-wheelers will be added to India's roads in the next 10 years (Emilsson and Dahllöf, 2019; Mann et al., 2020). Thus, the government has implemented numerous regulations that encourage the modernization of road transportation in response to the increase in CO_2 emissions. Over 1.3 million EVs of various types were electrified with the help of subsidies provided by the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme, which achieved between 55%–84% of its initial targets across a variety of vehicle types, including buses, passenger cars, and two- and three-wheelers (ICCT, 2024) (International Energy Agency, 2023). In addition, the Indian government also launched the Prime Minister Electric Drive Revolution in Innovative Vehicle Enhancement (PM e-DRIVE) program in September 2024 to encourage the purchase of more than 14,000 electric buses and 2.8 million electric two- and three-wheelers, and also promotes the installation of more than 22,000 fast chargers at different places across the country (Botejara Antúnez et al., 2024). Therefore, by producing batteries closer to their point of use, localized gigafactories can streamline supply chains and respond more swiftly to market demands. This approach is particularly beneficial for countries like India with burgeoning electric vehicle markets, as it allows for the rapid scaling of production to meet local consumption needs (Peshin et al., 2022; Ghosh et al., 2020). Moreover, the gigafactories establishment in India is relatively new and growing strongly has an added advantage of developing facilities and infrastructure which are flexible to new battery chemistries. Based on the current geopolitical scenarios most of the countries aims to reduce its dependence on imported batteries and materials, thereby enhancing self-sufficiency in the EV sector. For example, countries like in India the battery market is rapidly evolving, driven by government initiatives such as the Production-Linked Incentive (PLI) and National Electric Mobility Mission Plan (NEMMP) schemes. However, most battery production remains concentrated in a few large facilities, primarily focused on cell assembly rather than raw material processing and production, These are the focused areas to be stricken to reduce carbon emission (Kelly et al., 2021; Emilsson and Dahllöf, 2019).

It is observed that there are four major sectors in LIB manufacturing which contributes to greenhouse gas emissions (in kg CO_2eq/kWh) such as 1) mining and refining, 2) active material production, 3) logistics, and 4) cell manufacturing (Linder, 2023). This study assesses how a decentralized manufacturing ecosystem influences the carbon footprint of various battery chemistries and the percentages for calculating CF at each sector was captured from the literature (Xu et al., 2022; Khaleel et al., 2024; International Energy Agency, 2024; Verma et al., 2025; Kelly et al., 2020; Romare and Dahllöf, 2017; Manjong et al., 2024; Hao et al., 2017; Sadhukhan and Christensen, 2021; Dai et al., 2019; Shah et al., 2025; Bibra et al., 2021).

Figures 2b–g shows the comparison of 3 cell chemistries, namely, LFP (100 Ah), NMC811 (5 Ah), and NMC622 (4.5 Ah) and their corresponding emissions—under three scenarios: present value, projections for 2030, and projections for 2030 with localization strategies and the corresponding table is given in the Supplementary Table 4. Among them, LFP showed lower emission of approximately 152 kgCO_2eq/kWh starting from mining to final cell manufacturing in comparison to NMC811 (205 kgCO_2eq/kWh) and NMC622 cells (202 kgCO_2eq/kWh), respectively. The higher emission in NMC chemistries is mainly related to the raw material extraction of cobalt, and nickel due to their environmental impacts such as habitat destruction and high energy consumption. It is reported that by 2030, notable reduction (3%–4%) is expected in emissions at each sector due to adoption of advanced electrified equipment and machineries and a fast-growing reliance on renewable energy sources (Linder, 2023). The impact is further amplified under the 2030 localization strategy, which focuses on developing manufacturing and supply chains closer to end-use markets. This approach minimizes logistics-related emissions (expected less than 2 kgCO_2eq/kWh) and takes advantage of regional renewable energy and cleaner production technologies, resulting in reducing the overall emissions across all production steps of about 6%–7%. In addition, there will be a lot of reduction in production cost, and the relative number may vary from one company to the other. Nevertheless, there are few key challenges related to the establishment of decentralized battery manufacturing ecosystem such as 1) technology dependency in the initial stage of development starting from mining to final cell assembly. This can be overcome by a structured collaborations between R&D (academia, start-up) and OEMs that can strategically upgrade the manufacturing processes at different stages and the implementation of advance chemistries (Na-ion, LMFP) can also help in further reducing CF. [77,78] 2) countries like India have limited domestic availability of critical minerals (Co., Ni, Li and graphite), however, utilizing non-critical mineral such as iron and sodium precursor for CAM (LFP, Na-based cathodes) can reduce the dependency on critical minerals (Warrior et al., 2023). It is also expected that the integration of recycling and waste management plays a key role in further lowering the greenhouse gas emissions by decreasing the demand for raw material extraction and energy-intensive processes. Overall, this study emphasizes the substantial environmental benefits of decentralization of LIB ecosystem in lowering the CF of battery cell manufacturing across all evaluated chemistries (Khaleel et al., 2024; Kelly et al., 2020; Hanna et al., 2025; Scheller et al., 2020). Additionally, EVs not only helps in reducing GHG emissions from the transport sector but also support grid decarbonization through integration with smart energy systems (Kumar et al., 2025). For instance, Kumar. P et al. reported that the vehicle-to-grid (V2G) technologies enable EVs to act as distributed energy storage units, helping stabilize power systems and better utilize intermittent renewable sources like solar and wind (Kumar et al., 2025; Peshin et al., 2022). Moreover, EV adoption contributes to improved urban air quality, less noise pollution, and strengthened energy security, particularly in oil-importing countries (Amjad et al., 2010). As a result of this many governments in the developed/developing countries are promoting EV deployment through subsidies, tax incentives, zero-emission zones, and phasing out fossil-fuel vehicle sales by mid-century (Bork et al., 2015; Patil et al., 2024).

5 Conclusion

Sustainable gigafactories are crucial for expanding production capacities to meet the raising demand for EVs and renewable power storage. To fulfilling the current energy needs, these factories hold a central role in advancing technological innovations and driving down production costs over time. At present, LFP, NMC811 and NMC622 chemistries exhibits a greenhouse gas emission of approximately 152 kgCO_2eq/kWh, 205 kgCO_2eq/kWh and 202 kgCO_2eq/kWh, respectively, starting from mining to cell production. Therefore, a decentralized manufacturing ecosystem may help in reducing the environmental damage by cutting down the long-distance transportation. As a result of this the greenhouse gas emission of different chemistries such as LFP,NMC811,NMC622 is expected to be about 121 kgCO_2eq/kWh,163 kgCO_2eq/kWh and 160 kgCO_2eq/kWh respectively, therefore the overall CF across all production steps may be expected to reduce about 6%–7% by 2030. Localization also reduces the dependency on global supply chains, making the industry less vulnerable to interruptions such as geopolitical conflicts, environmental disasters, or pandemics. Moreover, the establishment of decentralized manufacturing hubs can create numerous job opportunities within local communities.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AJ: Conceptualization, Writing – original draft, Writing – review and editing. MP: Conceptualization, Writing – original draft, Writing – review and editing. ED: Conceptualization, Writing – review and editing. SM: Writing – review and editing. HE: Conceptualization, Writing – review and editing, Writing – original draft. JM: Conceptualization, Writing – review and editing.

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Conflict of interest

Authors AJ, ED, SM, HE, and JM were employed by Amara Raja Advanced Cell Technologies Private Limited.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2026.1630913/full#supplementary-material

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