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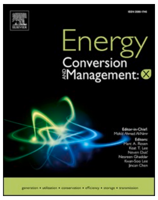

Low-carbon technologies and just energy transition: Prospects for electric vehicles

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ABSTRACT

The impacts of low-carbon technologies are spread across countries and lifecycle stages in ways that can compromise the achievement of an inclusive and equitable energy transition. Based on an exploratory review, this paper identifies the main activities of the electric vehicles (EVs) life cycle, where they occur, and potentially associated injustices. Through a whole systems approach, energy justice tenets are extended to the EV technology, highlighting how it might fail to fully support a low-carbon and just energy transition. Results provide insights into how EVs can contribute to flexibility justice through smart grids and vehicle-to-grid developments, cosmopolitan justice as a consequence of greenhouse gas (GHG) emissions and global resource depletion, and restorative justice through laws and standards that demand environmental restoration and social compensation over affected communities. However, reviewed documents indicate that efforts must be directed toward reducing distributional, procedural, and recognition injustices across the North-South divide, especially those related to mining activities in the resource extraction and processing stage. EVs upfront costs and charging infrastructure issues may also exclude poor and rural communities during its operational stage. Recommendations for future research include technical aspects such as battery composition and recycling, which will determine the overall impact of EVs on resource extraction and end of life stages, and social aspects of EV-technology such as social innovations that can promote its inclusiveness, the achievement of the Sustainable Development Goals, and the quantification of social impacts of low-carbon technologies.

1. Introduction

Energy transitions are socio-technical processes that encompass more than technological innovations. At the same time that energy transitions profoundly impact society, the economy, and the environment, their pace and reach also depend on social dynamics, such as social acceptance of technologies. Nevertheless, technocentric perspectives have dominated transitions' discourses [1], and social aspects have been commonly overlooked or instrumentalized with socio-economic gaps widening globally. From this background, efforts to include justice and equity as the focus of energy research have emerged. By assessing social impacts on individuals and communities, policymakers can implement measures that contribute to a just energy transition (JET). At first, the concept of a "just transition" originated in the 1970 s within trade union movements in the United States (US) [2], but since then it has been used in debates around "green new deals", "circular economy" [3], and even countries' Nationally Determined Contributions (NDCs), e.g., Chile [4]. Focused on energy systems and its social implications, the concept has evolved to the term JET, which has been applied to energy transitions research. The broad goal of a JET is to find ways of reconciling environmental sustainability with social and economic development globally, with a particular focus on countries that have a history of exploitation, low socioeconomic indicators, and struggle over energy access, security, and affordability [5].

Likewise, a just energy system would be "*a global energy system that fairly disseminates both the benefits and costs of energy services and one that has representative and impartial energy decision-making*" [6]. However, the benefits and burdens of an energy system go beyond its operational stage, i.e., energy supply and demand, and spillover to other life cycle stages. Particularly, the United Nations (UN) Climate Change Conference (COP26) held in Glasgow in 2021 highlighted the criticality of resource extraction and usage for sustainable development, as "*minerals demand for renewable energy technologies is projected to skyrocket, particularly for battery metals being used in electric vehicles - and the associated*

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environmental and human impacts are likely to rise steeply as well" [7]. Special mention was made to electric vehicles (EVs) in this statement because of their expected contribution to decarbonizing the transport sector [8] and resource requirements for EVs battery manufacturing [9]. According to the International Energy Agency (IEA), the number of EVs should increase from 11 million in 2020 to 350 million in 2030, reaching almost 2 billion vehicles in 2050, in addition to a fourfold increase in the number of electric two- and three-wheelers and 50 million electric buses [10]. Nevertheless, it is not only the largeness of the electrified fleet that dictates the demand for raw materials but also batteries' size and capacity. Light-duty EV batteries can have a specific energy or energy density from around 30 to 275 Wh/kg with capacities varying from approximately 10 to 200 kWh [11]. Comparatively, the battery capacity requirements for a cellphone (e.g., Apple iPhone 6, 6.9 Wh) can be ten thousand times smaller than for an EV (e.g., Tesla Model S 85D vehicle, 85 kWh) [12]. Accordingly, the average mass of batteries used in popular EV models in the US is around 350 kg [13].

Conversely to internal combustion engine vehicles (ICEs), EVs are powered by battery-stored electricity. They are among the most promising technologies to decarbonize road transportation, along with sustainable fuels (e.g., advanced biofuels and electrofuels produced from electricity and CO2 [14]) and advanced powertrain vehicles (e.g., hybrid and fuel cells [15]). As batteries are fundamentally composed of two electrodes in an electrolyte [16], several different materials qualify as candidates for battery manufacturing. Among the battery technologies available for electric mobility, we can mention lead-acid, nickel–cadmium, and lithium-ion batteries (Li-ion batteries), each with a variety of electrode chemistry options [16]. Nevertheless, Li-ion batteries remain one of the most efficient and reliable battery systems for EVs [16]. Still, increasing the autonomy of EVs through enhancing battery capacities or reducing cars' energy consumption (e.g., lightweight design [15] and energy requirements of auxiliary systems [17]) will continue to be an important research stream if the foresought EVs uptake is to be fulfilled.

However, this upsurge in transport electrification may disrupt EVs supply chain and worsen social and environmental issues where related activities take place. To compound the problem, EVs supply chain relates to mining activities in a politically unstable country, the Democratic Republic of Congo (DRC) [18], where cobalt is extracted for Li-ion batteries production, and environmentally sensitive areas such as the Salar de Atacama in Chile [19]. Drawing from extensive fieldwork, Sovacool et al. [20] focused on cobalt mining in the DRC and electronic waste in Ghana and perceived that "*decarbonization enhances existing vulnerabilities in the Global South, contributing to environmental degradation, ethnic and gender discrimination, and child labour*" [21]. It also highlighted that much of previously published research has focused on future innovations, such as EVs, "*but overlooks or obscures downstream and upstream processes, such as mining or waste flows*" [20]. Therefore, considering the entire lifecycle of technologies is essential "*from the front end where metals and minerals are extracted, to the back end where waste streams reside*" [20].

This systemic analysis is aligned with the so-called whole systems approach, in which downstream and upstream processes are considered when evaluating a particular project or technology chain [22]. In order to provide a theoretical basis for discussions on justice, a 'multi-scalar' or 'whole systems' energy justice (EJ) approach was employed herein to evaluate EVs contribution to a JET. EJ has been addressed from a conceptual perspective (see for example, the principled approach [23], whole systems approach [24], and tenet-based approach [25]) with some attempts to better understand how technologies can contribute to EJ (e.g., hydropower in Vietnam [23], solar and wind projects in Chile, India, Kenya, and Mexico [26], utility-scale wind power in Mexico [27], the afterlife of off-grid solar products in Sub Saharan Africa [28], energy service contracts, EVs, solar panels, and low-carbon heating [29]). For the association of EJ and technologies, Lacey-Barnacle et al. [30] provided a systematic review of theoretical frameworks and energy foci of academic works on energy justice in the developing world, concluding that the largest bulk of papers addresses renewables and only 4 % of secondary papers included in the review focus on EVs. Sovacool et al. [31] evaluated the energy injustices (distributional, procedural, recognition-based, and cosmopolitan) of four low-carbon transitions – nuclear power in France, EVs in Norway, solar energy in Germany, and smart meters in Great Brain – without employing a whole systems perspective. Along the same lines, Sovacool et al. [32] evaluated the same four cases using a whole systems perspective to give a spatial scale (micro, *meso*, and macro) for the injustices' extent. However, to the best of the authors' knowledge, the linkage between EV technology and JET considering a whole systems approach in association with the distributional, procedural, recognition-based, cosmopolitan, restorative, and flexibility EJ tenets is yet not explored. By employing a whole systems thinking, our study attempts to highlight the distribution of injustices across the globe that follow the EVs life cycle, from the extraction of resources for Li-ion battery manufacturing to the end of life of EVs. We focus on battery-powered light-duty road vehicles thanks to the significance of this low-carbon technology to decarbonize the transport sector and the larger sales volume of battery EVs in comparison to plug-in hybrid EVs [33].

Specifically, this work has the following objectives: (i) identify what are the main activities of EVs' life cycle, where they take place, and what are potential injustices associated with these activities; (ii) conceptually link potential injustices to EJ tenets; (iii) identify how EV uptake challenges the achievement of a JET, and (iv) highlight research gaps to be further addressed. The remainder of this paper is structured as follows. Section 2 provides a theoretical background on EJ, while Section 3 identifies this work's scope concerning the lifecycle activities of EVs. Section 4 describes the research methods and highlights potential EV-related injustices found in the exploratory review. The linkages between EVs lifecycle stages and EJ tenets, and the technology contribution or opposition to a JET are discussed in Section 5. Lastly, Section 6 summarizes the main findings, limitations, and recommendations for future research.

2. Theoretical background: Energy justice

Even though the concept of EJ was firstly used in academia as a defined concept only in 2013 [34], it shares the same philosophical foundation as environmental and climate justice movements that began decades earlier [24]. EJ "*aims to provide all individuals across all areas with safe, affordable and sustainable energy*", [35]. There are three main approaches in the literature regarding EJ: (1) the principled approach [23], (2) the whole systems approach [24], and (3) the tenet-based approach [25]. In the principled approach, Sovacool et al. [23] reframed energy decisions as justice and ethical concerns and developed a framework for decision-making based on eight core principles: availability, affordability, due process, transparency and accountability, sustainability, intra-generational equity, inter-generational equity, and responsibility. Nevertheless, the principled-approach is less used than the tenet-based [36] and most of its principles can be seen as aspects of the tenet-based approach [37], which are described in the next section.

2.1. *Energy justice tenets*

The tenet-based approach has three central tenets: distributional, procedural, and recognition justices [25]. A recent review proposed by Jenkins et al. [36] comprehensively reviewed the EJ literature topic and identified that these three tenets are the most commonly used within EJ frameworks. **Distributional justice** calls for an even distribution of environmental ills and benefits and associated responsibilities regardless of income, wealth, gender, and color [35]. It also relates to the physical distribution of burdens and advantages, which has been used as an argument in local activities against wind development [27] and hydropower [38] projects, for example. **Procedural justice** refers to including all stakeholders, particularly misrecognized parties, in the decision-making process in a non-discriminatory way [39]. Markedly, Jenkins et al. [25] explicitly took into account three mechanisms for achieving procedural justice: local knowledge mobilization, greater information disclosure, and better institutional representation. **Recognition justice** is about people being rightfully represented and having equal political rights [25]. It is concerned with political and institutional oppression, disrespect of local culture, and misrecognition of communities' interests and visions for the future [40].

In addition to these three main components, we highlight cosmopolitan and restorative justices [34]. **Cosmopolitan justice** suggests that "*the ultimate unit of concerns are human beings and persons, not communities or nation-states*" [41]. Therefore, it argues that moral and justice concerns apply to every-one equally as people are all members of a global community [41]. In contrast, **Restorative justice** calls for the energy sector to take responsibility (moral and financial) for negative impacts on the environment and surrounding communities and work towards restoring the landscape [34]. Finally, in a recent work evaluating justice in solar development, Heffron et al. [42] pointed to a new tenet: **Flexibility justice**, which is concerned with ensuring a market open to existing and new players and a flexible energy system. Flexibility justice is based on the idea of a flexible energy transition, in which all sectors have potential contributions if appropriately coupled, e.g., vehicle-to-grid technologies and smart mobility in the transport sector [43].

2.2. Whole systems

The whole systems approach supports a cradle-to-grave perspective for identifying the real impacts of energy projects through interactions among system components [24]. Without this systemic view, the impacts of extracting rare metals for manufacturing energy technologies, or biofuel production on biodiversity and land use, for example, cannot be wholly understood and, therefore, mitigated [44]. In energy systems modelling, a 'whole systems' appraisal would also consider the fuel supply chain [45]. Among the works that have employed a whole systems approach to EJ, we already mentioned Sovacool et al.'s work [32], which evaluated four European low-carbon transitions and identified several injustices classified according to their spatial scales. Also, Sovacool et al. [22] developed a cradle-to-grave framework to evaluate energy transitions, and Mejía-Montero et al. [27] evaluated a utility-scale wind power in Mexico, providing "*clear evidence against the notion that RETs (renewable energy technologies) […] are inherently good or sustainable*" [27]. Fig. 1 presents the combination of the tenet-based and the whole systems approaches to EJ that will be explored in this study for the case of EVs.

3. Scope definition: The lifecycle stages of EVs

In this section, we review battery-powered EVs' life cycle according to four lifecycle stages: (1) resource extraction and processing, (2) manufacturing, (3) distribution and operation, and (4) waste and disposal. Even though transportation of car components takes place between lifecycle stages, we are not able to consider it fully herein, thanks to the complexities of evaluating freighting of all EV components. Alternatively, we consider the distribution of finished vehicles in the distribution and operation phase, battery shipping in the manufacturing phase, and reverse logistics in the end-of-life stage.

3.1. Stage 1: Resource extraction and processing

The first lifecycle stage includes mining and refining activities. For EVs, first-stage impacts are mostly linked to the extraction and processing of raw materials for energy storage as batteries are a key component and high contributor to EVs' cost and environmental impacts [46]. As the Global EV Outlook asserts, "*depending on its size and assuming a typical range of emissions from battery manufacturing and the global average carbon intensity of electricity in the use phase, [EV battery] accounts for 10–30 % of the total life-cycle emissions*" of battery-powered EVs [47]. Even though there are different types of batteries that employ different negative and positive electrode materials (see [16]), we consider Li-ion batteries for their reliability and technical efficiency and the fact that lithium-cobalt-manganese oxide cathode formulations have prevailed in the battery industry [48]. Raw materials commonly needed for manufacturing Li-ion batteries are manganese, cobalt, lithium, copper, nickel, aluminum, titanium, and carbon [49], whereas iron, rare-earth metals, and silicon are essential for electric motors [50]. Cobalt and lithium, in particular, were labeled as critical raw materials by the European Commission [51] and the US Geological Survey [52] because of their economic importance and supply risk. Therefore, the extraction and processing of lithium and cobalt were considered the two main activities of the first stage of EVs' lifecycle because of these materials' critical supply [51] and potential environmental impacts of Li-ion batteries (e.g., global warming potential, resource depletion, ecological toxicity, and human health [53]).

Lithium can be mined from salt-lake brines, hard-rock pegmatitic lithium ores, or lithium-rich clays, but, even though its occurrence in nature is common, few countries have significant economic exploitation

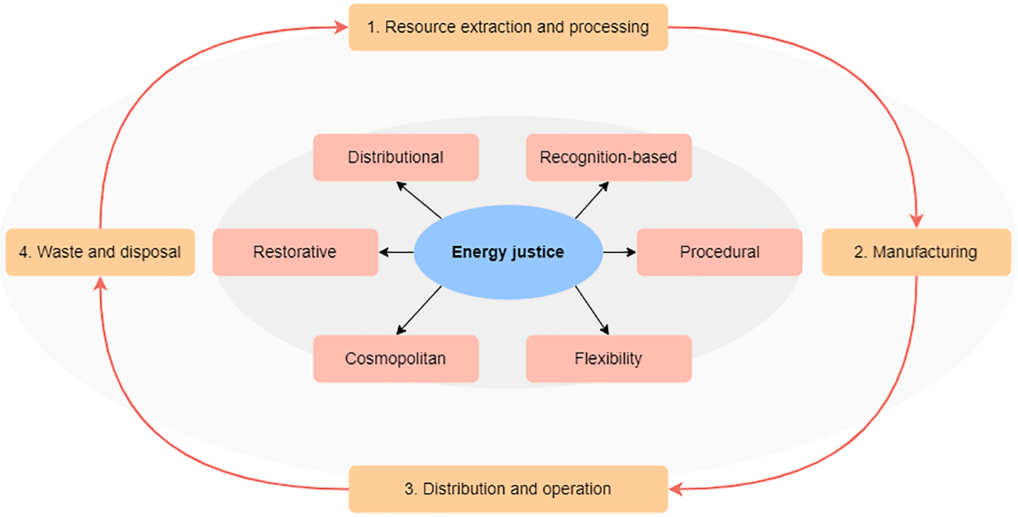


Fig. 1. The tenet-based and the whole systems approaches to EJ.

as is the case of Argentina, Australia, US, Chile, Bolivia, and China [19]. In Europe, Portugal has received attention thanks to its lithium reserves with the development of extraction and processing activities for EVs manufacturing being considered in the country [54]. According to the US Geological Survey, "*five mineral operations in Australia, two brine operations each in Argentina and Chile, and two brine and one mineral operation in China accounted for the majority of world lithium production*", [52]. Each of these countries produced over 5 million tons of lithium in 2020 [52]. After being mined, lithium must be further processed in chemical plants to remove impurities and produce lithium carbonate, which is then used for battery manufacturing. On the amount of raw material required, "*it takes 250 tons of the mineral ore spodumene when mined, or 750 tons of mineral-rich brine to produce one ton of lithium*" [55]. According to the Association of Mining and Exploration Companies, "*China dominates lithium processing, accounting for an estimated 89 percent of the world's lithium hydroxide. Chinese refineries produce lithium carbonate, lithium hydroxide and lithium chloride — the precursors to lithium-ion battery cathode materials*" [56]. Accordingly, China has the largest lithium consumption globally [12]. For cobalt, commonly produced as a byproduct of copper or nickel mining, the DRC was responsible for almost 70 % of the global cobalt mine production [52]. Apart from the DRC, which mined 95 million tons of cobalt in 2020, only Australia and Russia mined over 5 million tons of cobalt in the same year. The refinement of cobalt is also concentrated in China, the largest consumer of cobalt, which is used in the rechargeable battery industry [52].

3.2. Stage 2: Manufacturing

Resource extraction and processing are followed by manufacturing components and assembly into the final product. For EVs' batteries, refined raw materials have to be combined into cathodes, anodes, electrolytes, and separators [47]. The vast majority of battery components manufacturers are located in China, Japan, and South Korea [57]. After components are manufactured, they have to be combined into battery cells, which takes place mainly in China, the US, Europe, South Korea, and Japan [57]. Nevertheless, battery cell manufacturing has been taken near EVs manufacturing and assembly plants in Europe and the US mainly because of geopolitical tensions, risks and costs associated with shipping, and the security of supply [57]. Lithium can become highly inflammable when not packed and shipped appropriately, requiring temperature control, product enclosing, and stability during battery transportation. Therefore, if current trends continue, China will have 140 battery factories, Europe around 30, and the US, ten factories by 2030 [32]. Additionally, most EV assembly plants are found in China, the US, Japan, Germany, France, and the UK [57]. As the demand for EVs grows, so does manufacturing capacity, and some of the largest automotive companies have built or planned gigafactories to meet future demand (see [58]).

3.3. Stage 3: Distribution and operation

For distribution and operation, we consider the activities related to the sales and distribution and also re-charging and operation. Among the 40 countries with the largest total imports (US$) of battery EVs, plug-in hybrid EVs, and full hybrid models, including Hong Kong as separate from mainland China, 31 are located in the Global North [59]. The five largest importers are Belgium, Norway, China, Netherlands, and Germany [59]. Similarly, considering total battery, plug-in hybrid, and full hybrid EV exports (US$), among the top 40 countries, 34 are in the Global North [59]. The five largest exporters are Germany, the United States, South Korea, Belgium, and Slovakia [59]. Nevertheless, as our focus consist of battery-powered EVs, the next section evaluates injustices and trade values related to vehicles with electric propulsion only and Li-ion batteries. Once bought by end-users, EVs enter their operational lifetime (around ten years [47]). The largest concentration of EVs is in China, Europe, and North America. In 2020, China had 3.5 million battery electric cars and 1.0 million plug-in hybrid EVs, Europe 1.8 and 1.4 million, the US 1.1 and 0.6 million, and the rest of the world around 0.4 and 0.3 million [33].

3.4. Stage 4: Waste and disposal

The final stage comprises the waste and disposal of technologies, i.e., recycling, re-use, and waste. Recycling and reusing are part of a circular economy proposal, in which resource consumption and waste are reduced through the optimized utilization of by-products and the establishment of closed loops [60]. EVs recycling concerns, first, the dismantling of different components. The vehicle (without battery) and its traction battery follow different recycling paths. While some materials are wasted in landfills, vehicles undergo a shredding and post-shredding process for metal scrap [61]. For batteries, some commercial recycling processes are available such as pyro-metallurgy, hydro-metallurgy, hybrid and bio-processes, each with its advantages and disadvantages (see [62]), aiming to recover metals and cathode materials. In this lifecycle stage, once again, Li-ion batteries have been considered the primary concern as batteries re-use and recycling can reduce waste flows and raw materials extraction [63]. In other words, "*widespread battery recycling can create a more stable domestic source of materials for battery production, reduce the demand for raw materials, and minimize the risks of geopolitical disruptions of the supply chain*" [64]. However, there are some challenges such as the low volumes of spent batteries [62], the hazards of shipping and dismantling batteries [62], the incomplete recovery of valuable metals in commercial processes and the low economic value of some recovered materials [55]. As it is estimated that less than 5 % of Li-ion batteries get recycled at their end of life [65], most of them still end up in common landfills worldwide. Currently, Asia seems to dominate the battery recycling market with Sony Corporation in Japan [62] and companies such as Green Eco Manufacturing Resource (*GEM*), Hunan Brunp Recycling Technology, and Wuzhou Huayou Cobalt New Material in China [57].

At the end of EVs operation, batteries are assumed to retain 80 % of their initial capacity [47], making them eligible for use in several applications such as urban e-mobility and renewable energy storage, both at residential and utility scales [46]. Giving batteries a second-life is the focus of some pilot projects of car manufacturing companies such as General Motors (GM), Renault, Nissan, and BMW, and it has taken place mainly in Europe and the US [66]. Fig. 2 depicts the main regions where EV's life cycle activities occur. Also, it illustrates what would be a simplified flow for the typical trades across continents, including raw materials, batteries, and EVs.

4. Identifying injustices across EVs lifecycle stages

4.1. Research methods

This work explored works indexed in Science Direct, Scopus, and Web of Knowledge databases to identify potential injustices associated with EVs lifecycle activities. Sources in English were considered and research from 2012 onward was included in this study. A combination of EV- and justice-related terms were used, resulting in works linked to energy justice frameworks, as well as environmental and social life cycle analysis of EVs and associated materials/components. Given the wide scope and geographical resolution of this work a systematic literature review of works covering all EVs lifecycle stages would not be practicable.

When linking potential injustices to EJ tenets, six energy justice tenets of the tenet-based approach, i.e., distributional, procedural, recognition, restorative, cosmopolitan, and flexibility justices, were considered. Even though relevant to EJ literature, this work did not consider the principled approach as most of the latter's principles can be seen as aspects of the tenet-based approach [37]. Intra and intergenerational equity, for instance, which are pillars of sustainable

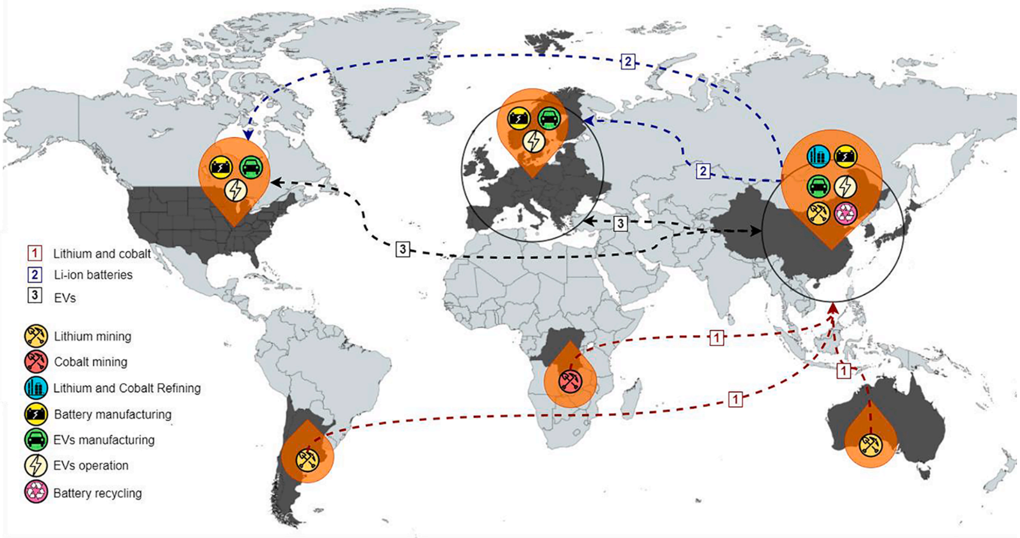


Fig. 2. Simplified map of EV's life cycle activities. The arrows represent flow of (1) lithium and cobalt for processing, (2) Li-ion batteries, and (3) EVs.

development, can be framed within distributive and cosmopolitan justice [41]. The six EJ tenets were combined with the whole systems approach to be as comprehensive as possible when evaluating the relationship between EVs and a JET across lifecycle stages. The proposed approach can also be extended to analyze other technologies' lifecycles. In the following subsections, injustices gathered from the exploratory review are synthesized according to related lifecycle stages and performed activities.

4.2. *EVs and resource requirements: The burdens of cobalt and lithium mining*

Mining activities have been linked to environmental justice issues due to air, soil, and water pollution [67], effects on human health and local biodiversity [68], water consumption [69], energy intensity [68], and conflicts with local and indigenous people [69]. Increasing demand has advanced mining activities toward more remote and unmined regions, which happen to overlap or be in the proximities of global protected areas in some cases [70]. Mining activities at the Lithium Triangle, i.e., Chile, Argentina, and Bolivia, are an example of overlapping with nature conservation areas [71]. In particular, lithium mining and low-efficient evaporitic technologies [72] in Chile have been linked to the forced delocalization of natives [71] and the depletion of water resources [67]. In Bolivia, as an opportunity for developing the national mining industry, it has generated local biodiversity concerns [73], whereas in the US, attempts to increase local production have produced conflicts with local communities [74].

Conflicts between mining companies and indigenous people are not new in the lithium supply chain and have already been documented in the lithium triangle [69]. Locals also seem to be blind-sighted due to poor knowledge sharing and are traditionally excluded in the decision-making process, even though their lives can be drastically affected by new mining activities [71], as they raise local pollution and health issues, for example [67]. In Portugal, even though lithium mining for battery manufacturing is only in the prospection and research stage, the initiative has already faced opposition from local communities thanks to poor communication and lack of transparency from companies and the government's side [75] and the negative impacts associated with the activity, e.g., effects on ecotourism, local agriculture, water consumption and pollution, and environmental degradation [76].

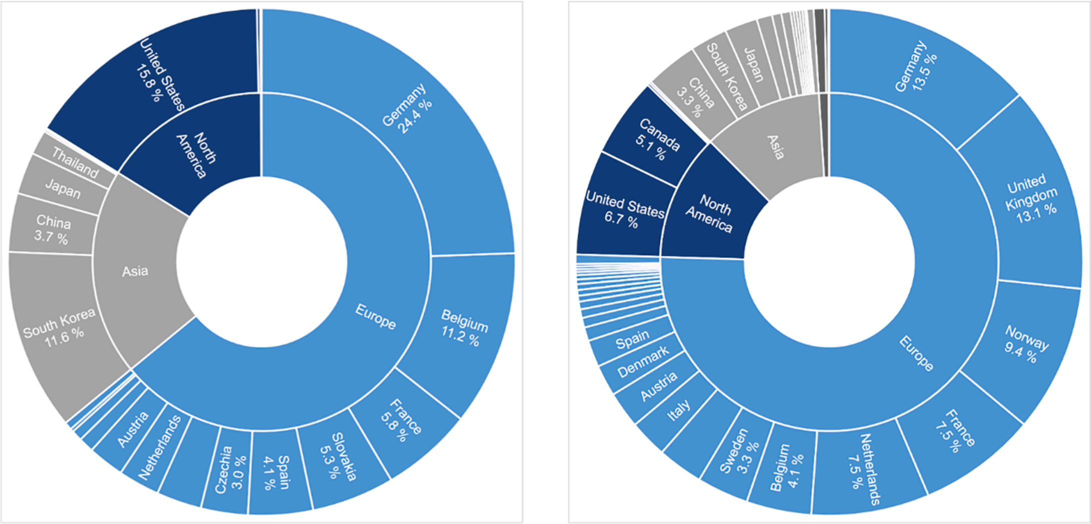
Concerning cobalt extraction, the struggles faced by Congolese people due to cobalt mining have been well documented by Sovacool [18], which highlighted pollution and health issues, terrible work conditions for artisanal miners, conflicts between small and large-scale miners, corruption and malfeasance, exploitation and unfair market practices, forced delocalization of native people, and child labor [20]. Once batteries with cobalt and nickel cathodes have the highest potential for environmental impacts, reducing their use and/or exposure to these materials has been recommended [53]. Some progress has been made in replacing cobalt, but lithium is expected to continue as a critical element in batteries for energy storage and e-mobility [77]. In 2018, China dominated the production of refined cobalt with a 63 % share being responsible for producing of 78,152 tonnes per year [78]. According to Piçarra et al. [78], the Herfindahl-Hirschman Index (HHI) for cobalt refining indicates a problematic "*monopolistic hold of the market from China*", which increases the vulnerability of other countries due to refined cobalt dependencies. The Chinese hold on the cobalt supply chain after cobalt extraction from DRC is also highlighted in Gulley et al. [79]. Lithium extracted from brines can be used in end-markets, whereas lithium extracted from hard rocks has to be further processed before being used in Li-ion batteries [56]. Australia, as the largest producer of lithium from spodumenes, has most of its lithium shipped to China for further processing in lithium carbonate, lithium hydroxide, or lithium chloride [56]. China is also the world's largest consumer of lithium thanks to its developed energy storage industry [12]. However, when comparing the manufacturing of battery components in China and the US, Hao et al. [80] found that the Chinese manufacturing industry can emit more than twice as much GHG emissions compared to the American due to the electrical grid composition and the energy intensity of industrial activities. Nevertheless, in average, the factory construction cost and the skilled labor rate is lower in China than other countries. For instance, the factory construction cost is around US$ 333/m^2 in China, US$420/m^2 in Poland, and US$656/m^2 in the US, whereas the skilled labor rate for these same countries is US$5/h, US$6/h, and US$85/h, respectively [56]. However, in addition to environmental aspects, there have been no social impacts and injustices related to lithium and cobalt processing alone documented in the reviewed literature.

4.3. *Jobs, health, and emissions: Impacts of an electrified automotive industry*

As China dominates the Li-ion batteries supply and is expected to continue at the top of raw material processing and manufacturing of battery cell components and cell manufacturing for the next years [55], it is reasonable to assess the Chinese manufacturing company's work conditions potential injustices. According to Sovacool [81], low-wage factory workers in countries such as China and Malaysia are the ones "*inhaling toxic fumes and exposed to hazardous materials*" and seeing "*their lives shortened and environments degraded so that climate mitigation options can be used or exported elsewhere*" [81]. Furthermore, attention must be paid to the effects of low-carbon technologies on labor and employment rates. There is a concern about job losses and employee retention in the automotive manufacturing industry because of the substitution of ICE vehicles for EVs [82]. As gigafactories are being planned and constructed in Europe and the US [57], they can create work opportunities and foster regional and national economic development. On the other hand, their construction activities may negatively impact the environment as a large area is required for their establishment, and their operation requires high water and energy availability, which has created conflicts with local communities [83].

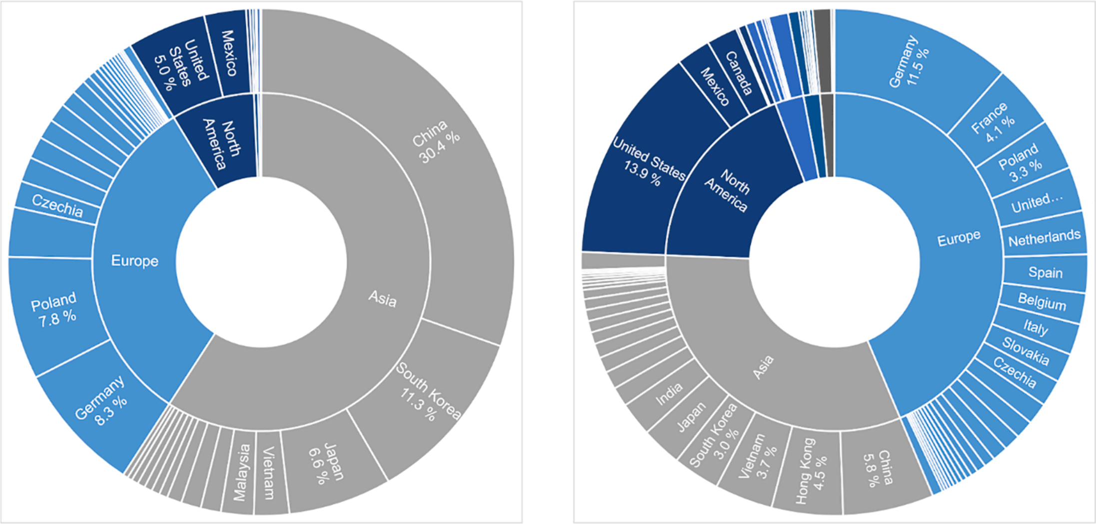
Moreover, it is not only the number of jobs that must be considered but the different skillsets needed in an electrified powertrain industry and the locations where these skills will be needed. Among the findings of Günther et al. [84] when evaluating the effects of fleet electrification mainly in China and Germany, there is a positive trend in job results from a whole location perspective [84]. However, the majority of jobs would be created in Eastern Europe (+3.9 million) against a + 0.1 million in China, which can be considered unsatisfactory figures due to the country's population size and demand for labor [84]. According to the IEA, the development of more sustainable battery supply chains alone could create + 10 million jobs worldwide [47]. However, Onat et al. [85] underscored that, even though EVs can create more green jobs, ICE and hybrid vehicles have the largest long-term employment potential, as they demand labor force in the petroleum and fossil fuel distribution industries. This is also highlighted by Di Felice et al. [82], who, after comparing different employment projections, stated that less labor and more energy seem to be required in the electric powertrain industry.

Nevertheless, a growing demand for EVs does not impact jobs alone. In the same way that the fossil-fuel industry brings health risks to society (e.g., it is estimated that fossil-fuel-related emissions are responsible for about 65 % of the excess mortality rate related to air pollution [86]), EVs



(a) Exporters of vehicles with only electric motor for propulsion

(b) Importers of vehicles with only electric motor for propulsion



(c) Exporters of electric batteries

(d) Importers of electric batteries

Fig. 3. Trade values by country as a percentage of total. .
Adapted from [90]

and Li-ion batteries manufacturing can also affect populations' health and must receive governments' attention [13]. As a still-evolving technology, only recently is that the health hazards of Li-ion batteries started to be assessed, e.g., Sironval et al. [87] on the respiratory hazard of Li-ion batteries particles. In China, Shen et al. [88] analyzed the presence of heavy metals, including cobalt, on individuals from local communities in the Chinese battery industrial capital and identified dust as the main vector, being young children the most affected ones. Concerning environmental impacts, EVs manufacturing has been linked to higher GHG emissions than the fossil-fuel counterpart, but again, this is subject to the country's electricity mix and the efficiency of industrial processes [80]. In this vein, Xiong et al. [89] evaluated the lifecycle of EVs based on China's energy mix, and concluded that vehicle body and battery manufacturing account for the largest amount of energy consumption and GHG emissions.

4.4. *Potential consequences of EVs ownership*

As the EVs and electric batteries exports-imports trade values show in Fig. 3, EVs and battery trades are highly concentrated in Europe, Asia, and North America, highlighting a distributional injustice. Moreover, apart from China and South Korea, only few countries in the Global South are among the largest importers and exporters of EVs and electric batteries. For EVs importation and exportation, Europe dominates the market, whereas for batteries, Asia figures as the largest exporter with China holding an expressive 30 % share of total trade values [90]. The five largest importers of battery-powered EVs are Germany (13.5 %), UK (13.1 %), Norway (9.4 %), France (7.5 %), and Netherlands (7.5 %) [90]. On the other hand, main exporters are Germany (24.4 %), US (15.8 %), South Korea (11.6 %), Belgium (11.2 %), and France (5.8 %) [90]. For battery imports, these are the trade value shares amongst continents: Europe (43.7 %), Asia (32.0 %), North America (18.7 %), Africa (2.8 %), South America (1.6 %), and Oceania (1.4 %) [90]. Even though it can be perceived a more distributed demand for batteries across countries, imports in Asian countries are most likely linked to an internal market. Conversely, the five largest exporters of electric batteries are China (30.4 %), South Korea (11.3 %), Germany (8.3 %), Poland (7.7 %), and Japan (6.6 %) [90].

Summed to these evident geographical disparities, EVs also highlight socio-economic imbalances as their purchase is limited to consumers of higher social classes due to high upfront costs [66], which has been referred to as the 'elitism of EVs' [41]. The current high purchase price is due mainly to battery costs [91]. However, Liu et al. [91] highlighted that, compared to some ICE models, the initial cost of EVs can be recovered in five years after purchase. Yet, authors advised that the economic advantages of powertrains vary according to geographic specificities due to electricity prices and matrix [91]. Moreover, the operation and distribution of EVs directly affect jobs related to vehicles' maintenance and fuelling. Furthermore, despite EVs job creation potential, created jobs are "*often in different locations, skill sets, and sectors than the jobs that will be lost as fossil fuel decline*" [10]. Around the 5 million jobs that could be lost by 2030, many are well paid and in the proximities of fossil fuel resources, "*meaning structural changes can cause shocks for communities with impacts that persist over time*", [10].

Besides distributional inequalities and job losses due to EVs distribution and operation, the substitution of ICE vehicles may pour millions of environmentally non-regulated second-hand vehicles into developing and less developed countries [92]. According to the UN Environment Programme, the three largest exporters of used vehicles are the European Union (EU), Japan, and the US, with 54 %, 27 %, and 18 % of the 14 million used light-duty vehicles exported between 2015 and 2018, respectively [92]. About 70 % of exported vehicles go to developing countries, which in the majority have limited or no regulations on safety and emissions standards of imported vehicles [92]. In Africa, for example, used vehicles comprise 85 % of the fleet, and most African countries do not have used vehicle standards or age restrictions in place [93]. For instance, Doumbia et al. [94] evaluated the fleet composition in Abidjan, Côte d'Ivoire during a field study and identified that more than 60 % of personal cars are older than 10 years, with 6 % surpassing 30 years on the road. In opposition to newer vehicles holders of higher Euro standards, older cars in the fleet have been linked to worse air quality [95]. Betancourt et al. [96], when evaluating the exposure to air pollution from urban buses in Bogotá, Colombia, identified that "*average exposure levels inside Euro II and Euro III (older buses) was twice as large as those measure inside vehicles with stricter emission standards, Euro IV or superior*". In their study, the authors considered concentrations of fine aerosol particles, equivalent black carbon, and carbon monoxide, concluding that a fleet renewal would significantly reduce population exposure to them [96].

Furthermore, EVs have been linked to the rural–urban divide during their operation due to range constraints and lack of infrastructure to recharge vehicles, which may exclude distant communities, contributing to the urban–rural divide [32]. There is also a concern about the marginalization of other forms of mobility such as cycling and public transport, due to the predominance of battery-powered private cars [41]. Additionally, in countries with fossil fuel-based electricity mixes (e.g., China and India), the utilization of EVs causes emissions to be offset from tailpipe to power plants [82]. Dillman et al. [97] evaluated the GHG intensities of electric grids across the European Economic Area and concluded that for some countries, "*EVs could lead to greater life-cycle GHG emissions than a comparable diesel counterpart*" [97]. On the other hand, according to Moro and Lonza [98], the use of EVs instead of gasoline-fueled in EU member states can avoid, on average, 60 % of GHG emissions. However, this reduction may not be evenly distributed across countries since, if a Well-to-Wheel methodology that considers the carbon intensity of the electricity sector as well as electricity imports-exports is employed, GHG emissions might increase [98]. This emphasizes the need for holistic and cross-sectoral approaches that connect energy supply to transport, industrial, and residential sectors, increase the share of renewable energy in electricity matrices [91], and develop smart grids [99]. Such holistic approaches can also avoid negative effects on electricity prices due to increased peak-load [100] since electrifying end sectors increases the electricity demand and grid flexibility requirements.

In this regard, vehicle-to-grid (V2G) technologies arise as options that allow a bidirectional flow of electricity from EVs to smart grids [99]. V2G can provide unused energy back to the grid during high peak demand periods [99], for instance. In a study in Portugal, Nunes and Brito [101] showed that even a small share of EVs for load balancing can positively affect grid flexibility as a means to reduce natural gas usage and energy excess. Accordingly, Zhou et al. [102] focused on building energy management systems and numerically modeled the contribution of EVs and batteries to balance peak and off-peak periods, identifying a positive contribution.

4.5. *Used batteries: trouble-maker or proponent of a regulated circular economy?*

Spent Li-ion batteries are considered hazardous due to their content of heavy metals and have four main disposal routes: recycling, landfilling, illegal disposal, and informal processing [103]. If not disposed properly, batteries can contaminate water, soil, and air through a series of pollution routes such as leaching and dissolution [103]. Generated pollution can bring harm to the environment and human health, accumulate in soils, plants and crops, being battery toxicity harmful to various trophic levels [103]. Accordingly, Sovacool et al. [20] pointed out that informal processing and inappropriate disposal of Li-ion batteries are likely to expose workers and local communities to hazardous materials. Given the hazardous nature of Li-ion batteries, fire accidents at recycling stations, transport vehicles, and landfills have been reported in connection to used Li-ion batteries, for instance [104]. These fire accidents have impacted the waste facilities and surrounding communities through injuries, service disruptions, and monetary losses [104].

Nevertheless, recycling and reusing activities can go beyond environmental and health aspects and can create millions of jobs thanks to the "*job-intensive nature of the logistics and industrial facilities needed to realize domestic recycling*" [47]. Nevertheless, for this industry to grow, recycling processes have to be further developed to avoid inefficient recycling processes and waste generation [19]. According to Qiao et al. [61], in a study evaluating the economic and environmental benefits of EV recycling in China, the total potential reduction of energy consumption and GHG emissions per technology cost is 241.3 MJ/US$ and 36.3 kg CO2eq/US$, respectively. Nonetheless, the reduction from recycling vehicles without batteries is larger than the reduction achieved with battery recycling, as the latter process is not completely developed and subject to large efficiency improvements [61]. To reduce the loss of circularity and take advantage of the opportunities that accompany battery recycling, laws and standards that enforce responsible and safe disposal of low-carbon technologies and promote sustainable supply chains must be in place, which is not the case for most developing and less developed countries [47]. The European Commission has recently taken action towards establishing rules for battery design, production, and disposal as means to enforce environmental and social sustainability [105]. However, there is no universal standard battery recycling [103], even though lithium and cobalt, in particular, can significantly contribute to the UN SDGs and a circular economy agenda [65].

According to what has been presented in this section (Section 4), Table 1 summarizes EVs lifecycle stages (LCS), associated activities, most representative countries where these activities take place, and potential injustices.

Table 1
Most representative countries and potential injustices of EVs lifecycle activities.

LCS	Activity	Most representative countries	Potential injustices
Resource extraction and processing	Lithium mining and processing	Chile, Australia, China, and Argentina [1]	Knowledge asymmetry among stakeholders [71]; forced delocalization of natives [69,71]; conflicts between mining companies and indigenous people [69]; depletion of water resources [67,71]; local pollution and health issues [67]; local biodiversity concerns [73];
	Cobalt mining and processing	Democratic Republic of Congo (DRC) [2]	Local pollution and health issues [18]; terrible work conditions [18]; child labor [20]; conflicts between small and large-scale miners [18]; corruption and malfeasance [18]; exploitation and unfair market practices [18]; forced delocalization of natives [18]; monopolistic hold of cobalt processing [78];
Manufacturing	Battery components manufacturing	China, Japan, and South Korea[3]	Low-wage factory workers (e.g., China) [81]; construction of gigafactories [57] and conflicts with local communities [83]; job losses in the automotive manufacturing industry [82]; health hazards [88];
	Battery cell manufacturing	China, US, Europe[4], South Korea, and Japan [57]	
	EVs manufacturing and assembly	China, US, Japan, Germany, France, and the UK [57]	
Distribution and Operation	Sales and Distribution	Main importers vs Main exporters[5]	Job losses in the fossil fuel industry [41]; EVs purchased by consumers with high socioeconomic conditions [41]; distributional inequality across countries due to uneven uptake [33,90]; price of EVs [66]; second-hand ICE markets [92];
	Re-charging and Operation	China, Europe, and the US [6]	Urban-rural divide [32]; marginalization of other forms of mobility [41]; job losses in the fossil fuel industry [10]; offset of emissions from tailpipe to power plants [82]; North-South divide [20]; adverse effects on electricity price due to increased peak-load [100];
End of life		Worldwide[7]	Spent Li-ion batteries have been linked to

(continued on next page)

5. The linkage between EVs lifecycle and EJ tenets

As one of the aims of this paper is the framing of injustices according to the energy justice tenets, this section brings, for the first time in the literature, the linkages between EVs lifecycle activities and distributional, flexibility, procedural, recognition-based, cosmopolitan, and restorative justices. By combining the energy justice topic with the EV technology, we intend to shed light on the most critical downsides of the road transport electrification, which are spread across EVs lifecycles, and provide policymakers and researchers with targets for action to counteract the identified downsides and strive for mitigating injustices.

5.1. *Distributional and flexibility justices*

The concept of distributional justice is especially relevant when investigating globalized supply chains to ensure that benefits and ills are evenly distributed. As it can be linked to both physical (environmental) and social burdens, distributional injustices are present in all EVs lifecycle stages. For lithium and cobalt extraction, burdens are borne by a small number of countries. The extraction of lithium from brines in the Lithium Triangle, i.e., Chile, Bolivia, and Argentina, has been linked to the regional depletion of water resources and local biodiversity concerns [72]. In contrast, cobalt extraction from the DRC has been linked to local pollution and health issues [18]. Cobalt and lithium processing are concentrated in China [56], and trade values indicate that economic gains through value-adding manufacturing activities in the EV lifecycle are contained in large economies in Asia, Europe, and North America [90]. The Chinese hold on lithium and cobalt processing activities gives it an almost monopolistic power over Li-ion batteries supply chain [78]. However, battery manufacturing has been linked to negative effects on local populations health in China [88]. Moreover, the construction of gigafactories in Europe, in an attempt to localize manufacturing activities in the continent, raised concerns over local water, land, and energy use [83]. Given the location of lifecycle activities with the most injustices, we can say that EVs contribute to the North-South divide. On

Table 1 (*continued*)

LCS	Activity	Most representative countries	Potential injustices
	Waste and re-use of batteries (Second life)		pollution and health hazards [103], accidents and injuries [104], informal recycling and inappropriate disposal to environmental and health issues [20]; inefficient recycling processes and waste generation to resource depletion and loss of circularity [19];
	Recycling of batteries	China (>60 %) and South Korea [57]	

[1] Countries with a lithium mine production of over 5 million tons in 2020 [52]. [2] DRC is responsible for 70 % of global cobalt production in 2020 [52]. [3] China, Japan, and South Korea are home to a significant share of Li-ion batteries components manufacturing capacity: cathodes (85 % of global capacity), anodes (97 %), separators (84 %), and electrolytes (64 %) [106]. [4] Battery-cell manufacturing in Europe is concentrated mainly in the United Kingdom, France, and Germany [57]. [5] Main importers: Germany, UK, Norway, France, Netherlands, and Main exporters: Germany, US, South Korea, Belgium, France [90]. [6] EV stock in 2019: China 3.3 million, Europe 1.8 million, and the US 1.5 million [33]. [7] Battery second life projects: Germany, US, France, UK, Netherlands, Japan [66].

the discussion over job creation and losses, even though some works point to an overall positive net employment, there will be a possible mismatch between created jobs and the skills and the location of available workforce [82], which highlights a both positive and negative effect of EVs on employment.

Likewise, benefits due to emissions and air pollution reduction, which are expected in EVs' operational phase, are likely to materialize in urban environments in a selected number of countries in the Global North, depending on countries' electricity matrices [98]. China, for instance, even though concentrating the largest number of EVs, has seen an increase in emissions from the transport sector as 65 % of its electricity was generated from coal in 2019 [53]. This offset of emissions from tailpipes to powerplants [107] stresses the importance of integrating renewable energy into energy mixes and having flexible demand strategies. Nevertheless, there is a clear advantage when offsetting tailpipe emissions from power stations since it is simpler to manage and reduce emissions from a few sources than from countless ICE vehicles on the road [108]. Besides, an asymmetrical EV uptake across continents has consequences for the market of used ICE vehicles, commonly directed to developing countries in Africa and South America and linked to air pollution and safety, energy efficiency, and operational costs issues [92]. On the other hand, a second-hand EV market can help less developed countries accelerate their fleet electrification if electric cars reach domestic markets with accessible purchasing prices [92] since another aspect that contributes to the distributional injustice of EV technology is its high upfront costs, which limits its acquisition to wealthier socio-economic groups. Nevertheless, costs are expected to considerably fall with technological development [109].

Lastly, good management of used EVs at the end-of-life stage can help establish sustainable supply chains through reuse and recycling loops of batteries. This is a determinant aspect of Li-ion batteries impact so they do not end up in common landfills or are dismantled by workers under unsafe and unhealthy conditions, affecting local health and biodiversity, as already reported in the literature [20]. Batteries' recycling is currently dominated by Asia and is subject to efficiency improvements before it becomes financially and environmentally attractive [61]. Flexible production and waste management processes are also linked to a flexible energy transition [43] in conjunction with reusing batteries for energy storage systems. The flexibility justice tenet relates to EVs thanks to sector coupling and its effect on energy demand and storage.

Concerning costs for re-charging at the operational phase, appropriate market pricing mechanisms and strategic charging can help avoid large-scale EVs charging at times of peak demand, which would impact grid stability and energy price. Higher electricity prices have been linked to energy poverty issues as raising prices inflict an extra burden on a household that do not have large disposable incomes [110]. V2G technologies can also help reduce costs of infrastructure changes [111] and contribute to a flexible energy transition by balancing variable energy supply from RES and demand [43]. V2G services depend on several technical aspects, but it could "*unlock up to 600 GW of flexible capacity distributed across the main electric vehicle markets in 2030 and moderate intermittency of variable renewables during peak demand*" [47]. Fig. 4 represents the main aspects to be considered concerning distributional justice and flexibility justice according to the lifecycle stages together with a positive (+), negative (-), or combined sign (-+) indicating the potential effect of EVs. As it can be seen, distributional injustices, which indicate a potential negative effect of EVs and offer opposition to a JET, are fairly distributed across lifecycle stages. On the other hand, EVs seem to have the potential to positively affect flexibility justice mostly during the distribution and operation phase. Accordingly, Li-ion batteries recycling and reuse rate will dictate whether the technology contributes to or opposes a JET concerning natural resources usage at resource extraction and waste and disposal lifecycle stages.

5.2. *Procedural and recognition justices*

Knowledge asymmetry and stakeholder conflicts are particularly relevant for justice issues at the resource extraction and processing stage. Increasing demand has advanced mining activities toward more remote and unmined regions, which happen to overlap or be in the proximities of global protected areas in some cases [70], as in the Lithium Triangle [71]. Even though Chile ratified the ILO Indigenous and Tribal Peoples Conventions in 2008, internal factors and governmental policies have limited the participation of indigenous people in decision-making processes about land requirements and water use, once their participation can harm the mining industry interests and intensify conflicts between indigenous people and the mining industry [69]. This is associated with the injustices presented in the previous section related to the forced delocalization of native people and the abandonment of ancestral settlements due to water scarcity as the mining industry requires large amounts of water to operate in one of the driest regions in the world [67,71]. As ensuring lithium supply becomes one of the priorities of carmakers, countries want to become independent in both sourcing and manufacturing EV technology. However, this rush to extract more lithium can lead to more conflicts, environmental degradation, and disregard for local communities' interests. Even at the European level, conflicts about the potential expansion of lithium exploitation activities are emerging, as mentioned in the previous section for the case of Portugal, where mining locations pose challenges to local communities' wellbeing and functioning [76]. Concerning cobalt mining, besides critical environmental and human health issues [68], mining activities have been associated with the displacement of indigenous communities, corruption, malfeasance, political oppression, and conflicts in the DRC [18]. Moreover, the construction of gigafactories for battery manufacturing may also generate conflicts with local communities and produce procedural injustices [83]. And not only gigafactories, but industrial practices that negatively affect the health and safety of surrounding populations often lack the participatory processes and decision-making that should be in place concerning people's interests. Fig. 5 summarizes the linkages between EVs lifecycle stages and procedural and recognition justices. As it can be seen, activities at resource extraction and processing and manufacturing stages have been

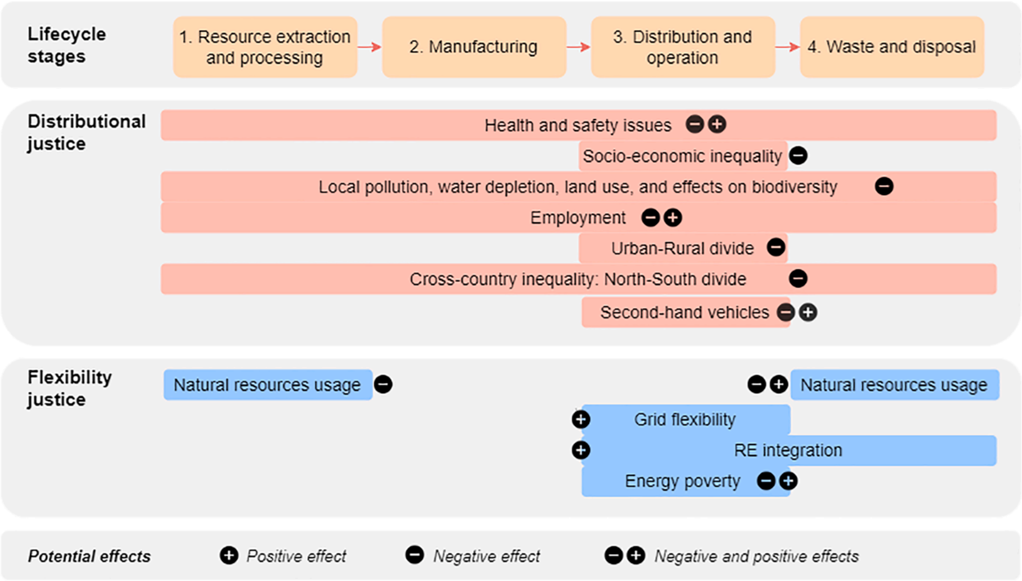


Fig. 4. Distributional and flexibility justices: Potential effects of EVs.

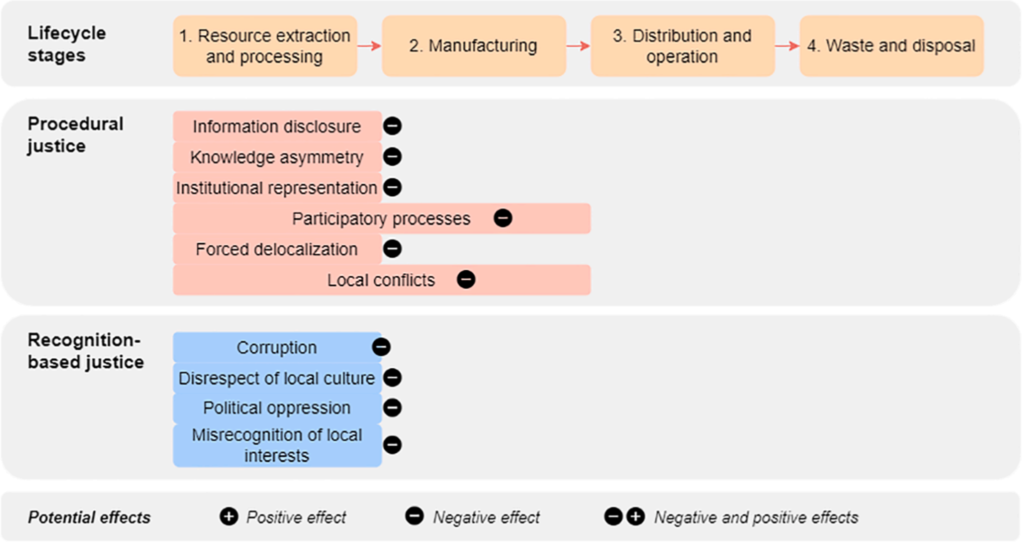


Fig. 5. Procedural and recognition-based justices: Potential effects of EVs.

offering opposition to establishing a JET.

5.3. *Cosmopolitan and restorative justices*

Concerning cosmopolitan justice, EVs have been related to the consumption of finite mineral resources [9], toxicity increase [48], water scarcity [76], and a shift from tailpipe to power plant emissions in cases where electricity supply is heavily dependent on fossil fuels [85]. These issues inflict a burden on the environment as a whole and have intra and intergenerational consequences through GHG emissions, natural resource depletion, and climate change. In case EVs fail to reduce overall GHG emissions, this technological choice will not help the world stay below the 1.5 °C global average temperature threshold, which will bring serious and damaging effects to the current and future generations. These aspects must compel us to act as global citizens towards building and inclusive and resource efficient future [112], in the same way they prompt interlinked and holistic sustainability assessments for intergenerational ‘strong sustainability’ [113]. In circumstances in which social and environmental damage is unavoidable, such as mining activities, restorative justice must compel companies to take responsibility for optimizing processes as much as possible, maintaining sustainable practices, and compensating the most impacted people by improving local working conditions, respecting local cultures and interests, as well as access to essential services in order to avoid ‘green colonialism’ practices [114]. This is clearly not the case in many mining sites around the world, where the environment is not appropriately restored and surrounding communities are not given the means to thrive after the end of mining activities (e.g., Annandale et al. [115] on the impacts of mining on Indigenous livelihood and the importance of pre- and post-mining management).

Restorative justice may also imply establishing specific laws and standards according to the activities developed in each region, such as mandatory recollection of used batteries by manufacturers through reverse logistics to avoid dumping in inappropriate fields [47]. These laws and standards are expected to establish socially and environmentally sustainable supply chains, as referred to in EU regulations over batteries sourcing and recycling [105]. Therefore, restorative justice obliges companies to take moral and financial responsibility for their operations when they negatively impact society, as well as biding to laws and standards, restoring the environment in cases of degradation, decurrent pollution, and accidents, and social compensation through the improvement of essential local services and job opportunities, for instance.

Fig. 6 encapsulates the aforementioned relationships. Within restorative justice, negative effects on social compensation and environmental restoration are contained to the resource extraction and processing stage, while we attribute to laws and standards a potentially positive effect on the sustainability of the entire EVs supply chain. Nevertheless, similar to V2G technologies, this potential positive effect is yet to materialize. As expected, aspects linked to cosmopolitan justice are evenly spread across lifecycle stages. Particularly, pollution and effects on biodiversity receive a potential positive effect in addition to the negative as, in the long term, the substitution of ICE vehicles by EVs can reduce the carbon dioxide concentration in the atmosphere and, therefore, climate change effects.

6. Conclusion

A whole systems perspective over low-carbon technologies can contribute to a JET since, by analyzing what activities are performed in each lifecycle stage, where they take place, and which communities are affected, injustices can be identified and further addressed. However, there can be no one-size-fits-all solution, given each country's different challenges. Decarbonizing the transport sector is essential for reducing GHG emissions, and EVs are undoubtedly playing a key role in this process. However, our exploratory review shows that efforts must be directed toward reducing injustices that are spread across lifecycle stages and countries. Among the most critical aspects of this work, we highlight the distributional injustices caused by: (i) the disregard of social and environmental aspects in lithium and cobalt mining activities, (ii) work, emissions, and health-related issues during manufacturing stages, (iii) the concentration of value-adding activities in China and developed countries which can potentially widen cross-country and continent inequality, (iv) EVs infrastructure and charging requirements that can exclude rural communities, (v) EVs price which sustain the technology's elitism [41] (vi) the market of used ICE vehicles which can transfer emissions and health issues associated with ageing and less efficient fleet mostly to developing and less developed countries in South America and Africa, and (vii) the lack of recycling and reusing activities at waste and disposal waste of Li-ion batteries and its associated health and environmental hazards. Also, the extension of flexibility justice to EVs shows the relevance V2G technologies can have in ensuring a more reliable and flexible energy system. The effects of EVs on this EJ tenet are mostly contained to the distribution and operational stage due to energy-transport coupling. Also, considering that a flexible energy system would also imply compliant resource management practices, EVs can positively or negatively contribute to a reduction in resource usage depending on recycling and reuse rates. Conversely, EVs can burden electric grids due to high peak demand and poor households in case demand and supply are ill-coordinated. This may cause electricity prices to go up, restricting the fight against energy poverty and the achievement of SDG7.

The framing of injustices according to procedural and recognition-based tenets showed that the most critical stage for attaining a JET from this side is the resource extraction and processing lifecycle stage. Our review showed that lithium and cobalt extraction impacts on surrounding communities are commonly neglected, causing local conflicts, and the forced delocation of native people. Moreover, activities in the DRC have been linked to corruption and unethical work aspects [20]. In the manufacturing phase, injustices may also appear within industries and their vicinities as participatory decision-making is also missing. For sustainable and ethical supply chains, adequate international laws and standards are critical. These standards are directly connected to companies legal obligation to restore the environment and the communities affected by their activities. These are key aspects of restorative justice, which are currently and mostly required at the resource extraction stage. Lastly, the use of finite resources, global emissions, and climate change put a lot of pressure on EV-technology development and uptake as the ultimate goal of EVs is to reduce transport emissions and fossil fuel dependency. However, even though EV-related GHG emissions reductions can be contradictory in the literature, especially when a lifecycle perspective is employed, low-emission electricity matrices, technological development, and flexible energy systems can provide the technology with the means to fulfil its purpose. Concerning resource usage, EVs' positive or negative effects continue to depend on the enhancement of recycling processes, their regulation and distribution across countries, as well as the development of energy storage technologies.

Therefore, in relation to whether EVs contribute to or oppose a JET, our exploratory review shows that it depends. From one side, EVs have a great potential to reduce GHG emissions, create jobs in the electric powertrain and recycling industries, enhance energy systems flexibility, improve health in urban environments, and reduce energy and resource consumption. On the other hand, they can increase socio-economic inequalities across countries, perpetuate stories of green colonialism, stretch gaps between socioeconomic classes, add a load to natural resources extraction, negatively affect health and biodiversity through air,

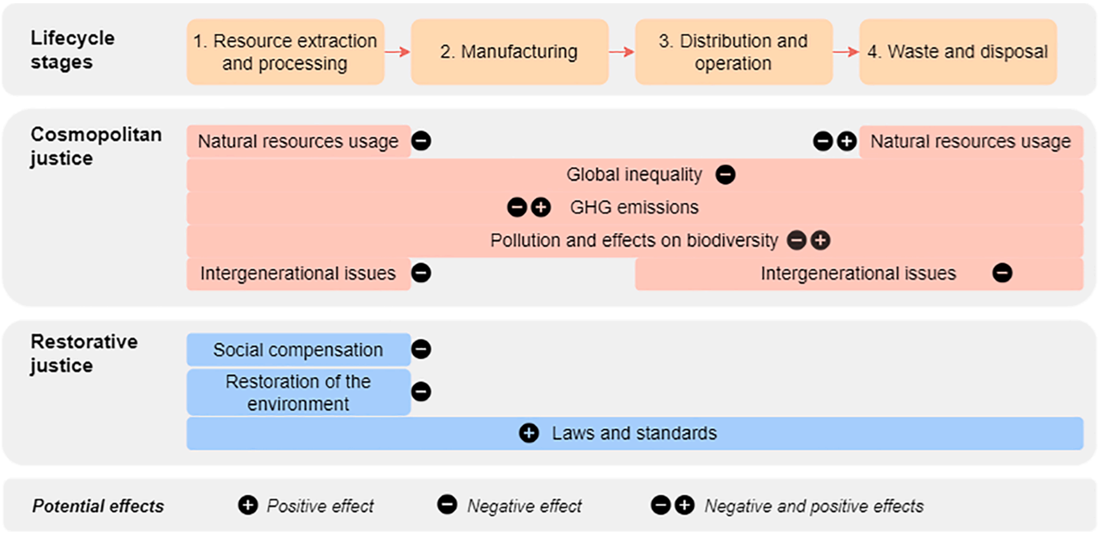


Fig. 6. Cosmopolitan and restorative justices: Potential effects of EVs.

water, and soil pollution, and even increase GHG emissions across the whole lifecycle if renewable energy integration does not happen in tandem with EVs uptake. Nevertheless, even though we do not discuss the injustices associated with fossil fuel chains and ICE vehicles, we acknoledge they are many and widespread. As EVs are an essential part of transport decarbonization plans, they should have its most critical environmental and social aspects identified and addressed. Since low-carbon technologies are not essentially just or inclusive, as our analysis of EVs shows, action must be taken to reduce inequalities and unintended negative impacts.

Among the limitations of this work, we could cite the exploratory nature of the review and the lack of quantitative analysis to support justice claims for the case of EVs. The extent to which these findings have wider relevance should be further evaluated. Moreover, our assessment of EVs lifecycle and associated injustices at resource extraction and waste and disposal was limited to Li-ion batteries, which makes us recognize the scope limitations of this work. Accordingly, this work was also limited to energy storage technologies employing lithium and cobalt. However, as a rapidly evolving technology, battery chemistry can reach a point where neither of these raw materials is required [11].

Given the interdisciplinarity of this work, we have future research recommendations that include technical and social aspects. In technical terms, as already highlighted by many works (e.g., [46,116]), it is necessary to keep working on (i) the development of batteries that use less critical raw materials, e.g., cobalt and lithium, without impairing EVs performance; (ii) the improvement, regulation, and dissemination of battery recycling processes; (iii) research on battery re-use and development of pilot projects and (iv) grid stability and flexibility and the effects of large-scale EV charging on electric grid and price. Additionally, the appropriateness of EVs and other modes of transport in specific contexts and regions, following advances made in other transport-related technologies (e.g., biofuels [117]) must be analyzed. Ergo, research on the impact of policies on emissions, socioeconomic aspects, and alternative fuel vehicles' uptake is critical [118]. On the social side, we recognize the relevance of (v) research on social innovations and new business models for overcoming socio-economic barriers imposed by EVs upfront and infrastructural costs and associated distributional inequalities. Likewise, (vi) research and funding towards ensuring access to clean and affordable energy for all, as proposed by SDG7, can reduce wealth inequalities and, in the long run, contribute to EVs uptake. (vii) As car manufacturers rush toward ensuring supply, the impacts of localized supply chains on environmental, social, and market dynamics both at international and national, must be further explored. (viii) Lastly, research on justice aspects of low-carbon technologies that employ methods to quantify aspects related to technologies' justice can substantially contribute to a JET by providing ways of measuring progress.

CRediT authorship contribution statement

Alaize Dall-Orsoletta: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Paula Ferreira:** Conceptualization, Supervision, Visualization, Writing – review & editing. **Géremi Gilson Dranka:** Conceptualization, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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